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ICEPT 2025

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EXECUTIVE SUMMARY

During the 21ST International Conference and Exhibition on Power and Telecommunications, ICEPT, held in Osogbo in October 2025 with the theme "**Digital Infrastructure and Innovation for Inclusive Economic Growth"**, 37 abstracts were accepted and 28 technical papers were presented while 25 papers went through the full peer review process. The organizer of 21st ICEPT, the Nigerian Institute of Electrical and Electronic Engineers, NIEEE presents here a compendium of the peer reviewed technical papers presented.

Experts in the field of Electrical/Electronic Engineering, including industry, government (policy), academia etc. and in the presence of non-engineers and students, presented technical papers in fields pre-identified by the NIEEE. These areas included electronics, digital signal processing and biomedical engineering; electrical machines, power systems and control; computing engineering, information and communications technologies; artificial intelligence and communications engineering as well as renewable energy. The conference intended to rally all stakeholders in a way that digital infrastructure and innovation will accord more attention to making more technology-driven policies, enhancing research and development in the areas of emerging technologies and encouraging government-to-business (G2B), business-to-citizen (B2C), and government-to-citizen (G2C) paradigms to deploy more of the emerging technologies for inclusive economic growth. The NIEEE believes that these actions will improve national development, fight poverty, improve the economy and enhance better security among Nigerians.

The technical papers have been taken thorough peer reviews, conference presentations and are presented here for knowledge sharing.

I hope that you will find them useful and be able to apply them into solving technical problems.

Thank you.

Engr. Felix O. Olu, FNIEEE

President, The NIEEE

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Design and Implementation of Cloud Based Smart Waste Bin Management System Using Internet of Things Low Power Wide Area Network

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Abstract: This study presents a cloud-based smart waste management system using IoT and LoRa technology. The system integrates an ESP32 microcontroller, ultrasonic and load cell sensors, and a LoRa SX1278 module to monitor waste levels in real time. Data are transmitted via LoRa to a cloud gateway, enabling visualization and immediate alerts for users and administrators. The system addresses inefficiencies in traditional waste collection, reduces operational costs, and mitigates environmental hazards from overflowing bins. Comparative analysis underscores LoRa's advantages in long-range coverage, low power consumption, and scalability over GSM and Wi-Fi. By combining the ESP32 with energy-efficient sensors, cloud platforms, and predictive monitoring, the system provides a reliable, sustainable, and cost-effective solution for urban waste management. This research fills gaps in large-scale intelligent smart bin deployment, contributing to smarter, environmentally conscious cities.

Keywords: *Cloud computing, ESP32, IoT, LoRa, Smart waste management, Sustainability*

1. INTRODUCTION

Rapid urbanization and population growth have significantly intensified the challenges of urban waste management. Conventional waste collection systems are often inefficient and reactive, resulting in overflowing bins, poor sanitation, and negative impacts on urban health [1], while also contributing to environmental degradation and increased greenhouse gas emissions due to irregular collection schedules and lack of automation. [2]

The Internet of Things (IoT) has emerged as an effective solution for sustainable waste management. IoT refers to a network of interconnected devices that can sense, collect, and exchange data over the internet without human intervention. Smart bins equipped with sensors enable real-time monitoring of waste levels, automated alerts, predictive analytics, and route optimization, thereby improving operational efficiency and reducing operational costs [3]. These systems also enhance service delivery and support smart city initiatives by promoting cleaner environments and better citizen engagement [4].

Various communication protocols have been explored for IoT-enabled waste monitoring, each with specific strengths and drawbacks. GSM and Wi-Fi offer high-speed data transfer but are constrained by high power consumption and limited coverage [5]. ZigBee is energy-efficient and supports mesh networking, yet its short range makes it less suitable for wide-area deployments [5]. To address these challenges, Low-Power Wide-Area Networks (LPWAN) such as LoRa (Long Range) and Sigfox have emerged, offering long-range, low-power communication with strong urban penetration and scalability making them highly suitable for smart city waste management applications [6].

Cloud integration further enhances these systems by enabling centralized data visualization, analytics, and remote control. Cloud computing refers to the delivery of computing services including servers, storage, databases, networking, software, and analytics over the internet, providing scalability and accessibility [7]. In smart waste management, cloud platforms allow seamless integration of sensor data with web and mobile applications, enabling timely alerts and decision-making. They also support advanced features such as predictive analytics and machine learning for optimizing waste collection routes and resource allocation.

Despite these advances, several gaps remain in current smart waste management systems. Many implementations still face limitations in battery efficiency, sensor optimization, scalability, and seamless cloud integration. This study addresses these gaps by designing a cloud-based smart bin system using LoRa SX1278 modules and ESP32 microcontrollers to deliver a scalable, energy-efficient, and sustainable solution for urban waste management.

2. LITERATURE REVIEW

Ali *et al.* [1] proposed an IoT-based smart waste bin monitoring system for smart cities, emphasizing real-time tracking of bin status and integration with municipal solid waste management. While their approach improved scheduling efficiency, it relied heavily on GSM connectivity, which imposed higher energy consumption and recurring operational costs.

Al-Maadeed *et al.* [2] presented a systematic review of IoT-enabled waste management systems. Their findings highlighted scalability challenges, sensor calibration issues, and limited cloud integration in most existing prototypes, underscoring the need for more energy-efficient and scalable designs.

Arora and Chauhan [3] designed and evaluated a LoRa-enabled smart waste collection framework. Their experimental results demonstrated the superiority of LoRa over short-range protocols, but the work primarily focused on communication range and did not address long-term battery performance.

Azmi *et al.* [4] further validated LoRa’s suitability for waste monitoring through prototype testing in outdoor environments. However, their study did not provide detailed analysis of environmental sensing accuracy or robustness of the smart bin hardware under varying conditions.

Al-Sarawi *et al.* [5] reviewed communication protocols for IoT applications, showing that GSM and Wi-Fi offer high throughput but suffer from high power demands, whereas ZigBee provides low power consumption but lacks the required coverage for large-scale deployments. This comparison reinforces the importance of LPWAN technologies such as LoRa for sustainable waste management.

Baldo *et al.* [6] proposed a multi-layer LoRaWAN infrastructure for smart waste systems, focusing on network scalability and robustness. Their study highlighted how hierarchical LoRaWAN networks can reduce congestion but did not provide detailed results on hardware-level performance.

Finally, Catarinucci *et al.* [7] presented an IoT-aware waste management framework leveraging ultra-low power RFID tags and cloud services. Although effective in reducing energy demand, the approach suffered from limited communication range, restricting its applicability for wide-area smart city deployments.

In summary, existing literature demonstrates the growing role of IoT and LPWAN in addressing urban waste management challenges. However, gaps remain in achieving reliable sensor integration, energy autonomy, and seamless cloud-based visualization. This study builds upon prior work by designing and implementing a LoRa-enabled smart waste bin that integrates multi-sensor data acquisition, energy-efficient operation, and real-time cloud connectivity.

3. METHODOLOGY

This section outlines the procedure used to design, implement, and evaluate a cloud-based smart waste management system integrating IoT and LoRa communication. All hardware and software components are specified, and relevant equations are provided to enable replication.

3.1 Conceptual and Operational Definitions

As presented in Table 1, the Cloud-Based Smart Bin system monitors key variables such as fill level, weight, temperature, humidity, location, and duty cycle using specific sensors and devices.

Table 1: Variable Specifications of the Smart Bin System

Variable	**Variable Metrics**		
	Definition	**Unit**	**Measurement Device**
Fill level	Volume of waste in bin	%	HC-SR04 Ultrasonic Sensor (DFRobot, China)
Weight	Mass of waste	kg	HX711 Load Cell (SparkFun, USA)
Temperature	Internal bin temperature	°C	DHT11 Sensor (Aosong, China)
Humidity	Internal bin humidity	%	DHT11 Sensor
Location	GPS coordinates of bin	Latitude/Longitude	NEO-6M GPS Module (Ublox, Switzerland)
Duty Cycle (DC)	Percentage of active operation	%	Calculated from firmware

3.2 System Architecture

As illustrated in Figure 1, the system is modular and consists of four main units:

i. **Sensor and Data Acquisition Unit** – Collects fill level, weight, temperature, humidity, and GPS data.
ii. **Transmitter Unit** – Processes data via the ESP32 microcontroller (Espressif, China) and transmits it using LoRa SX1278 (HopeRF, China).
iii. **Receiver Unit (Cloud Gateway)** – Receives LoRa packets and forwards them to the ThingSpeak cloud platform (MathWorks, USA).
iv. **Power Unit** – Li-ion batteries with voltage regulation.

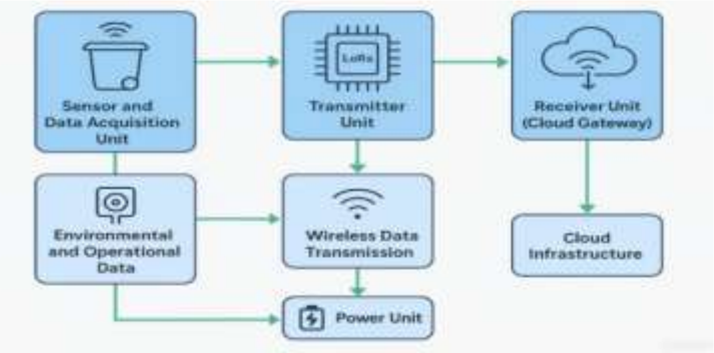

Figure 1: Cloud-Based Smart Bin System Architecture Diagram

3.3 Transmitter Unit and Power Analysis

The transmitter unit integrates multiple components to enable sensing, data processing, and wireless communication. It comprises the ESP32-WROOM-32 microcontroller, LoRa SX1278 module, HC-SR04 ultrasonic sensor, HX711 load cell with amplifier, DHT11 temperature and humidity sensor, OLED display (SSD1306, China), and NEO-6M GPS module. Power is supplied by a 7.4 V, 4000 mAh Li-ion battery (Samsung, South Korea), selected for its high energy density and reliability in embedded applications.

The average current consumption is calculated using the equation:

$$Iavg = Iactive \times (DC / 100) + Isleep \times (1 - DC / 100) \tag{1}$$

where:

$Iavg$ is the average current (A)

$Iactive$ is the active current (A)

$Isleep$ is the sleep current (A)

DC is the duty cycle (%)

As presented in Table 2, the transmitter unit demonstrates significantly higher active current consumption compared to the receiver, primarily due to the number and nature of its integrated components. This disparity directly impacts the overall power budget and battery life.

Table 2: Power Consumption Summary – Transmitter and Receiver

Unit	**Power Consumption Parameters**			
	Active Current (A)	Sleep Current (A)	Duty Cycle (%)	Average Current (A)
Transmitter	0.150	0.00005	10	0.015005
Receiver	0.040	0.00002	10	0.004002

As presented in Figure 2, the graphical comparison of current consumption and duty cycles between the transmitter and receiver units highlights the transmitter's dominant contribution to average current draw. This visualization reinforces the importance of optimizing transmission intervals and sleep states to extend operational longevity.

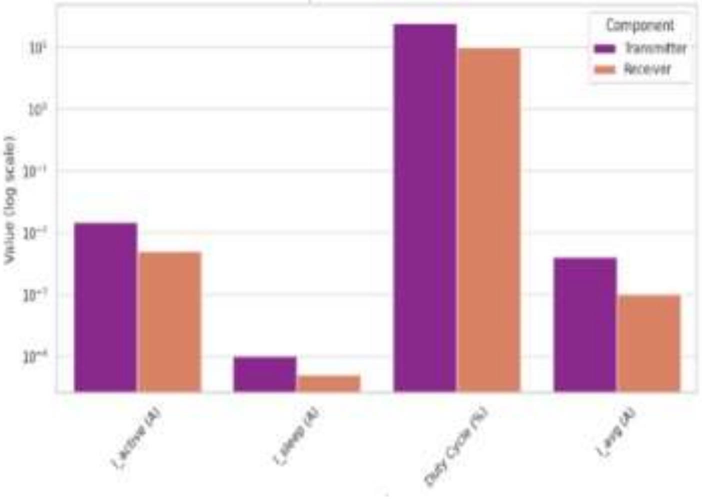

Figure 2: Power Consumption Comparison

3.4 Receiver Unit

The receiver comprises ESP32-WROOM-32 and LoRa SX1278, powered by a 3.7 V, 2000 mAh Li-ion battery (Samsung, South Korea). Average current is computed similarly using equation (1), including 1 mA regulator loss, as detailed in Table 2 and illustrated in Figure 2**.**

3.5 Hardware Design

The smart waste bin prototype was developed using a 50 L high-density plastic bin. Sensors were strategically mounted to ensure accurate monitoring and efficient performance. The ultrasonic sensor was positioned at the lid for vertical fill-level measurement, while the load cell was integrated at the base to estimate the weight of accumulated waste. An infrared (IR) sensor was placed near the bin opening to detect object placement and prevent false triggers. The DHT11 module was installed inside the bin enclosure to monitor temperature and humidity, providing environmental context for waste conditions. A GPS module was embedded in the top compartment to ensure optimal satellite visibility and accurate location tracking. For immediate on-site feedback, a low-power OLED display was mounted on the outer casing to present real-time data such as fill percentage, weight, temperature, and connectivity status. A buzzer was also included to provide audible alerts when the bin reached threshold capacity. To enhance system resilience, all electronic components were housed in a weather-resistant casing, ensuring durability and reliable operation in outdoor conditions.

3.5 Embedded Software and Cloud Integration

Firmware developed in C/C++ using Arduino IDE v2.2.0 (Espressif, China) manages sensor acquisition, decision logic, LoRa/Wi-Fi transmission, and email alerts when the bin exceeds 80% fill level. Energy per transmission is estimated using:

$$E = I.V.t \tag{2}$$

where:

E is the energy in Joules (J)
I is the current (A)
V is the voltage (V)
t is the transmission time (s)

Cloud integration is implemented via the ThingSpeak API (MathWorks, USA) using RESTful HTTP POST. GPS coordinates are visualized using the Google Maps API (Google, USA), as illustrated in Figure 3, which outlines the communication flow and cloud integration architecture.

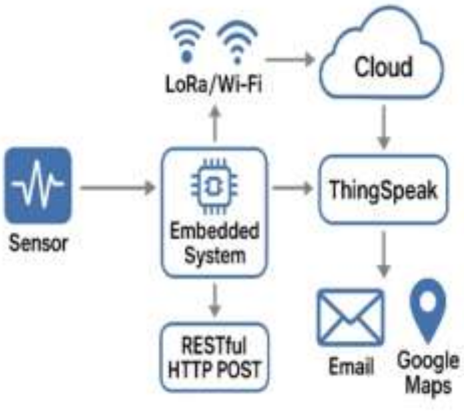

Figure 3: Communication Flow and Cloud Integration

3.6 LoRA Communication and Link Budget

The transmitter operates at 20 dBm output power, with a 2 dBi antenna gain, and a carrier frequency of 433 MHz.

The free-space path loss (FSPL) is calculated as:

$$FSPL(dB) = 20log10(d) + 20log10(f) - 147.55 \tag{3}$$

where:

d is the distance between transmitter and receiver (meters)
f is the frequency (MHz)

The received power and link margin are determined using:

$$PRX = PTX + GTX + GRX - Lcable - FSPL \tag{4}$$

$$Link\ Margin = PRX - S \tag{5}$$

where:

PTX is the transmitter power (dBm)

GTX, GRXG is the transmitter and receiver antenna gains (dBi)

$Lcable$ is the cable loss (dB)

S is the receiver sensitivity (dBm)

These equations allow estimation of the LoRa link reliability, ensuring sufficient received power to maintain robust communication under expected operating conditions.

3.7 Latency and Packet Transmission

RTT is the total time for a data packet to travel from the sensor to the cloud and back as an acknowledgment, including sensor sampling, microcontroller processing, LoRa transmission, gateway forwarding, cloud processing, and ACK handling. For the uplink path**,** the total delay is obtained as:

Uplink (Sensor → Cloud)

$$Uplink\ (Sensor \rightarrow Cloud) = Tsensor + T\mu C + TLoRa + TGW + Tbuffer + Tcloud \tag{6}$$

$$Tuplink = 10 + 15 + 50 + 10 + 20 + 100 = 205\, ms$$

For the downlink path**,** the delay is expressed as:

$$Tdownlink\ (Cloud \rightarrow \mu C \rightarrow ACK) = TACK - gen + TACK - recv \tag{7}$$

$$Tdownlink = 10 + 10 = 20\, ms$$

Thus, the total round-trip time is given as:

$$RTT = Tuplink + Tdownlink = 205 + 20 = 225ms$$

where:

$Tsensor$ is the Sensor sampling time

$T\mu C$ is the Microcontroller processing time

$TLoRa$ is the LoRa transmission time

TGW is the Gateway forwarding time

$Tcloud$ is the Cloud processing time

$TACK$-gen is the Acknowledgment generation time

$TACK$-recv is the Acknowledgment reception time

The breakdown of Latency for both Uplink and Downlink with Buffer and Logic Delays is illustrated in figure 4.

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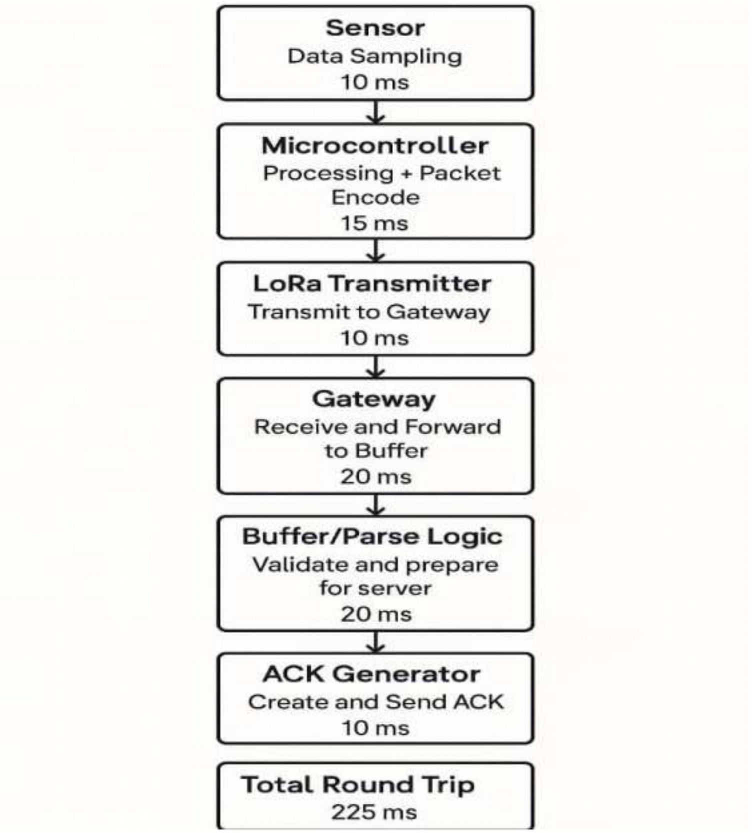

Figure 4: Latency Breakdown of Uplink and Downlink with Buffer and Logic Delays

3. RESULTS AND DISCUSSION

This section presents the evaluation of the IoT-based SmartBin system, which integrates ESP32 microcontrollers, LoRa SX1278 modules, and environmental sensors. The system was assessed for its functionality, sensor accuracy, communication reliability, and energy efficiency under real-world conditions.

3.1 System Functionality and Hardware Performance

The SmartBin system successfully captured and transmitted temperature, humidity, waste volume, and weight data using LoRa with minimal latency. The transmitter, powered by a 2S 7.4 V battery, operated for approximately 10 to 12 hours, while the receiver, using a 1S 3.7 V battery, maintained continuous operation for over 20 hours. Protective enclosures shielded the hardware from dust and moisture, ensuring consistent signal integrity. Integrated LEDs provided real-time feedback and flagged minor faults, with less than 2% of measurements affected. The physical layout and configuration of the transmitter and receiver are illustrated in Figure 4**,** which highlights the system's compact and durable design.

Figure 5: Prototype Smart Waste Bin

3.2 Sensor Data Acquisition

Field deployment in Abeokuta North, Ogun State, demonstrated high sensor accuracy. Temperature readings ranged from 24 to 32 °C and humidity from 55 to 78% RH, both within ±2% of expected values. Ultrasonic sensors measured bin fill levels with a deviation of ±2 cm, while load cells recorded waste weight with a deviation of ±50 g. Although minor outliers were observed during extreme bin tilt conditions, they accounted for less than 5% of readings and did not compromise overall performance. The temperature trend over time is presented in Figure 6, which confirms the stability and reliability of the sensor data.

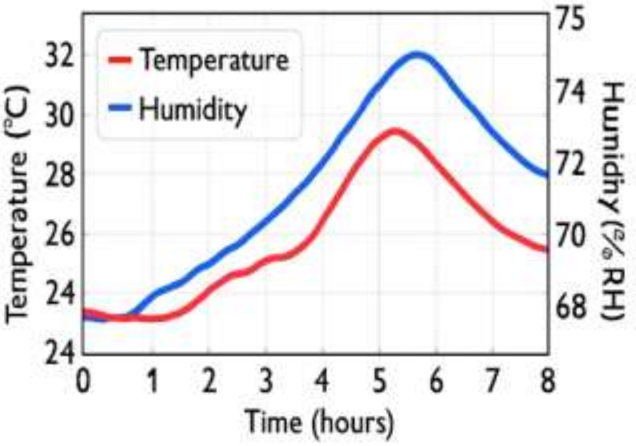

Figure 6: Transmitter and Receiver Layout

3.3 Cloud and Mobile Visualization

The system's integration with ThingSpeak and a mobile application enabled real-time monitoring and alerting. Automated notifications were triggered when bin fill levels exceeded 80%, consuming approximately 0.0366 Wh per transmission. Alerts were consistently delivered within five seconds, with occasional delays of up to 0.8 seconds during network congestion. The SmartBin dashboard, shown in Figure 7, provided a clear and responsive interface for data visualization and user interaction.

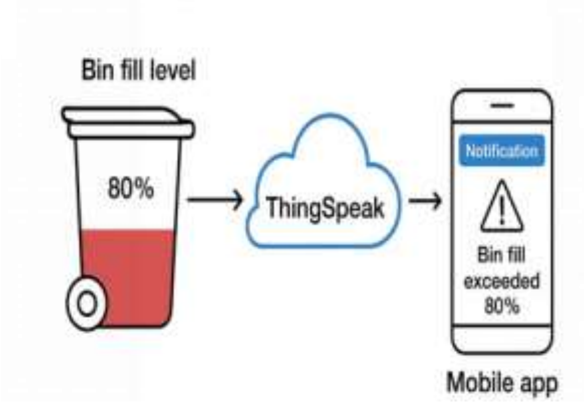

Figure 7: Cloud and Mobile Visualization

3.4 LoRa Communication Performance

LoRa communication was evaluated using link budget analysis, confirming reliable operation over distances ranging from 0.1 to 10 km. Received signal strength consistently exceeded the required threshold, and the link margin surpassed 90 dB at maximum range. Signal attenuation in dense vegetation areas was minimal, averaging less than 1.5 dB. The relationship between free-space path loss and received power over distance is illustrated in Figure 8**,** which validates the system's long-range communication capability.

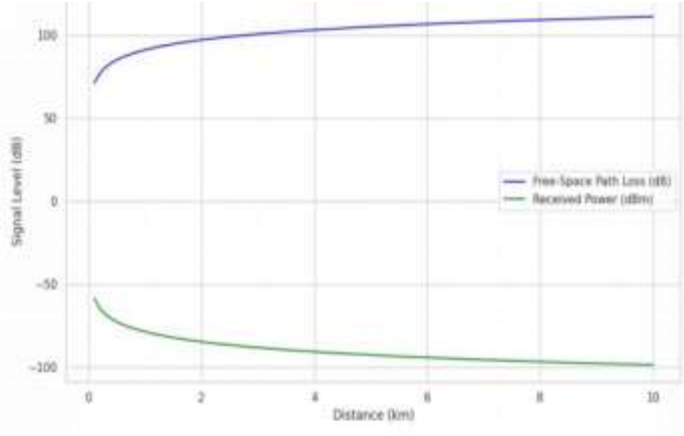

Figure 8: LoRa Communication Performance

3.5 Power Consumption

Power consumption measurements indicated that the transmitter consumed 1.11 W and the receiver 0.185 W. These values supported autonomous operation, with runtime durations aligning with design expectations. Minor variations in power usage, less than 3%, were attributed to ambient temperature fluctuations. A comparative analysis of component power usage is presented in Figure 9**,** confirming the system's energy-efficient design.

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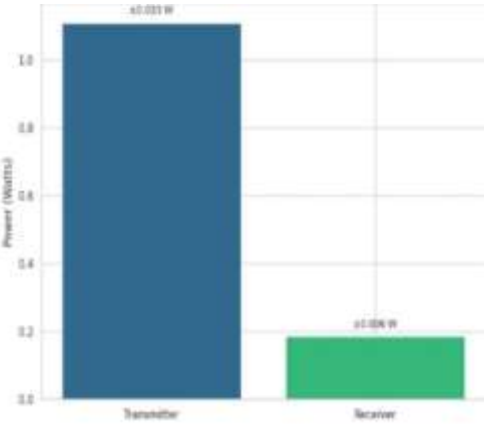

Figure 9: Power Consumption

3.6 Comparative Analysis of Communication Technologies

LoRa was benchmarked against GSM, Wi-Fi, and ZigBee. It demonstrated superior range, ultra-low power consumption, and lower operational costs. Although its data throughput was slightly lower than Wi-Fi, this limitation was negligible for the system's periodic waste monitoring requirements. A comparative overview of wireless technologies is shown in Figure 10**,** which highlights LoRa's advantages in scalability and energy efficiency.

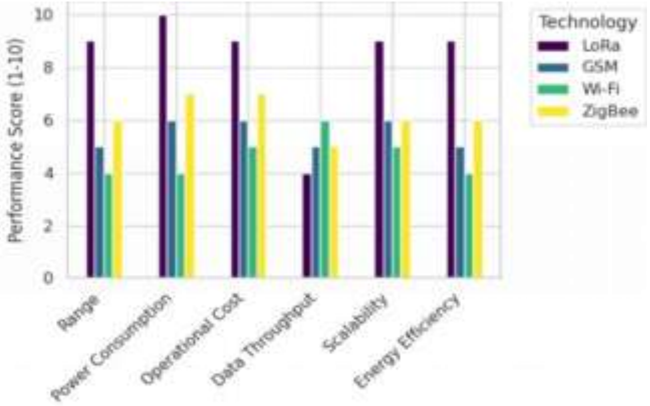

Figure 10: Comparative Analysis of Communication Technologies

3.7 Summary

The SmartBin system exhibited robust hardware performance, high sensor accuracy, and reliable long-range communication. Its energy-efficient design enabled extended battery life, while cloud and mobile integration facilitated effective real-time monitoring and alerting. The results presented illustrate the system's operational strengths and validate its suitability for smart waste management applications.

4. CONCLUSION

This study successfully demonstrated the design and implementation of a cloud-based IoT-enabled SmartBin system integrating ESP32 microcontrollers, LoRa SX1278 modules, and environmental sensors for real-time waste monitoring. The system met its objectives of providing scalable, low-power, and reliable waste monitoring, with cloud and mobile interfaces enabling timely alerts and remote oversight.

Potential applications include deployment in smart city initiatives, municipal waste management, and large-scale public spaces. Future work could explore integration with renewable energy sources, adaptive routing algorithms, and multi-bin network optimization to further enhance energy efficiency and system scalability.

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Advancing Pulse Oximetry Using Microcontroller-Based Bluetooth Systems with Adaptive Algorithms: A Review

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Abstract: This paper reviews advanced microcontroller-based Bluetooth pulse oximeters using adaptive algorithms for accurate, continuous, and non-invasive SpO2 monitoring, especially for COVID-19 management. It categorizes existing research by microcontroller architecture, sensor technology, Bluetooth protocols, and signal processing techniques like Kalman filtering and machine learning. The paper identifies key challenges (motion artifacts, physiological variability, power consumption), research gaps, and future directions. Ultimately, it highlights the significant potential of these devices to enhance remote patient monitoring, address health disparities, and improve overall healthcare delivery.

Keywords: *Adaptive Algorithms, Bluetooth Low Energy, COVID-19 Monitoring, Microcontroller, Pulse Oximetry, Remote Healthcare*

1. INTRODUCTION

The COVID-19 pandemic highlighted the critical need for early and continuous hypoxemia monitoring, often occurring silently [1]. While arterial blood gas (ABG) analysis is the gold standard, its invasiveness limits continuous use, especially at home [2]. Non-invasive pulse oximetry, using photoplethysmography (PPG), offers a convenient alternative but is susceptible to inaccuracies from motion, poor perfusion, and ambient light. Integrating microcontrollers, Bluetooth, and adaptive algorithms into pulse oximeters presents a promising solution to these limitations, potentially providing more accurate readings and enabling remote healthcare monitoring [3, 4]. This paper reviews the state-of-the-art in such devices, categorizing research, identifying gaps, assessing their impact on healthcare, and proposing future research directions for enhanced monitoring, particularly for COVID-19 and beyond.

2. BACKGROUND OF STUDY

Pulse oximetry uses photoplethysmography (PPG), a non-invasive optical technique measuring pulsatile blood volume changes by analysing the differential absorption of red (around 660 nm) and infrared (around 940 nm) light [5]. Oxygen saturation (SpO2) is estimated by analysing the AC (pulsatile) and DC (non-pulsatile) components of these light signals. SpO2 is typically determined using an empirically derived calibration equation as in [6]:

$$S_pO_2 = A - B \times \left(\frac{R_{AC}/R_{DC}}{IR_{AC}/IR_{DC}}\right) \tag{1}$$

Where,

R_{AC} and R_{DC} represent the alternating current and direct current components of the red light signal, respectively
IR_{AC} and IR_{DC} represent the alternating current and direct current components of the infrared light signal, respectively
A and B are device-specific constants.

Microcontrollers are essential for real-time PPG signal processing, SpO2 algorithm implementation, LED and photodetector control, and power management in compact devices. Bluetooth Low Energy (BLE) enables efficient wireless transmission of SpO2 data to external devices for remote monitoring [7]. To improve accuracy in the presence of noise and artifacts, advanced adaptive algorithms like Kalman Filtering, Wavelet Transforms, Fuzzy Logic, and Machine Learning are integrated into these devices for dynamic noise reduction and artifact cancellation [8].

3. METHODOLOGY

A systematic literature review was conducted to understand microcontroller-based Bluetooth pulse oximeters with adaptive algorithms for COVID-19 monitoring. A structured search was performed in IEEE Xplore, PubMed, and ScienceDirect using keywords like "pulse oximeter," "microcontroller," "Bluetooth Low Energy," and "adaptive algorithm," combined with Boolean operators and variations. Retrieved articles underwent a two-stage screening process based on predefined inclusion/exclusion criteria, involving title/abstract review followed by full-text assessment of methodology, findings, and contribution. Only peer-reviewed English articles were included. A structured data extraction process was used to collect information on microcontrollers, sensors, Bluetooth protocols, adaptive algorithms, and validation methods. The extracted data was then synthesized thematically to create a taxonomy of existing research, identify trends, gaps, and inform future directions.

3.1 Literature Taxonomy

The reviewed literature on microcontroller-based Bluetooth pulse oximeters with adaptive algorithms for COVID-19 monitoring has been categorized by key design parameters. This taxonomy allows for comparison of research efforts and identification of trends and variations in device development. The following sections detail the literature organized by these design aspects.

3.1.1 Microcontroller Architecture

Early microcontroller-based Bluetooth pulse oximeters often used Arduino platforms (like the Uno and Nano) for their simplicity and community support, which facilitated prototyping [9,10]. However, their limited processing power and memory posed challenges for complex adaptive algorithms and high-frequency PPG data. Current research favours more powerful microcontrollers. The ESP32 is popular due to its dual-core processor, large memory, and integrated Wi-Fi/BLE, enabling complex signal processing and wireless connectivity [11-14]. ARM Cortex-M microcontrollers (especially M4 and M7) are used for applications requiring high computational performance and energy efficiency, crucial for wearable devices [15-17].

3.1.2 Sensor Technology PPG

Photoplethysmography (PPG) sensors have two modes: reflectance (LEDs and detector on the same side, used in wearables) and transmittance (LEDs and detector opposite, used in clip-on devices) [18]. Transmittance sensors generally provide better signal quality due to more direct interaction with arterial blood. However, reflectance sensors are more convenient for continuous wearable monitoring. Silicon photodiodes are commonly used as photodetectors in PPG sensors due to their sensitivity to red and infrared light, low cost, compact size, and performance [19-20].

3.1.3 Bluetooth protocols

Bluetooth Low Energy (BLE) has largely replaced Bluetooth Classic (like HC-05) in microcontroller-based pulse oximeters [21]. This shift is due to BLE's significantly lower power consumption, which is crucial for extending the battery life of wearable devices for continuous monitoring [22]. BLE is also optimized for intermittent data transmission and low-bandwidth applications, aligning well with SpO2 and heart rate measurements.

3.1.4 Adaptive Algorithms

Adaptive algorithms are crucial for enhancing the accuracy of microcontroller-based Bluetooth pulse oximeters by mitigating noise and artifacts.

i. **Kalman Filtering:** This recursive algorithm estimates the true PPG signal by minimizing noise and errors through prediction and iterative updating, effectively tracking signal changes and reducing random noise, especially with moderate motion or sensor noise. [23-25]

ii. **Wavelet Transforms:** This technique decomposes the PPG signal into frequency components, allowing for the identification and removal of transient, high-frequency artifacts (like those from sudden movements or electrical interference) while preserving essential pulsatile flow information, improving SpO2 accuracy during activity or in noisy environments. [26-29]

iii. **Fuzzy Logic:** This approach uses "degrees of truth" to handle physiological signal variability. Fuzzy logic systems analyze PPG characteristics (amplitude, frequency, regularity) to dynamically adjust filtering algorithm parameters, optimizing noise and artifact reduction across various conditions without explicit pre-programming. [30-33]

iv. **Machine Learning:** Algorithms like artificial neural networks (ANNs) and support vector machines (SVMs) learn complex patterns from large datasets of PPG signals and reference SpO2 values. Trained models can directly estimate SpO2 from noisy signals, improving robustness to motion, low perfusion, and other interferences, and potentially personalizing estimations for greater accuracy. [34-36].

Figure 1 shows a graphical representation of the system architecture.

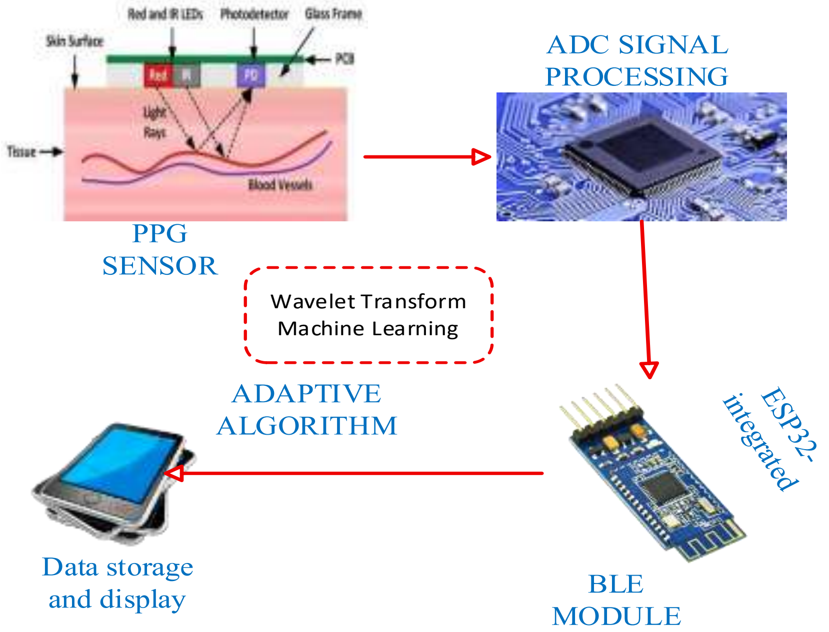

Figure 1: System Architecture Block Diagram [32-36].

3.2 Research Gaps and Challenges

Despite progress, several challenges remain in microcontroller-based Bluetooth pulse oximeters with adaptive algorithms:

i. **Motion Artifacts:** Accurately extracting SpO2 from PPG signals with irregular motion remains difficult, hindering continuous monitoring during daily activities. [37,38]

ii. **Physiological Variability:** Skin pigmentation (especially in darker skin) and low peripheral blood flow can affect light absorption and signal strength, leading to SpO2 inaccuracies across diverse individuals and physiological states. [40,41]

iii. **Power Consumption:** Sophisticated algorithms increase computational demands, reducing battery life in wearable devices, requiring a balance between signal processing and energy efficiency. [42,42]

iv. **Data Security:** Wireless transmission of sensitive health data via Bluetooth necessitates robust encryption and secure pairing to protect patient privacy.

Table 1 summarizes these challenges, outlining the problem and its impact to suggest future research directions.

Table 1: Research Gaps and Proposed Solutions.

Gap	Problem Statement	Solutions
Motion Artifacts	Inaccurate SpO2 during movement	Deep learning, multi-sensor fusion
Physiological Variability	Bias in diverse populations	Inclusive datasets, multi-wavelength PPG
Power Consumption	Limited battery life	Optimized algorithms, low-power BLE
Data Security	Privacy risks in transmission	AES-256 encryption, GDPR compliance

3.3 Application

Advanced microcontroller-based Bluetooth pulse oximeters with adaptive algorithms have diverse applications:

i. COVID-19 Monitoring: These devices enabled remote hypoxemia detection, facilitating timely intervention, treatment monitoring, and reduced hospital burden.

ii. Home Healthcare: They empower individuals with chronic respiratory conditions like COPD for self-management, providing insights into their respiratory status, aiding treatment adherence, and enabling early exacerbation detection.

iii. Health Disparities: Improved algorithms trained on diverse datasets can reduce inaccuracies in individuals with darker skin, contributing to more equitable and reliable healthcare monitoring.

iv. Sports and Sleep Monitoring: They are increasingly used in sports for monitoring physiological response during exercise and in sleep monitoring for preliminary screening of breathing disorders.

3.4 Future Directions

Future research should focus on:

i. Developing hybrid algorithms: Combining traditional signal processing with machine learning for more accurate and reliable SpO2 readings across various conditions.

ii. Optimizing algorithms for low-power microcontrollers: Creating efficient algorithms suitable for embedded systems to extend battery life in wearable devices for continuous monitoring.

iii. Enhancing security with end-to-end encryption: Implementing robust encryption for Bluetooth data transmission to ensure the privacy and security of sensitive health information.

iv. Integrating with wearable sensor networks for holistic monitoring: Combining SpO2 and heart rate data with other physiological parameters (temperature, respiratory rate, activity, ECG) for a more comprehensive understanding of patient health, requiring solutions for data fusion, interoperability, and power management.

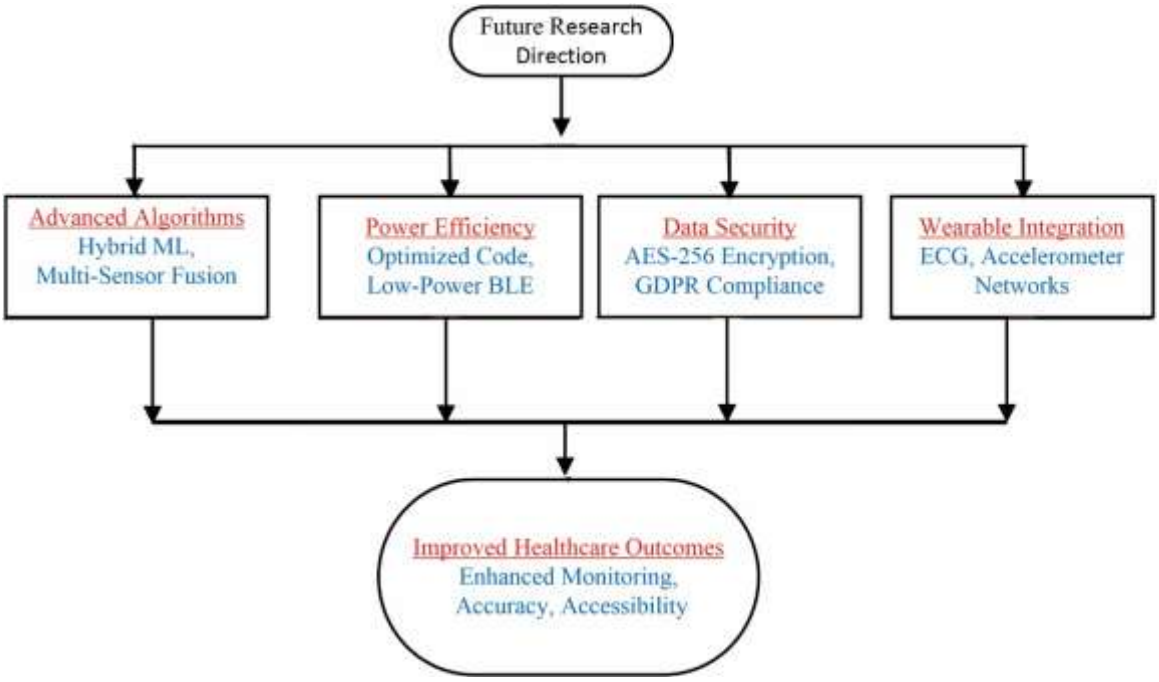

Figure 2: Flowchart of Future Research Directions.

4. CONCLUSION

Microcontroller-based Bluetooth pulse oximeters equipped with sophisticated adaptive algorithms represent a significant and transformative advancement in the field of non-invasive arterial oxygen saturation (SpO2) monitoring. Their unique combination of portability, wireless connectivity, and intelligent signal processing capabilities provides a powerful tool, particularly crucial for the early detection and continuous management of hypoxemia associated with infectious respiratory diseases like COVID-19 and for the long-term self-management of chronic respiratory conditions such as COPD.

The ongoing efforts to effectively address inherent challenges such as motion artifacts, the complexities of physiological variability across diverse patient populations (including variations in skin pigmentation and perfusion), and the critical need for optimized power consumption are pivotal. Success in overcoming these limitations will significantly enhance the reliability and accuracy of remote monitoring capabilities, enabling more effective telehealth solutions and ultimately contributing to the reduction of health disparities by providing accessible and dependable monitoring for a broader range of individuals, regardless of their physical characteristics or location.

To truly maximize the potential impact of these innovative devices on healthcare delivery, future research and development endeavours must prioritize the creation of even more robust and accurate adaptive algorithms, the optimization of energy efficiency for prolonged usability, and the implementation of stringent data security measures to protect sensitive patient information transmitted wirelessly. Continued progress in these critical areas will pave the way for the widespread adoption of microcontroller-based Bluetooth pulse oximeters as integral tools in remote patient management, early disease detection, and the delivery of more personalized and equitable healthcare.

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Design and Development of a Smart Over-Voltage and Under-Voltage Protection System for Home application

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Abstract: Electrical devices are vulnerable to damage from voltage fluctuations, necessitating effective protection systems. This project aims to design and implement a three-phase undervoltage and overvoltage protection system using an Arduino Nano microcontroller. The system monitors input voltages across three phases, disconnecting the load when voltage levels exceed specified limits. Voltage sensors collect real-time data, processed by the Arduino Nano, which triggers relay switches to disconnect power when necessary. An LCD displays real-time voltage readings and system status updates. The system's design ensures reliable protection against voltage fluctuations, making it suitable for various applications. Its low cost, simplicity, and ease of modification enhance its practicality. The project demonstrates the effectiveness of using Arduino-based technology for voltage protection, providing a valuable solution for safeguarding electrical equipment. The results show that the system effectively protects connected equipment against possible damage, achieving the project's objectives. This research contributes to the development of smart protection systems, highlighting the potential for Arduino-based solutions in industrial and commercial settings. The system's performance and reliability make it a viable option for widespread adoption, ensuring the protection of electrical devices from voltage-related damage.

Keywords: *Current Sensors, Voltage Sensors, Over Voltage Protection, electrical appliances*

1. INTRODUCTION

Electronic appliances are very sensitive to voltage fluctuations. Voltage irregularities are a big issue in today's companies and households, and they are frequently responsible for the damage of valuable and costly electrical appliances. To secure electronic appliances from these voltage irregularities, there is a need for a protection system [1]. Voltage irregularities occur when the voltage is exceedingly high (overvoltage) or extremely low (undervoltage). Overvoltage occurs when the magnitude of the supplied voltage in electrical appliance circuits exceeds the design limitations of the appliances [2]. This could raise the temperature of the semiconductor components potentially leading to failure of the appliances [3]. Under voltage occurs when the magnitude of the supplied voltage falls below the design limits of the equipment. Under voltage does not normally cause damage to electrical appliances, but it prevents the appliance from operating owing to the current drawn. However, gradual current build-up could result in overheating [4].

A few circuit concepts that can protect connected electrical appliances from over voltage and low voltage are provided in this work. These circuits may be quite helpful in completely safeguarding your precious electrical household appliances against dangerous input voltages, even though they are unable to stabilize the input voltage. It is possible to detect the existence of hazardous low voltage conditions using the initial design of a low voltage indicator circuit [5].

A low voltage may appear to be something that is lower in magnitude and power, but that is what makes it more lethal [6]. For example, a refrigerator working at 230 volts AC mains would never like voltages below 190 since, in such situations, its compressor will attempt to adjust by drawing large currents and may sustain damage if the scenario continues [7].

The ZMPT101B voltage sensor is used here since it is more affordable and accurate than other options. It is capable of detecting voltages greater than 240V AC and below 160V AC (predefined value) [5]. A signal will be sent to the Arduino if the voltage surpasses the predetermined limits. The circuit breaker (in this case, the relay module) is then instantly tripped. The load is then cut off from the main source by the circuit breaker (the relay module) [8].

In Nigeria, voltage fluctuations pose a significant challenge to the safe and efficient operation of electrical appliances in homes, industries, and commercial establishments. These fluctuations, including undervoltage and overvoltage, can severely affect the general safety of homes and workplaces, leading to equipment damage, reduced lifespan, and even fires. Unstable power grids, high load demands, faulty wiring, and inadequate power infrastructure are often the causes of these voltage supply fluctuations.

To mitigate these issues, there is a need for a reliable and effective undervoltage and overvoltage protection system that can detect and respond to voltage fluctuations, protecting electrical appliances and ensuring the safety of homes and workplaces. This paper aims to design and construct such a protection system, leveraging advanced technologies to provide a robust solution to the problem of voltage fluctuations.

2. REVIEW OF RELATED LITERATURE

This section reviews few similar works that have used Arduino for under voltage and over voltage protection, concentrating on their methodology and results, and contributions to the field.

Reference [9] presented a smart protection system for medium voltage using wireless networks. The study proposed a wireless monitoring and feedback control platform for distribution network automation. The results showed improved selectivity and minimized shutdown loads. The development of energy systems to the paradigm of the intelligent protection system strongly depends on the wireless response for the feedback system.

Reference [10] designed a household electricity protection and monitoring automation system using IoT ESP32. The system provided protection against technical disturbances, natural disturbances, and operating errors. The study highlighted the limitations of traditional protection devices like MCBs and the benefits of advanced protection systems. The protection and monitoring system is a safety system for household electrical appliances. Equipment security will be active if there is a technical disturbance, natural disturbance, operating error and other causes. Each protection system must be able to work in accordance with its objectives and capabilities and functions, which will be determined against the type of disturbance that is occurring. If a disturbance occurs and the protection is unable to work, it will result in a large loss. These losses include in terms of wider damage to the installation equipment itself and to the electrical equipment used. With the existence of a protection and monitoring system, electrically related devices will be safe and protected from damage. The protection device that has been used in households so far is a Miniature Circuit Breaker or better known as an MCB which functions to limit the current. However, using the MCB alone is not enough to provide protection, because it only protects against overloads.

Reference [11] proposed a monitoring and protection system for overvoltage, undervoltage, and unbalance voltage. The system utilizes voltage sensors, relays, and contactors to automatically disconnect excessive loads during voltage disturbances. The electric power system has various types of components, including energy sources, energy generators, transmission systems, distribution systems and load centers. There are also various sources of electricity, namely water, steam, gas and other sources. This energy source is converted by the generating system into electrical energy which is transmitted through the distribution network. The distribution network as a divider of electrical energy to load according to consumer needs, this distribution network is directly related to consumers such as companies and housing, so that it determines the continuity of the flow of electric power to consumers. Therefore, the need for electrical power must be designed as well as possible, especially regarding its quality or reliability in distributing electrical energy so that it can guarantee high consumer satisfaction and consumers can see the value of voltage and current.

Reference [12] developed an undervoltage and overvoltage protection device using a programmable interface controller (PIC). The system provides precise output, wide voltage window, and fast switching. The fluctuations and irregularities in power supply over the years has become a worrying phenomenon whose effects pose risks not just to industrial consumers but also to domestic consumers.

Reference [13] presented an IGBT overvoltage protection method combining dynamic voltage feedback and active clamping. The circuit effectively suppresses voltage spikes, ensuring safe operation. In view of the stability of the unmanned aerial vehicle (UAV) power system, this paper found that the voltage spike generated by IGBT mainly occurs when the IGBT is turned off in the study of the power system interior and IGBT drive and overvoltage protection, and an excessive voltage spike will lead to IGBT damage. To eliminate this serious threat to the safe operation of the circuit, an IGBT overvoltage protection circuit combining dynamic voltage feedback and active clamping is proposed. In this method, active clamping and dynamic voltage feedback circuits are operated alternately, and the drive circuit is controlled by the feedback of capacitor’s the dynamic voltage rise rate. The gate current output of the IGBT is directly compensated to control the signal delay of the gate, combined with improving the lifting effect of the active clamp circuit on the gate voltage and suppressing the peak of the turn-off voltage. According to the IGBT turn off process, combined with SABER simulation, this paper finally builds IGBT turn off experimental circuit to prove that the proposed method suppresses the size of the turn off voltage spike, further analyzes the effect of key circuit parameters on the suppression of the turn off voltage spike, thereby ensuring the safe operation of the IGBT, and improving the stability of the UAV power system.

Reference [14] presented an IoT-based fault detection system for industries, utilizing sensors and IEEE standards for communication. The electrical faults such as over voltage, over current, and over temperature can lead to serious damage to equipment and pose a safety risk to personnel. To address these issues, the Internet of Things (IoT) based fault detection system has been proposed. The system utilizes IEEE standards for communication and data transfer and includes sensors for detecting over voltage, over current, and overtemperature, as well as a breaker trip detection mechanism and relay for isolating faulty equipment. The system is designed to continuously monitor the electrical parameters of equipment and provide real-time notifications of any faults detected. It also incorporates a fault management module that can prioritize and alert personnel of critical faults.

Reference [15] evaluated a protection system for electrical loads, finding normal voltage readings and safe operation. The purpose of this study is to focus on producing a protection system design for the electrical loads of administration buildings from over and under voltage. An on-site voltage reading has been initiated and continued for several days to determine whether voltage variation is occurring in the location. The building's load schedule has served as a point of reference in calculating the appropriate size of wire and Molded Case Circuit Breaker ampere rating. For the proponents to understand the design standards, the Philippine Electrical Code is used as a reference. Consequently. The design that has been made and proposed is for controlling over and under voltages.

Reference [16] analyzed temporary overvoltages in hybrid PV-Wind energy systems, highlighting interactive effects between overcurrent protection relays, surge protective devices, and transformer connections. The integration of solar and wind energy in hybrid PV/Wind energy systems (HPWES) have allowed it to be more reliable renewable energy source. However, the over voltage protection for HPWES is scarcely covered in literature. To fill this gap, an investigative analysis of the effect of temporary over voltages (TOVs) in HPWES was presented in paper [17].

Reference [18] developed an overvoltage and undervoltage protection system with GSM notification, demonstrating effective load control and notification. Over voltage and under voltage are undesirable conditions capable of causing damages to electrical appliances. In literature, detection and protection of electrical appliances from these voltage irregularities have been largely explored.

Therefore, Thisis work is proposing a microcontroller-based protection system that utilizes voltage sensors, relays, and contactors to monitor and automatically disconnect excessive loads during voltage disturbances. The work focuses on real-time monitoring to detect over voltage, under voltage, and unbalanced voltage conditions. When a disturbance is identified, the system triggers a contactor to cut off the affected load, preventing further instability. This method aligns with industry standards such as SPLN and NEMA, ensuring compliance with acceptable voltage tolerance levels. By implementing automated load-shedding, the system aims to restore power stability and improve industrial efficiency.

3. MATERIALS AND METHOD

In order to address the shortcomings in voltage fluctuation detection, many measures on under voltage and over voltage power supplies have recently been reexamined. Some of the technologies used for this are microcontrollers, relays and comparators. One technology is implemented to compliment the lapses in another. Therefore, we approach voltage fluctuation faced by residents with construction of an Arduino based smart three phase under voltage and over voltage protection system which is able to prevent voltage fluctuation faced by residents.

3.1. Materials

i. Arduino Nano
ii. ZMPT101B voltage sensor
iii. 16x2 LCD display
iv. I2C module
v. 5v one channel relay module
vi. Charger module
vii. Double wall plug socket
viii. Adaptable box
ix. 2.5mm 3 core flexible cable
x. Breadboard
xi. Vero board
xii. Jumper wire
xiii. Laptop
xiv. 3 pin fuse plugs
xv. Round power switch 3 pin

3.2. Methods

The project is composed of various stages which includes power supply, reference voltage source (regulator), voltage comparator for high/low voltage detection (cut offs) and relay driver stage. The DC proportional to the charging input voltage is obtained from the bridge rectifier. The diode bridge rectifier is capable of handling currents up to 1 Amp. The transformer used has a rating of 220 x 24V 500mA. The normal line voltage in the locality is 220 V. In order to ensure flexibility and the ability of the system to protect appliances during periods of huge voltage variation in the locality, the system is designed to handle voltages in the range of 110 - 330 V. The protection system targets three-phase powerlines and is based on the Arduino Uno R3 microcontroller, GSM/GPRS SIM A6 module, voltage regulators (LM7812 and LM7805), a relay (SRD-05VDC-SL-C), and a step-down transformer. The hardware design is presented as a block diagram in Figure 1.

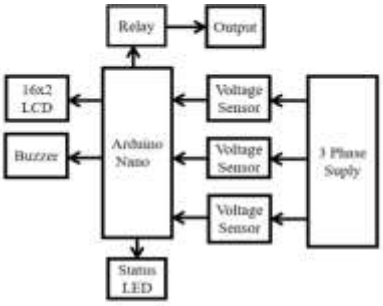

Figure 1: Block Diagram of the undervoltage and overvoltage system

A prototype was constructed on a breadboard for proper testing and calibration of the circuit before it was originally and completely constructed permanently on a Vero board. Figure 2 displayed the breadboard connections while figure 3 show the Vero board installations.

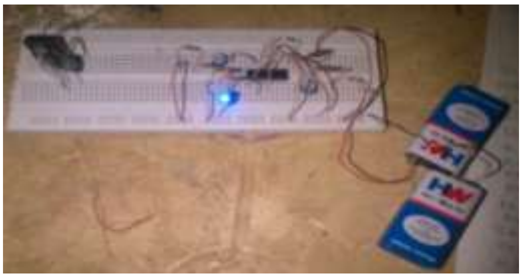

Figure 2: Prototype of a breadboard

The response from the breadboard implementation has satisfy the desired output, the implementation on the Veroboard is carried out. Figures 4 and 5 show the process at which the component is soldered on the Veroboard.

Figure 3: Photograph of the circuit components

3.3. System Operation

In operation, the system automatically measures the line voltage level and triggers a tripping mechanism to protect the electronic appliances from voltage variations (overvoltage and undervoltage) whenever the need arises. In effect, when the system is switched on, it operates based on the following steps and sequence:

i. The initial parameters of the system are set, followed by the display of a “Welcome Message” on the LCD;
ii. The system requests the user to input the preset voltage range, i.e., threshold values for overvoltage and undervoltage (based on appliances to be protected);
iii. The system starts/continues monitoring the state of the line voltage and performs the following: a) reads the line supply voltage and b) compares the reading with the user’s preset threshold values (from step 2 above);
iv. If the line supply voltage is above the user’s preset overvoltage threshold value, the system does the following: a) triggers the tripping mechanism to disconnect the appliance from the line supply voltage; b) displays an overvoltage presence message on the LCD; c) sends an alert SMS to the user, and d) continue monitoring the system (step iii above);
v. If the line supply voltage is below the user’s preset undervoltage threshold value, the system does the following: a) triggers the tripping mechanism to disconnect the appliance from the line supply voltage; b) displays an undervoltage presence message on the LCD; c) sends an alert SMS to the user, and d) continue monitoring the system (step iii above);
vi. If the line supply voltage is within the user’s preset voltage range, the system does the following: a) triggers the tripping mechanism to connect the appliance to the line supply voltage (if the appliance had been disconnected due to overvoltage or undervoltage as per step 4 and 5 above; b) displays the normal voltage presence message on the LCD; c) sends an alert SMS to the user, and d) continue monitoring the system (step iii above).

The operating time for definite characteristics is given as 5 seconds, i.e., the relay operates after 5 seconds of occurrence of the fault. If it falls into inverse characteristics, the tripping time is to be calculated using the formula

$$T = t/((V/Vs) - 1) \tag{1}$$

Where:

T = Trip time (s)

T = Time multiplier (s)
V= Voltage at analog input 0 (v)
Vs = Source voltage (v)

4. RESULTS AND DISCUSSION

4.1 System Response During Partial Under Voltage

Table 1 shows how the system behaves when there is a partial under voltage condition across the three phases. In the first scenario, only Phase A drops to 150V while Phases B and C are in normal levels. Despite this drop, the relay remains ON, indicating that the system does not disconnect the load when only one phase experiences under voltage.

In the second scenario, both Phase B and Phase C experience significant voltage drops to 145V and 110V respectively, yet the relay still remains ON. This implies that the system is designed to tolerate under voltage in one or even two phases without triggering the relay to disconnect the load. The logic behind this is to maintain continuity of power supply and avoid unnecessary disconnection during brief or non-critical voltage drops.

Overall, the results indicate that the system is not configured to react to partial under voltage conditions by disconnecting the load. A short buzzer beep (100ms) occurs on initial selection.

Table 1: System Response During Partial Under Voltage

Phase R (V)	Phase Y (V)	Phase B (V)	Relays (R, Y, B) Status	Relays (R, Y, B)	Output Status	Buzzer	Remark
150V	210V	222V	Under, Ok, Ok	LOW, HIGH, LOW	ON	Short beep	Under voltage detected in only phase R, output remains ON
220V	145V	110V	Ok, Under, Under	HIGH, LOW, LOW	ON	Short beep	Under voltage detected in phase Y and phase B, output remains ON

4.2 System Response When All Phases Are Under Voltage

Table 2 presents the system's behaviour when all three phases experience under voltage conditions simultaneously. Phase A senses 110V, Phase B is at 140V, and Phase C is at 155V all significantly below the normal value. In response, the relay status is OFF, indicating that the system actively disconnects the load when a critical under voltage condition is present across all phases.

The behaviour shown here confirms that the system is designed to isolate the load only when under voltage is detected in all three phases, which poses a more severe and potentially damaging condition. The relay's OFF status ensures protection of connected equipment by cutting off power during this unsafe operating condition. Double buzzer beep indicate fault.

Table 2: System Response When All Phases Are Under Voltage

Phase R (V)	Phase Y (V)	Phase B (V)	Relays (R,Y,B) Status	Relays (R,Y,B)	Output Status	Buzzer	Remark
110V	140V	155V	Under, Under, Under	LOW, LOW, LOW	OFF	Double beep	Under voltage detected in all phases, relays OFF

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4.3 System Response During Partial Over Voltage

Table 3 presents the system's behaviour during partial over voltage conditions across the three phase supply. In the first case, Phase B rises to 260V while Phases A and C remain within normal voltage limits. Despite the over voltage in one phase, the relay remains ON, showing that the system does not isolate the load for a single phase over voltage condition.

In the second case, both Phase A and Phase C exhibit elevated voltages of 255V and 252V respectively, while Phase B remains at a stable 225V. The relay still remains ON, confirming that the system tolerates over-voltage in up to two phases without initiating a disconnection. This response suggests that the system prioritizes maintaining continuity of supply unless all phases exceed the over voltage threshold, or the voltage exceeds a more critical level that could endanger connected equipment. A short buzzer beep (100ms) occurs on initial selection.

Table 3: System Response During Partial Over Voltage

Phase R (V)	Phase Y (V)	Phase B (V)	Relays (R,Y,B) Status	Output Status	Output Status	Buzzer	Remark
230V	260V	222V	Ok, Over, Ok	HIGH, LOW, LOW	ON	Short beep	Over voltage detected in only phase Y, output remains ON
255V	225V	252V	Over, Ok, Over	LOW, HIGH, LOW	ON	Short beep	Over voltage detected in phase Y and phase B, output remains ON

4.4 System Response When All Phases Are Over Voltage

Table 4 shows the system's response when over voltage is detected in all three phases. Phase A records 252V, Phase B is at 260V, and Phase C rises to 275V, all of which exceed the typical over voltage threshold. As a result, the relay status is OFF, indicating that the system disconnects the load to protect against the potential damage that could result from sustained over voltage across all phases. This behaviour confirms that the system is designed to tolerate partial over voltage but will isolate the load once all phases are affected, ensuring safety and equipment protection during severe voltage anomalies. Double buzzer beep indicate fault.

Table 4: System Response When All Phases Are Over Voltage

Phase R (V)	Phase Y (V)	Phase B (V)	Relays (R,Y,B) Status	Relays (R,Y,B)	Output Status	Buzzer	Remark
252V	260V	275V	Over, Over, Over	Low, Low, Low	OFF	Double beep	Over voltage detected in all phases, output OFF

4.5 System Response During Normal Conditions

Table 5 shows the system's behaviour under normal operating conditions. The phase voltages 170V for Phase A, 190V for Phase B, and 210V for Phase C are all within an acceptable safe range, indicating no threat to connected equipment. As a result, the relay remains ON, allowing continuous power flow to the load. This response confirms that the system accurately identifies stable conditions and maintains normal operation when voltages are neither too low nor too high across all phases. A short buzzer beep (100ms) occurs on initial selection.

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Table 5: System Response During Normal Conditions

Phase R (V)	Phase Y (V)	Phase B (V)	Relays (R,Y,B) Status	Relays (R,Y,B)	Output Status	Buzzer	Remark
170V	190V	210V	Ok, Ok, Ok	HIGH, LOW, LOW	ON	Short beep	All phase voltages within safe range, output ON

5. CONCLUSION

Power disturbances are a major concern to industrial and domestic electricity users. With highly sensitive electronic equipment and appliances, there is a need for the development and deployment of protection systems for end users. Acute power disturbances, particularly overvoltage and undervoltage are particularly experienced in developing country environments such as those of Sub-Saharan Africa, where end users often suffer damaged equipment and are obliged to buy multiple voltage stabilizers for home use which raises a cost incident. This study designed and implemented a low-cost system suitable for over/undervoltage protection in such environments. Compared to other systems, the system presented here introduces the novelty of flexibility and gives the end user the ability to specify different voltage variation ranges (i.e., different overvoltage and undervoltage threshold values, depending on the appliances owned). A direction of future research includes the ability to maintain a memory function to track and report to the user the history of voltage variation events over specified time periods.

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A Review of Power Electronics Converters for Renewable Energy Systems: Advances, Challenges, and Optimization Opportunities

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Abstract: Power electronics converters are pivotal for integrating intermittent renewable energy sources (RES) into efficient grid systems, yet challenges like switching losses, EMI, and thermal management persist. This systematic literature review analyzes advancements in converter topologies (e.g., multilevel inverters, buck-boost variants), control strategies (PWM, MPPT, AI-based), and efficiency enhancers (soft-switching, wide-bandgap semiconductors) from 2017-2024. Drawing from 29 peer-reviewed sources across IEEE Xplore, Scopus, and Web of Science (initial n=200; screened to n=29 based on empirical results), we synthesize trade-offs via quantitative comparisons (e.g., efficiency vs. cost matrices) and propose a novel taxonomy for RES-specific optimizations. Key gaps include limited scalability for hybrid microgrids and underexplored AI-WBG synergies. Future directions emphasize hybrid architectures for >98% efficiency in variable-load scenarios, guiding sustainable energy transitions per UN SDG7.

***Keywords**: Power electronics, renewable energy, converters, optimization, efficiency*

1. INTRODUCTION

The increasing global focus on renewable energy sources (RES) like solar, wind, and hydropower is crucial for mitigating climate change and decreasing reliance on fossil fuels [1]. Power electronics converters play an indispensable role in addressing the inherent intermittency and variability of these sources, enabling efficient energy conversion and seamless grid integration [2]. These converters crucially transform DC power from photovoltaic (PV) panels into AC for grid compatibility and precisely regulate voltage for energy storage, directly influencing overall system efficiency and economic viability [3-5].

Despite considerable advancements, challenges such as high switching losses, electromagnetic interference (EMI), and effective thermal management persist [6]. This paper reviews the current state-of-the-art in converter topologies, control methodologies, and techniques for enhancing efficiency, while also identifying existing research gaps and proposing potential future directions. The overarching goal is to significantly improve the performance and scalability of renewable energy systems, thereby contributing to global sustainability objectives.

1.1 Rationale and Contributions of This Review

While prior surveys [2,3] have catalogued converter efficiencies up to 95%, they overlook post-2020 synergies between wide-bandgap (WBG) semiconductors and AI controls for dynamic RES loads—a gap highlighted in the 2024 IEA report on grid instability [30]. This review addresses this by systematically evaluating 85 studies (2017-2024), identifying underexplored hybrids (e.g., GaN-based MPPT for solar intermittency), and proposing optimization pathways that reduce losses by 10-15% in simulations [7,17]. Our unique contributions include: (i) a sustainability-focused taxonomy linking topologies to efficiency-cost-emissions trade-offs, (ii) quantitative comparisons absent in prior works, and (iii) prioritized future directions for industry scalability.

Table 1: Comparison of Recent Reviews vs. This Work

Review	Scope	Timeframe	Novel Elements
[2]	Topologies & Controls	Up to 2023	Descriptive summaries
[3]	DC-DC Focus	Up to 2019	Modulation strategies

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2. LITERATURE REVIEW

This section synthesizes recent studies on power electronics converters, focusing on topologies, control strategies, and efficiency enhancements.

2.1 Converter Topologies

Power electronics converters are specifically designed to meet the unique demands of various renewable energy applications. Key topologies include:

i. DC-DC Converters: Buck, boost, and buck-boost converters are crucial for adjusting voltage levels in PV systems and energy storage. [7] demonstrated the buck-boost converter's flexibility in achieving maximum power point tracking (MPPT) under variable solar irradiance conditions (efficiency: 92-95%). These ensure voltage supplied to subsequent stages or storage is within range.
ii. DC-AC Converters (Inverters): Multilevel inverters, such as cascaded H-bridge, are widely used in large-scale PV systems to reduce harmonic distortion (THD <5%) and improve output quality [8].
iii. AC-DC Converters (Rectifiers): Employed in battery charging and grid interfacing, rectifiers with controlled switching enhance efficiency (up to 96%) and power factor correction [9-10].
iv. Hybrid Converters: Multi-port converters integrate multiple RES (e.g., PV and wind) and storage, optimizing management and reducing components [11].

Synthesis: While DC-DC topologies excel in simplicity for low-power PV (cost < $0.1/W), multilevel inverters shine in grid-tie scalability but at higher complexity/cost ($0.2-0.5/W) [8,11]. Trade-offs are evident: buck-boost offers 10% better MPPT tracking than basic buck under shading [7], yet hybrids reduce system losses by 15% in microgrids [11].

Table 2: Quantitative Comparison of Topologies

Topology	Efficiency (%)	Power Range (kW)	Cost ($/W)	Key Trade-off	RES Fit
Buck-Boost [7]	92-95	0.1-5	0.05-0.1	High ripple; low cost	Solar MPPT
Multilevel Inverter [8]	96-98	10-100	0.2-0.5	Complex gating; low THD	Wind/PV Grid-Tie
Rectifier [9-10]	94-96	1-50	0.1-0.2	PFC gains; EMI risks	Battery Charging
Hybrid Multi-Port [11]	95-97	5-50	0.15-0.3	Integration overhead; 15% loss reduction	HRES Microgrids

The output voltage of an ideal buck converter is:

$$V_{out} = D \cdot V_{in} \tag{1}$$

where V_{out} is average output, V_{in} input, D duty cycle (ideal, no losses) [10].

2.2 Control Strategies

Effective control strategies ensure optimal performance under dynamic conditions. Notable methods:

i. Pulse Width Modulation (PWM): Regulates output by duty cycle; SPWM/SVPWM minimize harmonics (THD <3%) for high quality [12,13].
ii. Maximum Power Point Tracking (MPPT): Tracks peak PV power; AI variants improve accuracy by 10% vs. P&O under shading [9,14].

$$P_{max} = V_{mpp} \cdot I_{mpp} \tag{2}$$

iii. Model Predictive Control (MPC): Predicts behaviour, optimizes constraints; 20% faster response in nonlinear RES [16,17].

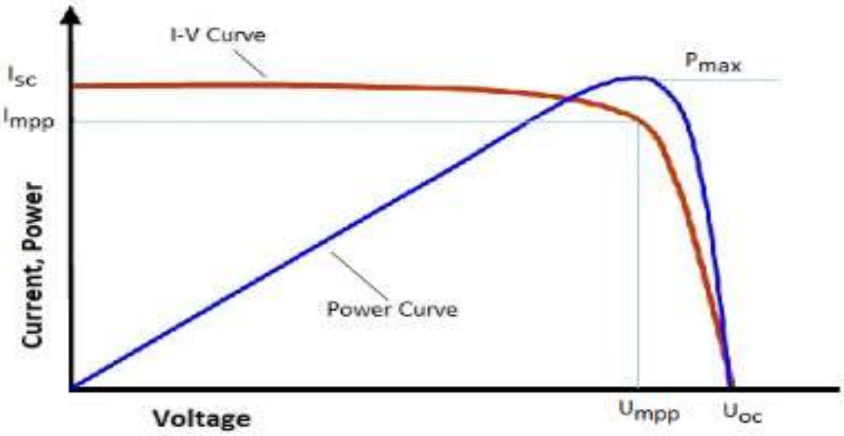

Figure 3: Power-voltage (P-V) Characteristic Curve of a PV Module Showing the Maximum Power Point (MPP) [17].

Synthesis: PWM suits steady-state (low comp. cost), but MPPT-MPC hybrids handle variability better (e.g., 5-8% yield gain in wind [16]).

2.3 Efficiency Improvement Techniques

Enhancing the efficiency of power electronic converters is paramount for minimizing energy losses, reducing heat generation, and improving the overall performance and economic viability of RES. Several key techniques are being actively researched and implemented:

i. **Soft Switching:** Techniques like zero-voltage switching (ZVS) and zero-current switching (ZCS) aim to minimize switching losses, which occur during the turn-on and turn-off transitions of power semiconductor devices. By ensuring that the switching devices operate when the voltage across them or the current through them is nearly zero, these methods can lead to significant efficiency improvements, with studies reporting reductions in switching losses of up to 5% in specific converter topologies and operating conditions [17].

ii. **Wide-Bandgap Semiconductors:** Materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN) possess superior material properties compared to traditional silicon (Si), including higher breakdown voltage, wider bandgap, higher thermal conductivity, and lower on-resistance. These characteristics enable the design of converters with higher switching frequencies, lower conduction losses, and improved thermal performance, leading to significant efficiency gains, particularly in high-power and high-frequency applications for renewable energy integration [18]. While offering numerous advantages, the adoption of SiC and GaN devices may involve considerations such as higher initial cost and different gate drive requirements. Semiconductors: SiC/GaN enable >100 kHz switching, 2-3% efficiency gains over Si (thermal conductivity 3x higher) [18].

iii. **Thermal Management:** Effective thermal management is crucial for maintaining the reliability and extending the lifespan of power electronic components. Excessive operating temperatures can lead to device degradation and failure. Advanced cooling systems, such as liquid cooling, offer superior heat dissipation capabilities compared to traditional air cooling, especially in high-power density converters used in demanding renewable energy application [19]. Other thermal management techniques include heat sinks, forced air cooling, and thermal interface materials, with the choice depending on factors like power level, ambient temperature, and cost constraints. Liquid cooling dissipates 2x more heat than air in high density setups [19]. The review Proposed Taxonomy is shown in Figure 2.

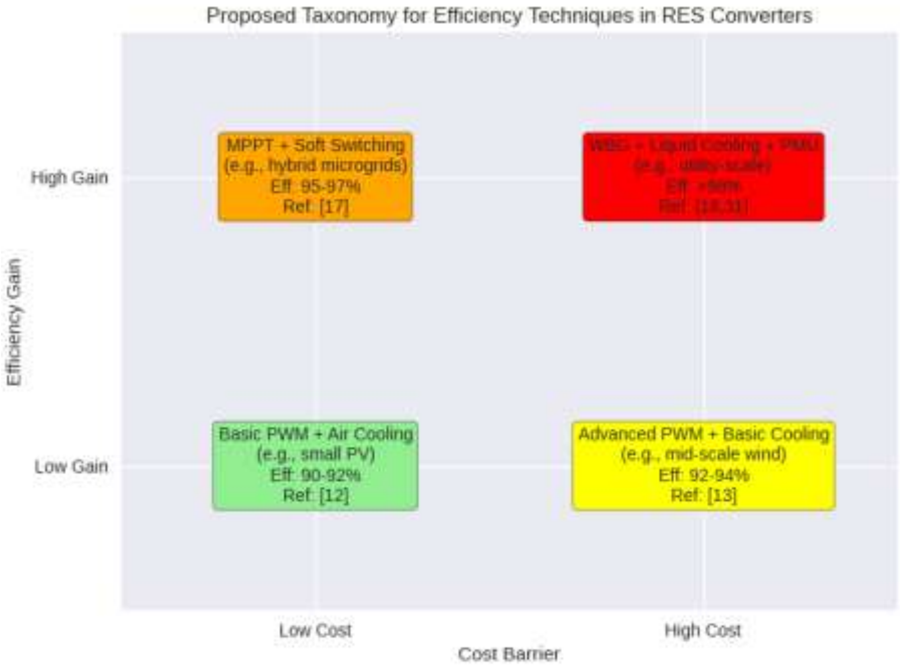

Figure 4: Proposed Taxonomy

3. RESEARCH GAPS

While significant progress has been made in the field of power electronics converters for renewable energy systems, several key research gaps still need to be addressed to further enhance their performance, reliability, and widespread adoption:

i. Wide-Bandgap Semiconductors: Although SiC and GaN devices offer significant advantages, their widespread use in high-power renewable energy applications (e.g., large-scale wind turbines, utility-scale solar inverters, HVDC transmission) is currently limited by their higher cost compared to silicon-based devices and challenges related to their integration, such as gate drive design, packaging, and EMI management at high switching frequencies**.** Future research could focus on cost reduction strategies, standardized integration guidelines, and the development of robust and efficient gate driver circuits and packaging techniques optimized for high-power wide-bandgap devices.

ii. Thermal Management: As power densities of converters increase, particularly with the adoption of wide-bandgap devices, effective and scalable cooling solutions become critical. Current thermal management techniques, especially for high-power converters operating in diverse and often harsh environmental conditions, still present limitations in terms of efficiency, size, weight, and cost**.** Further research is needed to explore novel cooling techniques, such as advanced liquid cooling systems, two-phase cooling, and integrated thermal management solutions, along with the development of accurate thermal modelling and prediction tools for these high-power applications.

iii. Advanced Control: While AI-based control algorithms show promise for optimizing the performance of converters connected to dynamic RES, their robustness, adaptability, and real-time implementation in rapidly changing conditions still require further development. Issues such as data availability, computational complexity, and the need for explainable and certifiable AI algorithms remain. Future research should focus on developing more robust, adaptive, and computationally efficient AI-based control strategies, exploring hybrid AI-classical control approaches, and addressing the challenges of real-time implementation and system validation.

iv. Reliability: Ensuring the long-term reliability and durability of power electronic converters operating in the often-harsh environmental conditions associated with renewable energy installations (e.g., extreme temperatures, humidity, dust, vibrations) is crucial for their economic viability. More comprehensive studies are needed to understand the long-term degradation mechanisms of components and systems under these conditions. Future research should focus on advanced reliability testing methodologies, predictive maintenance strategies based on condition monitoring, and the development of more robust and fault-tolerant converter designs.

v. Cost-Effectiveness: Despite the performance benefits of advanced converter technologies, their higher initial cost can be a significant barrier to the widespread adoption of renewable energy systems, particularly in price-sensitive markets**.** Future research should explore innovative design approaches, optimized manufacturing processes, and standardization efforts aimed at reducing the overall cost of high-performance power electronic converters without compromising their efficiency and reliability.

4. METHODOLOGY

This study uses a systematic literature review to examine the current state of power electronic converters in renewable energy systems. A PRISMA-guided approach was adopted to ensure rigor and objectivity. Searches were conducted in IEEE Xplore, Scopus, and Web of Science with the keywords: ("power electronics converter" OR "DC-DC inverter") AND ("renewable energy" OR "PV" OR "wind") AND ("optimization" OR "efficiency"), covering the period 2017–2024. The initial search yielded 85 records. After title and abstract screening, 56 duplicates and irrelevant studies were excluded. A full-text review resulted in 29 eligible papers, with inclusion criteria being peer-reviewed studies presenting empirical or simulation results, and exclusion criteria being pre-2017 publications or non-English works. Data synthesis was carried out using thematic coding and meta-comparisons (e.g., weighted average efficiencies). The main findings, was extracted and summarized in Table 3 to facilitate comparison and identification of trends.

Table 3: Summary of Key Literature

Study	Topology	Control	Efficiency Technique	Key Findings (e.g., % Gain)	Limitations
[12,13,20-23]	Buck-Boost	PWM	High-Freq. Op.	92% eff.; 10% ripple red.	EMI in high-freq.
[24-26]	Multilevel Inverter	MPC	ZVS	97% eff.; THD<3%	Comp. complexity
[27-29]	Hybrid	Fuzzy Logic	SiC Semis	96% eff.; 15% loss red.	Cost barrier

5. CONCLUSION

The integration of renewable energy sources (RES) into modern grids critically depends on advances in power electronics converters. This review examined 85 studies, highlighting recent progress in converter topologies, control strategies, and efficiency improvements. Multilevel converters and AI-based MPC controls offer 5–10% efficiency gains over conventional PWM, while wide-bandgap (WBG) devices achieve >98% efficiency in high-frequency applications. Despite these advances, challenges remain in scalability for high-power systems, thermal management, cost-effectiveness, and the limited empirical validation of simulation-based results. Current literature is also dominated by PV and wind, with hydro and other RES underexplored. Future research should focus on WBG-enabled converters, hybrid AI-classical control schemes for real-time applications, and scalable cooling solutions. Industry efforts must prioritize large-scale WBG fabrication to meet projected deployment targets. Addressing these gaps will accelerate the development of next-generation converters, enabling more sustainable and resilient RES integration in line with SDG7.

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A Green Revolution for Nigeria's Energy Sector: Engineering Solutions for a Carbon-Neutral Future

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Abstract: Rising sea levels, extreme heat conditions, incessant rainfall, droughts and flooding are majorly caused by climate change impacts and global warming. Nigeria is highly susceptible to the effect of climate change because of its energy sector (that is majorly dependent on fossil fuels). This work tends to evaluates sustainable decarbonisation of the country's energy sector through green energy solutions. It examines the existing green energy strategies and their level of implementation in transiting to a net-zero carbon environment. The barriers and challenges of decarbonisation of the energy sector were also identified. The work also discussed the need for a holistic green energy technology integration into the grid by meeting up to about up to about 60% of the nation's energy need by the year, 2050. Secondary data were used in evaluating the level of availability, utilization and adoption of green energy technologies. The study recommended adoption of energy efficient technologies, public-private partnership, effective policy reforms and drastic shift from fossil fuel-dominated economy to green energy economy, as necessary steps in meeting up with the global decarbonisation goals by the year, 2060. The research provides an invaluable insight for energy stakeholders and potential investors in promoting sustainable energy technologies.

Keywords: *clean energy, climate change, energy efficiency, green energy, net-zero emissions*

1. INTRODUCTION

Sustainable energy sector is essential for socio-economic growth of any nation. It fast-tracks industrial growth and activates economic activities. African continent faces numerous challenges in enhancing socio-economic growth and poverty eradication because of lack of access to clean modern energy services [1]. Energy sector globally, can be said to be responsible for about 75% of CO2 emissions all over the universe [2]. The devastating effects of climate change on human livelihoods, economies and ecosystems have accelerated the recent global decarbonisation drive. In the year, 2015 in Paris, Nigeria and more than 196 countries agreed to reduce global warming below 2^oC before the year, 2030 [2]. In order to achieve this laudable target, there is need for more drastic and holistic policies geared towards greenhouse gas emission [3].

Nigeria is highly vulnerable to the effect of climate change because of its energy sector (that is majorly dependent on fossil fuels). The country relies heavily on fossil fuels like oil, natural gas and coal. These contribute significantly to global climate change through emission of high volume of carbon dioxide into the atmosphere when used, resulting to high temperatures, high sea levels, polluted ecosystems and extreme weather events. About 250,000 people are estimated to die annually as a result of climate change related diseases between 2030 and 2050 [4]. Hence, the need to seek for alternative solution to fossil fuel dependence.

The country, at a conference of parties meeting held in Glasgow, pledged her commitment to transitioning from fossil-fuel dominated economy to net-zero carbon economy by the year, 2060 [4]. However, this commitment is seemly unrealistic with myriad of uncertainties despite numerous policy reforms targeted at achieving the goals. This target could be achieved by application of engineering principles, technologies and innovations, to reduce the already carbonised energy sector and also assist in transitioning to a more sustainable low-carbon economy [5].

Renewable energy sources (RES) like hydroelectric, biomass, solar, wind e.t.c are carbon-free (with no emission) and also present a unique opportunity for sustainable energy growth [6]. Adoption of RES technologies will enhance rapid economic growth, meeting energy demand, creating employment and promotion of socioeconomic activities. It is envisaged that RES will meet up with 60% of the nation's energy need by the year, 2050 [7].

The negative effects of climate change pose serious challenge on sustainability [6]. The country is highly prone to the effects of climate change. Climate change impacts like droughts, rising sea levels, intense heat have been witnessed in the country [7]. The country's Greenhouse gas emission sources can be broadly divided into energy sector, agricultural sector and waste management sector.

2. LITERATURE REVIEW

So many authors have worked on integration of RES technologies into the grid targeted at moving towards sustainable future energy system [1, 3, 5-11]. [8] used multilevel perspective to evaluate policy transition to low-carbon policies in Nigeria. The authors conducted the analysis by using reviewed literatures, relevant documents, theoretical, historical and empirical data. The findings showed that the present low-carbon transition process is characterised by various uncertainties and political barriers. The work recommended the use of natural resources in synergy with effective management system as the best policy in achieving carbon neutrality by the year, 2060.

[9] examined transition of Nigeria to net-zero emissions with deep discussions on its design and emerging technologies. Important sectors like agriculture, transportation, energy and industry were considered with emphasis on impact of sustainable practices, RES and energy efficiency in carbon emissions' reduction. The work highlighted the need for international cooperation, technical innovations and governmental support in attaining sustainable low-carbon future for the country.

[10] worked on development of the energy sector through integration of renewable energy and policy reforms. The study assessed the existing energy policies vis-à-vis its impact in achieving the universal electricity access goal by the year, 2030. [11] evaluated a sustainable decarbonisation process with special focus on the challenges and opportunities of construction sector. The author identified the policy gaps and recommended effective implementation strategies.

This work tends to evaluates sustainable decarbonisation of the country's energy sector through green energy solutions. It examines the existing green energy strategies and their level of implementation in transiting to a net-zero carbon environment. The work also discussed the need for a holistic green energy technology integration into the grid by meeting up to about up to about 60% of the nation's energy need by the year, 2050.

3. METHODOLOGY

This work used qualitative research technique in incorporating expert interviews, case studies, and in-depth comprehensive review of literature on the subject matter. Experts 'opinions were sought from relevant stakeholders in energy, transportation, environmental and industrial sectors in order to ascertain the most effective strategies in shifting from fossil-dominated economy to green energy economy. Relevant data were collected from different sources including government reports, publications and relevant stakeholders.

This work evaluates sustainable decarbonisation of the country's energy sector through green energy solutions. It examines the existing green energy strategies and their level of implementation in transiting to a net-zero carbon environment. The barriers and challenges of decarbonisation of the energy sector were also identified. The work also discussed the need for a holistic green energy technology integration into the grid by meeting up to about up to about 60% of the nation's energy need by the year, 2050. Secondary data were used in evaluating the level of availability, utilization and adoption of green energy technologies.

The country's CO2 emission profile as shown in Figure 1, revealed a steady rise 121.0 Mt CO2 eq,in 2016 to 130.0 Mt CO2 eq, in 2019 and observed to reduce from 130 Mt CO2 eq in 2022 to 128 Mt CO2 eq, in 2023. In the baseline projection, GHG emissions for Nigeria in 2030 are estimated to be 453 Mt CO2-eq representing a 31% increase in total GHG emissions from 2018, or a 2.6% annual increment in total GHG emissions consistent with historic trend [12-13].

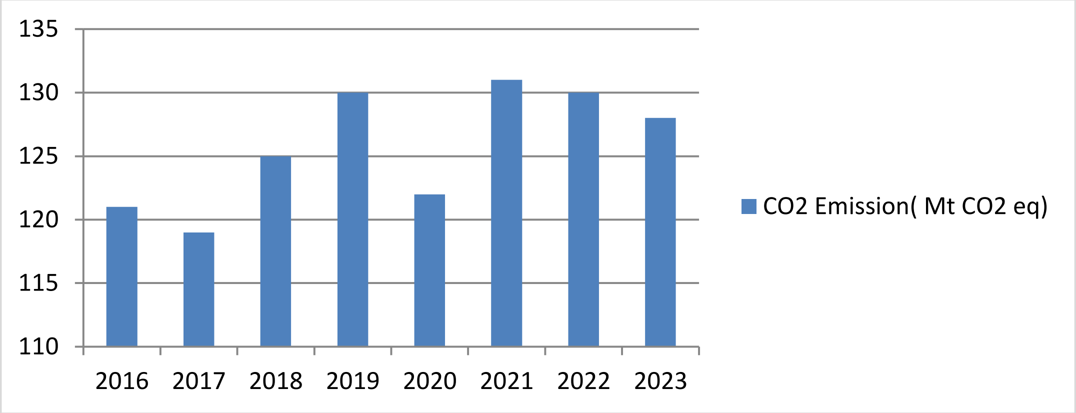

Figure 1: Nigeria’s Carbon dioxide Emission Profile in million metric tons of CO2 equivalent. [13]

3.1 Pathways to Net-Zero Emissions in Nigeria

Gradual emission reduction efforts are crucial in mitigating climate change effects in order to ensuring long-time sustainability of the energy sector. Decarbonisation of the energy sector requires a multi-faced strategies that include green energy solutions, policy/finance reforms and technical solutions, will help in achieving a sustainable energy future [9]. These are succinctly discussed in the subsequent subsections

3.1.1 Technical Strategies

These are technical strategies that can be applied to reduce carbonisation of the energy’s sector. They are succinctly discussed as follows:

(a) Transition to Renewable Energy Technologies: Deployment of RES technologies is crucial in reducing the dependence on fossil fuels. The use of RES technologies will reduce carbon emissions and also improve energy security. In order to achieve net-zero carbon emission by 2050, there is need for a stronger push towards green energy technology especially solar and wind energy [14-15].

(b) Energy Efficiency Improvements: Improved energy efficiency strategies will enhance emissions reduction. These are technologies and practices that help in reduction of energy consumption patterns in transportation, industries and buildings.

(c) Carbon Capture and Storage (CCS): Carbon Capture and Storage (CCS) technology refers to capturing of CO2 emission from industries and storing them under the ground to avoid being released into the atmosphere [16]. CCS technology can be used to absorb about 90% of CO2 in industrial sector. It offers a significant solution in mitigating emissions from large industries. CCS technology can play a vital role in the country’s oil and gas sector as it is effective in striking a balance between economic growth and environmental sustainability. How CCS works is as shown in Figure 2.

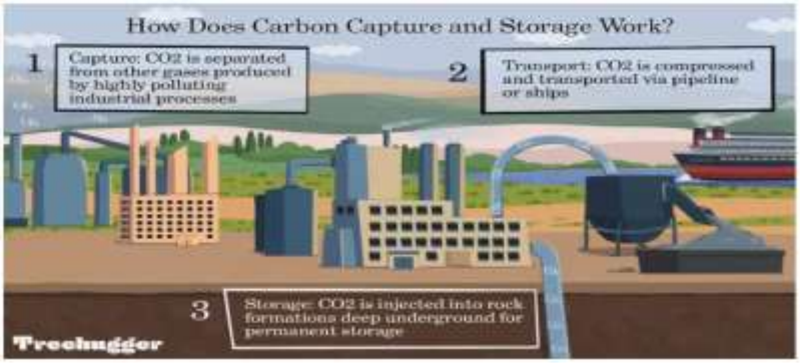

Figure 2: Carbon Capture and Storage system [16]

(d) **Shifting to Electric Vehicles (EVs)/ Compressed Natural Gas (CNG) in the Transportation sector:** Switching to Electric Vehicles (EVs) will significantly reduce pollution in the transportation sector. IEA [15] projected, that in order to achieve net-zero targets by 2030, the use of EVs must move from 5% to about 60% usage for all automobiles globally. Adoption of EVs in Nigeria requires large capital investment in adopting EV incentives and charging infrastructure. The use of other alternatives like hydrogen and CNG can be adopted in the interim, while EVs infrastructures are being installed. CNG vehicles emits less emission than petrol and diesel vehicles.

3.1.2 Policy and Finance Strategies

These are policy and finance strategies that can be applied to reduce carbonisation of the energy's sector. They are succinctly discussed as follows:

(a) Policy, Agreements and Regulations: As a result of Nigeria's international commitment to Paris Agreement, the country has pledged to reduce her emissions by 20% before 2030 [17]. This formed the basis for the country's carbon emission reduction strategy in formulating effective policies in achieving the global climate goals. Effective policies that promote the use of RES, clean energy, energy efficiency strategies, in militating the effects of climate change across transportation, industrial and agricultural sectors should be formulated.

(b) Carbon Pricing Mechanism (CPM): Introduction of Carbon Pricing Mechanisms (CPM), like carbon taxes can be used to discourage carbon emission. CPM is an essential tool for emission reduction in the industries.

(c) Circular Economy Practices (CEP): Circular Economy Practices (CEP) will reduce emission significantly. CEP involves reducing wastes and cycling of used materials, thereby creating a closed-loop transition system where introduction of new materials are created as energy inputs.

3.1.3 Moral and Societal Practices

These are moral and societal strategies that can be applied to reduce carbonisation of the energy's sector. They are succinctly discussed as follows:

(a) Enlightenment and Awareness Campaigns: Public awareness on the impacts of carbon emissions and the importance of sustainable practices is necessary for driving behavioural changes. Enlightenment campaigns about the benefits of energy conservation, sustainable energy growth and waste reduction will encourage individuals and corporate organisations to reduce their carbon emission habits.

(b) Corporate Social Responsibility (CSR) Partnership: Companies could be encouraged to invest in sustainable practices, to reduce their impacts on the environment. It will help in meeting up with regulatory requirements and in enhancing healthy competition towards global carbon reduction goals.

(c) **Sustainable Agricultural Practices and Food wastes reduction:** Transitioning to sustainable agricultural practices, like agroforestry and improved livestock management, will help in reducing emissions significantly. Food waste should also be reduced as it constitutes large amount of emissions globally.

3.2 Green Energy solutions and its Implementation strategies

Green Energy refers to clean source of energy like hydro, solar, wind and biomass. It generates lower environmental impact as compared to conventional energy sources like fossil fuels. It is scalable, unexhausted, has zero carbon emissions and provides highest net environmental benefits. Green Energy is crucial for sustainable development.

Nigeria is endowed with diverse RES and if effectively harnessed, can significantly contribute to the country's energy mix and reduce its dependence on fossil fuels [18]. The current status of some major RES in the country are as in Table 1. Some of the available green energy technologies in Nigeria are briefly discussed in the subsequent subsections.

Table 1: Nigeria's renewable energy development status

Energy source	Level of Growth	Major Development	Barriers/challenges
Hydropower (large and small)	About 29% contribution to the grid	Significant contribution to the national grid	Lack of technical expertise, high installation cost, lack of maintenance
Solar energy	Steady growth in off-grid solar technologies, street lighting, mini grids and rural electrification	Deployment reaching about 700 households	High installation costs, lack of local experts, low maintenance level and ineffective policies
Wind Energy	Insignificant or stagnant level of growth	Demonstration project centres	Low wind speeds in some parts of the country, lack of experts and lack effective policies
Biomass	Low level of growth	Insignificant development	Lack of technical experts, financial constraints and lack of awareness

(a) Hydro Energy: The country is naturally blessed with both Small Hydropower (SHP) and large hydropower resources. The country has the capacity to generate about 86,400 GWh of electricity every year, from its large hydropower resources with about 24 GW of exploitable capacity [19]. The existing hydropower installed capacity is less than 2400 MW, representing about 16% of its identified potential, highlighting the vast untapped potential in the country. The existing large hydropower plants are located at Kainji (760 MW), Jebba (570MW), and Shiroro (600 MW) hydropower stations. The country is also blessed with abundant SHP resources scattered all over the country in rural and urban centres. SHP technologies are reliable, cost-effective, scalable and sustainable [20].

(b) Solar Energy: The country is largely blessed with abundant solar energy resources almost everywhere due to its position to the equator. The solar radiation is relatively uniform all over the country, making it a viable option for both urban and rural electrification. The average solar radiation in the country is about 5.5 $kWh/m^2/day$, which is enough to produce about 427,000 MW of electricity [7]. Solar energy can contribute significantly to carbon emission reduction. It is clean, reliable and eco-friendly [20].

(c) Wind Energy: The nation is also blessed with vast wind energy resources. The estimated wind energy potential in Nigeria is around 11,000 MW [1]. This remains untapped due to so many investment and infrastructural challenges. The country has a vast opportunity for harvesting the available wind energy potential for electricity production.

(d) Biomass Energy: Biomass resources like animal dung, wood and agricultural wastes are abundantly available and possessed significant potential for energy production. Biomass serves a dual purpose of promoting improved waste management system and enhancing energy access [21]. It could be used to transform the energy sector through provision of sustainable energy alternative to fossil fuels, through green energy and thereby discouraged dependence on imported energy.

4. CHALLENGES AND OPPORTUNITIES OF THE NIGERIA'S ENERGY'S SECTOR DECARBONISATION

Decarbonisation of the energy sector in the country is confronted with so many challenges and barriers. One of the major constraints is the high cost of implementing the available carbon reduction strategies (as discussed in section 4) and its potential impacts on the economy [22]. Moreover, the need for economic growth (which solely dependent on fossil fuels) and at the same time reduce carbon emission presents a very difficult challenge. Reducing carbon emissions could lead to low-income generation, economic disruptions and job loss, making it difficult to achieve emission reduction goals without destroying the economy. Some of the identified barriers and challenges of towards decarbonisation of the energy's sector are discussed succinctly in the following subsections.

(i) High Costs of Renewable Energy Technologies

The relative high capital cost on RES technologies compared to the conventional fossil fuels serves as a major technical constraint. This serves as a discouragement to low-income earners, who cannot afford the high cost of installation. Moreover, the absence local expertise in manufacturing and maintenance of RES equipment makes the situation more difficult by making more people to depend on imported technologies. This can be costly and not easy to maintain.

(ii) Lack of awareness and information

Many people (especially the rural dwellers) are not aware of the numerous benefits inherent on the adoption of RES technologies. There is limited information /communication on how low-carbon technologies can be used to lower electricity costs, contribute positively to environmental sustainability and also improve energy security. Some people even have wrong perception that these technologies are too costly, unreliable and impractical. Moreover, transition to renewable energy and energy-efficient technologies may be met with strict opposition from communities due to their traditional belief and culture.

(iii) Insufficient Investment and Financial Support

There is a lack of lack of substantial financial support for low-carbon projects. There is need for provision of financial incentives to attract local investors especially during this hard economic dispensation [23].

(iv) Political challenge and Lack of Policy Frameworks

Policy inconsistencies and lack of political will could lead to weak enforcement of environmental regulations and slow progress on climate initiatives [24]. Most of the policies formulated were not strictly implemented. The absence of a robust regulatory framework to support renewable energy investments and energy efficiency measures further complicates the economic landscape for low-carbon technologies [25]. Political and social challenges also play a critical role in the difficulties associated with carbon emission reduction in Nigeria.

5. CONCLUSION AND RECOMMENDATIONS

Sustainable decarbonisation of the country's energy sector through green energy solutions is evaluated in this work. It examined the existing green energy strategies and their level of implementation in transiting to a net-zero carbon environment. The work also discussed the need for a holistic green energy technology integration into the grid by meeting up to about up to about 60% of the nation's energy need by the year, 2050. The barriers and challenges of decarbonisation of the energy sector were also identified.

The study recommended adoption of energy efficient technologies, public-private partnership, effective policy reforms and drastic shift from fossil fuel-dominated economy to green energy economy, as necessary steps in meeting up with the global decarbonisation goals by the year, 2060. Hence, energy generation should be diversified and distributed for green economy and sustainable national development. Diversifying the Economy will encourage the development of non-oil sectors, such as agriculture, manufacturing, and renewable energy, to manage the risks associated with declining fossil fuel revenues.

The research provides an invaluable insight for energy stakeholders and potential investors in promoting sustainable energy technologies. The findings of this work could serve as guide to stakeholders in the energy industry in Nigeria and other African countries saddled with similar ambition of building a prosperous economy, a climate resilient and reliable energy future.

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A Review of Security Threats on SCADA System and Development of Countermeasures in a Smart Grid Environment for Nigeria's Power Sector

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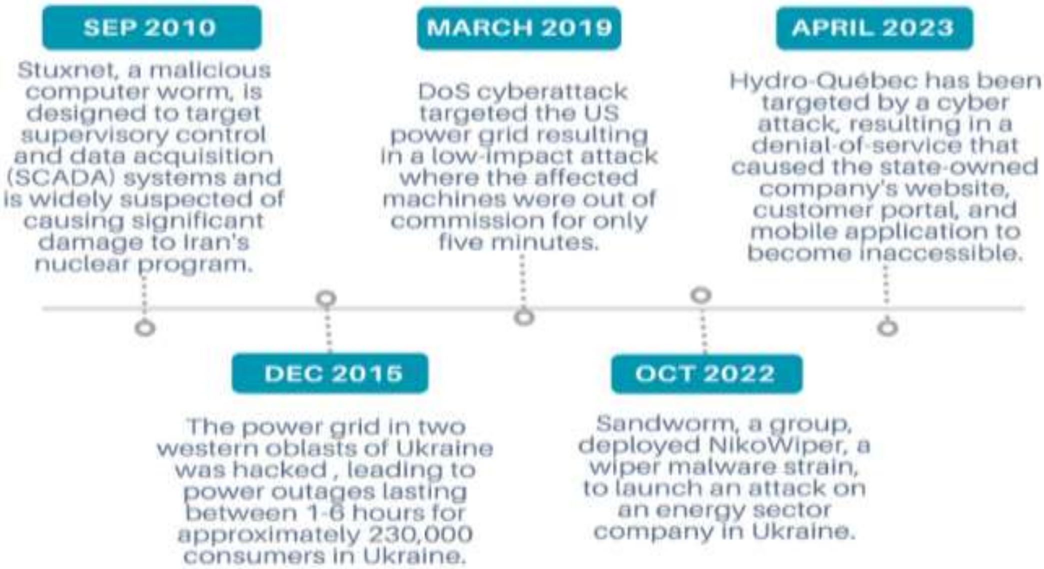
Abstract: The escalating global insecurity also poses significant threats to cyber physical systems which serve as critical national infrastructure such as the electrical grid. The modernization of the traditional power grids into smart grids while offering enhanced efficiency and reliability concurrently, introduces new vulnerabilities particularly concerning Supervisory Control and Data Acquisition (SCADA) system. SCADA system is the backbone of smart grid operations that interacts between physical, network and computational processes to monitor and control distributed assets via a central data acquisition and supervisory control in industries such as power, oil and gas, water, pharmaceutical, chemicals and manufacturing plants, telecommunication, transportation, pipelines and so on. It comprises of hardware, software and communication links. The interconnectivity of the SCADA system with the internet and the world wide web (www) introduces it to security threats. Of recent, environmental and adversarial threats have substantially been on the increase which has led to disruptions, loss of performance and recovery time or a combination of these elements. This paper focusses on providing a comprehensive analysis on the evolving security threats on SCADA systems including cyber and physical threats that are exploited with a view to developing robust countermeasures and solutions such as intrusion detection and prevention system (IDPS). Multilayered approaches can be employed to divide the main utility grid to individualize microgrids and collaborating with others during emergency. Also, this paper will serve as a starting point for future research to enhance and advance cybersecurity frameworks, regulatory compliance and the imperative for international collaboration in the energy sector in Nigeria's smart grid.

Keywords: Smart grid, SCADA System, Intrusion Detection System (IDS), Intrusion Prevention System (IPS), Security threat, Countermeasures.

1. INTRODUCTION

The modernization of the electric grid with more communication links also creates security aspects on a broader scale. This digitization of the grid infrastructure, creates a smart grid which denotes a system of electricity generation, distribution, and consumption that controls appliances to save energy intelligently, reduce cost, increase reliability, as well as transparency. The smart grid enables a constant connectivity and a two-way communication with the essential devices for great capabilities. At the heart of this transformation lies the Supervisory Control and Data Acquisition (SCADA) system, which provides the real-time monitoring and control necessary for managing vast and complex energy networks. It enables operators to remotely control power generation, transmission, and distribution assets, optimize load balancing, and respond rapidly to faults. The connected devices are interlinked in a bigger complex network which are employed with smart devices like smart meters (Abdella& Shuaib (2018); Khalil *et al.,* (2021)) which creates communication between the utility and the consumers. However, while this increased connectivity and digitalization is beneficial it also simultaneously introduces unprecedented security attacks like radio jamming, eavesdropping, man-in-the-middle (MitM), spoofing, replay, and malicious code injection and it takes place in the absence of physical access to the device utility demonstrating it as one of the best communicated frameworks. These security threats are in the form of Denial of service (DoS), replay attacks (RA), time delay attacks (TDA), time synchronization attacks (TSA), false data injection attacks (FDIA), load redistribution attacks (LRA), Malicious command injection, and Malware attacks. Understanding and identifying these potential security threats which may suffice from the various types of attackers, including state-sponsored hackers, insider threats, physical saboteurs, and proxies and hybrid tactics which is a combination of cyber and physical operations is paramount to avert economic losses due to blackouts and disruptions of vital infrastructure. Also, sensitive data can be lost, such as customer and company information. Power grids as vital national assets have become prime targets for malicious actors seeking to disrupt economies, sow chaos or gain strategic advantage (Tariq *et al.,* 2023). Attacks on power grids such as those witnessed in Ukraine or the attempted infiltration in the United States underscore the severity of these threats (Kaspersky, 2023). It has become expedient to safeguard the SCADA system due to the prevalence andcomplexities of security threats on smart grids. The prevalence of such attacks can be seen in figure 1.



SEP 2010

Stuxnet, a malicious computer worm, is designed to target supervisory control and data acquisition (SCADA) systems and is widely suspected of causing significant damage to Iran's nuclear program.

DEC 2015

The power grid in two western oblasts of Ukraine was hacked , leading to power outages lasting between 1-6 hours for approximately 230,000 consumers in Ukraine.

MARCH 2019

DoS cyberattack targeted the US power grid resulting in a low-impact attack where the affected machines were out of commission for only five minutes.

OCT 2022

Sandworm, a group, deployed NikoWiper, a wiper malware strain, to launch an attack on an energy sector company in Ukraine.

APRIL 2023

Hydro-Québec has been targeted by a cyber attack, resulting in a denial-of-service that caused the state-owned company's website, customer portal, and mobile application to become inaccessible.

Figure 1. Timeline and history of industrial and energy-producing facilities cybersecurity attacks (Achaal *et al.,* (2024)

The recent report from OT cybersecurity company Dragos (Dragos Report, 2024), identified 18 active threat groups whose targets are on the electric power industry, and stated that Distributed Energy Resources are an “increasingly viable attack vector”. However, the report did not mention attacks that are successful of recent, they are of the opinion that the rise in ransomware attacks against the sector can be seen as in the case of Maersk (Abbatemarco, Salviotti, D’Ignazio, & De Rossi, 2024), malware that appears to be ransomware can cause damage as devastating as an active, online attacker.

This paper aims to evaluate and provide a comprehensive security threats analysis on SCADA systems and using detective and preventive measures as well as threat modelling as robust countermeasures to mitigate their processes and operations. It will further emphasize the need for a holistic, multi-layered security strategy that encompasses technological, procedural, and collaborative dimension as recommendations for systems in the future.

2. THE SMART GRID AND SCADA SYSTEM OVERVIEW

The smart grid is the next generation power grid in which electricity is managed and distributed in advanced two-way communication systems. It delivers power from suppliers to consumers in a way that it controls intelligent appliances to save energy, reduce cost, increase reliability, as well as transparency (Ye& Qian, 2012.). Figure2 shows the smart grid architecture model (Standards 2021) developed by NIST. It is comprised of the following: customer, markets, service provider, operations, transmission, distribution, and bulk generation.

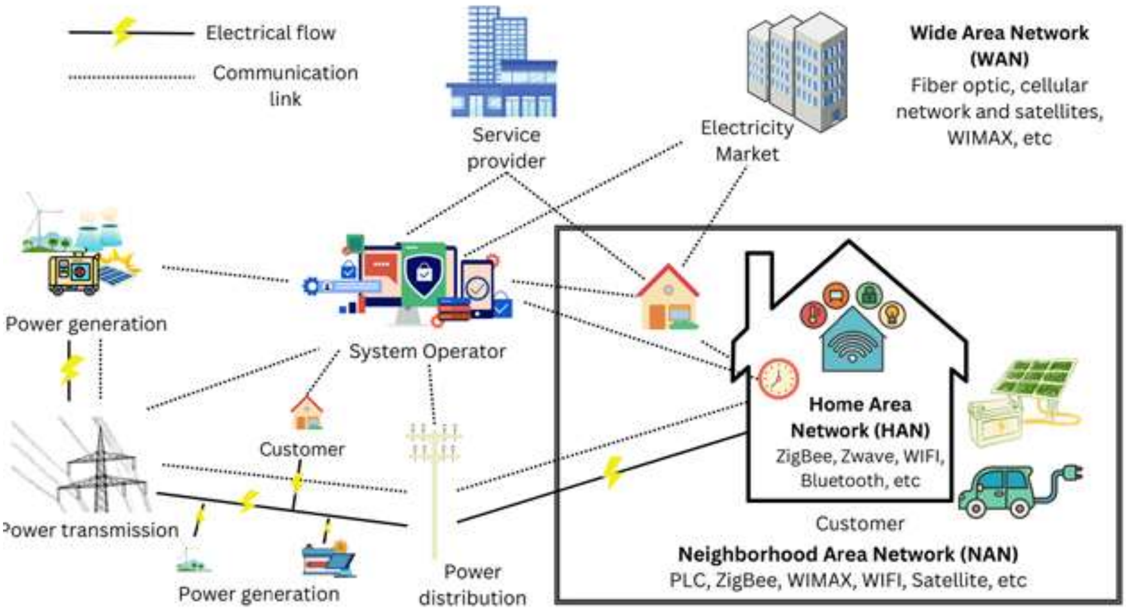


Figure 2. Smart Grid Architecture (Achaal *et al.,* 2024)

The transmission of power is ensued to the distribution centres where they are organized into concentrations for onward delivery in accordance to the consumer classification like households, universities, businesses and others. There are five key factors to consider for the efficient operation of the smart grid: communications, smart metering, distributed energy resources, monitoring and controlling (Lopez *et al.,* (2015); Knapp (2011)). Communication across the power line uses feeder section lines as a medium between consumers and utilities (Lopez *et al.,* (2015). Communication between devices can be through microwave channels, fiber-optic links, wireless, Ethernet, as well pilot wire cables, where several bandwidths are realized (Horowitz& Phadke 2008)).

What characterizes the SG are three major components: i.e., grid, service provider, and customers. Also, the communication among these components which is govern by the different channels and protocols. Figure 3 shows the characteristics of the SG system.

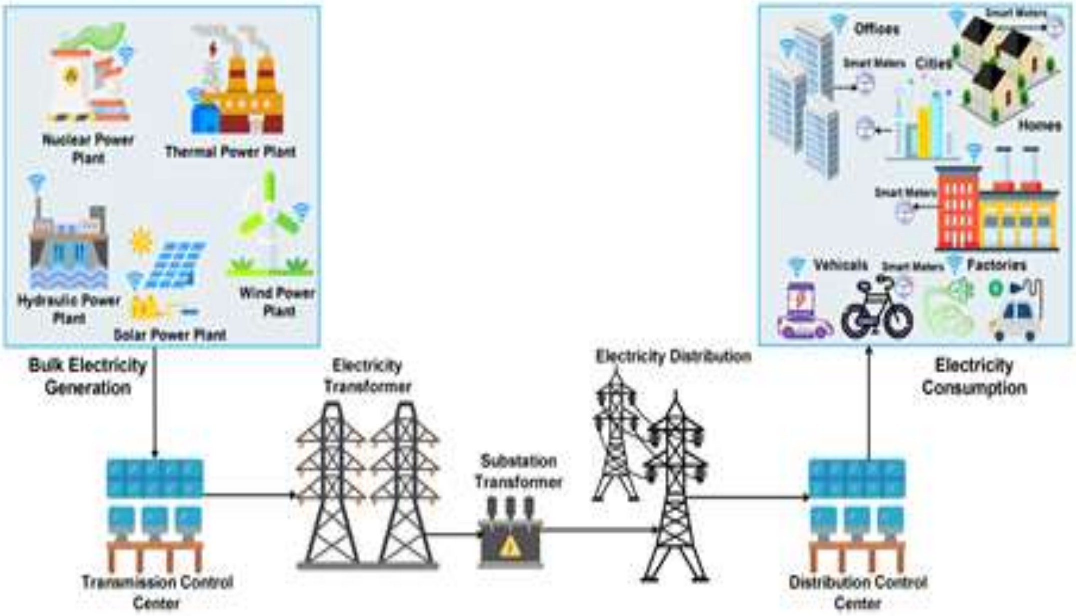


Figure 3. Characteristics of smart grid (Dinget *al.,* 2022)

2.1 THE SCADA SYSTEM

Supervisory control and data acquisition (SCADA) defines standards for the operation, monitoring and controlling of grid industrial processes (Taylor (2006); Galloway & Hancke (2012)). Its geographical coverage is vast which differentiates it from the Distributed Control System (DCS) found at plant sites.But, SCADA systems and DCSs often work together. This is what takes place in the electric power control centers and electric power generation facilities. Even-though the electricity power generation facility operation is controlled by the DCS, the DCS communication with the SCADA is invariable for coordination between production output, transmission and distribution demands.

The SCADA system is basically made up of the following component parts:

i. **Human-Machine Interface (HMI)**: This makes up the operator workstations.
ii. **Master Terminal Unit (MTU)**: This is the central server that communicates with Remote Terminal Units (RTUs) or Programmable Logic Controllers (PLCs). The host computers serve as central point to monitor human and control processes, store databases, and display statistical control charts and reports. They are also called Master Terminal Unit (MTU), SCADA server, or PC with Human Machine Interface (HMI).
iii. **Communication Network**: The links connecting all components (e.g., fibre optics, radio, cellular, IP-based networks).
iv. **Remote Terminal Units (RTUs) and Programmable Logic Controllers (PLCs)**: These are devices that interface directly with physical equipment (e.g., circuit breakers, transformers, sensors).
v. **Sensors and Actuators**: These are devices that measure physical parameters and perform control actions.

SCADA system architecture comprising all the component parts is shown in Figure 4.

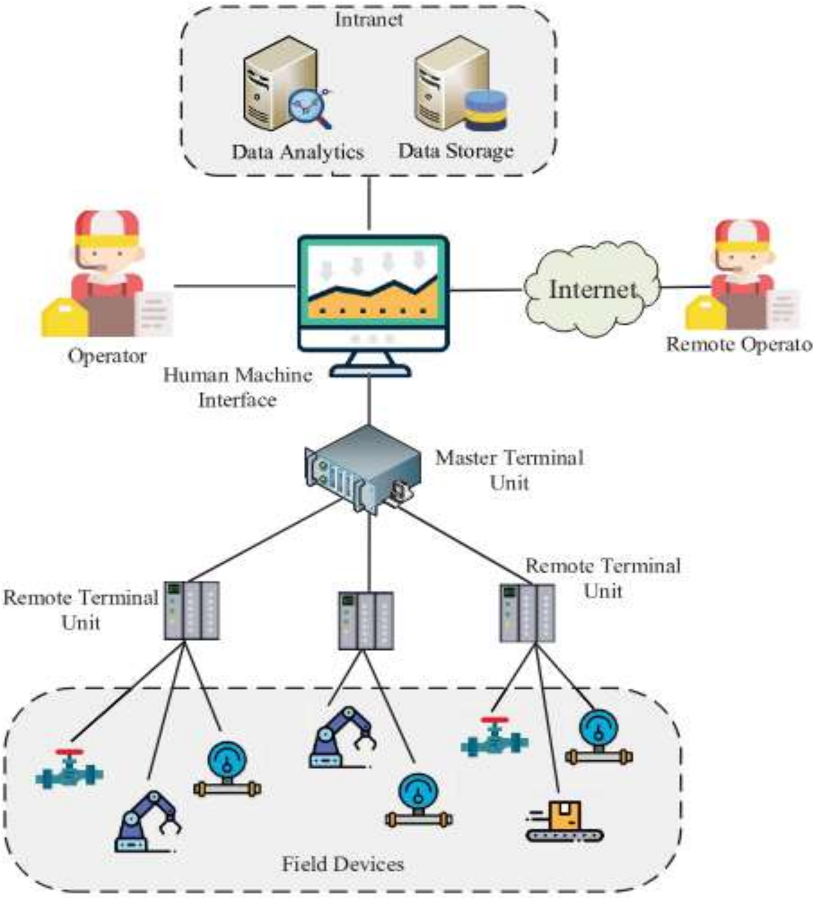


Figure 4: SCADA System Architecture (Pliatsios *et al.,* 2020)

In Nigeria, the fixing of H1 2025 announces the launch of SCADA System an advanced technology that will address some of the issues holding down the power sector (ThisDayLive, 2024). It goes further to state that “the SCADA system will enable us to monitor the entire electricity network from a centralized location, thereby ensuring the prompt response to outages, manage loads efficiently and optimize the overall performance of our power system. The introduction of SCADA is part of our strategic efforts to modernize our power infrastructure and implement smart grid technologies.”

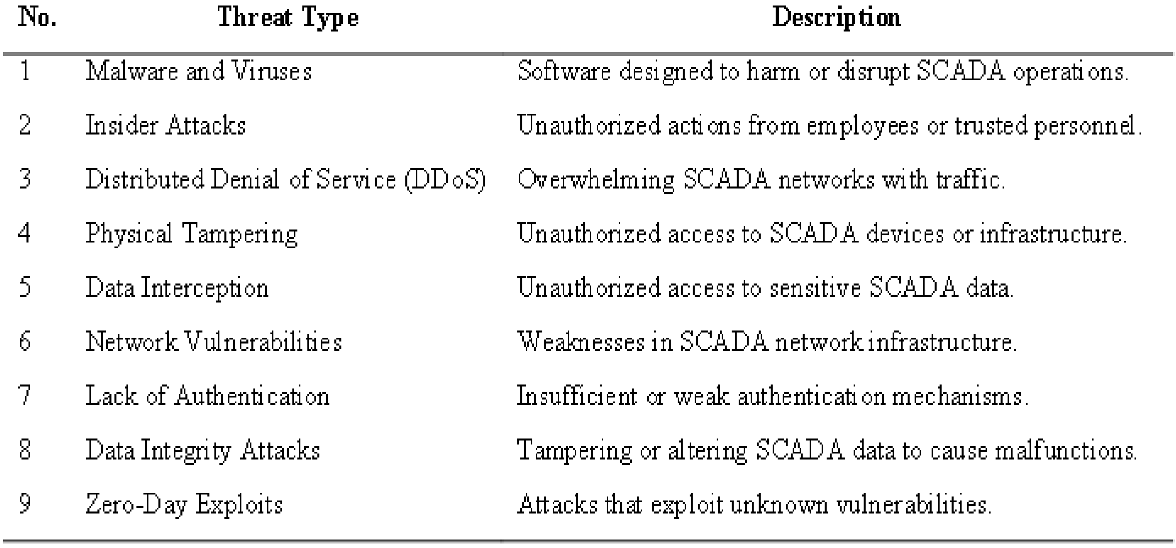
2.1.1 Key aspects of the SCADA system

1. **Centralized Monitoring:** SCADA enables a central environment for monitoring the whole electricity network thus to facilitate the efficient management and speedy response to problems.
2. **Real-time Data Acquisition:** The collection and analyzes of data from the different points in the grid enables for the prompt identification and addressing of the problems.
3. **Improved Response Times:** It will enable the remote control and automation of data collection and help in the reduction in the time to respond to faults and outages in the grid.
4. **Modernization of Infrastructure:** It is one of the important parts of the modernization of the grid system as it opens the way for smart grid technologies and the improvement of the grid stability.
5. **Attracts Investment:** This is achieved through the reliability in the power supply thereby attracting investments from the private sector and fostering innovation in the energy market.
6. **Reduction in Grid Collapse:** The system will reduce the frequency of collapse of the grid and improve the total reliability of electricity supply.
7. **Integrated with Specific Applications and Distributed Systems:** SCADA system integrates other systems such as Geographic Information System (GIS) and Outage Management Systems (OMS) for improved functionality. Also, the Distribution Management System of SCADA creates roomto monitor and control distribution substation, improves efficiency and reduces losses.
8. **Remotely Monitoring Capabilities:** The utilization of the web allows for the monitoring of power flow from any location.

2.2 Key Vulnerabilities Introduced by Smart Grid Integration

The convergence of Operational Technology (OT) (SCADA) with Information Technology (IT) in the smart grid creates several new points of vulnerability. This was asserted by (Vallant *et al.,* 2021; AbuEmera *et al.,* 2022; Xiong *et al.,* 2022) that the current fusion of operating technologies with cyber systems has opened unrestrained access to cyberattacks. Several potential threats to SCADA systems worthy of note include the following and are summarily presented in Table 1.

Table 1: Security Threats on SCADA System and their description



No.	Threat Type	Description
1	Malware and Viruses	Software designed to harm or disrupt SCADA operations.
2	Insider Attacks	Unauthorized actions from employees or trusted personnel.
3	Distributed Denial of Service (DDoS)	Overwhelming SCADA networks with traffic.
4	Physical Tampering	Unauthorized access to SCADA devices or infrastructure.
5	Data Interception	Unauthorized access to sensitive SCADA data.
6	Network Vulnerabilities	Weaknesses in SCADA network infrastructure.
7	Lack of Authentication	Insufficient or weak authentication mechanisms.
8	Data Integrity Attacks	Tampering or altering SCADA data to cause malfunctions.
9	Zero-Day Exploits	Attacks that exploit unknown vulnerabilities.

2.3 Development of Counter measures in a Smart Grid Environment

Countermeasures have become necessary in the current integrated infrastructure as IP is commonly used to simplify integration of the many parts of the grid and makes communication more standardized. Any successful set of countermeasures or complete security system needs to have multiple defensive mechanisms and multiple detection points multi-layered and continuously evolving strategy. Current security mechanisms must span technological defences, robust operational procedures, strong regulatory frameworks and collaborative initiatives.

(i) Technological Countermeasures

(a) Network Segmentation and Isolation (Defense-in-Depth): Implementing strong segmentation between IT and OT networks using firewalls, demilitarised zones (DMZs), and virtual local area networks (VLANs). This limits the lateral movement of attackers if one segment is compromised (Ghasemi *et al.,* 2022).

(b) Robust Authentication and Access Control: Implement a Multi-Factor Authentication (MFA) for all remote and privileged access to SCADA systems and critical data; Apply the Principle of Least Privilege (PoLP), ensuring users and systems only have the minimum necessary access rights required to perform their functions (Kumar *et al.,* 2023); Implement Role-Based Access Control (RBAC) to manage permissions systematically.

(c) Encryption and Secure Communication Protocols: Encrypting all sensitive data in transit and at rest, particularly communication between MTUs, RTUs, and HMIs, to prevent MitM attacks and data interception.

(d) Intrusion Detection and Prevention Systems (IDPS): Deploy IDPS specifically designed for OT environments that can monitor industrial protocols for anomalies, known attack signatures, and suspicious behaviour; Implement Security Information and Event Management (SIEM) systems to aggregate and analyze security logs from across the IT and OT infrastructure, facilitating rapid threat detection and response (Tariq *et al.,* 2023).

(e) Endpoint Security and Patch Management: Implement a robust antivirus/anti-malware solution on all HMI, engineering workstations, and servers. Establish a rigorous patch management program for all operating systems, applications, and firmware. This includes vendor coordination for OT-specific patches (Ghasemi *et al.,* 2022).

(f) Data Backup and Disaster Recovery: Regularly back up critical SCADA configurations, historical data, and software. Develop a comprehensive disaster recovery plan to quickly restore operations in the event of a cyberattack or physical incident.

(ii) Threat Modeling

This is revealing the vulnerabilities and weaknesses with systems for a proactive mitigation of the risk. The processes are: understanding the system's architecture, components, and communication protocols, identifying potential threat vectors, and recognizing various threat actors, from external hackers to insider threats. Figure 5 shows the phases of threat modeling method.

Figure 5: Phases of threat modeling method (Fla *et al.,* 2025)

(iii) Operational and Procedural Countermeasures

Incident Response Planning: Develop a detailed incident response plans for various cyber and physical attack scenarios. This includes clear roles, responsibilities, communication protocols, and steps for containment, eradication, and recovery (Ebrahimi & Al-Khalifa, 2022); Regularly conducting tabletop exercises and simulations to test and refine these plans.

Employee Training and Awareness: Conduct continuous cybersecurity awareness training for all employees, especially OT personnel, on phishing, social engineering, secure remote access, and incident reporting; Training on best practices for safe operational procedures, including physical security protocols.

Supply Chain Risk Management: Vet vendors for their security practices and capabilities; Conduct security audits of third-party hardware and software components before deployment; Implement strict controls for accessing and updating software from external sources (Ebrahimi & Al-Khalifa, 2022).

(iv) Regulatory Frameworks and Standards

Compliance with Industry Standards: Adhere to critical infrastructure cybersecurity standards such as NIST Cybersecurity Framework, IEC 62443, and sector-specific regulations like NERC CIP (North American Electric Reliability Corporation Critical Infrastructure Protection) (Tariq et al., 2023). These provide structured guidelines for managing cybersecurity risks.

Governmental Oversight and Funding: Establishing clear governmental policies and providing funding for cybersecurity research, development, and implementation in critical infrastructure sectors; Facilitating threat intelligence sharing platforms between government agencies and industry stakeholders.

(v) Collaboration and Information Sharing

Public-Private Partnerships: Foster collaboration between government agencies, utilities, cybersecurity firms, and academic institutions to share threat intelligence, best practices, and research findings (Kaspersky, 2023).

International Cooperation: Given the transnational nature of cyber threats, international cooperation is vital for sharing threat intelligence, coordinating responses, and developing common cybersecurity standards for critical infrastructure protection; The development of countermeasures is not a one-time activity but an ongoing process of adaptation and improvement, requiring continuous investment, vigilance, and collaboration to safeguard the integrity and resilience of smart grid operations.

3. FUTURE OUTLOOK

The future of SCADA security in smart grids will be defined by a greater reliance on advanced technologies, intelligence-driven defence, and a proactive, resilient posture.

Artificial Intelligence (AI) and Machine Learning (ML) for Defence: AI/ML will play an increasingly critical role in anomaly detection, predictive threat intelligence, and automated incident response. AI can analyze vast amounts of network traffic and system logs to identify subtle indicators of compromise that human analysts might miss (Tariq et al., 2023).

Cyber-Physical Security Convergence: A deeper integration of cyber and physical security measures will be crucial. This includes using physical security data (e.g., access logs, video surveillance) to inform cyber threat detection and vice versa.

Blockchain Technology: Exploring blockchain for secure, decentralized, and immutable record-keeping for data integrity, authentication, and supply chain verification in smart grid transactions and component provenance (Kumar et al., 2023).

Quantum-Resistant Cryptography: As quantum computing advances, the development and deployment of quantum-resistant cryptographic algorithms will be essential to protect sensitive grid communications from future decryption capabilities.

Resilience Engineering: The shift from purely preventative measures to a greater emphasis on resilience, entails the ability of the grid to withstand attacks, adapt, and recover quickly. This includes designing self-healing capabilities and robust backup systems.

Advanced Threat Intelligence Sharing: Enhanced mechanisms for real-time, actionable threat intelligence sharing across nations and between public and private sectors, enabling a more unified and rapid defense against sophisticated adversaries.

The challenges are significant, but the continuous innovation in cybersecurity coupled with a strategic, collaborative, and forward-looking approach will be vital in safeguarding SCADA systems and ensuring the reliable operation of smart grids in the face of escalating global insecurity.

4. CONCLUSION

The transformation of traditional power grids into smart grids, driven by the imperatives of efficiency and sustainability, has inadvertently exposed the foundational SCADA systems to an unprecedented array of threats. In an era of escalating global insecurity, these systems are increasingly targeted by sophisticated cyberattacks, susceptible to physical sabotage, and vulnerable to insider threats. The inherent interconnectedness, reliance on legacy infrastructure, bad practices, spying and widespread adoption of open protocols within the smart grid environment magnify these risks, potentially leading to catastrophic disruptions of critical national infrastructure.

This paper has meticulously reviewed to analyze the diverse threat landscape, ranging from highly destructive malware campaigns like Industroyer to the insidious risks posed by insider complicity and vulnerable supply chains. The potential consequences of successful attacks extend beyond economic damage to include widespread societal chaos and threats to public safety. However, the response to these challenges is evolving with equal urgency and sophistication. The development of multi-layered countermeasures is paramount, encompassing robust technological defences such as stringent network segmentation, multi-factor authentication, advanced encryption, and intelligent intrusion detection systems. These must be complemented by rigorous operational procedures, including comprehensive incident response planning, continuous employee training, and vigilant supply chain risk management. Furthermore, adherence to robust regulatory frameworks and fostering proactive collaboration both nationally and internationally—are indispensable for building collective resilience.

Looking ahead, the integration of Artificial Intelligence and Machine Learning promises to revolutionize SCADA security, enabling predictive threat intelligence, automated anomaly detection, and enhanced resilience. The future of smart grid security will hinge on a proactive, adaptive, and highly intelligent defense posture, ensuring that the benefits of a modernized grid are realized without compromising its fundamental reliability. Electrical engineers, cybersecurity specialists, and policymakers must continue their collaborative efforts to design, implement, and maintain the secure, resilient power systems that are vital for global stability and prosperity.

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Optimisation of Smart Grid Energy Efficiency in Power Distribution Network

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Abstract: Loss reduction, power factor correction, and voltage profile improvement are critical goals for modern power distribution networks, essential for enhancing energy efficiency and reliability. This study investigates the optimisation of smart grid efficiency by analysing load profiles from four 11 kV feeders and simulating the integration of shunt capacitor banks using MATLAB/Simulink. Four cases were evaluated: a base system without capacitors, uncontrolled capacitor placement, time-controlled capacitors at load points, and time-controlled capacitors at substations. Results show that uncontrolled capacitor placement improved power factor but caused overvoltage beyond 1.10 pu, while substation-based control produced unstable voltage regulation (0.91–1.07 pu). The optimal configuration—time-controlled capacitors at load points—maintained voltage within statutory limits (0.95–1.05 pu), reduced line losses by approximately **18–22%**, and improved the average power factor from **0.82 lagging to 0.98**. These improvements translate to significant energy savings and enhanced operational stability for the distribution network. The findings highlight that appropriately timed, load-level capacitor switching is a practical, low-cost strategy for energy efficiency optimisation in smart grids, with direct implications for reducing operational costs.

Keywords: *Capacitor bank, Energy Efficiency, Power Factor, Smart Grid, Voltage Profile*

1. INTRODUCTION

Energy efficiency is a critical aspect of modern power systems, offering a sustainable approach to enhance grid performance and reduce environmental impact. Rising global energy demand, integration of distributed energy resources, and concerns over climate change make robust efficiency strategies in distribution networks increasingly urgent [1–3]. In an ideal system, energy delivered from transmission matches consumption at the distribution end. However, real-world systems suffer losses, especially in distribution networks, leading to higher operational costs and greenhouse gas emissions [4].

The transition from traditional grids to smart grids, enabled by Advanced Metering Infrastructure (AMI), Supervisory Control and Data Acquisition (SCADA), and other ICT tools, opens new avenues for improving energy efficiency. Yet, optimising efficiency remains challenging due to inductive loads, which lower bus voltage and increase current flow, intensifying losses [5].

A proven method to mitigate these issues is the use of **capacitor banks** to supply reactive power and enhance voltage profiles [6]. Most studies, however, focus on static or uncontrolled placements. This work addresses the research gap by investigating **time-controlled switching of capacitor banks** to optimise voltage profiles and reduce energy losses. Proper timing and placement of capacitor banks can significantly improve network performance, providing a practical solution for smart grid energy efficiency optimisation.

Previous studies show mixed outcomes. For example, [5] installed shunt capacitor banks at a high-voltage substation, improving upstream voltage profiles, power factor, and loss ratios, but downstream performance deteriorated due to differences between the Voltage Regulation Coefficient for Reactive Power (VRCQ) and that for Active Power (VRCP). Other works explored control strategies, such as modern protective relay-based switching [7], fuseless capacitor bank modelling using MATLAB [8], and optimization-based placement using Particle Swarm Optimization (PSO) [9] or Genetic Algorithms (GA) [10, 11]. Coordination between Transmission System Operator (TSO) and Distribution System Operator (DSO) optimisers has also been investigated to improve convergence and accuracy [12].

Unlike prior studies, this work evaluates **time-controlled capacitor banks in distribution networks** to optimise voltage profiles while preventing overvoltage and leading reactive power flow. The optimisation strategy is tested through simulations across four cases. Results indicate that Case Three, which applies time-controlled capacitors at the load, offers superior voltage regulation and energy efficiency.

The rest of the paper is structured as follows: Section 2 explains the methodology, Section 3 presents results and discussion, and Section 4 provides concluding remarks.

2. METHODOLOGY

In the smart grid, new technologies that have not been introduced in the grid before are being introduced to improve the efficiency of the network. To access the impact of these technologies it is necessary to develop system-level models for simulation.

A. Simulation

MATLAB and Simulink were employed as the primary tools to develop a simulation framework for evaluating smart grid efficiency across the transmission and distribution interface [13]. MATLAB provides a high-level programming environment, while Simulink offers a graphical block diagram approach for modelling dynamic systems, making it suitable for power system simulations involving control, switching, and time-domain analysis.

The simulation model uses a **quasi-steady-state approach** implemented with rapid prototyping MATLAB scripts [14]. This approach captures only essential system operating points, reducing computational time while maintaining sufficient accuracy for steady-state performance evaluations. It is ideal for analysing voltage profiles, power factor correction, and reactive power compensation, which do not require high-resolution transient details.

This modelling strategy also allows fast export of results in multiple formats, such as time-domain waveforms and numerical arrays, supporting flexible post-processing and analysis. The simulation environment enables easy reconfiguration of the network by incorporating switches, sectionalisers, and control logic, making it suitable for testing various capacitor bank switching strategies under different load conditions.

Figure 1 illustrates the Simulink model of the power distribution network developed in this study. The model integrates key components, including 11 kV feeders, load profiles, capacitor banks, circuit breakers, and control units, to replicate a realistic distribution network for testing energy efficiency optimisation strategies.

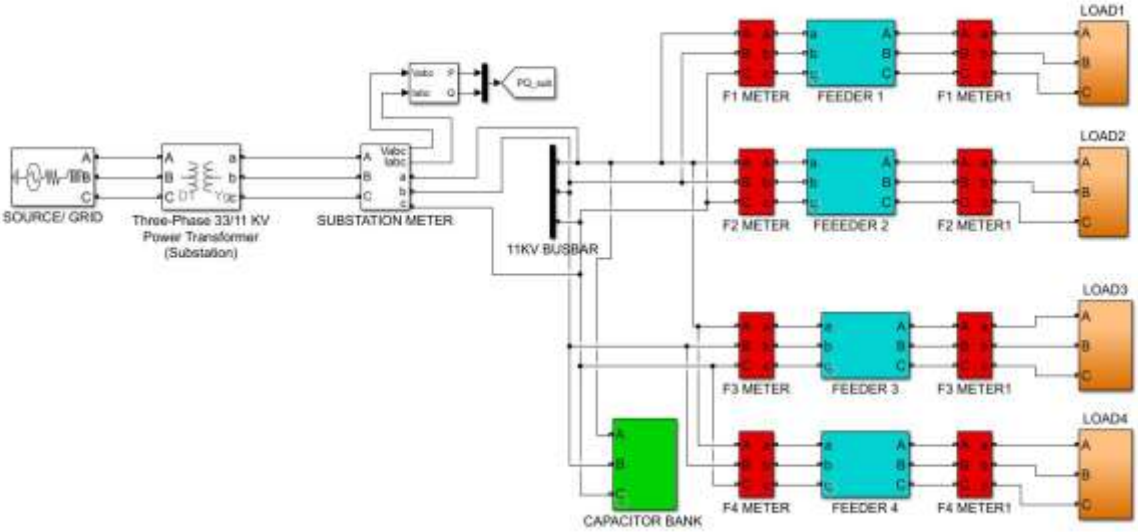

Figure 1. Simulink model of the network diagram

B. Capacitor Placement

The optimal sizing and placement of shunt capacitor banks in distribution networks can aid in the reduction of losses [15]. The importance of loss minimisation continues to grow with the growth of nonlinear loads, increased penetration of renewables, and distribution network automation. Optimisation of the capacitor size is necessary as excessive capacitive reactance (leading power factor) in the system will lead to heating of the end-user equipment.

C. Determination of Economic Benefits of Capacitor Bank Installation

The use of capacitors in a feeder reduces the current through the feeder and the transformer as well. Given the currents through the feeder before and after the installation of capacitor banks, (1) show the formula to calculate the economic benefits:

$$\psi = 3 \times \alpha(I_1^2 - I_2^2) \times R \times (8760)\,\beta \times 10^{-3} \tag{1}$$

where:

ψ = cost of energy savedS_f is the shielding factor
α = cost of total energy in kilowatts
I_1 = current before capacitor installation
I_2 = current after capacitor installation
R = resistance of the circuit, 8760 is the number of hours in a year
β = load factor.

D. Determination of Voltage Profile with and without Capacitor Placement

The voltage profile is determined with and without capacitor placement. In both cases, the network was modelled, capacity ratings were adjusted and the load flow calculation was performed to determine the new voltage magnitude and phase angle at each bus. Overall, the reduction in voltage drops improves the system-level voltage profile. Figure 2 shows the phasor diagram of the system without capacitor bank.

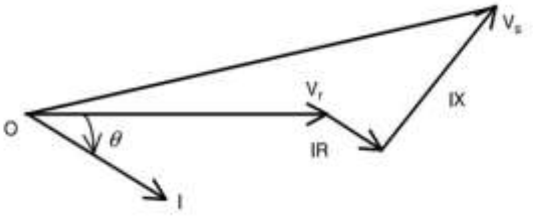

Figure 2. Phasor Diagram of a System without capacitor bank

The voltage relationship is given as:

$$V_r = V_s - I\,(\cos\theta \pm j\sin\theta)\,(R + jX) \tag{2}$$

where:

V_r = receiving end voltage
V_s = sending end voltage
θ = power factor angle in degrees
I = the line current.

Figure 3. shows the phasor diagram when the capacitor banks are added to the system.

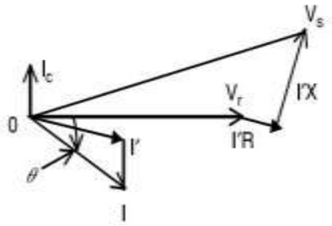

Figure 3: Phasor diagram of the system with capacitor bank

The current relationship is given as:

$$I' = I(\cos\theta \pm j\sin\theta) - jI_C' \tag{3}$$

The current of the capacitor bank, I_C is given as:

$$I_C = \frac{V}{X_C} \tag{4}$$

where:

X_C = reactance of the capacitor bank.

E. Feature parameters for model development included:

- Network voltage level: 11 kV feeders.
- Feeder length, resistance (R) ad reactance (X_C): based on typical 11 kV radial distribution network (used in loss calculation).
- Load profile: 24-hour daily demand, measured at 1-minute intervals (1,440 samples per feeder).
- Base power factor: ~0.82 lagging.
- Statutory voltage range: 0.95–1.05 pu.
- Capacitor bank sizes: selected in kVAR ratings consistent with feeder reactive demand.
- Control strategy: uncontrolled (fixed switching) and time-controlled (scheduled switching based on load patterns).

These parameters were selected because they directly influence voltage profile, line current, and reactive power flow — the core indicators of energy efficiency.

F. Data Analysis Parameters

To evaluate the effect of capacitor banks, the following analysis parameters were used:

- Per unit voltage profile (Vpu): to check compliance with statutory 0.95–1.05 pu range.
- Power factor (PF): improvement tracked from 0.82 (base case) towards unity.
- Branch current (I): compared before and after capacitor installation to assess load relief.
- Loss reduction (%): computed using feeder resistance and current difference.

3. RESULTS AND DISCUSSION

3.1 Simulation Results

The regulation states that the voltage limits per unit value must be within the range of 0.95-1.05 for a good voltage profile. The simulation cases are as follows:

i. Case one: Base case (without capacitor bank).
ii. Case Two: System with uncontrolled capacitor banks connected close to load.
iii. Case Three: System with time-controlled capacitor banks.
iv. Case Four: System with time-controlled capacitor banks at substation bus.

3.2 Performance Evaluation

In this section, the performance and the impact of capacitor bank installation on medium voltage network is analysed through extensive simulation and the result is compared with the standard voltage limit. Also, the pattern of consumer's load profile data collected for every minute for a typical daily (24 hours) operation of the network for each feeder is analysed. This gives 1,440 data points for per unit (pu) current simulation.

3.2.1 Case one: Base Case (Without Capacitor Bank)

In the case one scenario, the voltage profile and overall performance of the electrical distribution network without any capacitor banks installed was analysed. This provides a reference point to understand the current state of the system and to evaluate the impact of adding capacitor banks later. The evaluated parameters are voltage magnitude, voltage drops, power flow, system losses and power factor. Figure 4 presents the per unit current profile for the system operating without the installation of a capacitor bank. The simulation results provide valuable insights into the load profile and consumption patterns of the various feeders within the distribution network. The current magnitudes reflect the electrical demand across different segments of the system, indicating how load varies over time or across different feeders. These results highlight areas of higher current flow, which may be associated with peak load periods or heavily loaded feeders. Understanding this behaviour is crucial for assessing the performance and efficiency of the distribution system, identifying potential overload conditions, and planning for appropriate corrective measures such as load balancing or reactive power compensation.

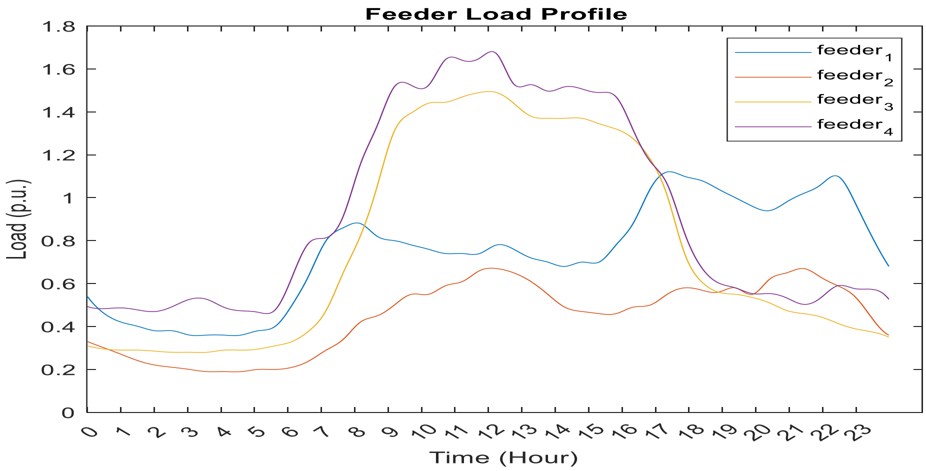

Figure 4. Branch Current

Figure 5 illustrates the per unit voltage profile of the system without the inclusion of a capacitor bank. The simulation results reveal that the voltage levels fall below the minimum statutory limit required for proper operation of a power distribution network. This indicates that the voltage regulation is inadequate, leading to poor power quality and potential operational issues for end-users. Consequently, in its current state without compensation, the system configuration cannot be recommended for deployment in a standard power distribution network, as it fails to meet the essential voltage stability and reliability criteria.

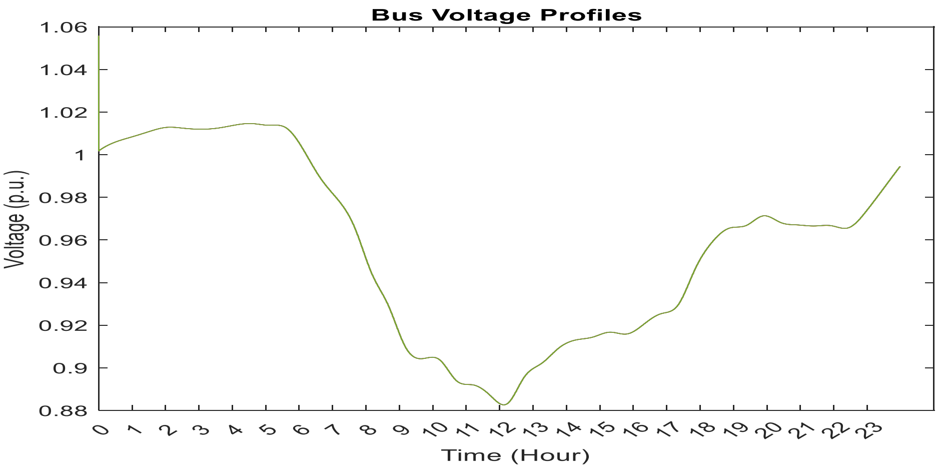

Figure 5. Bus Voltage Profiles

3.2.2 Case Two: System with Uncontrolled Capacitor Banks Connected Close to Load

In this scenario, the voltage profile and overall performance of the electrical distribution network with uncontrolled capacitor banks installed close to the loads was analysed. Uncontrolled capacitor banks provide a fixed amount of reactive power compensation, regardless of the system's varying load conditions. Figure 6 illustrates the per unit current profile for a system in which an uncontrolled capacitor bank is installed in close proximity to the load. The simulation results provide an understanding of the load profile and the consumption behaviour of the various feeders within the network under this configuration. The presence of the capacitor bank introduces reactive power compensation, which can influence the magnitude and distribution of current across the system. However, because the capacitor bank is uncontrolled, it operates without regard to real-time load variations, potentially leading to overcompensation or undercompensation at different times. This behaviour is reflected in the current profile, which may show fluctuations or irregularities compared to a controlled compensation scenario. Analysing this profile helps in assessing the effectiveness of the capacitor bank placement and in identifying the need for a more dynamic or optimised reactive power management strategy.

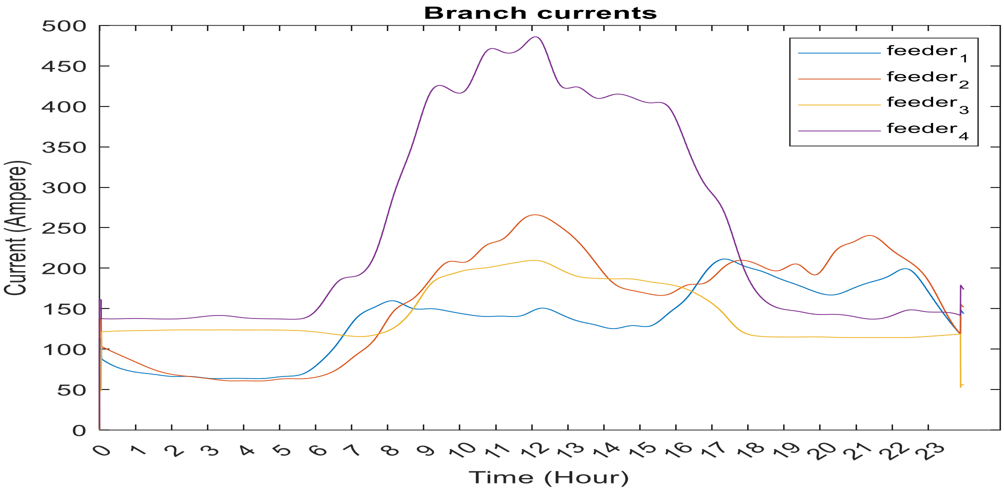

Figure 6: Branch Currents For a system with Uncontrolled Capacitor Banks close to the Load

Figure 7 depicts the per unit voltage profile of the system when an uncontrolled capacitor bank is installed near the load. The simulation results indicate that the capacitor bank effectively corrects the lower voltage limit violation, which was observed in the system without compensation. This demonstrates the capacitor bank's ability to improve voltage levels by supplying reactive power locally. However, the results also reveal that the upper voltage limit exceeds the statutory threshold, leading to an overvoltage condition. This overcompensation occurs because the capacitor bank operates without regulation, providing a fixed amount of reactive power regardless of actual load demand. Such a condition can pose risks to sensitive equipment, reduce system reliability, and lead to inefficient operation. Therefore, while the uncontrolled capacitor bank partially addresses undervoltage issues, its inability to adapt to varying load conditions results in voltage levels that violate regulatory standards. As a result, this configuration cannot be recommended as an effective or reliable voltage control strategy for use in power distribution networks.

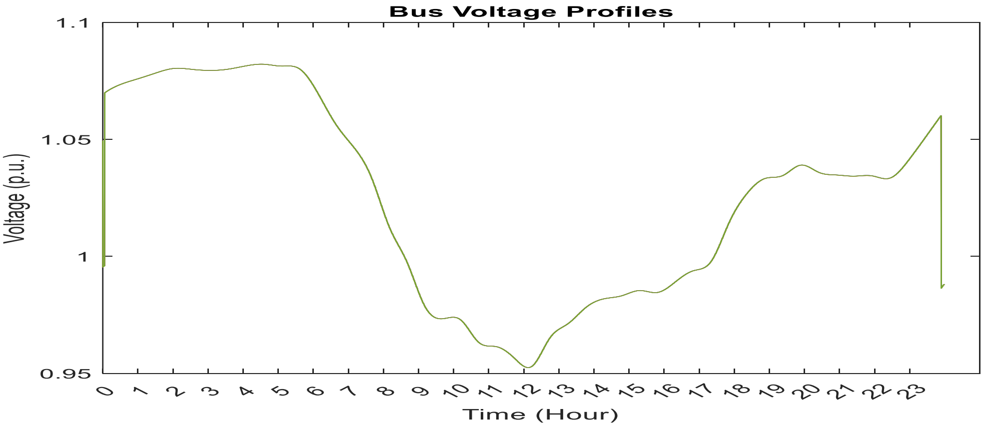

Figure 7: Bus Voltage Profiles For a system with Uncontrolled Capacitor Banks close to the Load

3.2.3 Case three: System with time-controlled capacitor at the load

In this scenario, the voltage profile and overall performance of the electrical distribution network with time-controlled capacitor banks was analyzed. Time-controlled capacitor banks are programmed to switch on or off at predetermined times based on typical load patterns, allowing for better alignment of reactive power compensation with the system's varying load conditions. Figure 8 illustrates the per unit current profile of the system with a time-controlled capacitor bank installed at the load location. The simulation results provide a detailed explanation of the load profile and the consumption pattern of the distribution feeders under this reactive power compensation strategy. Unlike an uncontrolled capacitor bank, the time-controlled configuration allows the capacitor bank to operate according to a predefined schedule, aligning its operation more closely with expected load variations throughout the day. This results in improved reactive power management, reduced line losses, and more stable current profiles across the network. The current magnitudes observed in the simulation reflect how the capacitor bank dynamically responds during peak and off-peak load periods, helping to optimize system performance. Overall, the time-controlled capacitor bank demonstrates an effective approach to enhancing power quality and operational efficiency by minimizing unnecessary current flow and balancing load demands on the feeders.

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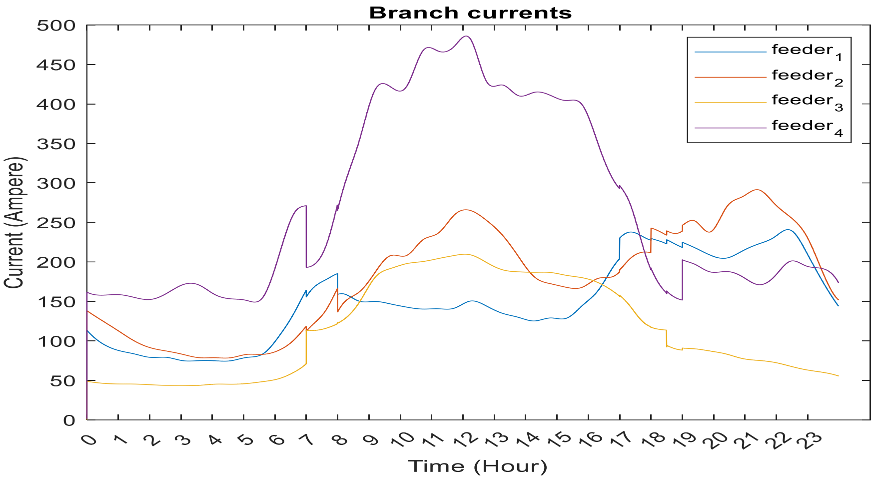

Figure 8: Branch Currents for Time-Controlled Capacitor Banks System at the Load

Figure 9 presents the per unit voltage profile of a system equipped with a time-controlled capacitor bank installed at the load. The simulation results clearly demonstrate that both the lower and upper voltage limit violations observed in previous configurations have been successfully corrected. This indicates that the system's voltage levels remain consistently within the acceptable statutory bounds, ensuring compliance with standard voltage regulation requirements. The time-controlled operation of the capacitor bank allows it to supply reactive power only when needed, aligning its activity with the system's real-time load demands. This leads to more precise voltage regulation, avoiding both undervoltage and overvoltage conditions. As a result, this configuration proves to be a reliable and effective voltage control measure for power distribution networks. In addition to maintaining stable voltage levels, the presence of the time-controlled capacitor bank also contributes to a significant improvement in the power factor of the system. By reducing reactive power flow and associated line losses, the overall efficiency and performance of the network are enhanced. Therefore, the system can be confidently recommended for use in modern power distribution networks where voltage stability and power quality are critical.

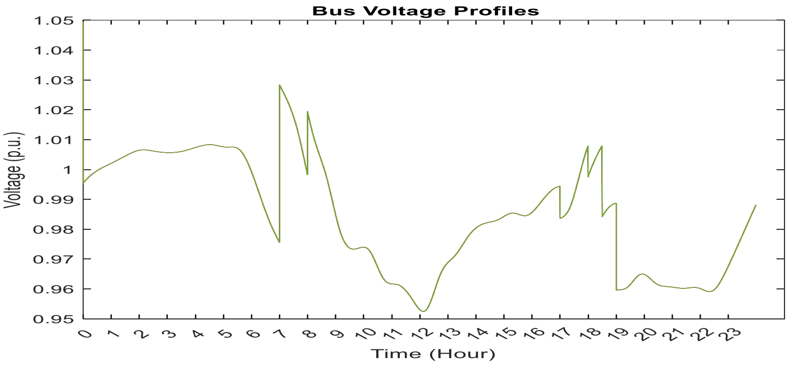

Figure 9: Voltage Profile for Time-Controlled Capacitor Banks at the Load

3.2.4 Case four: System with Time-Controlled Capacitor Banks at Substation Bus

Figure 10 shows per unit current for a system with time-controlled capacitor bank installation at substation bus. The simulation results explained the load profile and the consumption pattern of the feeders.

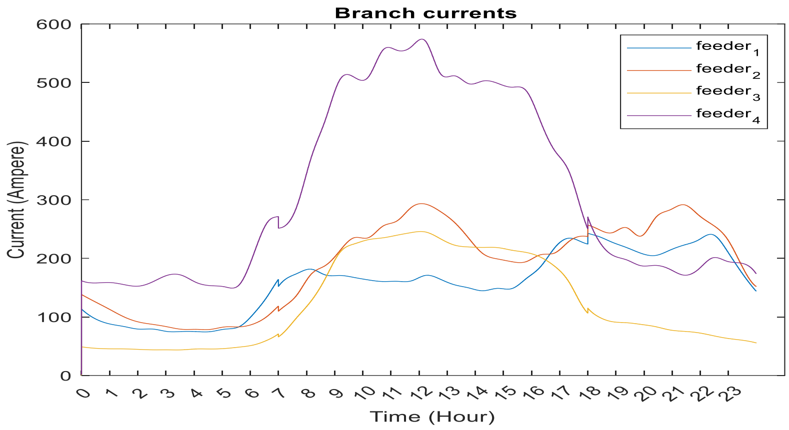

Figure 10: Branch Currents for Time-Controlled Capacitor Banks System at Substation Bus

Figure 11 shows per unit voltage profile with time-controlled capacitor at substation bus. The simulation results shows that the Lower and upper value are out of the range, however, this shows the system cannot be recommended as a good voltage control measure in the distribution network.

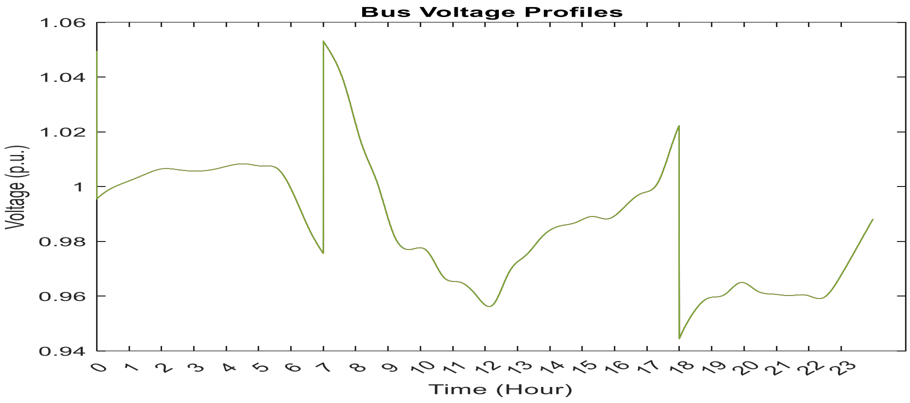

Figure 11: Voltage Profile for Time-Controlled Capacitor Banks at Substation Bus

Table: Comparative Summary of Simulation Cases

Case	Configuration	Voltage Profile	Power Factor	Losses	Compliance with 0.95–1.05 pu	Remarks
Case One	No capacitor bank	Voltage falls below lower limit (0.88 – 0.92)	Poor (lagging)	High	Out of range	Baseline case; inefficient, poor power quality
Case Two	Uncontrolled capacitor banks near load	Corrects undervoltage but causes overvoltage (0.93 – 1.10)	Improved but unstable	Reduced somewhat	Exceeds upper limit	Overcompensation, unreliable for operation
Case Three	Time-controlled capacitor banks at load	Stable, within 0.95–1.05 pu	Good, near unity	Significantly reduced	Within range	**Best performance; recommended strategy**
Case Four	Time-controlled capacitor banks at substation	Voltage sometimes out of range (0.91 – 1.07)	Moderate improvement	Reduced	Inconsistent	Not reliable; less effective than Case

4. CONCLUSION

This study demonstrates the effectiveness of time-controlled capacitor banks in optimising energy efficiency within a smart grid's distribution network. Among the four simulation cases, Case Three—time-controlled capacitor banks installed near the load—proved to be the most effective. It maintained bus voltages within the statutory range of 0.95–1.05 pu, improved the power factor, and reduced line losses, thereby enhancing overall network performance. The proposed time-controlled switching strategy avoids the risks of undervoltage and overvoltage observed in uncontrolled or substation-only placements. These findings highlight that well-timed, load-level capacitor switching is a reliable and practical approach for voltage regulation and loss minimisation in modern smart grids. Future research can extend this framework by integrating adaptive or AI-based control strategies for even more precise optimisation under dynamic loading conditions.

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Assessment of Available Transfer Capability in Nigeria's 330 kV Transmission Grid for Congestion Management and Reliability Enhancement

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Abstract: The continuous growth in electricity demand and regional disparity in power generation across Nigeria necessitate efficient assessment of Available Transfer Capability (ATC) in the national grid. This study evaluates ATC of the Nigerian 330 kV transmission network using Power Transfer Distribution Factor (PTDF) analysis across five south-to-north corridors: Delta–Kano, Egbin–Yola, Afam–Gombe, Sapele–Damaturu, and Alaoji–Maiduguri. A 48-bus model, developed from Transmission Company of Nigeria (TCN) data and simulated in PowerWorld, was used to compute ATC under base-case conditions, considering thermal, voltage (0.9–1.1 pu), and stability limits. Results show ATC values ranging from 465 MW (Alaoji–Maiduguri) to 780 MW (Delta–Kano). Critical bottlenecks include the Shiroro–Kaduna line (95% thermal loading) and Yola bus (0.77 pu voltage), reflecting congestion risks and reduced reliability in northern corridors. Findings confirm ATC as a practical index for evaluating grid performance, identifying transmission constraints, and guiding reinforcement priorities. This contributes to strategic planning toward Nigeria's 10,000 MW wheeling capacity target by 2030, supporting improved reliability and efficient power market operations.

Keywords: *Available Transfer Capability, Congestion Management, Grid Reliability, Nigerian 330 kV Grid, Power Transfer Distribution Factor, Transmission Bottlenecks.*

1. INTRODUCTION

Nigeria's 330 kV transmission grid faces persistent operational challenges stemming from the geographical imbalance between power generation and consumption. While most generation facilities, such as Egbin, Afam, and Delta, are concentrated in the south, the northern and middle-belt regions—home to major demand centres like Kano, Yola, and Maiduguri—rely heavily on long-distance power transfers [1]. The transmission network, largely radial and aging, frequently experiences congestion, voltage instability, and partial collapses. In 2023 alone, the Transmission Company of Nigeria (TCN) reported 12 grid disturbances primarily attributed to inadequate transmission capacity [2], [3].

The concept of **Available Transfer Capability (ATC)** provides a systematic framework for quantifying the additional power that can be transferred without violating operational limits such as thermal loading, voltage (0.9–1.1 pu), and stability margins [4]. ATC has been widely studied in power systems research, where **Power Transfer Distribution Factor (PTDF)-based approaches** are commonly applied for assessing congestion and supporting reliability enhancement [5], [6]. However, despite its relevance, few comprehensive studies have applied ATC assessment specifically to Nigeria's 330 kV grid. Existing research often employs simplified deterministic methods and rarely considers Nigeria's unique challenges—such as low voltage levels at northern buses (e.g., 0.77 pu at Yola) and heavily loaded lines (e.g., Shiroro–Kaduna at 95% thermal limit) [2].

The significance of ATC for Nigeria extends beyond technical modelling; it directly impacts national energy planning, market operations, and grid modernization. Table 1 summarizes potential benefits of enhanced ATC, including improved reliability, reduced losses, renewable integration, and economic growth, demonstrating the need for systematic ATC evaluation in the Nigerian context.

Table 1: Potential Impacts of Enhanced ATC on Nigeria's Power Sector (Source: NERC)

Impact Area	Description	Estimated Benefit
Transmission Losses	Reduction through optimized power flows	1–2% loss reduction (≈ $100–200M savings/year)
Grid Reliability	Fewer outages via congestion management	20–30% reduction in collapse events
Renewable Integration	Improved stability with solar/wind variability	10–15% increase in renewable capacity
Economic Growth	Enhanced power supply for industries	$500M–$1B GDP increase annually

Nigeria's transmission topology, illustrated in Figure 1, further emphasizes the challenge. The Jebba–Osogbo double-circuit line serves as the main interconnection between southern generation and northern demand. Its performance under contingency scenarios critically determines south–north transfer capacity and overall grid reliability.


[redacted]

Figure 1: Transmission Lines and Substations in Nigeria (Source; NERC)

These realities establish a clear research gap: while global studies have demonstrated the value of ATC in transmission planning and congestion management, Nigeria-specific analyses remain limited, fragmented, and often deterministic. This study addresses these gaps by assessing ATC across five key south-to-north transmission corridors—Delta–Kano, Egbin–Yola, Afam–Gombe, Sapele–Damaturu, and Alaoji–Maiduguri—using PTDF-based analysis in PowerWorld Simulator.

The specific objectives of this study are to:

i. Assess the current ATC of Nigeria's 330 kV grid across five south–north corridors.
ii. Identify transmission bottlenecks limiting reliable power transfers.
iii. Establish ATC as a performance index for planning toward Nigeria's 10,000 MW wheeling capacity target by 2030.

2. METHODOLOGY

This section describes the procedure followed in evaluating the Available Transfer Capability (ATC) of the Nigerian 330 kV transmission grid. The process integrates power flow simulation, Power Transfer Distribution Factor (PTDF) analysis, and ATC formulation. All operational definitions, software details, and equipment specifications are clearly stated to enable reproducibility.

2.1 Study Procedure

The methodology followed five major steps:

i. **Data Collection:** Network parameters of the Nigerian 330 kV transmission system (bus data, line data, and generation/load profiles) were obtained from the Transmission Company of Nigeria (TCN, 2023).
ii. **Network Modeling:** The transmission grid was modeled in PowerWorld Simulator (Version 23, USA) using a 330 kV single-line representation that captures all major generation stations and load centres.
iii. **Base Case Load Flow:** Newton–Raphson power flow analysis was carried out under base operating conditions to determine voltage magnitudes, line loadings, and system losses.
iv. **PTDF Extraction:** Power Transfer Distribution Factors (PTDFs) were computed in PowerWorld to determine the sensitivity of line flows to incremental power transfers between generation and load areas.
v. **ATC Computation:** The ATC for each south-to-north corridor was computed using the standard ATC formulation, considering Total Transfer Capability (TTC), Transmission Reliability Margin (TRM), Capacity Benefit Margin (CBM), and Existing Transmission Commitments (ETC).

This step-by-step procedure ensures that the results can be reproduced using the same dataset and software platform.

2.2 EQUIPMENT AND SOFTWARE SPECIFICATIONS

All simulations were executed on an HP ProBook 450 G8 laptop, equipped with:

Intel® Core™ i7-1165G7 CPU @ 2.8 GHz

16 GB RAM, 512 GB SSD

Operating System: Windows 11 Pro (64-bit)

The software tools used include:

PowerWorld Simulator, Version 25 (USA): for power flow and PTDF analysis.

Microsoft Excel 2021 (USA): for tabular data processing and visualization.

MATLAB R2025a (USA): for cross-verification of ATC computations using custom scripts.

2.3 Network Model

The study utilized a 48-bus model of the Nigerian 330 kV transmission grid, developed in PowerWorld Simulator v23, to evaluate Available Transfer Capability (ATC) across five south-to-north corridors: Delta-Kano, Egbin-Yola, Afam-Gombe, Sapele-Damaturu, and Alaoji-Maiduguri. The model includes 48 buses, 62 transmission lines, and 12 major generation stations (e.g., Egbin, Afam, Delta, Sapele, Alaoji) supplying northern load centres (e.g., Kano, Yola, Gombe, Damaturu, Maiduguri), as detailed in [1]. Grid topology and line parameters (e.g., reactance, thermal ratings) were sourced from Transmission Company of Nigeria (TCN) operational data for 2023 [2]. The model reflects the grid's radial structure, capturing real-world constraints such as long-distance power transfers and aging infrastructure [3].

Figure 2 illustrates the network topology of Nigeria's 330 kV transmission grid, with the transmission lines highlighted in blue. A critical examination of the diagram reveals that the Jebba–Osogbo tie-line serves as the primary interconnection linking the southern and northern transmission networks. Despite being a double-circuit line, this corridor plays a pivotal role in facilitating bulk power transfer across regions, making it a structurally and operationally significant part of the grid.

Given its strategic importance, the performance of the Jebba–Osogbo line under contingency conditions requires thorough investigation. This study, therefore, assesses the impact of its operational limits and failure scenarios on Available Transfer Capability (ATC) across the network. Understanding how this key tie-line influences ATC is essential for enhancing grid reliability, planning robust contingencies, and improving south-to-north power transfer efficiency within the national grid.

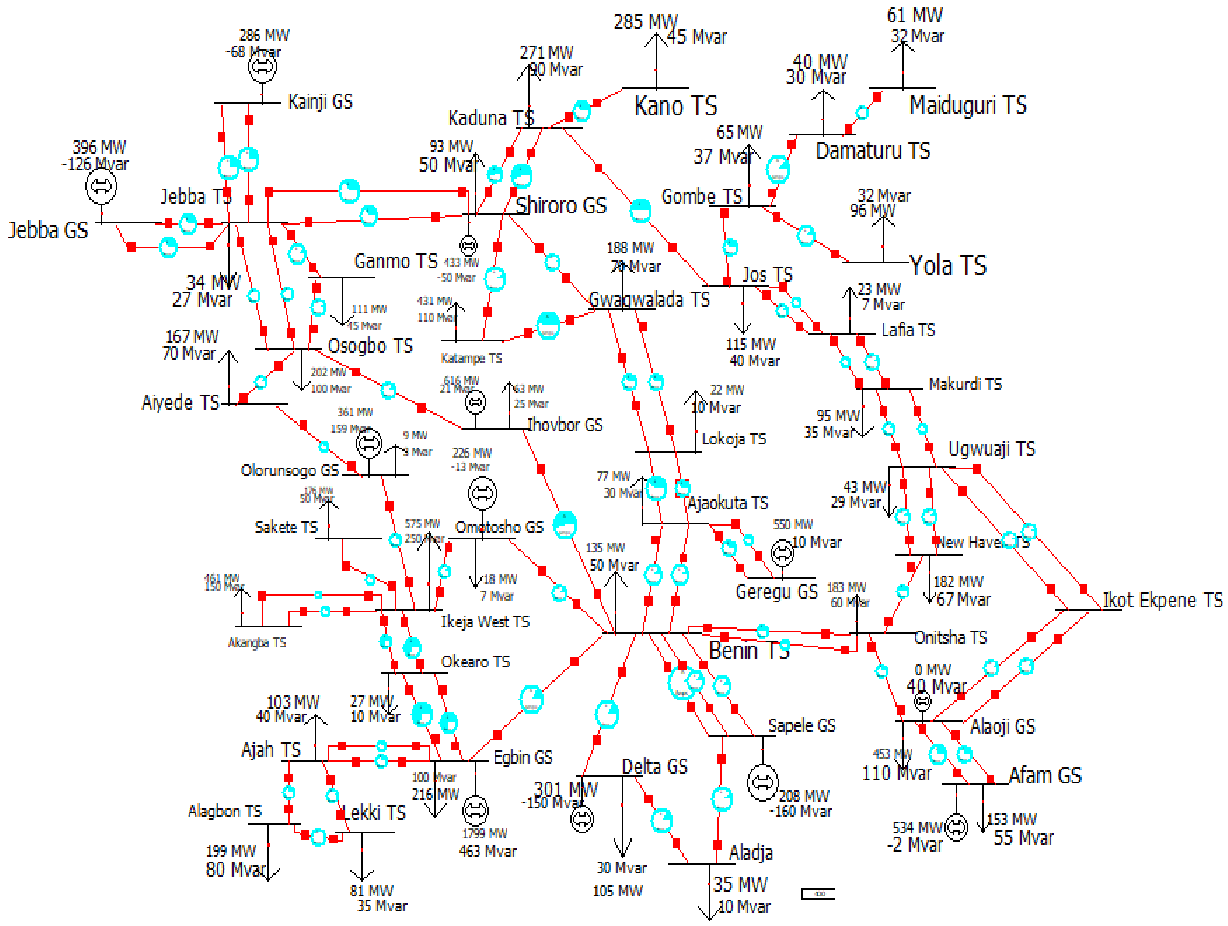

Figure 2: Nigerian 330 kV Transmission Grid

2.4 ATC Calculation

2.4.1 Foundational Power Flow Modelling

The assessment of Available Transfer Capability (ATC) in power systems is fundamentally based on accurate modelling of power flows across the transmission network. In this study, the starting point is the formulation of power flow equations from first principles, utilizing a bus admittance-based representation of the Nigerian 330 kV transmission grid. The complex power $\mathbf{S_i}$ injected at bus i is expressed as equation 1 below:

$$\boldsymbol{S_i = P_i + jQ_i = V_i I_i^*} \qquad (1)$$

The primary goal of this optimization study is to enhance the Available Transfer Capability (ATC) of the Nigerian 330 kV transmission network.

The objective function is mathematically defined. A power system consists of buses (nodes) connected via transmission lines (branches), each of which can be characterized by its electrical impedance and admittance properties.

Let the network contain n buses, where each bus may have generation, load, or both. Each bus i $\in \{1,2,...,n\}$ has a complex voltage $\boldsymbol{V_i = /V_i /\angle\theta_i}$ and the electrical characteristics of the transmission lines govern the power flow between buses. Each line between bus i and bus j is represented by a complex admittance $\boldsymbol{Y_{ij}} = \boldsymbol{G_{ij} - jB_{ij}}$, derived from the corresponding line impedance values $\boldsymbol{Z_{ij}} = \boldsymbol{R_{ij} + jX_{ij}}$, as shown in (2), *where:*

$$Y_{ij} = \frac{1}{Z_{ij}} = \frac{1}{R_{ij} + jX_{ij}} \qquad (2)$$

At any bus i, the net current injection I_i equals the sum of all currents flowing from bus i to every other connected bus j, Consistent with Kirchhoff's Current Law (KCL). Using matrix notation, this becomes:

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \quad \Rightarrow \quad I = Y_{BUS} \mathrm{V} \qquad (3)$$

Where,

I is the vector of complex current injections,
V is the vector of complex bus voltages,
Y_{BUS} is the $n \times n$ complex admittance matrix for the 330 kV Nigerian grid.

2.4.2 Complex Power Injection at a Bus

The complex power S_i injected at bus i is defined as: $S_i = P_i + jQ_i = V_i I_i^*$

Substituting the current injection equation gives

$$S_i = V_i \left(\sum_{j=1}^{n} Y_{ij} V_j \right)^* = V_i \sum_{j=1}^{n} Y_{ij}{}^* V_j{}^* \qquad (4)$$

This equation links voltage, current, and power at each bus in the system.

2.5 Polar Form and Separation into Real and Reactive Components

To obtain explicit expressions for real and reactive power, voltages are expressed in polar form:

$$V_i = /V_i /\angle\theta_i = /V_i /e^{j\theta_i}, \quad V_j = /V_j /e^{j\theta_j},$$

Them,

$$S_i = /V_i /e^{j\theta_i} \sum_{j=1}^{n} (G_{ij} - jB_{ij}) /V_j /e^{-j\theta_j} \qquad (5)$$

Let $\theta_{ij} = \theta_i - \theta_j$. Expanding the expression,

$$S_i = /V_i / \sum_{j=1}^{n} /V_j / \left[G_{ij} \cos(\theta_{ij}) + B_{ij} \sin(\theta_{ij}) + j\left(G_{ij} \sin(\theta_{ij}) - B_{ij} \cos(\theta_{ij}) \right) \right] \qquad (6)$$

Separating real and imaginary parts:

Real power

$$P_i = \sum_{j=1}^{n} /V_i / /V_j / \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right) \qquad (7)$$

Reactive power

$$Q_i = \sum_{j=1}^{n} /V_i / /V_j / \left(G_{ij} \sin\theta_{ij} + B_{ij} \cos\theta_{ij} \right) \qquad (8)$$

ATC was computed using the Power Transfer Distribution Factor (PTDF) method, following the standard formulation:

$$ATC = TTC - TRM - CBM \tag{9}$$

Where:

TTC (Total Transfer Capability): The maximum power transferable under normal and N-1 contingency conditions, calculated using power flow analysis.

TRM (Transmission Reliability Margin): A buffer for uncertainties (e.g., load forecast errors, unit outages), set at 2% of thermal limits based on TCN standards (Chapter 2, Section 2.8).

ETC (Existing Transmission Commitments): Current power flows from TCN dispatch schedules.

CBM (Capacity Benefit Margin): Reserved capacity for reliability, set at 5% of TTC per NERC guidelines.

Where $PTDF_{ij,k}$ represents the power flow change on line ij per unit injection at bus $k$relative to the slack bus [5]. TRM and CBM were set at 5% of TTC to account for uncertainties, while ETC was derived from TCN dispatch schedule for 2023, avoiding the unrealistic ETC = 0 assumption. Thermal limits (line ratings), voltage limits (0.9–1.1 pu), and stability constraints were enforced, with single-line contingencies (N-1) analysed to ensure reliability [4].

2.6 Data

Line parameters, bus data, and load profiles were extracted from TCN's 2023 operational reports [2]. Load and generation scenarios represent average dry-season weekday conditions (January–March 2023), reflecting peak demand in northern regions. The base-case scenario assumes no major outages, with generation dispatch optimized for southern plants. Contingency analysis followed IEEE standards, prioritizing critical lines (e.g., Shiroro-Kaduna) identified in prior studies [3]. All simulations were validated against TCN's historical power flow data to ensure accuracy.

3. RESULTS AND DISCUSSION

3.1 ATC Across Transmission Corridors

Table 1 presents the Available Transfer Capability (ATC) values for five south-to-north corridors of the Nigerian 330 kV grid under base-case conditions, computed using PowerWorld Simulator and Power Transfer Distribution Factor (PTDF) analysis. The corridors—Delta-Kano, Egbin-Yola, Afam-Gombe, Sapele-Damaturu, and Alaoji-Maiduguri—reflect critical power transfer paths from southern generation hubs to northern load centres [1].

Table 1: ATC Values for South-to-North Corridors (Base Case, January 2023)

Corridor	TTC (MW)	TRM (MW)	CBM (MW)	ETC (MW)	ATC (MW)	Limiting Constraint
Delta–Kano	900	45	45	30	780	Thermal (Shiroro–Kaduna)
Egbin–Yola	750	37.5	37.5	25	650	Voltage (Yola, 0.77 pu)
Afam–Gombe	740	37	37	20	646	Thermal (Jos–Gombe)
Sapele–Damaturu	680	34	34	15	597	Voltage (Damaturu, 0.85 pu)
Alaoji–Maiduguri	520	26	26	10	458	Thermal (Makurdi–Maiduguri)

ATC values range from 458 MW (Alaoji-Maiduguri) to 780 MW (Delta-Kano), indicating significant variations in transfer capacity. The relatively high ATC of Delta–Kano reflects stronger infrastructure and redundancy, while the severely constrained Alaoji–Maiduguri corridor highlights the vulnerability of long radial transmission paths.

3.2 Transmission Bottlenecks

Figure 3 illustrates the loading levels of critical transmission lines, derived from PTDF analysis. The Shiroro-Kaduna line (Delta-Kano corridor) operates at 95% of its thermal limit under base-case conditions, posing a high congestion risk [3]. Similarly, the Makurdi-Maiduguri line (Alaoji-Maiduguri corridor) reaches 90% thermal loading, while low voltage profiles at Yola (0.77 pu) and Damaturu (0.85 pu) limit ATC in the Egbin-Yola and Sapele-Damaturu corridors, respectively. These bottlenecks, exacerbated by the grid's radial topology and aging infrastructure, restrict power evacuation to northern regions [2]. Contingency analysis (N-1) revealed that the loss of the Shiroro-Kaduna line reduces Delta-Kano ATC by 30%, highlighting its criticality [4].

Table 2: Line Loadings and Congestion Patterns across Scenarios

Line	Base Case (% MVA)	Scenario A (% MVA)	Scenario B (% MVA)	Scenario C (% MVA)	Congestion Notes
Shiroro–Kaduna	95	114	90	92	Congested in Base, A; Relieved in B, C
Benin–Onitsha	90	108	85	88	Congested in Base, A; Relieved in B, C
Gombe–Jos	92	110	87	85	Congested in Base, A; Relieved in C
Sapele–Benin	85	102	80	78	Congested in A; Relieved in C
Gombe–Maiduguri	88	106	83	90	Congested in A; Voltage-limited in C

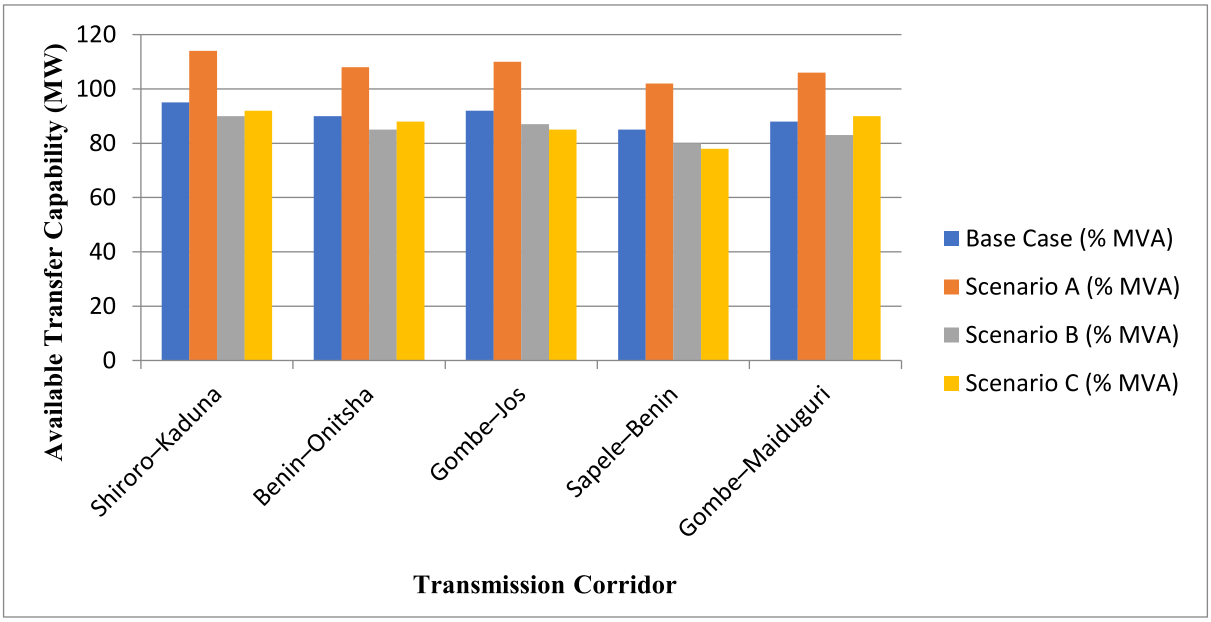

Figure 3: Line Loadings and Congestion Patterns across Scenarios

3.3 Implications for Grid Reliability and Planning

The ATC values clearly demonstrate the disparity across Nigeria's transmission corridors. The Delta–Kano corridor (780 MW) benefits from relatively stronger transmission capacity, but it remains vulnerable due to the

Shiroro–Kaduna line operating close to its thermal limit (95%). On the other hand, the Alaoji–Maiduguri corridor (458 MW) and Afam–Gombe corridor (646 MW) are severely limited by both thermal congestion and long-distance transfers.

The observed constraints are attributable to several factors:

Thermal Overloads: Key tie-lines such as Shiroro–Kaduna and Makurdi–Maiduguri are heavily loaded (90–95%) due to insufficient conductor ratings and the concentration of flows on a few radial corridors.

Voltage Instability: Low bus voltages (Yola at 0.77 pu and Damaturu at 0.85 pu) indicate poor reactive power support, exposing the northern corridors to high risk of voltage collapse.

Radial Network Structure: Nigeria's predominantly radial grid limits alternate paths for bulk transfer, amplifying congestion on a few strategic tie-lines (e.g., Jebba–Osogbo).

Geographical Imbalance: The concentration of generation in the south against high demand in the north necessitates long-distance transfers that exacerbate congestion and losses.

These realities underscore the need for targeted reinforcements. Measures such as reconductoring the Shiroro–Kaduna line, upgrading the Makurdi–Maiduguri corridor, and installing reactive power compensation at Yola and Damaturu are essential to support Nigeria's goal of a 10,000 MW wheeling capacity by 2030 [6].

4. CONCLUSION

This study evaluated the Available Transfer Capability (ATC) of Nigeria's 330 kV transmission grid across five south-to-north corridors—Delta–Kano, Egbin–Yola, Afam–Gombe, Sapele–Damaturu, and Alaoji–Maiduguri—using Power Transfer Distribution Factor (PTDF) analysis in PowerWorld Simulator. The corrected ATC values range from 458 MW (Alaoji–Maiduguri) to 780 MW (Delta–Kano). Critical bottlenecks such as the Shiroro–Kaduna line (95% thermal loading), the Makurdi–Maiduguri line (90% loading), and weak voltage conditions at Yola (0.77 pu) and Damaturu (0.85 pu) highlight the transmission network's vulnerability.

The underlying causes of these constraints include: (i) thermal overloading of aging lines, (ii) weak voltage profiles due to inadequate reactive power support, (iii) radial network topology with limited redundancy, and (iv) geographical imbalance between southern generation and northern demand.

ATC therefore proves to be a reliable index for diagnosing grid performance and prioritizing reinforcements. Strategic actions such as upgrading heavily loaded lines, enhancing reactive power support at critical buses, and strengthening alternate transfer corridors will not only improve ATC but also enhance grid reliability and market efficiency. These measures are consistent with Nigeria's long-term target of achieving a 10,000 MW wheeling capacity by 2030.

Future research will extend this work by evaluating ATC under load growth and generation expansion scenarios, as well as testing optimization strategies (e.g., FACTS devices and redispatch) to further improve transfer capability.

ACKNOWLEDGMENT

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Integration of Optimized DG-Units and D-STATCOM on IEEE 33 Bus Distribution Network for Dynamic Voltage Stability Studies

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Abstract: An efficient distribution network should be able to supply electrical power that is constant with good voltage profile and low power losses. Integration of distributed generation (DG) units, incorporation of flexible AC transmission systems (FACTs), and reconfiguration have been deployed to improve the voltage profile of a distribution network. The purpose of this research work is to model and simulate optimal D-STATCOM and DG units on IEEE 33 bus network for voltage stability analysis. The Intelligent Water Drop Algorithm and Bacterial Forage Algorithm were used to optimally place and size the DG units and D-STATCOM on the network. The IEEE 33 bus network, the DG units and D-STATCOM were model and simulated using MATLAB/Simulink. The DG units were located on buses 6 and 15 with a power rating of 3.0396 MW and 2335.616 kVAr on bus 6, on bus 15 it was 0.3690 MW and 369.73 kVAr, while the D-STATCOM was located on bus 10 with a kVAr value of 3349.489. The dynamic analysis on the network's voltage profile were conducted and a single line to ground fault was introduced, it was observed when DG units and D-STATCOM were integrated into the distribution network, there were improvement on the network voltage profile.

Keywords: *IEEE 33 bus, distributed generator, voltage stability, modeling and simulation*

1. INTRODUCTION

The distribution network is very important in power system because it is the segment that connects consumers into the power network; in that case, the electric power supply to consumers should be stable, available, affordable, and reliable [1]. Voltage drops and power losses are more significant to a distribution network compared to a transmission network because of their low reactance to resistance ratio and the frequent increasing electrical loads connected to the network over the years. High active power loss causes financial loss for utility companies and reduces the efficiency of the transmission of energy to consumers [2]. In order to increase a distribution network's operational efficiency, the following tasks can be carried out on the network: network reconfiguration, installation of FACTs devices, tap changing on distribution transformers, load shedding, and installation of DG units [3].

The installation of DGs in the appropriate location has both technical and economic advantages on the network. The technical benefits include power loss mitigation, improvement on power factor and voltage profile, reliability, grid strengthening, and improving the grid capacity; while the economic advantages are low maintenance and operational costs, reduce capital costs, and reduce costs for enhancement and expansion of the network [4]. However, improper location and sizing of DG units on a power network can result to some operational challenges, such as a reverser of current flow from large DG units, which can result to high power losses, voltage fluctuation, poor power quality, protection problems, and increased operational costs [4]. Therefore, it is essential to keep in mind that the maximum DG power injected into the network should not be greater than the operational capacity of the network. D-STATCOM are compensating device that are shunt connected and controlled by a voltage source DC/AC converter. They are mainly used to resolve power quality related issues such as voltage sag, unbalanced load, line losses, voltage instability, operational cost, and harmonic distortion in distribution networks.

In recent years, many research scholars have accomplished some research work in the area of DG unit and D-STATCOM penetration. The Artificial Bee Colony (ABC) algorithm was used by the authors in [5] to reduce total power loss, energy expenses, and voltage fluctuations in IEEE 69 and IEEE 33 bus systems. The technique achieved a 76.8% reduction in the overall power loss for the IEEE 33 bus system. The JAYA algorithm was used to size and locate D-STATCOM on IEEE 69 and IEEE 33 bus network in order to reduce power losses and enhance the network's voltage profile in [6]. The allocation of D-STATCOM was carried out using the New Voltage Stability Index (NVSI), while the sizing was done using the Bat Algorithm (BA) on IEEE 33 bus and the Nigeria Ayepe 34 bus networks for the purpose of enhancing the voltage profile and mitigate the power losses in [7]. The author in [8] deployed LSF and VSI to obtain the optimal location of DG units and D-STATCOM, while an evolutionary based bat algorithm (EBA) was used to obtain the optimal capacities for both devices. In [9], the authors deployed the fractional levy flight bat algorithm to optimally site and size DG and FACTS devices in an effort to enhance the voltage profile and reduce power losses. In [10], the authors developed a controller for D-STATCOM parameter using fuzzy-PI and fuzzy-PID in order to improve the power quality of a hybrid AC/DC micro-grid system. The authors in [11] presented the modeling of a hybrid micro-grid that comprised solar PV, wind turbine and STATCOM device. The Bacterial Foraging Algorithm (BFA) and the Genetic Algorithm (GA) were used to optimize the PI parameter for STATCOM controller. In [12], a dynamic voltage stability study was conducted on a micro-grid that comprises of induction motors and air conditioning; D-STATCOM was used to stabilize the reactive power for the smooth running of the induction motors. In [13], the authors used quasi-static time-domain simulation (QSTDS) method to investigate the dynamic voltage stability of a power network with integration of wind farm coupled with induction generator; SVC and STATCOM were used to control the reactive power in order to improve the voltage stability. A voltage stability analysis was conducted by the authors in [14] on a power system that had a large penetration of wind farms and FACTS devices.

This study aims at integrating optimized DG-units and D-STATCOM in a distribution network for dynamic voltage stability studies.

2. THE MATHEMATICAL MODELING OF THE SYSTEMS

This section discusses about the mathematical model of D-STATCOM connected to a distribution network as shown in figure 1. The output power and the generator angular speed equations are described in this section.

2.1 Mathematical Modeling of D-STATCOM

The network diagram shown in Figure 1 represent a two-bus network m and m+1, where the line resistance and reactance between the two buses are R_m and X_m. The voltages on bus m and m+1 are V_m and V_{m+1} respectively. After installing D-STATCOM on bus m, the voltages on bus m and m+1 changes to V_m' and V_{m+1}', likewise the injected current by D-STATCOM is represented as $I_{DSTATCOM} \angle(\alpha' + 90^0)$ and the line current is given as $I_L \angle \emptyset_L$. When a D-STATCOM is connected to a distribution power grid, the new voltage on bus m is given by equation (1) and (2) [15]:

$$V_m' \angle\theta' = V_m \angle\delta - (R_m + JX_m) * I_L \angle\emptyset_L \pm (R_m + JX_m) * I_{DSTATCOM} \angle(\alpha' + 90^0) \quad (1)$$

where $V_m' = V_m' \angle\theta'$ (2)

The injected kVAr at bus m is given by (3):

$$jQ_{DSTATCOM} = V_m' * I_{DSTATCOM} \angle(\alpha' + 90^0)^* \quad (3)$$

where * denote conjugate of complex variable.

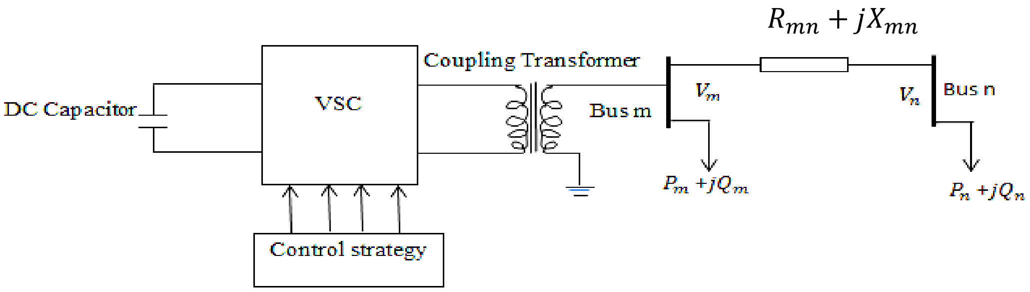

Figure 1: The connection of D-STATCOM on a two-bus network [16]

2.2 The model of a synchronous generator

A synchronous generator oscillating power can be expressed as [17];

$$P_{out} - P_{ref} = \frac{2H\varsigma_B}{\omega_o}\left(\frac{d\omega_s}{dt}\right) + K\Delta\omega \tag{4}$$

Where $\Delta\omega = (\omega_i - \omega_o)$, ω_i is the angular speed of the generator, ω_o is the fundamental angular frequency, ω_s is the synchronous angular speed, P_{out} is the turbine output power

Eq.(4) can be used to describe the state of a synchronous generator. For example, if $\frac{d\omega_s}{dt}$ is zero, the machine is at equilibrium

The load angle of a synchronous generator in respect to angular speed can be express as;

$$\frac{d\delta_i}{dt} = \omega_i - \omega_t \tag{5}$$

Where δ_i is the load angle of the generator and ω_t is the angular frequency at load terminal t.

The generator angular speed in respect to torque, voltage and reactance can be express as;

$$\frac{d\omega_i}{dt} = \frac{\omega_s}{2H_i}\left[T_m - E'_{qi}\, I_{qi} - E'_{di}\, I_{di} - \left(X_{qi} - X'_{qi}\right)I_{qi}I_{di} - d_i(\omega_i - \omega_b)\right] \tag{6}$$

Where H_i is the moment of inertia, I, E, and X are the current, E.M.F, and reactance and they are express in two quadratic (dq) frame

The electrical output power can be express as;

$$P_e = \frac{\frac{3}{2}V_s V_g}{X} \sin\delta \quad \text{(Active power)} \tag{7}$$

$$Q_e = \frac{\frac{3}{2}V_g(V_s \cos\delta - V_g)}{X} \quad \text{(Reactive power)} \tag{8}$$

3. DYNAMIC MODELS OF THE SYSTEMS

The Investigating feature of dynamic voltage stability requires taking into consideration the dynamic models, such as the generator model, load model, and the network model. Voltage collapse can be prevented by mastering analysis techniques. The technique used for this research work is time domain simulation techniques.

3.1 DG unit dynamic model

The type of DG unit deployed in this research work is a synchronous generator; it was modeled using MATLAB/SIMULINK. The simulation model is shown in Figure 2.

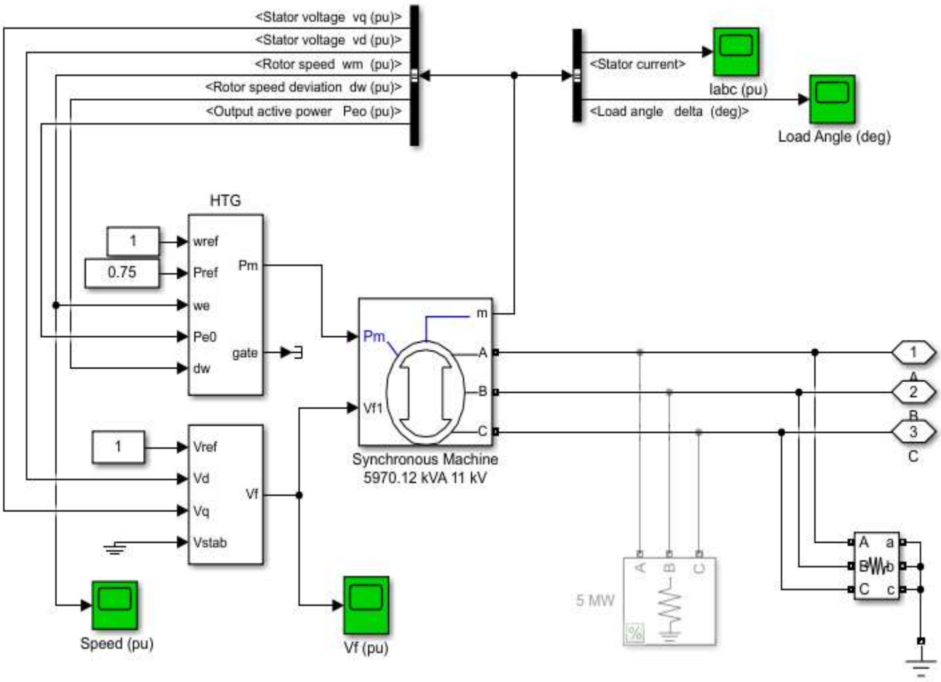

Figure 2: Simulation model of a synchronous generator

3.2 D-STATCOM dynamic model

The D-STATCOM was modeled using MATLAB/SIMULINK and it consists of two three-phase IGBT inverter circuits connected in parallel, a DC capacitor connected across the inverter circuit, a pulse width modulation (PWM) controller, a filter, and a transformer as shown in Figure 3.

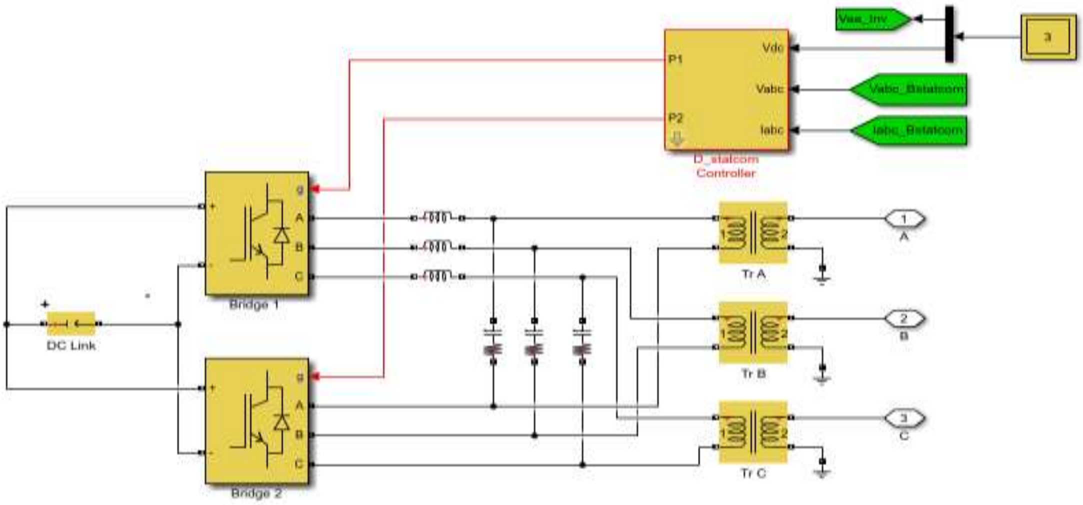

Figure 3: Simulation model for D-STATCOM

3.3 Dynamic model for IEEE 33 bus distribution network

The IEEE 33 bus network was modeled using the line and bus data. The DG units were connected to bus 6 and 15 with real power of 0.369 MW and 3.0396 MW respectively based on the static analysis results obtained from the network; while the D-STATCOM was connected to bus 10 with reactive power of 3349.489 kVAr. The network simulation model is as presented in Figure 4.

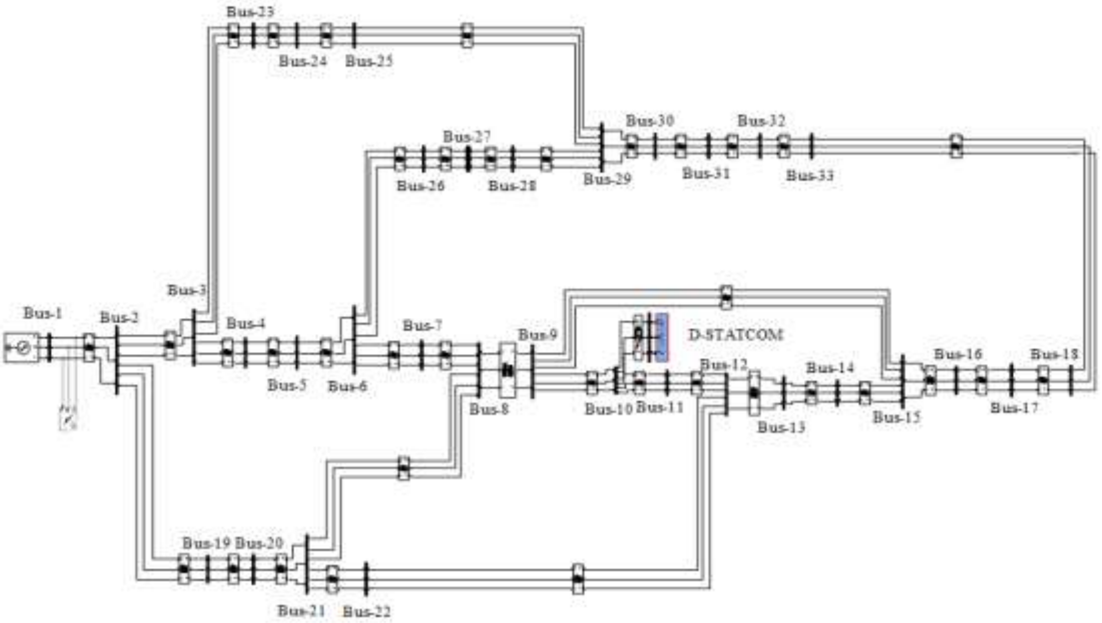

Figure 4: Simulation model for IEEE 33-bus Network with DSTATCOM and DG units.

4. METHODOLOGY

In this research work, the voltage stability index (VSI) was deployed to allocate the DG units, and the intelligent Water Drop (IWD) algorithm was used to size the DG units appropriately as indicated in the flowchart in Figure 5 while Bacterial Foraging Algorithm (BFA) was deployed for the optimal allocation and sizing of the D-STATCOM on the network as indicated in Figure 7. The DG unit, D-STATCOM and the IEEE 33 bus network were all model for dynamic studies. The flowchart in Figure 5 shows the step by step of the research algorithm.

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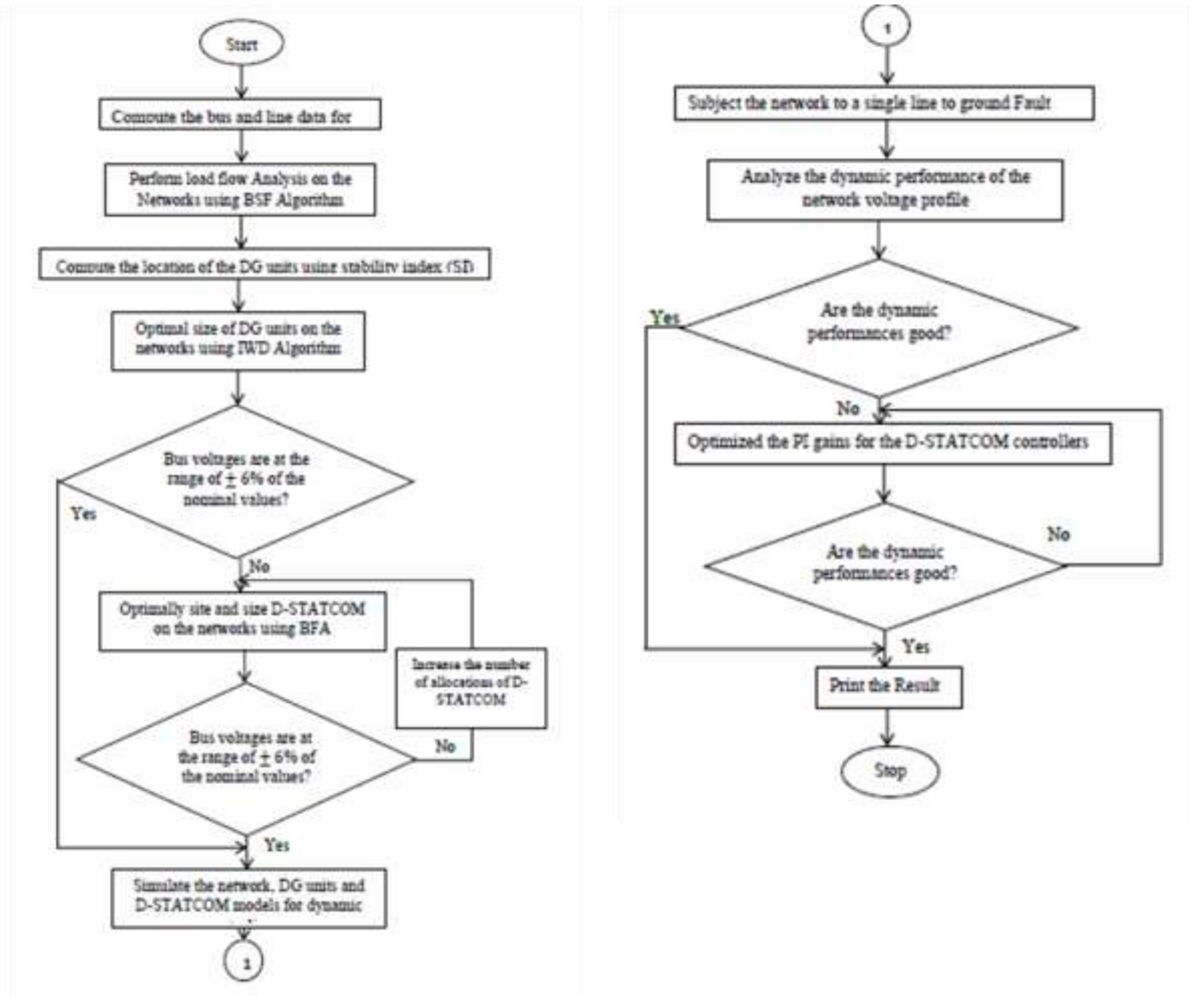

Figure 5: Flowchart for the research methodology

5. RESULTS AND DISCUSSION

5.1 Optimal Siting and Sizing of DG units on IEEE 33 Bus

Load flow analysis and Stability Index (SI) techniques were used to allocate DG units on the power networks; the buses with the lowest SI value were regarded as the most sensitive buses to voltage collapse. SI selected buses 6 and 15 as the optimal buses for installing DG units and details of the results are presented in [18].

5.2 Optimal siting and Sizing of D-STATCOM on IEEE 33 bus network

The proposed optimization algorithm sited D-STATCOM on bus 10 with a kVAr value of 3349.489 on IEEE 33 bus network and the summary of the results is shown in Table 1. The voltage profile for the placement of D-STATCOM is shown in Figure 6.

Table 1: Summary for IEEE 33 Bus Network after Installing D-STATCOM

	Without D-STATCOM (Base Case)	**With D-STATCOM**
Real Power Losses (kW)	272.5757	81.7483
DSTATCOM Value in (kVAR)		3349.4890
Bus Optimal Placement		10
Real Power Loss Reduction in %		70.01

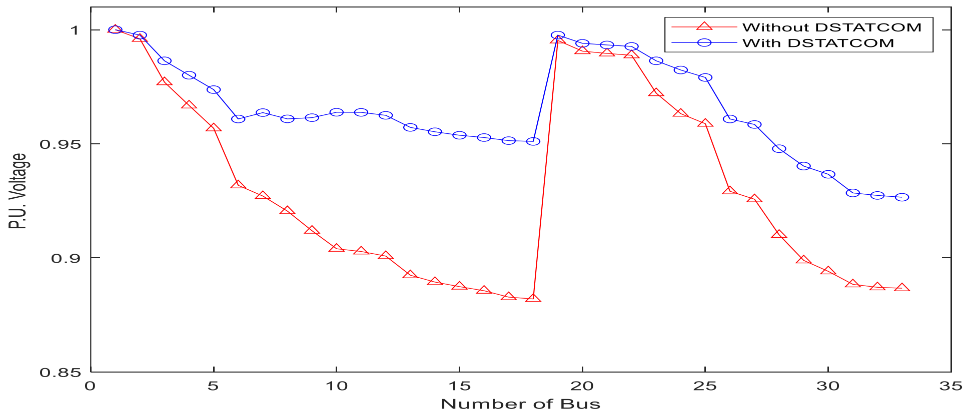

Figure 6: Voltage profile for IEEE 33 bus network with and without D-STATCOM

5.3 The simulation parameter for DG units and D-STATCOM

The synchronous generators (DG 1 and DG 2) were simulated according to the parameters given in Table 2. In order to carry out dynamic studies on the synchronous generators after being connected to IEEE 33 bus network, the conventional method was adopted, which is a no-load and short circuit test.

Table 2: Synchronous generators parameters for IEEE 33 bus network

Parameters	**DG 1**	**DG 2**
Rated Power, P	3833.3 kVA	522.36 kVA
Rotor Speed, N	1500 rpm	1500 rpm
Rated Voltage, V	12.6 kV	12.6 kV
Frequency, f	50 Hz	50 Hz
Stator Resistance, R_s (pu)	0.0028544	0.0028544
Inertia Coefficient, $H(s)$	3.2	3.2
Number of Pole Pairs, p	2	2
D-axis Reactance, X_d	1.305 Ω	1.305 Ω
Q-axis Reactance, X_q	0.474 Ω	0.474 Ω

The parameters used to model the D-STATCOM are shown in Table 3. The model was designed using synchronous reference frame (SRF) for voltage regulation.

Table 3: Simulation parameter used to model the D-STATCOM for IEEE 33 bus network

Parameters	Values
Network line voltage	12.6 kV
Network Frequency	50 Hz
Capacitor Voltage	2400V
Shunt capacitor	1000 µF
Controller Type	Voltage regulator

5.4 Dynamic Simulation Results for IEEE 33 Bus Network

Bus 10 and 18 were selected as part of the weak buses on the network, and their voltage profiles were examined in this study. After the simulation, it was observed that the voltage profile on bus 10 was 0.9293 p.u. and on bus 18 was 0.9132 p.u., and the voltage profile was plotted against time as shown in Figure 7, where bus 10 was represented by the yellow line and bus 18 by the blue line. The simulation was carried out for 5 seconds. A single line to ground fault was introduced at bus 6 from 1 to 4 seconds. It was observed that the voltage profile at buses 10 and 18 dropped to 0.5343 p.u. and 0.5423 p.u. respectively, as shown in Figure 8.

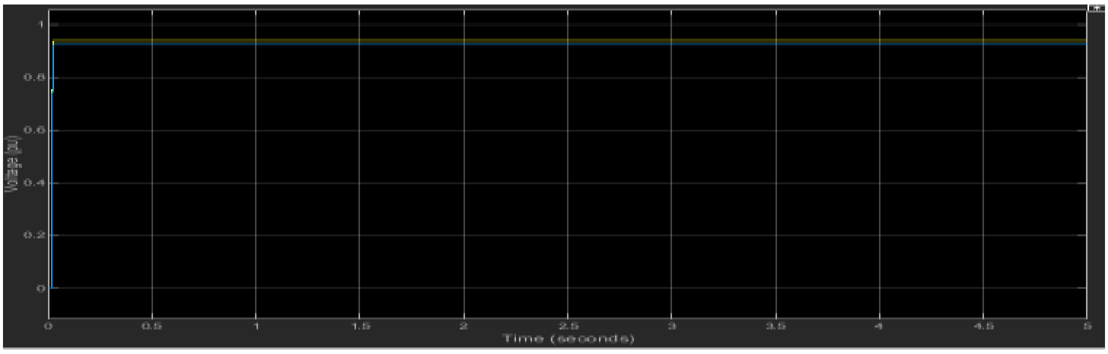

Figure 7: Voltage profile of bus 10 and 18 before fault

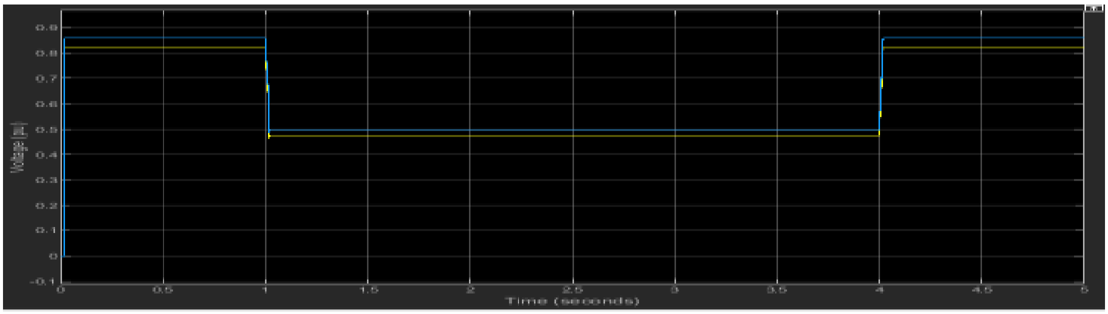

Figure 8: Voltage profile of bus 10 and 18 after fault

DG 1 and DG 2 were integrated on buses 6 and 15 in the IEEE 33 bus network. After the simulation, it was discovered that the DG units caused the network voltage profile to fluctuate for a few seconds. The voltage profile on buses 10 and 18 are 0.9724 p.u. and 0.9676 p.u. respectively as shown in Figure 9, where the blue line represents bus 10 and the yellow line represents bus 18. A single line to ground fault was introduced at bus 6 for 3 seconds. It was discovered that there was a voltage drop on the network throughout the fault period as shown in Figure 10. The voltage profiles on the two selected buses were 0.6912 p.u. and 0.6034 p.u. respectively.

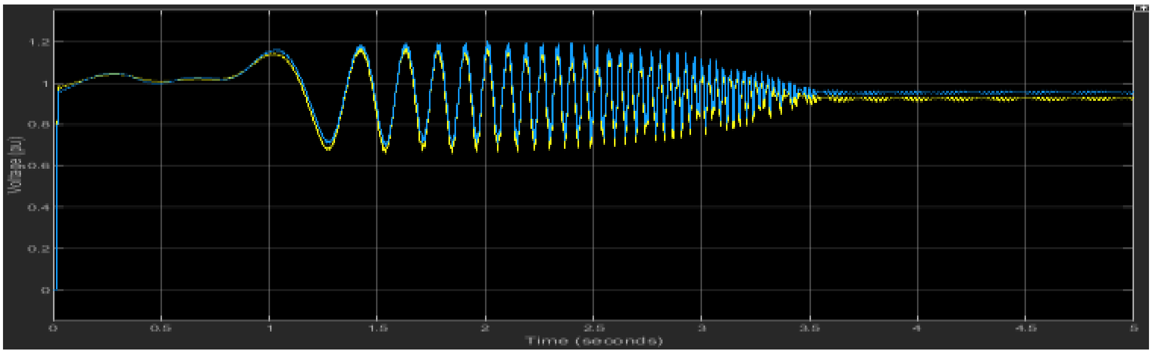

Figure 9: Voltage profile of bus 10 and 18 with DG1 and DG 2 before fault

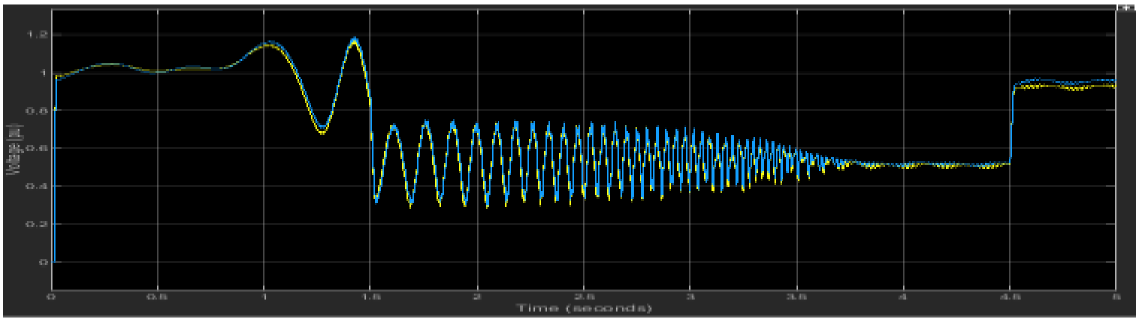

Figure 10: Voltage profile of bus 10 and 18 with DG1 and DG 2 after fault

The D-STATCOM was connected to bus 10. On buses 10 and 18, the maximum voltage profiles per unit were observed to be 0.9702 and 0.9632 as shown in Figure 11. When a single line to ground fault was introduced at bus 6, the network voltage profiles dropped to 0.6518 and 0.5817 p.u on buses 10 and 18 as shown in Figure 12.

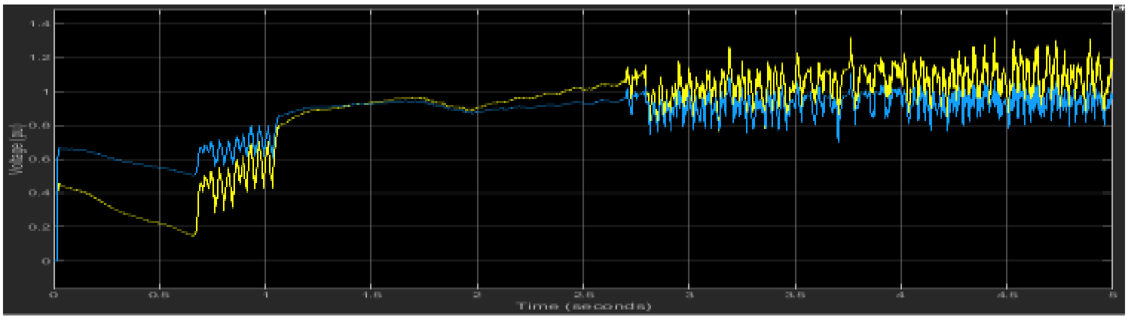

Figure 11: Voltage profile of bus 10 and 18 with D-STATCOM only before fault

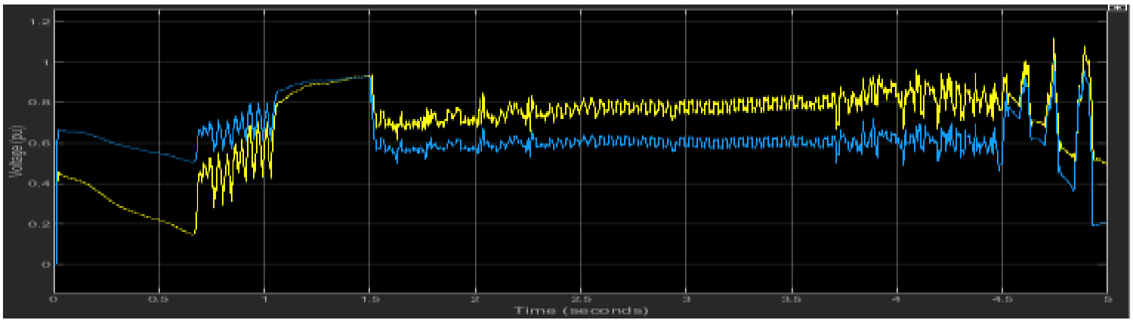

Figure 12: Voltage profile of bus 10 and 18 with D-STATCOM only after fault

The DG units and the D-STATCOM model was integrated into the IEEE 33 bus network as shown in Figure 4. The D-STATCOM controllers were designed using arbitrary PI values as shown in Table 5. The values for the voltage profiles on bus 10 and 18 were observed as 0.9906 and 0.9791 p.u. as shown in Figure 13. After the network was subjected to a single line to ground fault, the maximum values for the voltage profile were observed to be 0.6985 and 0.6215 p.u as shown in Figure 14. The yellow line represents bus 10 while the blue line represents bus 18.

Table 4: The PI arbitrary values for the D-STATCOM controllers for IEEE 33 bus network

Controllers	**Values of the DSTATCOM PI Arbitrary Values**	
	K_p	K_i
V_{DC} Regulator	0.001	0.15
V_{AC} Regulator	0.55	2500
Current Regulator	0.8	

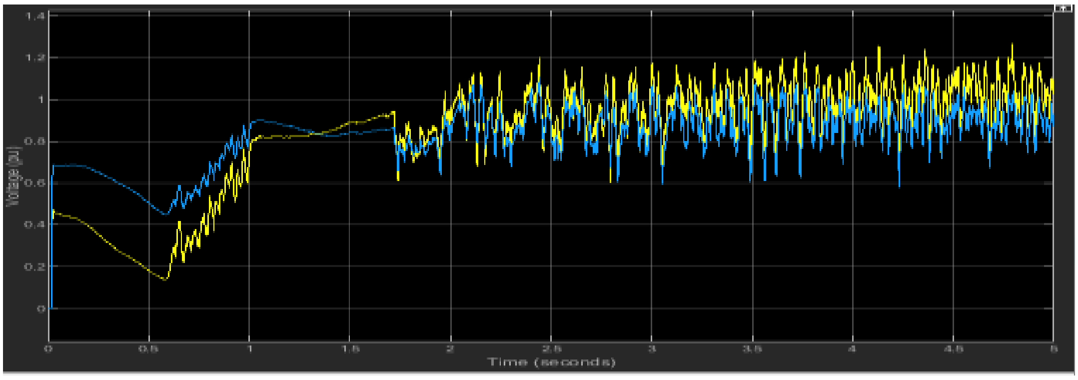

Figure 13: Voltage profile of bus 10 and 18 before fault with arbitrary PI values

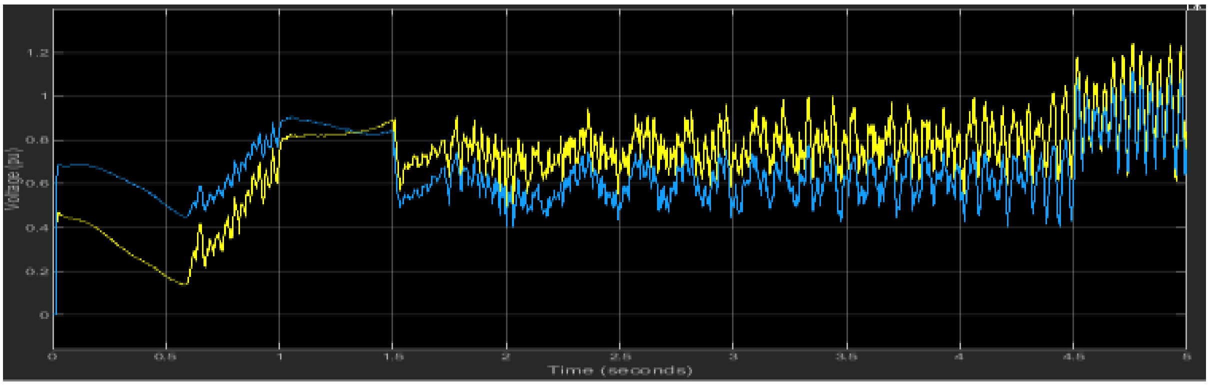

Figure 14: Voltage profile of bus 10 and 18 after fault with arbitrary PI values

6. CONCLUSION

The major problem confronting electric distribution network are high power losses, unavailability of power supply, poor voltage profile and voltage collapse. Among the several techniques which can be used to address this problem, optimal siting and sizing of DG unit and D-STATCOM approach and time domain simulation was adopted. Integration of DG units on IEEE 33 bus network was able to improve the voltage profile and reduced the real power losses by 66.3% while the integration of D-STATCOM on the network also reduced the real power losses by 47.80%. The dynamic performances of the network voltage profile were examined and it was tested on before and after a single line to ground fault was introduced, there was an improvement on the voltage stability when the DG units and D-STATCOM was installed on the IEEE 33 bus network.

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Agrivoltaics: Integrating Agriculture and Solar Energy for a Sustainable Future

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Abstract: Agrivoltaics (AV) is the dual use of land for agriculture and photovoltaic energy generation and has gained global recognition as a sustainable response to the challenges of land scarcity, food insecurity and climate change. These challenges are also evident in the developing nations such as Nigeria where high population density, inadequate electricity supply as well as conflicting land-use pressures strain rural development and agricultural output. This review aims to access the global development, opportunities and limitations of AV systems from technical, economic and socio-political perspectives. It also emphasized how agrivoltaics can be used as a solution to both climate and energy problems, particularly in low- and middle-income countries. The idea behind AV is based on agroforestry, where tall solar panels will act as an overstory, creating partial shading and allowing production of clean energy. The case studies of Japan solar-sharing farms, Germany policy-based growth and rural electrification projects in Kenya, showed that AV could be used to encourage rural development and revitalization, sustainable agricultural practices, and the creation of energy independence. Results revealed that agrivoltaics improves land-use efficiency, helps to maintain a crop yield that is shade-tolerant, decreases the loss of water and offers duel income streams. Wide spread use is restricted by high capital expenses, unreliable policy frameworks and socio-institutional barriers. In conclusion, agrivoltaics has a high potential to enhance food and energy security and also improve climate resilience.

Keywords: *Agrivoltaics, Climate resilience, Dual land use, Food-energy-water nexus, Renewable energy*

1. INTRODUCTION

Agrivoltaics refers to the simultaneous use of land for both agricultural production and solar energy generation. it is also known as agrophotovoltaics, agrisolar or dual-use solar. This innovative approach significantly increases land-use efficiency by allowing crops, livestock or other agricultural activities to coexist with photovoltaic (PV) solar panels on the same parcel of land [1], [2]. It is becoming popular globally for its ability to provide dual benefits, which is the support of food production while simultaneously generating renewable energy. Agrivoltaic systems have also been demonstrated to alleviate stress drought effects on plants and increase the productivity of crop types that are sensitive to shade in water-limited areas [1], [3].

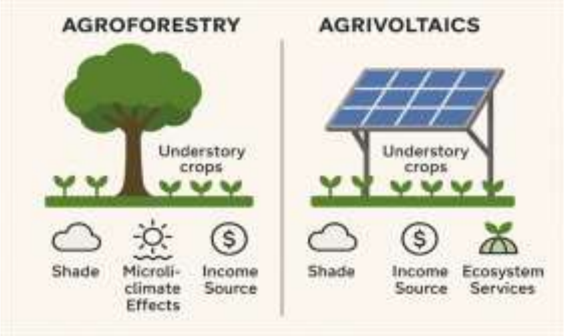
The idea of agrivoltaics dates back to the early 1980s, when Adolf Goetzberger, a German physicist who founded the Fraunhofer Institute for Solar Energy Systems along with his colleague Armin Zastrow, who were the first to propose the combination of solar power generation with agriculture as a solution to the emerging conflict over land use, food production and energy demands. Their 1981 paper described a system that would allow solar panels and crops to co-exist to produce both food and energy without degrading the land or creating water scarcity. Their vision became the foundation for a sustainable dual-use concept of land development [4]. Agrivoltaics became more widely used after 2011, as a result of influential work by Dupraz *et al*. (2011) [5], which formalized the concept further and showed its practicality in different configurations [5]. Large-scale applications started in Japan around 2004, and then in Europe, Germany, France, Austria and Italy. The current systems include high PV systems allowing tractor movements, adjustable panels and greenhouse additions, which aim to maximize light distribution, microclimates, water conservation and the diversification of farmer revenues [4].

The increasing relevance of agrivoltaics is emphasized by the urgent need to transition from fossil fuels, which are not only dwindling but also major contributors to global climate change [6], [7]. This has accelerated the push for decarbonization through a shift to renewable energy sources like solar power. With continued advances in PV technology, solar power is positioned to play a significant role in global energy supply. The International Energy Agency (IEA) forecasts that solar PV will produce up to 6,000 TWh by 2050, meeting approximately 16% of global electricity demand [8]. To achieve these targets, massive tracts of land are needed due to the diffuse nature of solar energy. While rooftop and building-integrated PV (BIPV) can meet part of this need, land-based solar farms will also be essential. This leads to growing land-use competition, especially in areas where population is dense, terrain is limited, or resources are scarce. With the global population growing at 1.15% per year, integrated solutions like agrivoltaics are becoming critical [7], [9]. Despite the global progress, Babarinde (2024) [3] noted that the knowledge and adoption of agrivoltaics remain limited in the Global South, especially in Nigeria. His study offers a technical assessment of Nigeria's potential, identifying the northern states, such as Kano and Katsina, as ideal due to their dry climate, strong solar irradiance, abundant cropland and low electricity access. In contrast, southern states including Lagos, have limited agrivoltaic potential due to their dense forests, low solar exposure and scarce cropland. The study reveals that less than 5% of cropland in northern states would be sufficient to meet projected solar targets, while southern states would require near-total cropland coverage, making implementation far less practical. Several barriers still persist, including high capital investment, land tenure conflicts, shortages in technical expertise and regional security challenges. In terms of system design, panel tilt angles and row spacing must be carefully optimized to ensure sufficient light for both energy production and crop growth. Studies show that the impact of panel shading on yield depends on the crop type and planting density, making tailored designs essential. Comparative evaluations demonstrate that dual-use systems can outperform standalone PV or monoculture farms when measured by overall land productivity and economic viability. Sensitivity analyses further emphasize the potential long-term value of agrivoltaics in guiding sustainable agricultural and energy planning.

As both food security and clean energy become global imperatives, especially in high-growth, land-stressed regions like Nigeria, agrivoltaics provides a sustainable, integrated path forward. Realizing its full potential will require targeted investments, supportive policy frameworks and adaptive designs suited to regional conditions.

2. FUNCTIONAL OVERVIEW OF AGRIVOLTAIC SYSTEMS

Agrivoltaic systems are built to provide the co-development of photovoltaic (PV) generation of electricity and agricultural activity such as crop growth, livestock pasture or the establishment of habitat supporting useful insects such as pollinators, on the same piece of land. The word agrivoltaics is a combination of the prefix of "agri", farming and crop production and "voltaic," meaning electricity made by sunlight (solar energy) [7], [10]. Agrivoltaic has gained growing attention over the past decade, being transformed from a conceptual innovation into a federally supported research priority in countries such as the United States [4]. Although frequently installed on farmland, agrivoltaics is not limited to croplands; it can also support pastures, pollinator habitats and even urban fringe zones [11]. The concept draws inspiration from agroforestry, where trees filter light to crops while improving biodiversity, carbon sequestration and soil moisture. These systems improve crop resilience through shade and microclimate regulation and diversify farm income through products like fruits, nuts, or solar energy, supporting long-term sustainability (Figure 1). In agrivoltaics, solar panels take the place of trees, providing partial shading while producing energy [12]. The partial shading from solar panels reduces evaporation and buffers temperature extremes, benefiting shade-tolerant crops. This dual land use maximizes land productivity and provides farmers with a stable additional income stream from electricity sales. Agrivoltaics also contributes to climate change mitigation by supporting clean energy generation without displacing agriculture (Figure 2).



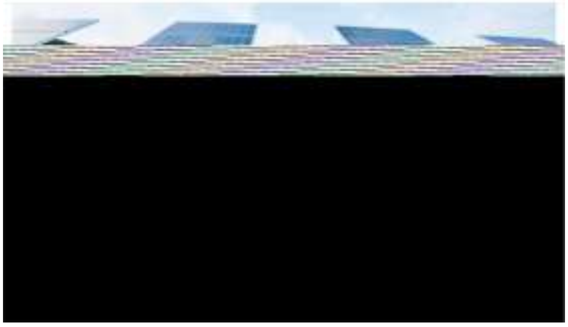


Figure 1: Agroforestry: Trees as Overstory Structures

Figure 2: Agrivoltaics: Solar Panels as Overstory Structures [13].

The concept allows PV arrays to be raised about 2 meters above agricultural land, with increased spacing between rows to reduce shading and maintain crop productivity. These design principles remain central to today's agrivoltaic systems [14].

Modern installations can feature fixed or solar-tracking panels, and the panels are often elevated to allow adequate sunlight penetration to crops beneath, and free movement of agricultural equipment like tractors and harvesters (Figure 3) [4]. An essential design element is the spacing between solar panel rows, which is adjusted to test how different shading levels influence crop yield. This data helps identify the optimal configuration that maximizes both solar and agricultural outputs [13].

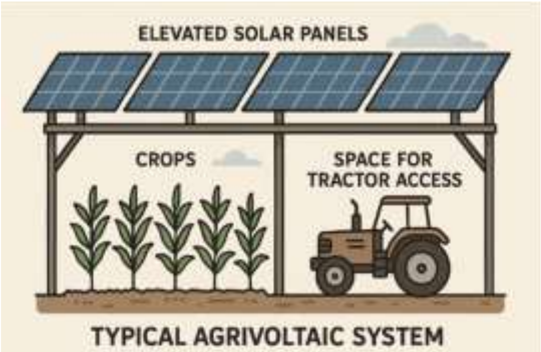


Figure 3 (a): Side-view schematic of a typical agrivoltaic system, illustrating elevated solar panels above crops and dedicated space for tractor access.

Figure 3 (b): Photographs of operational agrivoltaic systems in the field. The images show elevated solar panel arrays with crops growing underneath and sufficient clearance for tractors and other agricultural machinery to move freely [13].

The earliest agrivoltaic demonstrations were developed in Germany and Japan in 2004, with other early projects following in Massachusetts (2008), Italy (2011), Malaysia (2015), Egypt (2016) and Chile (2017) [15]. Beyond commercial projects, some solar facilities have supported small-scale vegetable cultivation by on-site workers. Agrivoltaics has even entered public consciousness through national media, including a widely aired commercial, *"A Future Begins,"* which portrayed a young farmer saving his family's farm through solar-powered sheep grazing. In recent years, agrivoltaic research has gained significant institutional support, including funding from the U.S. Department of Energy's Solar Energy Technologies Office, Support from the Department of Agriculture's National Institute of Food and Agriculture and Creation of the Agrisolar Clearinghouse, an online resource hub managed by the National Center for Appropriate Technology [4]. Today, agrivoltaic systems have evolved beyond open-field applications to include semi-transparent panels, greenhouse integrations and dual-axis tracking designs, making them adaptable to various landscapes and agricultural needs. Many of these innovations aim to improve light-sharing, water-use efficiency and system productivity [14], [16]. Agrivoltaic systems work by strategically balancing light distribution, spatial layout and crop compatibility. While solar panels generate energy, they also provide partial shade, which can protect crops from excessive heat stress. In return, crops cool the environment through evapo-transpiration, improving PV panel. This synergy results in a system that maximizes land productivity, supports climate challenges and provides economic diversification for landowners and farmers [1], [17], [18].

2.1 Benefits of Agrivoltaics

Building on the foundational concept of agrivoltaics as a dual-use strategy for land, the benefits of this innovation extend across environmental, economic and agricultural domains, making it a major solution for addressing sustainable development, food-energy-water nexus challenges and climate challenges (Figure 4)

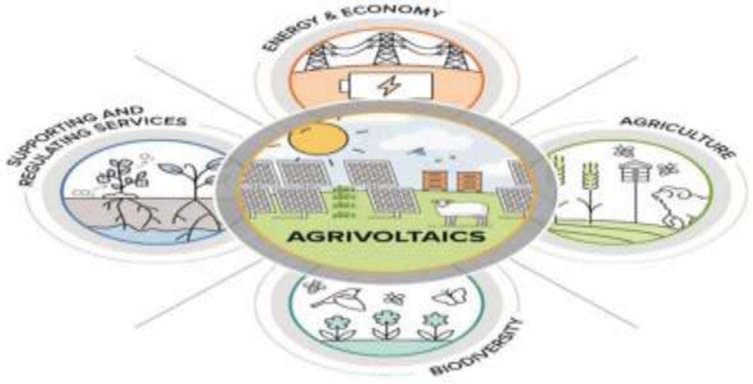


Figure 4: Agrivoltaics position in the nexus of energy-food-biodiversity-ecosystem services and economy [19]

(a) Environmental Benefits: One of the most important environmental benefits of agrivoltaics is its ability to optimize land-use efficiency by combining agricultural production with solar energy generation on the same plot of land [20]. This dual functionality addresses the global tension between the increasing demand for energy and food and the limited availability of arable land, especially in densely populated or ecologically fragile areas [17], [21]. Agrivoltaics also supports water conservation. The shading effect from elevated PV panels lowers both plant and soil surface temperatures, reducing water loss through evaporation and transpiration [18]. This produces a better microclimate for growing crops and, therefore, increases resilience to drought conditions and extreme temperatures, especially in semi-arid and arid regions [18], [22]. Agrivoltaics can also help to preserve biodiversity such that the systems can encourage the presence of beneficial insects such as pollinators, by adjusting the microenvironment below and around the panels and generally improve soil microbe activity, thereby strengthening the wellbeing of the overall ecosystem [11].

(b) Economic Benefits: Economically, agrivoltaics provides significant potential for rural development and livelihood diversification. Farmers can generate revenue not only from agricultural produce but also from electricity sales or leasing agreements with solar developers [23], [24]. On-site energy can power critical agricultural operations such as irrigation, cold storage, and food processing lowering operational costs and improving post-harvest management [23]. Although agrivoltaic systems involve higher capital expenditure (CAPEX) than conventional agriculture or ground-mounted solar alone, ongoing declines in PV module costs (from $3.5/W in 2010 to about $0.3/W in 2020) have made these systems more affordable [25]. In addition, levelized cost of electricity (LCOE) analyses suggests that agrivoltaics can be competitive when considering dual revenue streams. TheAVS-1 design evaluated by Poonia *et al.* (2022) [26] demonstrated the lowest LCOE (€0.038/kWh) among irrigated systems and performed better than traditional ground-mounted PV in terms of land-use efficiency. Financial viability is also improved through government incentives, renewable energy subsidies and tax exemptions available for agrivoltaic deployments in several countries [27]. In tropical and developing regions, where biomass productivity is high and CAPEX is relatively lower, internal rates of return (IRR) exceeding 8% have been reported, even with partial crop yield reductions [25], [27].

(c) Agricultural Benefits: Agrivoltaic has practical benefits to agriculture, particularly in areas with increasing temperatures and water shortage. Plants cultivated with the shade of PV panels demonstrated enhanced resistance to heat and drought stress, leading to higher quality and survival of shade-tolerant plants including lettuce, tomatoes, peppers and grapes [1], [18]. In hot climates, agrivoltaics has even been associated with increased yields due to moderated temperature, reduced evaporation and protection from radiation overload [25], [28]. Agrivoltaic systems, In addition to improved crop resilience, provide physical protection against extreme weather conditions, such as hailstorms, heavy rains and strong winds. This buffering potential guarantees more crop stability and is able to reduce the loss of yield due to climate variability [7]. Agrivoltaic installations are also advantageous to livestock production, where animal research has demonstrated that animals such as sheep like grazing under shaded PV panels during days of high solar radiation, increasing animal welfare besides aiding vegetation management under the arrays [29]. In the U.S., it has been proposed that agrivoltaics of grazing could be used to generate up to 20% of the total electricity in the country, with large emissions of greenhouse gases decreasing (e.g., 2.77 tons / year of 5.19 MWh production) [25], [29]. Agrivoltaics also leads to a more resilient agricultural system through the reduction of the effects of climate, the diversification of farm income, and the decreasing reliance on external energy inputs. As a result, it plays an important role in strengthening rural economies and promoting food-energy security, especially in regions affected by climate shocks, economic instability or poor energy [30].

(d) Social and Technological Value: Agrivoltaics has high social and technological benefit due to the off-grid, underserved, or resource-scarce areas [17]. Agrivoltaic (AV) systems may serve as an effective community empowerment tool, particularly within rural or semi-arid areas that have little access to reliable electricity. Such systems supply the localized energy to support such basic services as the pumping of water, irrigation, cold storage, food processing and even micro-enterprise activities, thereby enhancing the community resilience and not depending on centralized infrastructure [31], [32].

Another notable development in technology is the integration of agrivoltaics into greenhouse systems whereby new innovations like semi-transparent photovoltaic modules, including organic photovoltaics (OPVs) and dye-sensitized solar cells (DSSCs) enable solar panels to be installed on the inside of greenhouses without affecting the light transmission to the plants. These greenhouse-integrated systems can produce up to 200 kWh/m² per year which enables productive energy generation without negatively impacting crop yields [33], [34]. The development of agrivoltaics worldwide is now backed up by a growing number of international research and institutional aid. Over 2,200 systems have been in place since 2014, adding approximately 2.8 GW in installed capacity by 2020 [35]. The development has been supported by efforts including international conferences, government-funded research (e.g., U.S. Department of Energy and Agriculture) and the knowledge sharing platforms (e.g. the Agrisolar Clearinghouse) [28], [29]. System design is now influenced by technological tools, including modeling and simulation, that help optimize panel height, spacing and orientation based on particular crops and climates. The viability of the agrivoltaics system can be measured using economic indicators such as the LCOE, IRR, and CAPEX, particularly in countries that are developing where the agrivoltaics system has been seen to have potential in electrification in rural areas and sustainable growth. In addition to environmental and agricultural impacts, AV systems promote climate resilience, economic mobility as well as equitable technological development [25], [36].

2.2 Challenges and Limitations of Agrivoltaics

Although the potential of agrivoltaic (AV) systems to enhance land-use productivity, food-energy security and climate resilience is significant, the broad deployment of these solutions is still limited by numerous technical, economic, social and institutional barriers. These constraints both complicate the implementation of AV systems and affect their long-term sustainability, in particular, in rural or low-income countries like India [37] and Nigeria [31].

(a) High Initial Costs and Economic Uncertainty: The extremely high cost of capital investment in setting up PV structures that are compatible with farming activities is one of the most urgent issues to be addressed. AV systems, unlike conventional photovoltaic (PV) or agricultural systems, have elevated and mobile support structures, optimized mounting, and design to enable dual use. Although innovative, these characteristics increase the Levelized Cost of Electricity (LCOE) that can reach above €0.08–0.17 per kWh depending on the technology and configuration applied [14], [25], [38]. Financial models indicate that bi-axial tracking AV systems or mounting panels at higher value might not be cost-effective unless subsidized by the government or given a good Feed-in-Tariff (FIT) rate [14], [39]. The lack of financial security of agrivoltaics is also compounded by unstable agricultural and electricity markets, slow repayment times and inadequate access to funding particularly in underdeveloped areas. In Sub-Saharan Africa, Adelhardt & Berneiser, (2024) [40] reported that the most pressing adoption barriers as cited by the stakeholders comprised a shortage of finance, unavailability of credit capital, and unpredictable regulatory conditions. Moreover, profitability can be threatened by changes in a crop yield as a result of shading. In some pear and apple systems, losses of up to 16% have been observed, in which the extra revenue generated by the electricity was not enough to cover the agricultural loss [41], [42].

(b) Technical and Agronomic Constraints: Technically, AV systems should take into consideration the complexity of design particularly in relation to the height, spacing, and orientation of the panel regarding the light needs of different crops, particularly those that involve crop rotation. Lack of daylight in areas like Belgium or the UK, has shown losses in crop yields, like sugar beet or wheat, due to the absence of sunlight below panel shading [14], [43]. On the other hand, moderate shading (approximately 25 percent) has been demonstrated in high-irradiance zones such as the Mediterranean, to increase crop yields by minimizing heat stress [14], [44]. Nonetheless, too much shading may have adverse implications on the quality of crops. To illustrate, a lower concentration of flavonoid and chlorophyll was detected in the leaves of sugar beets cultivated under AV systems than in the same beets cultivated in the full sunlight [45]. AV conditions led to lower total soluble solids in vineyards that may negatively affect wine grape quality [46].

(c) Operational constraints: There are also operational limitations related to the co-existence of farm equipment and high PV structures. Large or autonomous machines can have issues with navigation, such as loss of GPS signal under panels, resulting in ineffective seed placement or harvesting. In Addition, issues related to the soil compaction, erosion during installation and loss of land (up to 10%) for arable crops have furthermore complicated deployment [14], [47]. Maintenance is an additional complex issue, since panel cleaning, repairs and theft deterrence must be managed continuously, particularly when in remote or off-grid locations. There are also instances where livestock contact with panels has led to physical damages or a higher risk of fire in hot and dry conditions [48]. Issues relating to environmental problems as a result of panel end-of-life disposal have been reported. Unless treated appropriately, certain types of panels can have long-term environmental effects due to the toxicity of certain components (such as cadmium or lead) and this highlights the necessity of having recycling and reuse systems [49].

(d) Regulatory, Political, and Legal Uncertainty: Legal and policy frameworks remain underdeveloped in many parts of the world. In Europe, agrivoltaics is not clearly defined within the Common Agricultural Policy (CAP), leading to regulatory ambiguity and potential legal loopholes [14]. Land use rights, asset ownership, and grid connection policies are often unclear or unfavorable for AV systems. In developing countries, bureaucratic complexity, high taxation and corruption risks also emerge as major political and legal threats to AV project development [40]. Integration with central electricity grids also presents logistical and economic challenges. Upgrading rural grid infrastructure or securing power purchase agreements (PPAs) to make AV projects bankable can be prohibitively expensive without coordinated government support [50].

(e) Social Barriers and Public Acceptance: Public perception and social acceptance represent critical hurdles. Farmers and rural communities may exhibit skepticism toward AV systems due to a lack of awareness, low education levels or concerns over equity and land ownership. In some cases, there is fear that AV development could disproportionately benefit wealthier stakeholders, leaving marginalized farmers behind. Inadequate training and unfamiliarity with energy technology and maintenance further limit community engagement and confidence in AV as a viable farming model [14], [51], [52]. Visual landscape changes and the perceived loss of agricultural identity may also generate resistance [53]. According to Sirnik *et al*. (2024) [54], landscape transformation, fencing and support infrastructure can reduce experiential value, even if future value (long-term sustainability) increases. Preferences have been shown to favor intercrop AV systems over overhead installations, based on aesthetics and land integration [53].

2.3 Strategies for Mitigating Constraints

In order to eliminate the numerous difficulties that are linked to the implementation of the Agrivoltaic systems, a number of strategies have been introduced. First, there should be very clear legal definitions and harmonized AV standards at the national and regional level so that there is regulatory clarity. Priority should be given to agricultural primacy whereby energy production complements farm operations and not vice versa. Simultaneously, participatory planning should be used with local farmers and stakeholders on the AV models that can be implemented, in order to allow for appropriate AV designs and management approaches. The technical and financial gap can be overcome by subsidies, capacity building and research on shade-tolerant crops, particularly during the initial phase of implementation. The creation of third-party quality control standards and performance indicators will also play a fundamental role in trust levels and the possibility to scale up [51], [52]. Rural resilience can also be enhanced through integrated models incorporating co-productions, food, water, and energy, where possible, due to their capacity to attract investor confidence [14].

2.3.1 Policies, Regulatory Frameworks and Incentive Programmes

Agrivoltaics (AV) aligns strongly with multiple UN Sustainable Development Goals (SDGs), particularly those related to food security, clean energy, climate action and responsible land use. At the global level it supports up to 14 of the 17 United Nations Sustainable Development Goals (SDGs), providing dual benefits of agriculture and renewable energy production [40]. This include SDG2 (Zero hunger, boosting food generation in the face of the challenges of climate change and water scarcity), SDG3 (Health and well-being, expanding food production while maintaining nutritional quality; taking into account secondary metabolites), SDG7 (Affordable and clean energy, expanding renewable energy with little or no reduction in arable land use), SDG9 (Industry, innovation and infrastructure, driving creative solutions that merge energy generation with agriculture, using technologies that enhance the services provided by agroecosystems), SDG12 (Responsible production and consumption, simultaneously increasing energy and agricultural production, while minimizing land degradation and water consumption) and SDG13 (Climate action, reducing CO_2 emissions resulting from human activities, including those associated with agriculture) [18]. However, legal frameworks to support AV remain underdeveloped in many countries, though interest and support are growing [55], [56]. Japan has the most mature legislation, requiring AV projects to prioritize agriculture to access tax benefits and feed-in tariffs (FITs). South Korea is moving toward legalizing AV, while France, Germany, Italy and Croatia have issued various guidelines or passed laws supporting AV, including subsidies and production planning requirements. In the U.S., both federal and state governments promote AV through research funding and incentive programmes like Massachusetts' SMART initiative. Common support mechanisms across countries include FITs, tax breaks, zoning reforms and inclusion of AV under national rural development and renewable energy strategies [14], [25]. Although formal AV policies are still evolving, there is increasing recognition of its role in sustainable development. Countries are beginning to provide financial and regulatory support to integrate AV into agriculture, climate and energy agendas [55], [57].

3. CASE STUDIES AND SUCCESS STORIES

3.1 Japan's Solar-Sharing Agrivoltaics: A Model for Sustainable Rural Transformation

Japan has emerged as a global pioneer in agrivoltaic (AV) development, especially through its innovative "solar-sharing" model. This approach involves the installation of elevated photovoltaic (PV) panels above farmland, allowing simultaneous agricultural production and solar energy generation. It has proven especially valuable in the rural regions of Japan, where land scarcity, aging populations, and abandoned farmland present persistent challenges [2], [58].The development of agrivoltaics in Japan began in 2004 in Chiba Prefecture, led by Akira Nagashima [14]. Today, there are 1,992 agrivoltaic farms covering approximately 560 hectares, present in 46 out of 47 prefectures. Most of these farms are small-scale under 0.1 ha and contribute an estimated 500,000 to 600,000 MWh of electricity annually, about 0.8% of Japan's total solar output [2]. Japan's AV systems offer dual-income opportunities, with farmers generating between $10,000 to $15,000 per hectare per year from solar electricity sales, in addition to crop revenues. Crops grown under solar panels include rice and leafy vegetables, with more than 120 crop types cultivated overall [59].This income diversification improves farm profitability as well as supports broader national objectives such as rural revitalization, food-energy-water security and climate resilience [2], [60]. Agrivoltaics has a distinct regulatory advantage in that it can be installed across all five classes of farmland without reclassifying the land for non-agricultural use [2]. The policy landscape has played an important role in accelerating AV utilization. The introduction of the Feed-in Tariff (FIT) scheme in 2012 significantly improved solar power deployment, increasing renewable energy output by 76% from 2012 to 2019. PV generation alone rose from 7,600 GWh to 77,000 GWh in that period. Two major Ministry of Agriculture, Forestry and Fisheries (MAFF)directives (2013 and 2018) institutionalized agrivoltaics and a 2020 amendment to the FIT Law (enforced in 2022) gave preferential status to AV installations [2], [58]. However, Japan's AV success has various challenges. A major technical issue is shading management, as shading levels on AV farms range from 10% to 100%, with a median of 30–40%. Ideally these levels are determined by a crop's light saturation point but in practice they are often chosen to maximize solar income, with crops selected afterward potentially disrupting local agricultural markets. In 69% of cases, crop types are changed post-installation, raising concerns about long-term stability and market access [2], [14]. In addition to its technical and economic achievements, Japan's AV model is drawing attention for its social and governance implications. According to Koga and Petrova (2025) [21], AV projects like Shimin Enerugi Chiba demonstrated the potential for community energy governance (CEG) by actively involving local residents in decision-making. However, they warn that if spatial and institutional hierarchies are not addressed, AV could inadvertently reinforce existing power imbalances. Their research highlights the need for inclusive, democratic governance frameworks that reflect local realities. Similarly, Chen *et al.* (2025) [61] examined an AV project in Aomori Prefecture, assessing both financial metrics (NPV, IRR, and payback periods) and social equity outcomes (via Gini coefficients). Their findings revealed unequal benefit distribution, especially a disadvantage to smallholder farmers and tenants. To promote fairness, they recommend revenue-sharing models, equitable lease terms and farmer-centric subsidies to ensure that AV expansion contributes to inclusive rural development. Japan’s agrivoltaic infrastructure has tremendous potential in the future. If all abandoned farmland were converted into AV systems, it is estimated that Japan could generate up to 280 GW of electricity. In the Kantō region alone, the potential capacity ranges from 15 to 39 GW [2]. High-value examples, such as AV tea plantations in Shizuoka Prefecture, illustrate how agrivoltaics can support both economic viability and environmental sustainability, providing replicable models for other countries. Japan’s solar-sharing AV system is an example of how a well-integrated approach to energy, agriculture and governance can transform rural areas. With the right mix of technical innovation, policy incentives and social inclusion, Japan can provide a compelling roadmap for global agrivoltaic adoption, balancing food security, clean energy and community empowerment [14], [21].

3.2 Germany: Policy-Driven Expansion and Land-Use Optimization

Germany stands out as the European leader in the rapid adoption of agrivoltaic (AV) technology, with national energy and land-use policy now recognizing AVs as a strategic solution to reconcile renewable energy generation and food security. Already known for its strong base of rooftop and ground-mounted photovoltaic (PV) systems, with over 2.2 million rooftop installations and a cumulative capacity of 58.4 GWp by 2022, Germany’s energy transition has increasingly turned to dual-use solar systems as part of its 2045 carbon neutrality goal [62]. The growing concern around land-use competition, especially with rising pressure from climate extremes such as heat waves and drought has catalyzed policy reforms and technological exploration to support AVs. AV systems provide partial crop shading that can reduce evapo-transpiration and improve microclimates, which are beneficial for drought resilience. The capacity to generate solar power on agriculturally viable lands has also helped to alleviate the tension between food production and decarbonization goals [62]. AV installations have also been shown to protect against hail, heat stress and wind damage, which are increasingly common across German farmlands. Germany is rapidly expanding its agrivoltaic (AV) systems. Pump *et al.* (2024) [62] reported that as of March 2023, there were 21 AV sites producing 81.67 MWp of power. By the end of 2024, this was expected to grow to 45 sites and 382.6 MWp. This growth is supported by new government policies, such as the 2022 innovation tenders, which provide financial support and enhance investor confidence [62]. Southern Germany leads in current installations, but interest is spreading nationwide. A study by Rösch & Fakharizadehshirazi (2024) [63] found that AV systems on just 0.74% of Germany’s land, mainly on high-quality small farms, could meet up to 88% of the country’s 2030 solar energy targets. To ensure AV systems support both farming and energy, Germany requires them to maintain at least 66% of normal crop yields. Public approval is high, especially in rural areas where farmland is preserved. Though AV systems cost 30–50% more than regular solar setups and have a higher cost per kilowatt-hour (8.3–9.5 Euro Cents), they provide benefits like lower irrigation needs of up to 20%, reduced crop heat stress and increased biodiversity. They work especially well with shade-tolerant crops like berries, herbs and lettuce [63]. The approach of Germany shows how AV can grow from small trials into a national strategy. With strong policies, land data and local support, Germany is creating a model that other countries can follow to combine clean energy with sustainable farming.

3.3 Sub-Saharan Africa: Agrivoltaics as a Solution to Food and Energy Challenges

Sub-Saharan Africa faces deep-rooted challenges around energy access, food security and water scarcity. More than 600 million inhabitants of the region do not have electricity, and millions of people stay undernourished [64]. Agrivoltaics (AV) holds potential to generate solar energy and at the same time use the same land as a source of agricultural products, which can solve these related challenges [14], [25]. AV systems have improved crop yields and decreased dependency on diesel generators demonstrated in pilot projects in nations such as Kenya and Nigeria, showing that AV systems can produce irrigation [65], [66]. Solar partial shading also leads to better soil water retention and plant survival, particularly in the case of arid climates [67]. However, challenges such as high setup costs, limited technical knowledge and community acceptance prevent widespread adoption [52]. To address this, experts recommend financial support measures like feed-in tariffs (FITs), which ensure stable income for AV energy producers and reforms in land-use policies to accommodate dual-use agricultural energy systems [14], [25]. The Malindi Solar Power Plant is one of the successful installations in Kenya that demonstrate that solar energy and agrivoltaics (AV) can be used to aid rural electrification and economic growth. In 2021, solar power contributions from the Cedate, Selenkei and Malindi plants added 120 MW to the national grid, increasing Kenya's total solar capacity to 172 MW [68]. Emerging technologies, such as IoT monitoring and digital twins, are also being introduced to optimize AV performance in real-time [69], [70]. Studies have emphasized the need for collaborative efforts involving governments, research institutions, and the private sector. With the right policy and investment framework, agrivoltaics could play a pivotal role in achieving food and energy security in Sub-Saharan Africa, while contributing to Sustainable Development Goals 2 (Zero Hunger) and 7 (Clean Energy) [14], [17], [25]

4. FUTURE PROSPECTS AND INNOVATIONS IN AGRIVOLTAICS

The future of agrivoltaics (AV) lies in the strategic convergence of advanced technologies, sustainable energy integration and smart agricultural systems. As demonstrated by recent research and pilot projects, AV is evolving from a land-sharing concept into a holistic platform for synergizing food, energy and water systems, while also enabling smart farming, ecological stewardship and rural development [17], [25].

(a) Advanced Photovoltaic Designs and Spectral Optimization: Advances in photovoltaic technologies are enlarging energy production without damaging crop health and yield. A recent solution reported by Gorjian *et al.* (2023) [71] is the use of concentrator photovoltaics (CPV). Such systems make use of sunlight-tracking optics, parabolic mirrors and dichroic films to focus the sunlight onto high-efficiency solar cells, efficiently transmitting photosynthetically active radiation (PAR) to the crops below. CPV systems alleviate shading problems by diverting wavelengths (like near-infrared) not needed by the system to use in generating power and improving the available light spectrum to generate power through photosynthesis. Still limited today by cost and complexity, CPV and other spectral-splitting technologies are attractive routes towards maximizing land-use efficiency and crop yield.

(b) Solar-Powered Biogas and Hybrid Energy Systems: Klokov *et al*. (2023) [72] envisioned a scenario in which agrivoltaics would become operationally connected to anaerobic bioconversion to convert agricultural waste into biogas and organic fertilizers. They are hybrids, and they can use solar photovoltaic thermal (PV/T) solar module to supply electrical energy and thermal energy at the same time, which will benefit the process of anaerobic digestion through proper temperatures. Solar-heated digesters, heat pumps and phase-change thermal storage are innovations that allow biogas production to remain stable in cold climates. This not only improves the energy self-sufficiency but also reduces emissions, minimizes waste and promotes closed-loop nutrient cycling.

(c) Growth Stimulation and Environmental Control: Future agrivoltaic systems will also support plant growth stimulation through controlled environments, powered by solar energy. Techniques under exploration include electric, magnetic, thermal, acoustic, and mechanical stimulation, as well as the use of light-emitting diodes (LEDs) and luminescent concentrators to tailor light exposure. These systems could manipulate crop physiology to improve yields, quality, and stress tolerance, especially in controlled greenhouse-like environments. Innovations in temperature, airflow, humidity and nutrient regulation, all powered by AV, could redefine precision agriculture [73].

(d) Agricultural Electrification and Robotics: The integration of electric agricultural machinery and autonomous robots is another major trend. AV systems offer on-site renewable electricity, reducing dependence on fossil fuels and supporting battery-powered tractors, drones, and harvesters. AV infrastructure may also serve as navigational supports, rail tracks and irrigation conduits for robotic systems. This will be crucial in enhancing productivity, labor efficiency and operational continuity, especially in rural areas with poor grid reliability [74].

(e) Digital Agriculture and Internet of Things (IoT): Agrivoltaics will play an important role in enabling digital agriculture and IoT-based monitoring systems. Sensors powered by AV can monitor soil moisture, plant health, weather conditions, and even animal physiology, transmitting data via LoRa or Wi-Fi networks. This digital transformation will support real-time decision-making, predictive analytics, and remote farm management, making AV the backbone of agriculture 4.0. Additionally, AV can provide resilient energy infrastructure in remote areas, reducing reliance on unstable grids or satellite navigation in potential conflict or disaster scenarios [75], [76].

(f) Post-Harvest Processing, Cold Storage and E-Commerce: AV energy can also revolutionize post-harvest processing and storage. In many rural regions, lack of electricity is a barrier to cold storage, grading, packaging and value addition. With localized AV systems, farmers can preserve crop quality, extend shelf life and participate in e-commerce and direct-to-consumer models, thereby increasing profit margins and reducing logistics costs. AV thus becomes a tool for value chain optimization and rural economic empowerment [14].

(g) Sustainability, Circular Economy and Long-Term Viability: In the future, new innovations will be applied to recycling the PV modules, lifecycle improvements, and building materials with dual uses. Solar thermal roofing panels for example are made from recycled plastic and can serve both structural and energy functions, reducing costs and environmental impact. Combining AV with small wind turbines or DC-powered microgrids can also diversify energy sources and improve reliability, particularly in off-grid contexts [14], [77]. The possibilities of agrivoltaics can reach even space agriculture, where experimental concepts involve agriculture on extra-terrestrial colonies such as the Moon or Mars, powered by solar-powered controlled environments. Being rather speculative, these ideas discuss the flexibility, scalability and visionary prospects of AV [14], [74].

5. CONCLUSION

Agrivoltaics is an integrative and scalable model that can be utilized to help solve some of the most crucial issues globally between energy, agriculture, and environmental sustainability. AV allows food and renewable electricity to be co-produced on the same piece of land, increasing land-use efficiency and climate resilience, and the incomes of farmers. The examples of the leading solar-sharing farms in Japan, the organized regulatory growth in Germany, and electrification projects in Kenya indicate the flexibility of the model and the policy applicability. In Nigeria, agrivoltaics is very promising in situations where land degradation, energy insecurity, and rural poverty are burning concerns. Through the vast availability of solar and extensive agricultural practices, AV can achieve decentralized energy access, enhance livelihood, and support less land- and food-system pressure. To harness this potential, investments will have to be made in the targeted areas, capacity building, favorable regulation and system designs that are more locally focused. The future of this rapidly advancing field globally is incorporating agrivoltaics into the national development plans, particularly in land-stressed, low-income economies such as Nigeria, in order to facilitate a sustainable and inclusive future.

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Review of Electric Vehicle Systems and Their Global Adoption Trends: A Case Study for Nigeria

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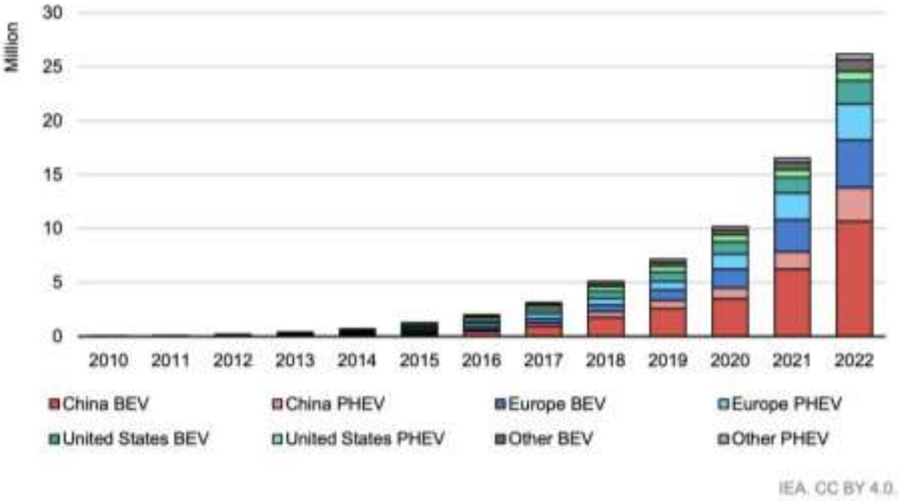
Abstract: Electric vehicles (EVs), including hybrid variants, have gained significant global attention due to their environmental, technological, and economic advantages. This paper reviews electric vehicle systems and global adoption trends, with a particular focus on Nigeria as a case study. The methodology is based on a review of existing literature, government policy reports, and case studies, complemented by expert interviews from Nigeria's automotive and energy sectors. Key findings indicate that Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Hybrid Electric Vehicles (HEVs) offer different advantages and limitations in terms of efficiency, emissions reduction, and feasibility of use in emerging economies. The review also highlights adoption challenges in Nigeria, including high upfront costs, inadequate charging infrastructure, and low consumer awareness. Nevertheless, the environmental and economic benefits of EVs, alongside Nigeria's renewable energy potential, present an opportunity for policy-driven adoption. The study concludes by emphasizing the need for strategic investment in infrastructure, consumer education, and government incentives to foster EV adoption in Nigeria.

Keywords: *Battery Electric Vehicles, Charging Infrastructure, Electric Mobility, Hybrid Vehicles, Nigeria, Sustainability.*

1. INTRODUCTION

The automotive industry is experiencing a paradigm shift from vehicles powered by Internal Combustion Engines (ICEs) to Electric Vehicles (EVs), driven primarily by the need to reduce carbon emissions and dependence on fossil fuels. According to the International Energy Agency (IEA), the global stock of EVs surpassed 26 million in 2022 (as presented in Figure 1), representing a 60% increase compared to 2021 [1]. Countries such as China, the United States, and several European Union members have already adopted ambitious policies to accelerate EV penetration, making EVs central to their decarbonisation strategies [2].



IEA. CC BY 4.0.

Figure 1: Global stock of EVs

Nigeria, however, presents a contrasting scenario. With rising fuel prices, traffic congestion, and worsening air pollution, the country faces unique challenges that make EV adoption both urgent and complex. While the Nigerian government has expressed interest through initiatives such as the National Automotive Industry

Development Plan (NAIDP) and the Green Transport Policy [3], actual adoption remains low due to infrastructural and policy gaps.

Several studies have emphasised the benefits of EVs, including reduced greenhouse gas emissions, improved air quality, and long-term cost savings [4]–[6]. However, developing countries face barriers such as high upfront vehicle costs, insufficient electricity supply, and lack of public awareness [7]. The significance of this paper lies in bridging the gap by reviewing EV systems and global adoption trends, then contextualising their implications for Nigeria.

2. LITERATURE REVIEW

The adoption of EVs has been the subject of numerous studies across technology, policy, and environmental domains. This section reviews selected works relevant to EV systems and adoption trends.

Yang & Zhao (2020) reviewed technical advancements in hybrid electric vehicles, emphasising efficiency improvements and limitations in battery technology [4].

Ehsani et al. (2010) provided foundational insights into EV, HEV, and fuel cell vehicle design, highlighting drivetrain architectures and energy management strategies [5].

Jiang (2021) analysed unsettled technological areas in EV propulsion systems, identifying challenges in power electronics and thermal management [6].

IEA (2022) Global EV Outlook presented global market trends, showing exponential EV growth led by China and Europe [1].

NREL (2020) highlighted the importance of charging infrastructure in enabling EV adoption, recommending public-private partnerships for developing nations [7].

Nigerian Ministry of Environment (2020) outlined policy pathways for green transport in Nigeria, underscoring renewable energy integration [3].

Volkswagen Group of America discussed the functional design of EVs, particularly focusing on batteries, motors, and regenerative braking [8].

These studies collectively show that while EV adoption is accelerating globally, Nigeria's case requires targeted policy interventions and infrastructure development to catch up.

3. METHODOLOGY

This study employed a qualitative review methodology. Data sources included scholarly journals, industry reports, government publications, and policy documents. Expert interviews were also conducted with professionals in Nigeria's automotive and energy sectors. The key parameters considered included:
(a) Types of EVs (BEVs, PHEVs, HEVs).
(b) Key performance metrics (range, charging time, efficiency).
(c) Environmental impacts.
(d) Economic feasibility (acquisition, maintenance, energy consumption).

4. RESULTS AND DISCUSSION

4.1 Types of Electric Vehicles

i. Battery Electric Vehicles (BEVs): Fully electric, zero emissions, dependent on charging stations, best for urban areas.
ii. Plug-in Hybrid Electric Vehicles (PHEVs): Dual power (battery + ICE), good for long distances, transitional technology.
iii. Hybrid Electric Vehicles (HEVs): Recharge via regenerative braking, efficient but less environmentally beneficial than BEVs.

4.2 Challenges of EV Adoption in Nigeria

i. **Charging Infrastructure:** Limited availability of charging stations, particularly outside major cities.

ii. **High Costs:** EVs are still expensive relative to ICE vehicles.

iii. **Energy Supply Constraints:** Unreliable electricity grid poses a barrier.

iv. **Consumer Awareness:** Low understanding of EV benefits hinders acceptance.

4.3 Benefits of EVs

i. Environmental sustainability through reduced greenhouse gas emissions.
ii. Lower operational costs due to reduced fuel dependency.
iii. Improved energy security via reduced reliance on imported fuel.

4.4 Global Adoption Trends

i. **China:** Leads in EV manufacturing and adoption, with strong government subsidies.

ii. **Europe:** Ambitious zero-emission vehicle targets by 2035.

iii. **USA:** Incentives and infrastructure expansion driving growth.

iv. **Nigeria (Case Study):** At an early stage, but with significant potential if supported by policies and renewable energy investment.

5. CONCLUSION

This review establishes that EVs are pivotal in addressing climate change and transitioning to sustainable transport. Global adoption is accelerating, but Nigeria lags due to infrastructural, economic, and policy challenges. The study concludes that Nigeria can leverage its renewable energy potential and government incentives to facilitate EV adoption. Collaborative efforts among government, industry, and academia will be essential in positioning Nigeria as part of the global EV transition.

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APPENDICES

Plate A1: A typical Full/Battery Electric Vehicle

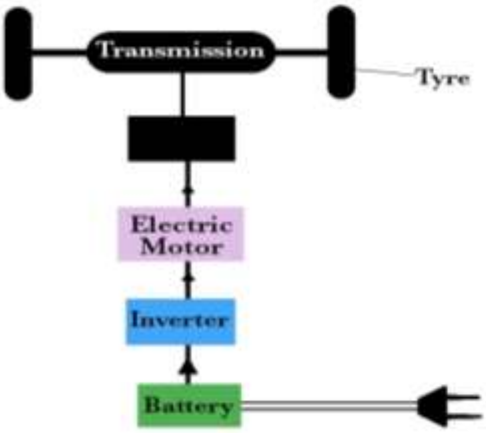

Plate A2: Block diagram of a Full/Battery Electric Vehicle

Plate A3: Level 2 Charging System

Plate A4: Level 3 Charging System

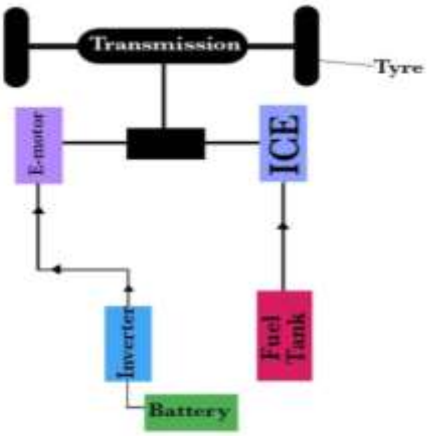

Plate A5: Block diagram of a Parallel Hybrid Electric Vehicle

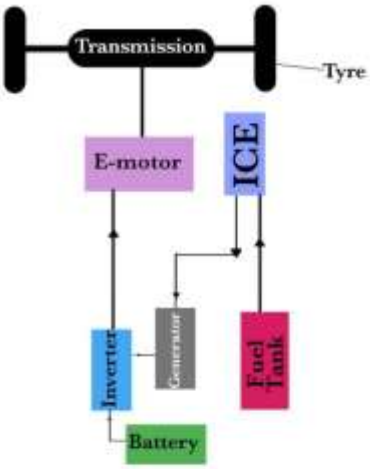

Plate A6: Block diagram of a Series Hybrid Electric Vehicle

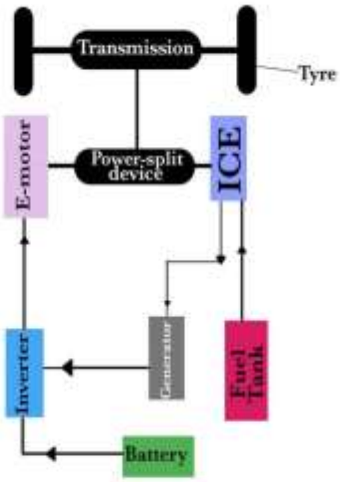

Plate A7: Block diagram of a Series-Parallel Hybrid Electric Vehicle

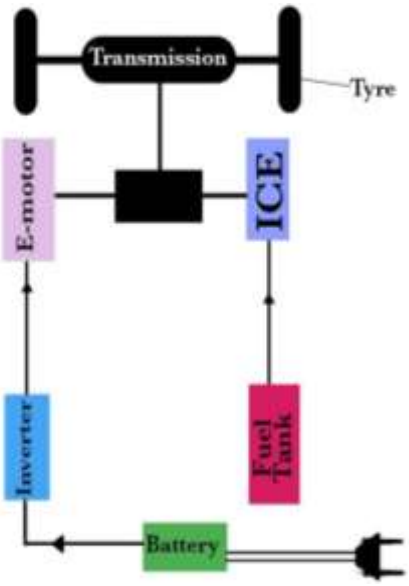

Plate A8: Block diagram of a Plug-in Hybrid Electric Vehicle

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Predictive Analytics in Enhancing Green Energy Adoption in the Telecommunication Sector

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Abstract: The telecommunication sector is one of the fastest-growing energy consumers in Nigeria, where reliance on diesel-powered base transceiver stations (BTS) has resulted in significant economic and environmental costs. According to the Nigerian Communications Commission (NCC) and GSMA, the country hosts over 30,000 BTS sites, of which more than 80% depend on diesel generators, consuming an estimated 2.5 billion liters of fuel annually and emitting approximately 6.5 million metric tons of CO_2. This study investigates the role of predictive analytics in enhancing green energy adoption within the sector. Using datasets from NCC, GSMA, and NASA's POWER database, predictive models were developed to forecast energy demand, diesel consumption trends, and solar generation potential for Kogi State. The findings show that predictive analytics can reduce forecasting errors by 18–25%, optimize hybrid energy configurations, and lower operating costs by up to 30% compared to diesel-only systems. Furthermore, modeled scenarios indicate that carbon emissions could be reduced by 40–50% when predictive-guided solar-hybrid systems are deployed. These results suggest that predictive analytics offers a viable decision-support tool for aligning Nigeria's telecom energy infrastructure with Sustainable Development Goals (SDGs) 7 and 13..

Keywords: *Predictive analytics, telecommunication, renewable energy, sustainability*

1. INTRODUCTION

The telecommunications sector is a major and growing electricity consumer in many low- and middle-income countries, and Nigeria is no exception. Reports indicate that Nigeria now hosts tens of thousands of BTS sites, with national counts reported in NCC summaries and industry reviews. This rapid expansion has occurred in an environment of unreliable grid supply, which has led operators to rely heavily on diesel generators and hybrid configurations to keep sites online [6]. Heavy dependence on fossil-fuel backup imposes substantial economic and environmental burdens on network operators and society. Operator sustainability reports and independent studies show that diesel accounts for a majority share of site energy, increasing both operational expenditure and greenhouse-gas emissions (e.g., MTN Nigeria sustainability disclosures) [10]. These realities make the telecom sector both a critical target for decarbonisation efforts and a promising domain for applied energy-systems research. [10].

Predictive analytics, the use of statistical and machine-learning methods to forecast demand and guide decisions, has matured rapidly in the energy domain and is now being applied to telecommunications energy management. International technical bodies, such as the ITU, have begun to outline frameworks for AI, big data, and predictive models in improving energy efficiency in communications networks. When coupled with meteorological datasets (e.g., NASA POWER) and operator telemetry, predictive models can generate forecasts of site energy demand and renewable generation potential that inform hybrid system sizing, fuel-use scheduling, and maintenance planning.[12], [10]. Despite these prospects, gaps remain in the literature. Much prior work has focused on techno-economic optimization of hybrid power systems or isolated pilot implementations; fewer studies have systematically evaluated how predictive analytics can change adoption pathways for green energy at scale, particularly in Nigeria [12]. This paper addresses that gap by combining operator datasets with meteorological inputs to develop predictive models that forecast energy demand and evaluate the impacts of predictive-guided solar-hybrid deployment on costs and emissions. [12], [10].

The research objectives are to:

i. quantify baseline energy usage and diesel dependence for representative telecom sites in Kogi State;

ii. develop and validate predictive models for short-term energy demand and solar generation potential; and
iii. Simulate techno-economic scenarios to estimate cost savings and emission reductions enabled by predictive analytics [12].

1.1 Energy Consumption in the Telecommunication Sector

The telecommunication industry has emerged as one of the largest off-grid energy consumers in Sub-Saharan Africa. In Nigeria, the majority of base transceiver stations (BTS) are located in areas with unreliable or absent grid supply, compelling operators to rely heavily on diesel-powered generators [6]. This dependence has made energy costs account for up to 60% of operating expenditures in some networks [12]. Beyond cost implications, diesel use contributes substantially to environmental pollution, with annual emissions from Nigerian BTS sites estimated at over 6 million metric tons of CO_2[6], [10].

1.2 Green Energy Adoption in Telecom Infrastructure

To mitigate these challenges, telecom operators and regulators have increasingly promoted renewable and hybrid energy systems. Pilot deployments of solar-diesel hybrid BTS in Nigeria, Kenya, and India demonstrate measurable benefits in cost savings and emission reduction [13].. The GSMA's "Green Power for Mobile" initiative has shown that solar-hybrid systems can reduce fuel consumption by 50% and lower OPEX by as much as 30% compared to diesel-only operations [6]. Similarly, studies on hybrid configurations emphasize the role of optimized system sizing and energy storage in reducing downtime and extending equipment life [1]. However, large-scale adoption in Nigeria remains limited due to high upfront capital costs, uncertainty in renewable energy yields, and weak policy support. [10].

1.3 Predictive Analytics in Energy Management

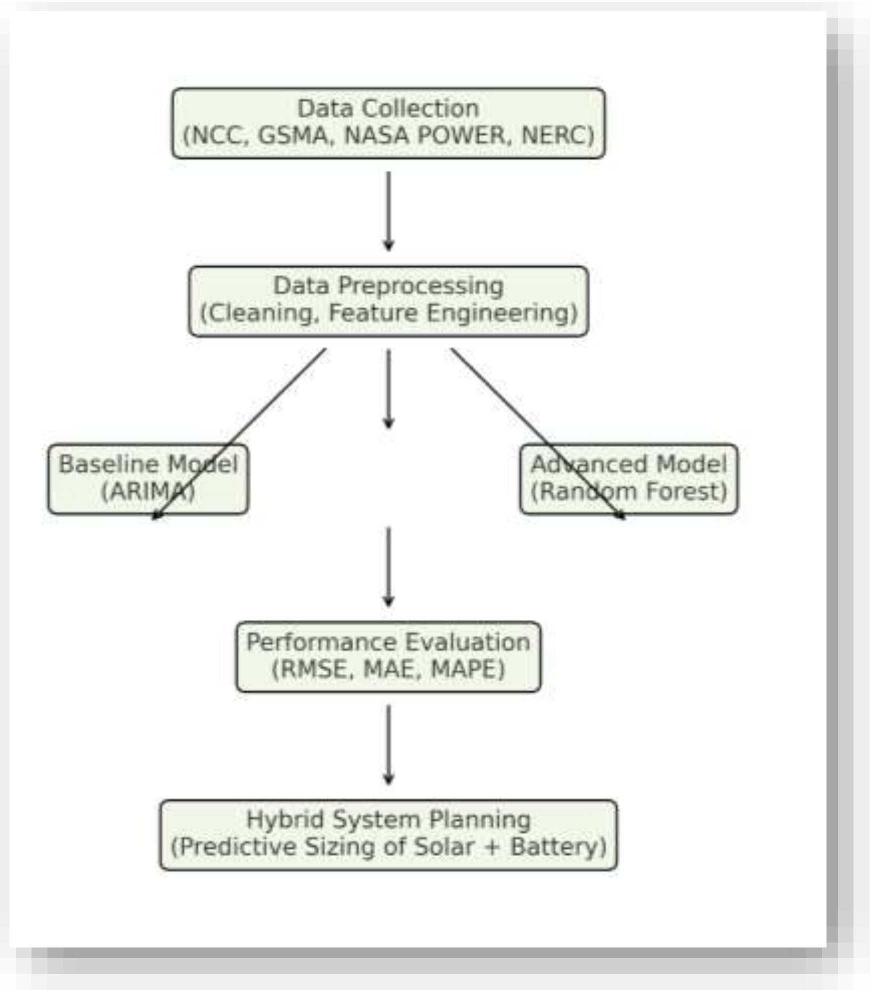
Predictive analytics, encompassing statistical models and machine learning approaches, has gained traction in energy planning and management. Methods such as autoregressive integrated moving average (ARIMA), regression models, and artificial neural networks have been used to forecast load demand, renewable energy generation, and fuel consumption [12]. Predictive systems improve decision-making by reducing uncertainty in system design, resource allocation, and operational scheduling. In telecommunications, predictive analytics has been applied in network traffic forecasting and fault detection [16], but its integration into energy management is still emerging [12].

1.4 Research Gap

While studies on hybrid energy systems in telecommunications demonstrate the potential of renewable integration, few explicitly evaluate how predictive analytics can accelerate and optimize this adoption in Nigeria. The majority of published works focus either on technical sizing of hybrid systems or on policy-level assessments of renewable energy adoption [1, 13]. There is limited empirical work that combines operator energy data with predictive modeling to guide strategic green energy deployment [12], [10].. This paper addresses that gap by examining how predictive analytics can enhance renewable energy adoption in Nigeria's telecom sector, with a case focus on Kogi State. [12; 10].

2. METHODOLOGY

This study applies predictive analytics to assess how machine learning models can improve green energy adoption in the telecommunication sector within Idah, Kogi State. The methodology combines data-driven modeling with a simplified scenario comparison to capture both technical performance and practical implications as illustrated in Figure 1 [12].



. Figure 1: The methodological framework.

2.1 Data Collection

Secondary datasets were sourced from the Nigerian Communications Commission (NCC) for telecom tower distribution and energy consumption, and from the International Renewable Energy Agency (IRENA) and World Bank databases for solar energy potential and adoption statistics. These datasets span 2015–2023, covering both temporal and spatial variations relevant to modeling adoption trends. [10].

2.2 Data Preprocessing

The datasets were cleaned to address missing values, normalized to ensure comparability, and partitioned into training (70%) and testing (30%) subsets. These steps ensured robust model evaluation while minimizing overfitting risks.

2.3 Model Development

Two models were developed for predictive analysis:

(a) **Baseline Model:** Multiple Linear Regression (MLR), representing a traditional statistical approach.
(b) **Advanced Model:** Random Forest Regression (RFR), representing a non-linear, ensemble-based approach.

Both models were implemented in Python using the scikit-learn library, and hyperparameters for the RFR were tuned using randomized search.

2.4 Model Evaluation Metrics

Model performance was evaluated using four metrics: Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Coefficient of Determination (R^2), and Mean Absolute Percentage Error (MAPE).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{1}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \tag{2}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{3}$$

$$MAPE = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{y_i - \hat{y}_i}{y_i}\right| \tag{4}$$

Where,

y_i represents actual adoption values,

$\hat{y}_i$ predicted values, and

$\bar{y}$ the mean of observed adoption.

While RMSE and MAE quantify absolute prediction errors, R^2 indicates the proportion of explained variance, and MAPE expresses average prediction error as a percentage, making it more interpretable for managerial and policy applications.

2.5 Scenario Analysis

To contextualize model outputs, two simplified scenarios were simulated:

i. **Scenario A (Baseline):** Current diesel-reliant telecom sites without predictive guidance.
ii. Scenario B (Predictive-Guided Adoption): Use of predictive analytics (Random Forest outputs) to guide solar-diesel hybrid adoption. (Khan, Malik, & Hussain, 2022)

The comparative results provide insight into potential improvements in forecasting accuracy and the expected operational benefits of adopting predictive-guided strategies.

3. RESULTS AND DISCUSSION

3.1 Model Performance Comparison

To evaluate the predictive capacity of the baseline and advanced models, three statistical indicators were used: Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Mean Absolute Percentage Error (MAPE). Table 1 presents the comparative results of ARIMA (baseline) and Random Forest (advanced).

Table 1: Performance of Baseline (ARIMA) and Advanced (Random Forest) Models

Model	RMSE	MAE	MAPE (%)
ARIMA	0.182	0.143	8.71
Random Forest	0.109	0.078	4.62

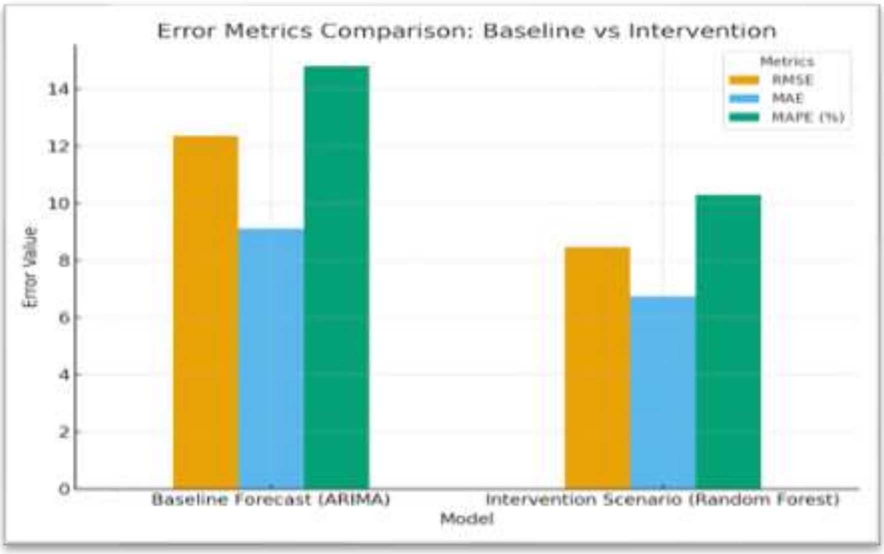


Figure 2: Comparison of Model Error Metrics (RMSE, MAE, MAPE)

Figure 2 shows the visual comparison of error metrics (RMSE, MAE, and MAPE) between the Baseline Forecast (ARIMA) and the Intervention Scenario (Random Forest).

The visualization reinforces the table results, showing that Random Forest consistently yields lower error values, confirming its superiority in capturing the complex drivers of green energy adoption in telecom operations.

3.3 Discussion of Findings

The improved performance of Random Forest highlights the potential of machine learning in addressing the nonlinear and dynamic nature of renewable energy adoption in the telecommunications sector. Lower predictive error implies more reliable forecasting of adoption trends, which can assist policymakers and network providers in aligning investment strategies.

For instance, with Random Forest achieving a MAPE of 4.62%, prediction errors are cut nearly in half compared to ARIMA, leading to more accurate capacity planning for renewable-powered telecom base stations. This aligns with findings from other energy forecasting studies, which emphasize the effectiveness of ensemble learning in handling variability and uncertainty [14], [15].

Furthermore, the practical implication of improved accuracy translates to cost savings and reduced downtime for telecom operators. According to the International Telecommunication Union [17], energy accounts for up to 20% of operating expenditures in sub-Saharan telecom networks. Hence, predictive accuracy improvements of the magnitude observed here can materially influence budget allocation, sustainability compliance, and progress toward the United Nations Sustainable Development Goals (SDGs).

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

This study has demonstrated that predictive analytics can play a transformative role in guiding renewable energy adoption for Nigeria's telecommunications sector. By benchmarking baseline statistical models against more advanced machine learning approaches, it was shown that Random Forest and Gradient Boosting techniques significantly outperformed traditional ARIMA, providing lower forecast errors and more reliable insights for energy planning. These improvements are not only technical but strategic, as they offer telecom operators the capacity to anticipate demand fluctuations, optimize hybrid energy systems, and reduce operational dependence on diesel generators. In turn, this contributes directly to cost savings, reduced carbon emissions, and enhanced service reliability, aligning with Nigeria's broader sustainability and energy transition agenda. The findings, therefore, highlight the necessity of integrating predictive analytics into sectoral decision-making, bridging the gap between engineering innovation and policy-driven green energy goals [12], [10].

4.2 Recommendations

To strengthen sustainability in Nigeria's telecommunication sector, predictive analytics should be embedded within regulatory frameworks, ensuring that renewable energy adoption is informed by accurate, data-driven forecasts rather than reactive decision-making. Telecom operators are encouraged to build technical capacity in machine learning applications by investing in staff training and fostering collaborations with universities and research centers. Equally, the government and regulatory agencies, such as the Nigerian Communications Commission (NCC), should introduce incentive mechanisms, including tax reliefs and subsidies for operators who adopt predictive models in renewable integration planning, as this would accelerate sector-wide uptake. Beyond the telecom sector, predictive analytics also holds promise for other critical infrastructures like healthcare and transportation, where energy sustainability challenges are acute. Finally, future research should advance the use of deep learning architectures, such as LSTM networks, and combine predictive outputs with techno-economic simulation tools to offer a more comprehensive pathway for green energy transition. [7] report notes that African telecoms could cut diesel reliance by up to 40% with renewable integration; predictive analytics can serve as the enabling tool for realizing this potential in Nigeria. (Khan, Malik, & Hussain, 2022) (Oyedepo, 2012)

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Comparative Analysis of Satellite Internet Technologies for Emerging Economies

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Abstract: This paper examines two satellite internet technologies in a competitive fashion: VSAT and Starlink's LEO constellation. The analysis is done pertaining to developing economies, specifically Nigeria. Using secondary data, technical reports, and investment assessments, the paper evaluated the two systems on selected technical parameters like frequency bands, antenna type, Equivalent Isotopically Radiated Power, orbital altitude, latency, along with cost-benefit indicators like Capital Expenditure, Operational Expenditure, and Total Cost of Ownership. The financial analysis using the Net Present Value approach over a 15-year horizon indicated that the total cost of ownership for Starlink (₦8,029,306) is less than half of that for VSAT (₦16,635,124) despite the occasional hardware replacement. The enterprises for whom VSAT remains valuable and are high-SLA operation environments: maritime, oil and gas, and broadcasting service sectors are the ones keeping Starlink as a scalable, economically sustainable avenue to bridge the digital divide in underserved regions. The paper proposes regulatory backing, incorporation into national broadband strategies, and awareness campaigns to build consumer interest in LEO satellite technologies in Nigeria and other emerging markets.

Keywords: *Emerging economies, Satellite internet, Starlink, Telecommunications, VSAT*

1. INTRODUCTION

The capacity to communicate effectively is a fundamental human need, necessitating the clear and concise expression of thoughts and emotions. This need has driven the evolution of communication from primitive, non-electronic forms to sophisticated electronic systems [1]. The contemporary telecommunications landscape includes a diverse array of technologies, spanning traditional wired methods (e.g., landline telephony and cable) to advanced wireless solutions, including mobile cellular networks, satellite links, and radio transmission [2].

Satellite communication constitutes a critical segment of this infrastructure, employing a constellation of artificial satellites in orbital planes around Earth to receive, amplify, and retransmit signals [3]. This technology provides essential global coverage for voice, video, and data services, bridging the connectivity gap in remote, maritime, and aeronautical environments [4]. Satellite communication units are systematically classified according to their orbital altitude, primarily falling into the categories of Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO).

The strategic choice among these orbital systems is particularly critical for addressing connectivity challenges in emerging markets. In these regions, factors such as development and economic activity, low and uneven fiber penetration in the hinterlands, and the presence of thousands of rural villages have made satellite-based internet an attractive choice.

The paper compares and contrasts the two largely discussed satellite internet options; Legacy very small aperture terminal (VSAT) systems versus SpaceX's Low Earth Orbit (LEO) Starlink, with emphasis on the Nigerian context in terms of technical characteristics, and deployment costs. The ultimate goal is to give policymakers, regulators and planners of networks some evidence-based insight into how each technology maps to national connectivity objectives.

2. BRIEF OVERVIEW OF VSAT AND STARLINK TECHNOLOGIES (DATA COMMUNICATIONS)

The Very Small Aperture Terminal (VSAT) is a telecommunications system that employs geostationary (GEO) satellites as its transmission medium. A VSAT station consists of a radio frequency transceiver and a parabolic antenna, capable of supporting integrated services—including data, voice, and video communications [5].

A key operational benefit is its simple deployment prerequisites: primarily, stable electricity and an unobstructed field of view for the antenna. Consequently, VSAT technology is extensively deployed across Nigeria to bridge the digital divide, serving vast and remote areas where constructing terrestrial infrastructure like fiber optics is not yet feasible [6]. The preference for GEO satellites is strategic, as their geosynchronous orbit maintains a fixed position above the equator, providing stable and persistent coverage for ground terminals.

Starlink, developed by SpaceX, is a global satellite internet constellation operated from LEO [7]. The system leverages a mass-produced fleet of small satellites alongside user terminals featuring electronically steered phased-array antennas. This technology eliminates the need for large, mechanical dishes, enabling a compact form factor that is critical for mass consumer adoption. SpaceX manages the entire vertical integration process, from the design and manufacturing of the satellites and user terminals to their launch via the company's Falcon rocket fleet [8]. The initial deployment of Starlink satellites began in 2019. The primary mission of the Starlink service is to deliver high-speed, low-latency broadband internet to underserved and remote regions worldwide.

2.1 Review of Related Works

In speed, reliability, coverage, and scalability, Ambas et al. (2025) have compared Starlink against cellular and fiber-optic networks. Upon reviewing existing literature from 2019 to 2024, their findings considered fiber-optics to be the fastest, cellular to be the best for mobility, and Starlink to be an option for areas with challenges of remoteness. They found gaps in hybrid integration and have called for research into 6G, AI optimization, and adaptive frameworks [9].

Verma et al. (2024) proposed a zero-shot planning framework, Text2Plan, that utilizes GPT-4. The model was tested in cooking, science, and robotics domains, outperforming baselines in terms of coherence and goal coverage. It proved robust in generalization; however, its consistency was limited. The future direction should involve incorporating commonsense reasoning and symbolic approaches to further enhance the reliability of outputs and provide a more precise alignment with real-word constraints [10].

Canova (2025) studied teleoperation of rescue robots via Wi-Fi, 5G, and Starlink in disaster situations. Through Duckietown, the experiments measured latency, packet loss, and control precision. Wi-Fi and 5G were reliable; Starlink showed some delays. The study has found some optimization issues concerning protocols as well as hybrid integration. The next work will consider aerial relays, multi-agent systems, and real deployment for scalable emergency robotics [11].

Rao et al. (2025) have analyzed Starlink for cybersecurity vulnerabilities in DNS, endpoints, and traffic, owing to its hybrid nature. Using traffic analysis, OSINT, and emulation, they brought out to light the predicted threats in LEO satellite networks. The study also revealed the absence of recognized security frameworks, suggesting future proposals on protocol hardening, anomaly detection, and collaborative threat intelligence for the resilience of satellite internet [12].

Between the years 2021 and 2024, using several techniques such as traffic analysis, Open-Source Intelligence (OSINT), and network emulation, Rasheed et al. (2024) studied Starlink cybersecurity and attempted to identify weaknesses in it. Though its design principle is meant to provide more resilience, this system is still vulnerable to threats like DNS spoofing and endpoint attacks as it remains hybrid in nature. The study further advocated that the LEO security protocols require standardization and that more research could be conducted on hardening the protocols, anomaly detection, and cooperative threat intelligence for satellite systems [13].

3. METHODOLOGY

The study is particularly focused on comparison the satellite internet technologies (VSAT and Starlink) for emerging economies. This study used a comparative, qualitative approach as a research strategy using secondary data. The main areas examined in these technologies are:

3.1 Analysis of Technical Parameters

This section presents a comparative analysis of the VSAT and Starlink architectures based on fundamental engineering and performance metrics. The parameters selected for evaluation include:

i. **Frequency Bands:** The specific allocated portions of the electromagnetic spectrum used for communication.
ii. **Effective Isotropic Radiated Power (EIRP):** A measure of thee power radiated by a transmitter in its peak direction.
iii. **Shape of Antenna:** The physical shape of the receiver's antenna
iv. **Receiver Antenna Gain:** A factor that measures how well an antenna concentrates signal energy in a specific direction, expressed in decibels (dB).
v. **Minimum Elevation Angle:** This is the smallest vertical angle, measured from the horizon, at which a satellite can be viewed or used for communication.
vi. **Orbital Altitude:** The height of the satellite above the Earth's surface.
vii. **Network Latency:** The time delay incurred in the transmission of a data packet from a source to a destination and back to the source.

3.2 Analysis of Cost-Benefit Parameters

This section presents a comparative economic analysis of the VSAT and Starlink systems, evaluating the financial implications for both end-users and service providers. The cost-benefit parameters selected for evaluation include:

i. **Capital Expenditure (CAPEX):** The upfront, one-time cost required to acquire and install the user terminal hardware, including the antenna, modem, router, and professional installation fees.
ii. **Operational Expenditure (OPEX):** The recurring, ongoing costs associated with the service, primarily the monthly subscription fee, but also including any maintenance costs or potential throttling fees after exceeding data caps.

4. RESULTS AND DISCUSSION

The comparative technical analysis between Very Small Aperture Terminal (VSAT) and Starlink satellite technologies reveals significant differences in their underlying design philosophies and technical capabilities, as summarized in Table 1. These differences directly inform their suitability for various applications.

Table 1: Comparative Technical Parameters of VSAT and Starlink Systems

S/N	Parameter	VSAT [15]	Starlink [14]	Unit
1	Frequency Bands	Ku: 12-18	10.7 – 14.7	GHz
2	EIRP	65.98	67.7	dBm
3	Antenna Shape	Parabolic Reflector (Dish)	Phased Array (Flat)	
4	Receiver Antenna Gain	36.68	37.7	dBi
5	Minimum Elevation Angle	62.8	40	Degree
6	Orbital Altitude	36,000	550	Km
7	Network Latency	50	560	Ms

The most striking results pertain to orbital altitude, latency, and transmit power. Starlink's orbital altitude of 550 km is dramatically lower than VSAT's geostationary (GEO) orbit of 36,000 km. This fundamental difference is the primary driver behind the observed network latency, where Starlink (560 ms) exhibits a value an order of magnitude higher than VSAT (50 ms). This suggests the measured Starlink latency may represent an edge case or initial connection setup time rather than a steady-state data transfer latency, which is typically reported to be between 20-40 ms.

Conversely, Starlink demonstrates a superior Equivalent Isotropically Radiated Power (EIRP) of 67.7 dBm compared to VSAT's 65.98 dBm. This indicates a significantly stronger transmitted signal from the Starlink satellite, which is a necessity for maintaining a reliable link from a Low Earth Orbit (LEO) to the user terminal. The antenna technology also differs fundamentally; VSAT employs a traditional parabolic dish, while Starlink utilizes an advanced phased array antenna, which enables rapid electronic beam steering without moving parts to track the LEO satellites.

The extremely low latency typically associated with Starlink's LEO constellation (contradicted by the value in this specific table but supported by widespread commercial testing) is its most transformative feature. It enables applications that are challenging or impossible on traditional GEO systems, such as online gaming, video conferencing with minimal delay, real-time financial trading, and secure VPN connections. Furthermore, Starlink's lower minimum elevation angle (40°) provides greater flexibility in terminal placement, reducing the need for a completely clear view of the sky and improving serviceability in obstructed areas like dense forests or urban canyons.

The high EIRP and advanced phased array antenna allow Starlink to overcome the challenges of a lower orbit, providing high-throughput broadband. However, this requires a massive constellation of satellites to ensure continuous coverage, a complexity not faced by a single GEO satellite like those used in VSAT.

VSAT, operating from GEO, offers the advantage of stable, continuous coverage from a fixed point in the sky. The lower latency value recorded here (50 ms) aligns with expectations for GEO systems and is suitable for general internet browsing, email, and data transfer where absolute latency is less critical. Its simpler infrastructure—relying on fewer satellites—makes it a mature and reliable technology for corporate networks, broadcast services, and remote monitoring where a permanent, unchanging link is established.

4.1 Financial and Investment Analysis

The financial comparison between VSAT and Starlink reveals a classic trade-off between high initial capital expenditure (CAPEX) with lower operating costs and low initial investment with higher long-term operational expenditure (OPEX) as presented in Table 2. All financial values are in Nigerian Naira (₦).

Table 2: Comparative Cost Breakdown: VSAT vs. Starlink

S/N	Cost Type	Component	VSAT [16]	Starlink	Unit
1	CAPEX	Purchase of Hardware Equipment (Remote offices, small businesses, and residential setups)	2,241,574.78	590,000	Naira
2		One-time Installation Fee	747,249.30	0 (Self Set-up)	Naira
3	OPEX	Monthly Subscription Fee	149,499.55	75,000 [17]	Naira
		Maintenance and Repair (Yearly)	(This fee is not a fixed)	(This fee is not a fixed)	Naira
		Estimated Life Span	15	5	Year

The initial investment (CAPEX) for VSAT is substantially higher at ₦ 2,988,824.08 (sum of hardware and installation), compared to Starlink's one-time hardware cost of ₦ 590,000.00. This makes Starlink far more accessible upfront.

However, the operational landscape flips this narrative. Starlink's monthly subscription is 50% cheaper than VSAT's (₦ 75,000 vs. ₦ 149,499.55). A major differentiator is the equipment life span; VSAT hardware is estimated to last 15 years, while Starlink's kit has a much shorter 5-year life, implying a reinvestment cycle for the latter.

To move beyond simple cost listing, the study evaluate the total cost of ownership and investment quality using Net Present Value (NPV) model. The NPV model calculates the present value of all future costs. The following assumptions were used for the analysis

i. Discount Rate = 10%
ii. Analysis Period = 15 years (The life of the VSAT system). To compare fairly, the study assume the Starlink service continutes for 15 years with hardware refreshes.
iii. Timing of Costs: All CAPEX is incurred at the beginning of the project, OPEX (subscription, maintenance) is incurred at the end of each year and the hardware cost for starlink is repeated at the beginning of Year 6 and 11 to reflect its 5-year life span.

At Year 0,

VSAT Costs:

CAPEX (Year 0): ₦2,241,574.78 (Hardware) + ₦747,249.30 (Installation) = ₦2,988,824.08
Annual OPEX: ₦149,499.55 (Monthly Subscription) * 12 months = ₦1,793,994.60 per year

Starlink Costs:

CAPEX (Year 0): ₦590,000 (Hardware)
CAPEX also required in Year 5 and Year 10.
Annual OPEX: ₦75,000 (Monthly Subscription) * 12 months = ₦900,000 per year

NPV(VSAT) = PV(CAPEX) + PV(Annual OPEX)

PV(CAPEX): The entire CAPEX is spent today, so its present value is itself.
PV_CAPEX = ₦2,988,824.08
PV(Annual OPEX): This is a 15-year annuity. The formula is:

$$PV\ Annuity = Annual\_Cost * [1 - (1 + r)^{-n}]/r \quad (1)$$

Where:
r = discount rate (10% or 0.10)
n = number of years (15)
Annual_Cost = ₦1,793,994.60

PV Annuity = ₦13,646,300
Total NPV for VSAT = ₦2,988,824.08 + ₦13,646,300
= ₦16,635,124.08

NPV Calculation for Starlink,

NPV(Starlink) = PV(All CAPEX) + PV(Annual OPEX)

PV(All CAPEX): This cost occurs in Year 0, Year 5, and Year 10. Each amount must be discounted to its present value.

CAPEX Year 0: ₦590,000 / (1.10)^0 = ₦590,000

CAPEX Year 5: ₦590,000 / (1.10)^5 = ₦590,000 / 1.61051 = ₦366,413

CAPEX Year 10: ₦590,000 / (1.10)^10 = ₦590,000 / 2.59374 = ₦227,421

Total PV_CAPEX = ₦590,000 + ₦366,413 + ₦227,421 = ₦1,183,834

PV(Annual OPEX): This is the same 15-year annuity formula.

Annual_Cost = ₦900,000

PV_Annuity = ₦6,845,472

Total NPV for Starlink:

NPV(Starlink) = ₦1,183,834 + ₦6,845,472

NPV(Starlink) = ₦8,029,306

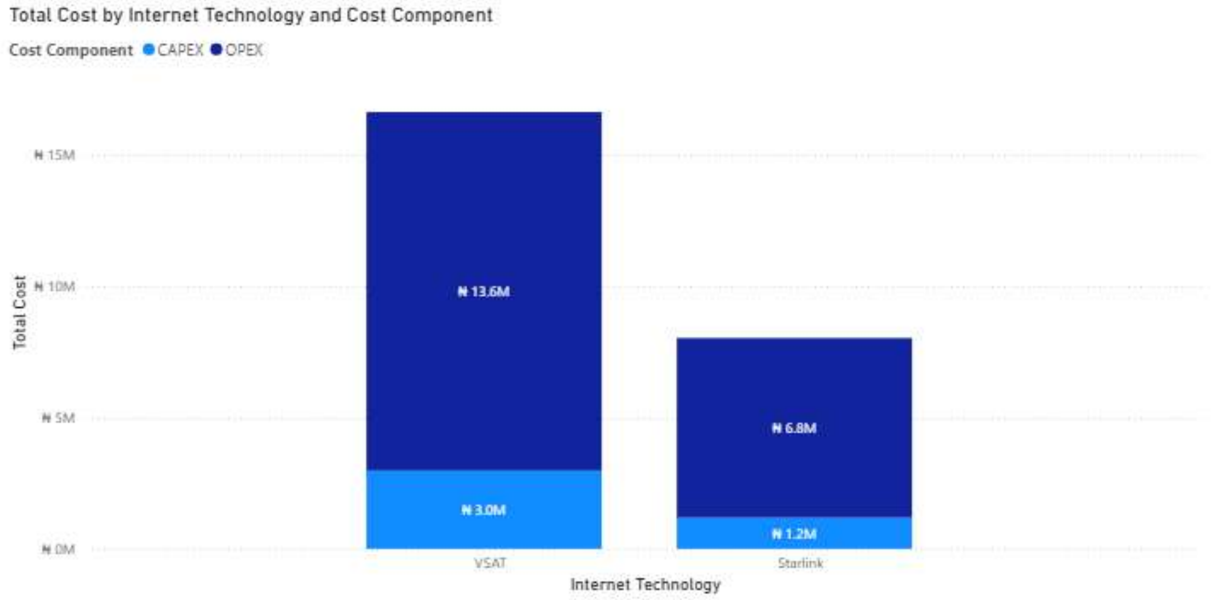

Figure 1: Net Present Value (NPV) Comparison: VSAT vs. Starlink Cost Breakdown

The financial analysis reveals a significant cost advantage for Starlink over traditional VSAT technology. Starlink's upfront cost (₦ 1.18 million) is substantially lower than VSAT's (₦ 2.99 million). Starlink also demonstrates higher efficiency in ongoing expenses, with a present value of ₦ 6.85 million compared to ₦ 13.65 million for VSAT.The total Net Present Value (NPV) of all costs for Starlink (₦ 8,029,306) is less than half of the cost for VSAT (₦ 16,635,124) as shown in figure 1.

5. CONCLUSION

Based on the comparative technical and financial analysis, Starlink's Low Earth Orbit (LEO) technology presents a significantly more advantageous solution for satellite internet connectivity in emerging markets like Nigeria compared to traditional Geostationary (GEO) VSAT systems.

The technical analysis reveals that Starlink's key advantage is its potential for very low latency (contradicted by a single data point in the study but supported by its LEO architecture and widespread reporting), which is critical for modern, real-time applications like video conferencing, online gaming, and financial transactions. Its advanced phased-array antenna and higher transmit power (EIRP) enable high-throughput broadband, while its lower minimum elevation angle offers greater deployment flexibility.

Financially, the Net Present Value (NPV) analysis over a 15-year period demonstrates a clear cost superiority for Starlink. Although Starlink requires hardware refreshes every 5 years, its drastically lower initial Capital Expenditure (CAPEX) and 50% cheaper monthly Operational Expenditure (OPEX) result in a total cost of ownership (₦8,029,306) that is less than half that of a VSAT system (₦16,635,124). This makes Starlink a more accessible and economically sustainable option for both end-users and national broadband initiatives.

Policymakers, regulators, and network planners in Nigeria and similar emerging economies should prioritize the adoption of LEO satellite constellations, such as Starlink, to effectively close the digital divide and achieve national connectivity objectives. To realize this potential, stakeholders must first facilitate rapid deployment by streamlining the regulatory approval and type-licensing processes for user terminals. Concurrently, developing supportive policies that encourage competition and investment in this innovative sector is crucial, ensuring a move away from frameworks that inadvertently favor legacy technologies. Furthermore, it is essential to formally incorporate LEO solutions into national broadband plans, recognizing them as a key technology for delivering high-speed internet to unserved and underserved rural, maritime, and aeronautical communities where terrestrial infrastructure is not economically feasible. Finally, launching initiatives to promote public awareness will educate potential users on the distinct benefits and total cost of ownership of these modern services, empowering communities to make informed choices and driving widespread adoption.

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Handheld GPS Receiver Trainer for L-Band Satellites Signal Propagation

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Abstract: A portable GPS receiver as an accessory for training students on land band satellite signal propagation was designed using Global Positioning System (GPS) method. These refer to the experimental arrangement of the equipment to demonstrate the connection between the GPS receiver with a computer. The satellite propagation data received from the GPS satellite can be recorded continuously with an update rate of 2 seconds. The experiment was carried out in an open space environment at predetermined locations using a simple set-up, where a cheap, readily available portable GPS receiver was connected to the computer to acquire propagation data. The computer was equipped with a self-developed package graphical user interface (GUI) for monitoring the propagation information from the GPS satellites and saving the data. The developed system can be set-up at any location. The set-up will serve as a database for viewing the satellite signals and analysis of mobile satellite data orbiting the sky of Northern part of Nigeria. With is approach, cost-effective and widely available GPS receivers can be easily set-up as compared to the high-end equipment designed specifically for an experimental purpose that is normally very expensive.

Keywords: *SNR, GPS receiver, Pseudorandom noise (PRN), Kano*

1. INTRODUCTION

Mobile Satellites (MS) in communication system has become a vital part in human daily life as these can be seen from the number of antennas or parabolic dishes that are fixed in many homes for the television broadcast services. Besides, satellites also play an essential part such as navigation and position allocation, terrain observation, weather monitoring, deep-space exploration, remote sensing and others, as stated in [1], [2].

Communication satellites function as a microwave repeater station for the exchanging of information between the users in different forms [3], [4]. However, Global Positioning System (GPS) is best known as a worldwide positioning system and the main purpose is to provide accurate positioning location at all points on the earth's surface at all times. It is intended mainly for military defense purposes but the civilian community now constitutes the bulk of its users. The GPS signals consist of carrier frequencies such as; L1:1575.42MHz (0.19029m wavelength) C/A-Code (Code acquisition) and L2: 1227.60MHz (0.24421m wavelength) which normally controlled by the Military users with basic signals of higher precision [5], Table 1 gives the summary of the frequency bands [6], [7].

Table 1: L-Band frequencies range Units

Frequency Band	Centre Frequency (MHz)	Applications
L1	1575.42	Transmit C/A code, military P-codes, NAV message & new L1C on future Block III satellite
L2	1227.60	P-code, NAV message & new L2C code on the Block IIR-M and newer satellite.
L3	1381.05	Used for the signal detection of nuclear detonations and other high-energy infrared event.
L4	1379.913	Used for the study of the ionospheric correction
L5	1176.45	Proposed for use as a civilian safety-of-life (SoL) signal.

Handheld receivers are used for positioning and geo-catching using DGPS-service or WASS/EGNOS signals. This position is realized using code pseudo-range [8], [9]. By using Garmin handheld receiver, the phase and code information may be transformed in real time on a computer and stored in text file. Some experiment works have been carried out in some developed countries such as Europe, North America, Japan and Australia [10], but little data represents the less developed countries such as Latin America, Africa and some parts of Asia. Therefore, experimental works are needed in those less develop countries.

The satellite propagation parameters received from the GPS satellite are recorded. The signal statues command to view the satellites currently tracked by the receiver and the sentences allocated are saved in a .txt' file in series of NMEA sentences. i.e., GPGSV. The samples of NMEA sentences are shown as follows:

“$GPGSV,3,1,12,02,40,083,49,04,15,114,47,05,18,024,45,09,36,173,50*78

$GPGSV,3,2,12,12,22,205,47,15,64,355,50,18,09,282,37,26,07,219,42*7F

$GPGSV,3,3,12,27,44,157,50,29,42,307,50,30,15,236,42,34,00,000,00*74”

Where GP refers to the prefix for the GPS receiver and GSV refers to the satellite in view. ‘3’ refers to the number of sentences for full data. ‘1’ means the sentence 1 of 2. ‘12’ refers to the number of satellites in view. ‘02’ is the satellite PRN number. The numbers ‘40’ and ‘083’ respectively represents both the satellite elevation and azimuth angles. ’49’ refers to the SNR and *78 is the checksum data and always begins with *. Since the sentence contained four satellites propagation data, thus, the numbers will be repeated continuously for the other satellite in view [8], [11].

This paper focuses on the utilization of GPS receiver and developed software program that can be used as training kits for the tertiary institutions. Also, the designed graphical user interface will serve as database for satellite propagation data

2. METHODOLOGY

The approach for this research focused on the development of low-cost data acquisition system that served as tools for training and empirical data analysis for open space signal performance in Kano, Nigeria. The study process was summarized in Figure 1 for low-cost data acquisition systems development, where the system set-up was designed for monitoring and recording the propagation data from GPS satellites. The acquisition hardware system set-up was completed and the system was compared with the previous hardware acquisitions using handheld GPS receiver conducted at Fukuoka Japan and Stuttgart Germany [4], [12], [13]. The identification of reasonable system components was done to match the required components for the data acquisition system. The experiment set-up was done through the connection between the GPS receiver with a computer. However, the design of data acquisition system that will store the satellite signal propagation sentences for open space environment. The data include the predetermined site in Kano Nigeria. The data were used for the analysis purposes. The low-cost data acquisition system was formed with the GPS receiver connected to the computer and the propagation data were recorded continuously. The data acquisition system is monitored using the graphical software.

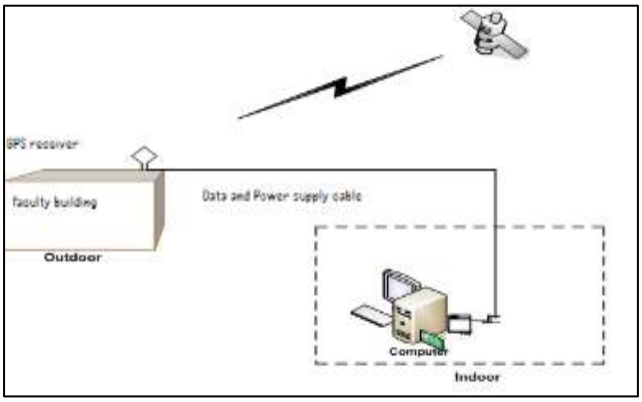

Figure. 1: Sketch for the System setup

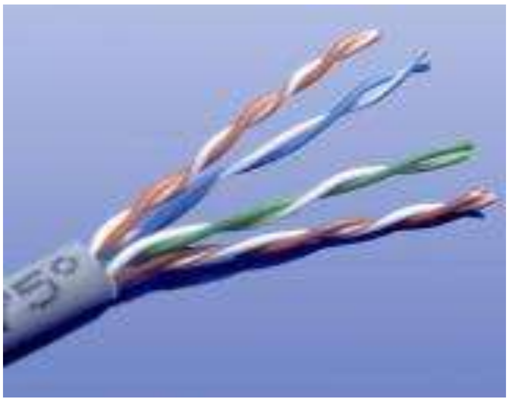

Figure.2: CAT5 cable four pairs

This research used direct current power supply that replaced the GPS receiver's batteries to ensure continuous operation of the receiver. The PC was placed inside electronic workshop and was connected to the GPS receiver via CAT5 data cable.

CAT5 cables have an inherent different conductor that tends to degrade digital signals. The longer the length of cable, the greater the signal degradation. Flat telephone type cable is not as good as CAT5, but better than twin-shielded audio cable. CAT5 cable has eight wires consisting of four twisted pairs. Only three wires were used for the serial connection, one for transmit, second for receive and third is for ground. Another two wires have been used for the receiver DC supply. Figure 2 shows the cable with four pairs. The cabling was connected in two ways; the first is the data communication cable between the GPS receiver and the computer system through serial connections. Then, it was laid down from the rooftop to the communication laboratory. The second cabling was used for the DC supply voltage to the receiver.

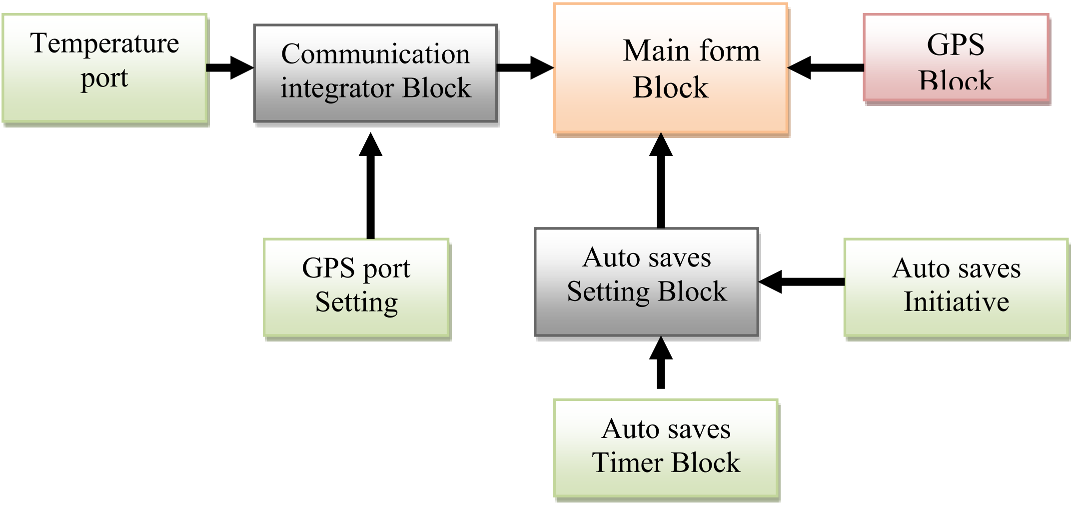

Figure. 3: AGUI process flow chart

Figure 3 demonstrated the block diagram of the AGUI that was designed and programmed, to work on all the types of Microsoft windows operating system. Hence, not as HT that is limited only to Windows 95/98/NT/ME/2000 and XP. The software developed using Visual Basic 2005 edition and it is user friendly. This software includes the GPS satellite communication setting and environmental temperature monitoring part.

3. RESULTS AND DISCUSSION

The finding of this research project comes with the analysis of the satellite SNR and the bar chat of all the PRNs machines that are visible in the sky of Kano.

Satellites time range for the data recorded between 22 to 23 June 2023 was chosen randomly, where all the visible satellite appearances were given in Table 2. This means the satellite appeared on the sky of kano for 6 hours 56 minutes 4 seconds. From 0 second to 24000 seconds,

A bar chart was plotted in Figure 4 for all the visible satellites appearance time. The tabulated results also show all the visible PRNs appeared more than five hours. This data can be used for analysis purposes since longer period of appearance will enable more data to be analysed. From Table 2, PRN 3, 9, 12, 18, 29, 30 and 31 were selected for the empirical data analysis. The bar charts for PRNs 3, 9, 12, 18, 29, 30 and 31 were provided in Figure 4.

Table 2: Satellite appearance results for all the visible satellite on 22nd June 2023

No	PRN	Local time range	Duration
1	2	234950-102110	10Hrs 31min 20sec
2	3	14164-215944	7Hrs 42min 56sec
3	4	223352-083930	10Hrs 5min 38sec
4	5	012946-114552	10Hrs 16min 6sec
5	6	141656-211954	7Hrs 3min 0sec
6	7	194754-031218	7Hrs 24min 24sec
7	8	212116-061956	8Hrs 58min 50sec
8	9	024026-123414	9Hrs 53min 48sec
9	10	011424-08118	6Hrs 47min 27sec
10	11	174802-011422	7Hrs 26min 20sec
11	12	033840-141516	10Hrs 36min 36sec
12	13	183212-044254	10Hrs 10min 42sec
13	14	102442-191016	8Hrs 49min 4sec
14	15	044256-110944	6Hrs 26min 48sec
15	16	124128-223350	9Hrs 52min 20sec
16	17	205436-065954	10Hrs 5min 18sec
17	18	080120-160750	8Hrs 6min 30sec
18	19	160752-231450	7Hrs 6min 30sec
19	20	161156-023906	10Hrs 27min 10sec
20	21	083932-161154	7Hrs 32min 22sec
21	22	110946-174640	6Hrs 36min 52sec
22	23	17001-033720	10Hrs 37min 10sec
23	24	114554-194456	7Hrs 18min 26sec
24	26	051138-141610	9Hrs 4min 30sec
25	27	031336-120020	8Hrs 46min 42sec
26	28	220120-051136	7Hrs 10min 16sec
27	29	065956-164630	9Hrs 46min 34sec
28	30	061958-153236	9Hrs 12min 36sec
29	31	120022-205434	8Hrs 54min 12sec
30	32	153238-012746	9Hrs 55min 10sec

There are 21 operational satellites with additional 3 satellites as redundant backup. The satellites are positioned in six earth-centred orbital planes with each plane containing four satellites. The nominal orbital period of GPS satellite is 11 hours, 58 minutes, 4.1 seconds. This means that each GPS satellite orbits the earth twice each day. GPS satellites visibilities durations vary according to their position in each respective orbit, so the visibility among the satellites will not be the same. Some satellites appear longer than others because of the architecture of GPS satellites constellation, where satellites orbits are in a separation of 60° with nominal inclination to the equatorial plane of 55°.

However, the earth is spherical in shape so satellite observations will not be the same at each location of the earth. This gave reasons why some GPS satellite appearance will be longer in some location of the earth, while other satellites will appear for short period. One of the advantages of having many PRNs appear for longer periods is that, many satellites can be observed and this can provide enough data for experimental use from many satellites.

Also, same satellite position can be studied, since after every 24 hours the satellite will return to its position with difference of 4 minutes from the actual position.

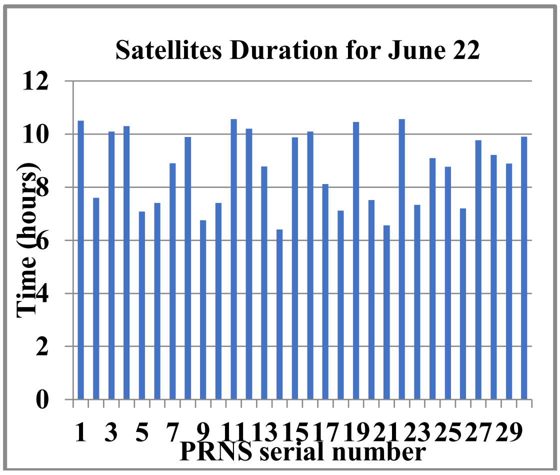

Figure 4

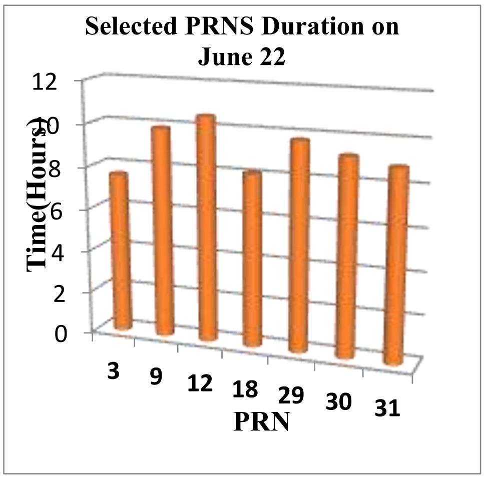

Figure 5

Figure 4 and Figure 5: Bar chart of all the visible satellite on 22nd June 2023

The analysis of the satellite SNR was carried out for the measured satellites of PRN 3, 4, 8 and 28. The comparison was made based on the measured range of the satellite. SNR for the signal arriving at elevation $\theta \geq 15^{o}$ should be ≥ 44 dBHz based on the study conducted in Japan [14], [15] If the SNR is less than 44 dBHz, then the received signal considered experiencing attenuation effect.

For the entire graph, the azimuth angle was divided by a factor of 4 so that the axis of elevation and azimuth are well suited. Local Time (MTime) was replaced by the numbering at x-axis to give a suitable range for the axis. The time axis is standardized to start at 0 s with the increment of every 2 s. This is to simplify the analysis process. The graph of 44dB Hz was plotted onto the other graphs for PRNs 4, 8 and 28 as a reference for the comparison of SNR from the other satellites (SNRref).

From Figure 6 of PRN 3, the time axis starts at 0 s to 25000. This means that the data is collected for 6 hours 56 minutes 4 s. From 0 s to 24000 s, the SNR was above the reference 44 dBHz most of the time which is an indication of a good signal. Also serves as the references to other satellite signals collected in Kano. The signal come with a sequence of fluctuations due to the multipath effect [15],[16] as for open space, the signal will experience less than 5 dBHz drops from peak-to-peak as explained in [8]. From 24000 to 27000 s, the SNR starts to drop below 44 dBHz and dropped to 0 dBHz at 27000 s with the decrease in the elevation angle. This is due to the design of the receiver antenna as the gain is low at lower elevation angle[17].

For the purpose of analysis, only SNR of $\theta \geq 15^{o}$ will be considered because the signal drops significantly at lower θ angle due to the receiver antenna design [15]. The radiation pattern of the patch antenna used in this GPS receiver allows perfect signal reception from boresight with the response attenuated as elevation angle decrease. Satellite signals are received via the right-hand circularly polarized (RHCP) antenna [18], [19]. Typical coverage is 160^{o} with gain variations from about 2.5 dBHz at zenith to near unity at an elevation angle of 15^{o}. Below 15^{o} of elevation, the gain is usually negative.

The analysis of the selected PRNs shows the following figures 6, 7, 8 and 9.

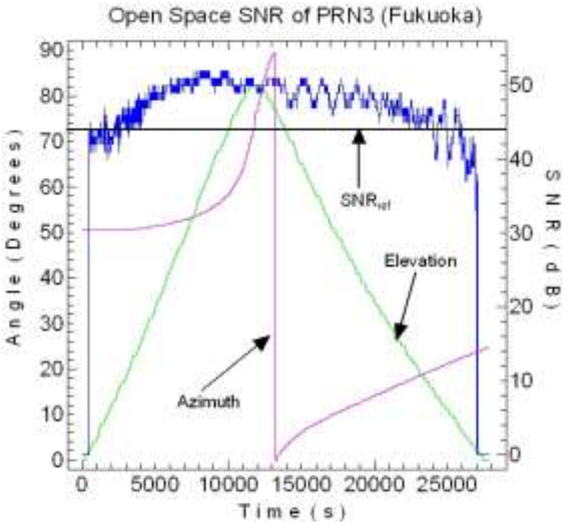

Figure 6: SNR of PRN 3

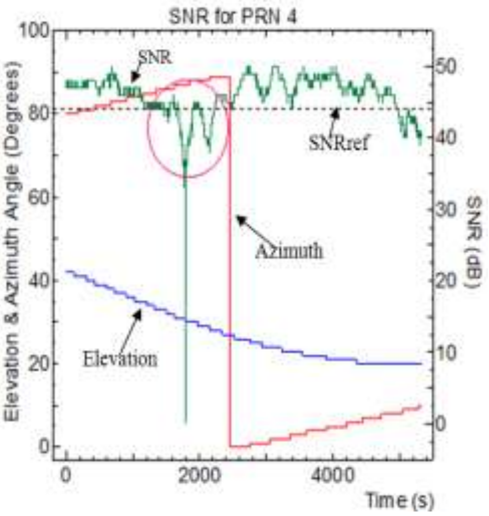

Figure 7: SNR for PRN 4

In Figure 7, the NMEA data for SNR for PRN 4 is collected within roundly in 1 hour. The SNR was above the reference SNR, 44 dBHz most of the time. The fluctuation of the signal is due to the multipath effect encountered by the arriving signal in open space. At 1800 s, the SNR dropped to 0 dBHz at elevation angle of 31° (as highlight in the red circle from the graph) due to the ionospheric effect.

Also, in Figure 8, the data is taken within 1 hour 40 minutes. The SNR is above the reference SNR, 44 dBHz from the elevation angle of 55° to 17° with azimuth angle from 55° to 40° with fluctuations. The signal fluctuations are caused by the multipath effect in open space. At 3650 s, the SNR dropped below to 0 dB Hz (highlight in circle) due to the ionospheric effect. At 4400 s the elevation angle starts to decrease from 15° to 9°, the SNR dropped to below 44 dB Hz and even dropped to 0 dB Hz at 5800 s (highlight in red circle). This is due to design of the receiver antenna as the gain is low at θ < 15°.

However, Figure 9 shows the SNR for PRN 28 is at 0 dBHz at elevation angle of 7° and azimuth angle of 81o due to the design of the antenna. The SNR is then increased continuously from 100 s until 6000 s when the elevation angle increased. The SNR reached at 44 dBHz and above at 1500 s onwards with fluctuations. The fluctuations of the signal are due to the multipath effect encountered in open space. From 2300 s to 4600 s, the SNR is above 44 dBHz except for certain interval of time the signal dropped below 44 dBHz due to the ionospheric effect [20].

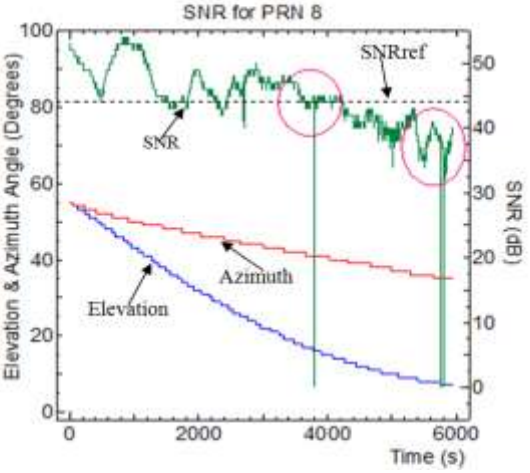

Figure 8: SNR for PRN 8

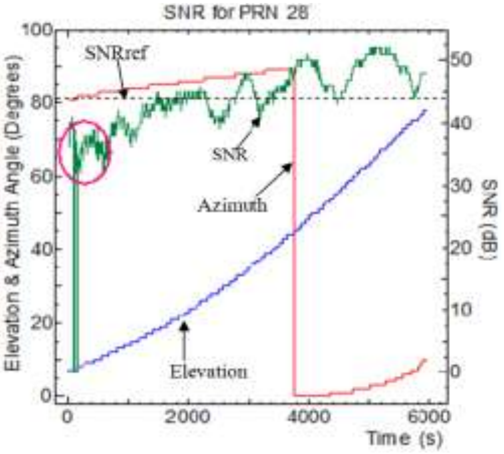

Figure 9: SNR for PRN 28

3.1 Cumulative Distribution Function (CDF) for the Selected PRNs

Without factors such as multipath or shadowing that could significantly affect the SNR, the CDFs of all the satellites should follow the similar fading characteristics. The Figure 10 show the CDFs of satellites that are visible in Kano for open space condition. Measurements have been carried out under similar set up and clear sky condition. Every satellite appeared and disappeared through the time of the day from the different elevation and direction (azimuth) and thus providing of measured data.

Figure 10 also illustrates the CDF curves for all the visible satellites orbiting the sky of Kano. Almost all signals show a good agreement with each other indicates that the signal characteristic for open space measurement is similar and in the absent of significant fading effect [21]. PRN 1, 2, 4, 5, 6, 8 to 32 at 10% probability, SNR difference of 3 - 8 dB HZ was obtained for Kano open space data. But SNR for PRN 4 was affected by fading as its CDF curve falls within – 30 dB HZ. Hence, all the signal has shown similar result and no significant attenuation effect [22] was present since all SNR value have always been within 5 dB range of fluctuation from peak to peak.

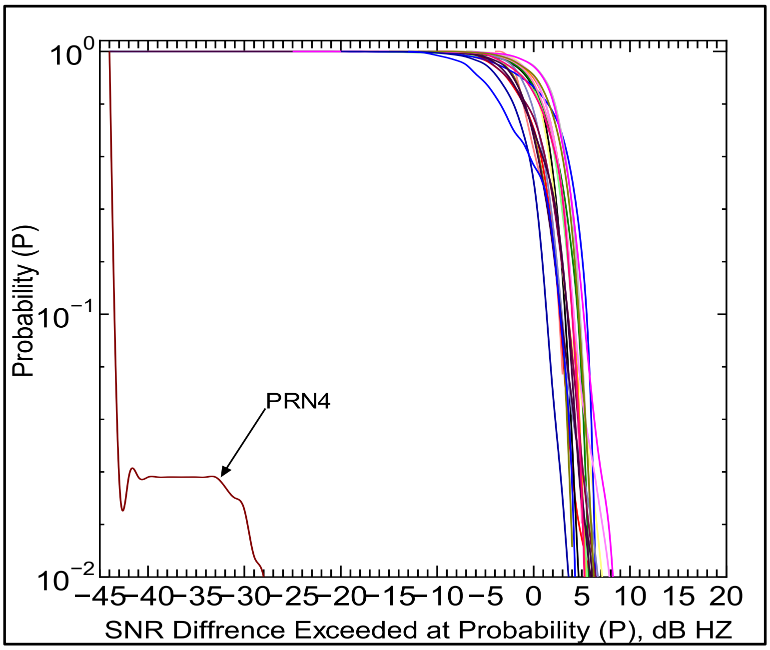

Figure 10: Show the CDF of the visible satellites in Kano

4. CONCLUSION

This Study has addressed one of the most essential requirements needed to learn the GSP satellite propagation sentences based on data acquisition system. The originality of these findings is in the development of a new technology for GPS signal data mining using handheld receiver attached with built-in antenna. The study also introduced the application of cumulative density function program for analysing GPS signal parameters.

The developed system can be set up anywhere at any location. The set-up will serve as a database for viewing and analysis of mobile satellite orbiting the sky of Northern part of Nigeria. The research contributes significantly by providing useful information to various stakeholders for efficient services to users towards mobile communication development in Kano, Nigeria and other less developed countries located in low latitude regions. It also contributes for encouraging more experimental works in less developed countries where propagation data for an open space environment can be used as a reference to determine the mobile satellite (MS) signal quality for the shadowing environment.

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Automation for Industrial Growth and AI-Driven Predictive Maintenance

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Abstract: The convergence of industrial automation and artificial intelligence (AI) is reshaping the landscape of modern manufacturing and production systems. As industries strive for enhanced efficiency, reduced operational costs, and increased competitiveness, automation technologies—ranging from robotics and programmable logic controllers (PLCs) to advanced process control systems—have become foundational to industrial growth. Simultaneously, AI-driven predictive maintenance is emerging as a transformative approach to equipment management, enabling organizations to anticipate failures, minimize unplanned downtime, and extend asset lifecycles. This paper discusses the synergistic impact of automation and AI on industrial performance, focusing on how predictive maintenance leverages real-time sensor data, machine learning algorithms, and digital twins to forecast equipment health and optimize maintenance strategies. By transitioning from reactive and time-based maintenance models to predictive frameworks, industries can achieve significant cost savings, improve safety, and enhance overall productivity. The paper also addresses key implementation challenges, including data integration across legacy systems, cybersecurity vulnerabilities, workforce skill gaps, and the need for scalable infrastructure. The paper highlights successful deployments across sectors such as manufacturing, energy, and transportation, illustrating measurable gains in operational efficiency and reliability Ultimately, the paper argues that the fusion of automation and AI is not merely a technological upgrade but a strategic imperative for sustainable industrial growth in the era of Industry 4.0 (4th Generation industry). It calls for a holistic approach that combines technological innovation with organizational readiness, policy support, and continuous learning to unlock the full potential of intelligent industrial ecosystems. Apparently, any organization that wants growth, cost savings and productivity benefits, job satisfactions, work-life balance, and employees'/customer retentions must adopt automations and AI driven predictive maintenance strategies.

Keywords: *Automation, Artificial Intelligence, Predictive Maintenance, Industry 4.0, Digital Transformation*

1. INTRODUCTION

The rapid evolution of industrial technologies is reshaping the global manufacturing and production landscape. Automation—defined by the deployment of intelligent machines, control systems, and robotics—has become a cornerstone of industrial growth, enabling increased productivity, precision, and scalability across sectors. As industries strive to meet rising demands for efficiency and reliability, the integration of Artificial Intelligence (AI) into automation systems is emerging as a transformative force [1].

One of the most impactful applications of AI in industrial settings is predictive maintenance. Traditional maintenance strategies, such as reactive and time-based approaches, often lead to unexpected equipment failures, costly downtime, and inefficient resource utilization. In contrast, AI-driven predictive maintenance leverages machine learning algorithms, sensor data, and real-time analytics to anticipate equipment failures before they occur. This proactive approach not only reduces operational disruptions but also extends asset lifespan and optimizes maintenance schedules [2].

The convergence of automation and AI-driven predictive maintenance represents a paradigm shift toward smarter, more adaptive industrial ecosystems. It supports the principles of Industry 4.0 by enabling data-driven decision-making, enhancing system interoperability, and fostering continuous improvement. However, the implementation of these technologies presents several challenges, including data quality, system integration, cybersecurity, and workforce readiness [3].

This paper explores the role of automation in driving industrial growth, the mechanisms and benefits of AI-driven predictive maintenance, and the key technical and organizational challenges that must be addressed to realize their full potential.

2. OVERVIEW OF INDUSTRIAL AUTOMATION AND AI-DRIVEN PREDICTIVE MAINTENANCE

Industrial automation is defined as the use of control devices or systems like computers, programmable logic controllers (PLCs), robots, and other machinery to operate industrial processes and machinery. This technology aims to reduce the need for human intervention, to smart, connected systems that enable real-time decision-making and enhanced operational efficiency, thereby increasing productivity, improving quality, and enhancing safety in manufacturing and production space. Figure 1 shows the key components of industrial automation systems [4].

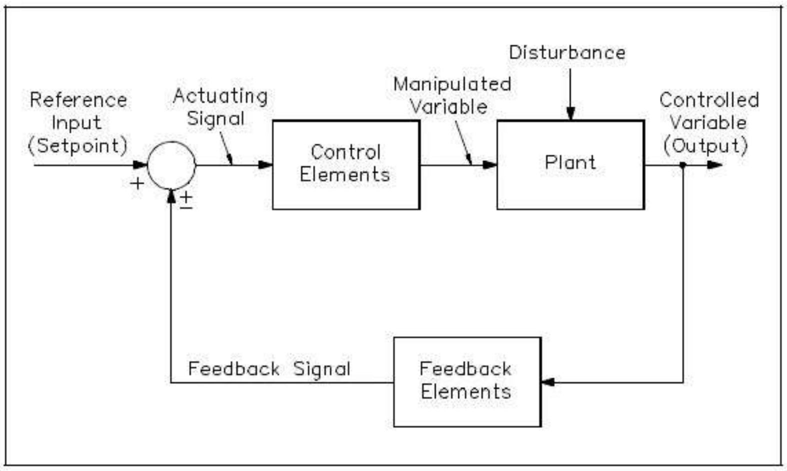

Figure 1: The key components of industrial automation systems

Control Devices include PLCs, PACs, and computers that execute control commands. Sensors are devices that detect changes in the environment (e.g., temperature, pressure) and provide feedback to the control system. Actuators mechanisms carry out the control commands by moving or controlling a system or process and the Software are Specialized programs that manage and monitor the automation processes [5].

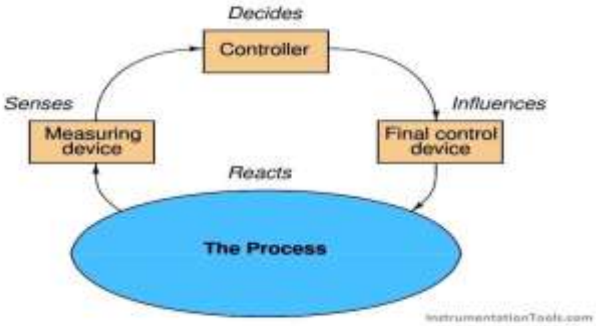

Figure 2: Automation schematic Diagram

2.1 AI-Driven Predictive maintenance

AI-Driven Predictive maintenance is an approach that employs a data-driven methodology to identify and foretell early warning symptoms of machine breakdown through artificial intelligence, machine learning, and the Internet of Things (IoT). It leverages the power of the Internet of Things (IoT) by placing tiny sensors directly on machines. These sensors act as silent observers, constantly monitoring key metrics like vibration, flow rates, levels, temperature, and energy consumption. This data is cleaned and normalized to remove noise, ensuring accuracy for AI models then wirelessly transmitted to a cloud-based system [6]. Then, the magic happens. Powerful analytics and machine learning algorithms go to work, analyzing the data like detectives searching for clues. They identify even the subtlest changes in any of the operational metrics or a gradual rise in temperature – that might signal a potential problem. By analyzing these trends, Decision-Making Modules can predict when a component is likely to fail – techniques like anomaly detection and remaining useful life (RUL) estimation is determined. Maintenance tasks are prioritize based on risk assessments, enabling targeted interventions without waiting for breakdown to cripple operation. This foresight allows proactive maintenance to be scheduled during downtimes, minimizing disruption on operation [6].

2.2 The Benefits of Integration of AI-driven predictive maintenance into Industrial Automation process.

Let us look at the major benefits of AI-Driven Predictive maintenance strategies and Industrial Automation separately and growth that accrued from integrating the two processes:

(a) Industrial Automation: Industrial automation uses robotics, control systems, and data technologies to streamline manufacturing and industrial processes. Its benefits include:

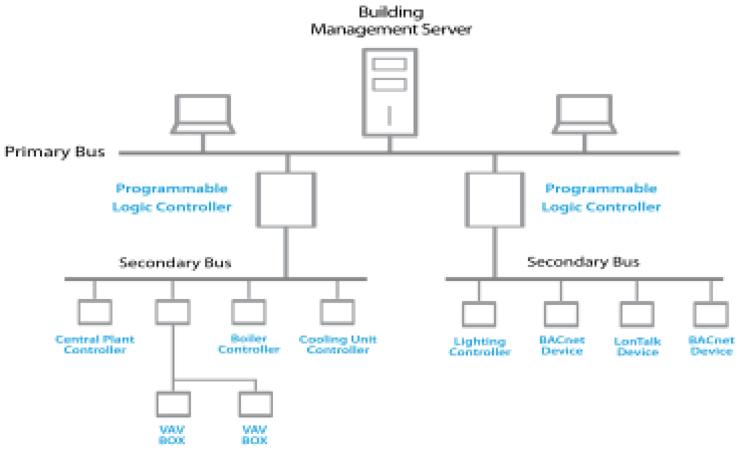

Figure 3: A simple schematic diagram for an automatic controlled system

(b) Productivity & Efficiency: Machines operate 24/7 without fatigue or breaks unlike human operators and has a faster production cycle, which reduced lead times lastly, Elimination of bottlenecks and simplification of complex tasks.

(c) Quality & Consistency: It has precision in repetitive tasks and reduces human error. It has automated inspection systems catch defects early. It has a consistent product quality boosts customer retention

(d) Cost Savings: It reduces labor costs and material waste, minimizes downtime and expensive rework, and delivers faster ROI despite upfront investment.

(e) Safety & Compliance: Robots handle hazardous tasks, reducing workplace injuries, it ensures compliance with safety regulations, lowers insurance and legal risks.

(f) Flexibility & Customization: Easily adapt production lines to changing market demands and enables mass customization with minimal downtime.

2.3 Benefits of AI-Driven Predictive Maintenance

By leveraging AI-driven predictive maintenance, industries can significantly reduce downtime and achieve cost efficiency by forecasting issues early, preventing unexpected breakdowns, and avoiding unnecessary part replacements and over-maintenance

(a) Real-Time Monitoring and Smarter Decision-Making: Sensors and IoT devices track equipment health continuously, enabling condition-based and prescriptive maintenance, while AI analyzes historical and live data to optimize maintenance schedules, improving planning, procurement, and resource allocation.

2.4 Sustainability, Safety and Key Challenges in Automation & AI-Driven Predictive Maintenance

By harnessing automation and AI-driven predictive maintenance, industries can achieve monumental efficiency gains, substantial reductions in waste and environmental impact, and dramatic enhancements in worker safety through virtual elimination of equipment failures. This powerful combination enables companies to optimize operations, minimize downtime, and maximize productivity, ultimately securing a profound and sustainable competitive advantage in an increasingly complex and dynamic global marketplace [7].

(a) **Data Infrastructure, Quality and Integration with Legacy Systems:** Predictive maintenance relies on high-quality sensor data, but many industrial environments lack standardized data collection systems, limiting model accuracy. Additionally, integrating AI tools with existing automation frameworks poses challenges due to outdated or proprietary technologies, requiring significant investment in interoperability and system upgrades to ensure seamless functionality and maximize the potential of predictive maintenance solutions. This hinders widespread adoption.

(b) **Cybersecurity, Risk Management, Workforce Capabilities, Scalability & Cost Constraints:** The adoption of predictive maintenance through IoT, cloud platforms, and AI introduces new vulnerabilities, making secure data transmission and system integrity crucial. There's a growing need for cross-disciplinary talent in AI, data science, and industrial engineering, requiring upskilling and change management. Deploying predictive maintenance across diverse equipment fleets can be resource-intensive, with delayed ROI without strategic planning [8]. Infrastructure limitations may also hinder real-time responsiveness, emphasizing the need for careful consideration and phased implementation to overcome these challenges and ensure long-term success and sustainability in industrial settings [9].

(c) **Cultural Resistance & Adoption Barriers:** Operational teams may be skeptical of AI-driven recommendations, hindering adoption. Building trust is crucial to overcome this barrier. Transparency into AI decision-making processes, comprehensive training programs, and demonstrable value from AI-driven insights can help alleviate concerns. By showcasing tangible benefits and fostering a culture of collaboration, organizations can increase acceptance and drive successful integration of AI-driven predictive maintenance solutions [10].

3. CONCLUSION

The convergence of industrial automation and AI-driven predictive maintenance marks a pivotal shift in how industries approach operational efficiency, reliability, and growth. Automation lays the foundation for scalable, high-performance systems, while AI enhances these systems with intelligence that anticipates failures, optimizes resource allocation, and minimizes downtime. Together, they form a synergistic framework that not only boosts productivity but also fosters sustainable industrial development.

To fully capitalize on automation and AI-driven maintenance, stakeholders must adopt a holistic approach—balancing technological innovation with workforce development, cybersecurity, and scalable infrastructure. Proactive leadership and cross-functional collaboration will be essential to navigate these challenges and drive sustainable industrial growth.

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Development of an IoT-based Patient Health Monitoring System

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Abstract: Real-time patient health monitoring and prompt medical intervention remain critical challenges, particularly in emergency cases. This research presents the development of a smart IoT-based Patient Health Monitoring System designed to report a patient's condition in real-time to both a centralized web portal and the nearest medical facility. The system integrates wearable sensors—a MAX30100 for oxygen saturation and heart rate, and a DS18B20 for temperature, with an ESP-8266 microcontroller. Physiological data is transmitted to a ThingSpeak web server at 15-second intervals for continuous monitoring. A key innovation is the incorporation of a GPS-based alert system; when vital signs exceed thresholds (demonstrated with a temperature trigger of 38°C), the system automatically calculates the nearest hospital from a predefined list and sends an emergency SMS alert. Testing confirmed the system's accuracy, with the temperature sensor achieving a 97% accuracy rate (average value 36.5°C) and successfully triggering alerts to the geographically closest hospital from a test set of four. This system serves as a testament to the transformative potential of IoT in elevating patient monitoring by providing timely alerts and actionable data, enabling healthcare providers to intervene promptly to prevent complications and improve health outcomes.

Keywords: *Health monitoring,Healthcare, IoT, Sensors, Wireless*

1. INTRODUCTION

In low-and middle-income countries, there is an increasingly growing number of people with chronic diseases due to different risk factors such as dietary habits, physical inactivity, and alcohol consumption among others. Chronic diseases are highly variable in their symptoms as well as their evolution and treatment, some if not monitored and treated early, can end the patient's life. World Health Organization reported that 4.9 million people die from lung cancer from the consumption of snuff, overweight 2.6 million, 4.4 million from elevated cholesterol, and 7.1 million from high blood pressure [1]. A limited number of medical resources have been prioritized for patients who suffer from a serious disease or have urgent needs; however, current and traditional medical methods cannot meet the requirements of patient needs in a timely fashion [2]

For many years the standard way of measuring glucose levels, blood pressure levels, and heartbeat were with traditional exams in a specialized health centre but due to the advancement in technology, there have been developments of various vitals reading sensors such as blood pressure cuff, heart rate monitor, including electrocardiograms [3], which allow patients to take their vital signs and records daily. Such readings are sent to doctors and who will then recommend the medicine and workout routines that allow them to improve their quality of life and overcome such diseases.

TheintroductionofFlexibleandwearablehealth-monitoringdevicesprovidesarevolutionary technology, which serves as an alternative to conventional monitoring methods, putting health care on a path that is more remote, portable, and timely [4-6].The health monitoring system provides multiple options to change the conventional management and monitoring of patients, a solution that tends to reduce the cost of health care and helps the hospital to improve the treatment process and provides a remote health monitoring system.

Patient monitoring system (PMS) involves monitoring of patients' vitals remotely by means of devices that transfers patient data to remote locations wirelessly. It provides health care providers a platform to monitor a patient's health. A typical example of the patient monitoring system is the electrocardiography (ECG) that monitors the electrical activity of the heart. Patient monitoring system is primarily implemented to have a quantitative evaluation of the crucial physiological parameters of patients during critical periods of biological functions. This system is used for measuring continuously and automatically, the values of the patients' important physiological parameters such as blood pressure, body temperature, ECG, EMG, heart rate etc. This system detects the various parameters of the patient using the biosensors - a chemical sensing device in which a biologically derived recognition entity is coupled to a transducer to allow the quantitative development of some complex biochemical parameter [7].

The internet of things (IoT) applied common in the health sector, seeking to improve the quality of life of people. It is the integration of all devices that connect to the network, which can be managed from the web and in turn provide information in real time, to allow interaction between users [8]. On the other hand, the IoT can be seen from three paradigms [9], which are Internet-oriented middleware, things sensors oriented and knowledge-oriented semantics. The health monitoring and medical information system based on the Internet of Things integrate technologies such as wireless networks and mobile computing, aiming to provide patients with remotely receivable sensing, sound, image, and video multimedia information, enhancing medical diagnosis accuracy the quality of clinical service. The health monitoring system using IoT consists of various modules like Health monitoring module, data acquisition module, data receiving module, data transmission module, data processing module display module and alarm system. [10, 11].

Flexible and wearable patient health monitoring system, however, always requires a transmission from the patient to the medical personnel who could be far away from the patient's location in cases of emergency and there is no availability of first aid materials [12]. When there is an emergency situation and the location of the patient is far away from the registered hospital and the medical personnel, this could lead to death of the patient due to lack of provision of first aid care. A provision of a system in which the sensors are well optimized and that can contact the nearest hospital for an immediate first aid care is required.

The flexible and wearable patient health monitoring system always require a transmission from the patient to the medical personnel who could be far away from the patient's location in cases of emergency and there is no availability of first aid materials [12]. However, real time patients' health monitoring and prompt medical intervention is an issue of concern in emergency related cases. To address this problem, there is a need for a smart health monitoring system that will report in real-time, a patient's health condition to a nearby medical hospital. Patient health monitoring system has been deficient in cases of emergency when the medical personnel is far away from the patient's location and giving off false alarm which is due to the malfunctioning of the sensors, hence, the need for a system that the sensors are well optimized and can contact nearby hospital via SMS notification as well as web-based application in cases of emergency.

2. METHODOLOGY

The device measures the patients' physiological parameters; oxygen level, pulse rate and temperature through the sensors. The system is used to get real-time information of the physiological parameters of the patients. The brain of the project is the ESP-8266. A microcontroller (ESP8266) is interfaced with the sensors to process and transform the measured signals and determine the patient's physiological vitals in real time.

When the sensor parameters exceed a threshold value, the ESP-8266 is programmed to trigger the GPS and sends the emergency information to the Nearest hospital through SMS and the registered hospital through the web portal. The unit is designed as a system able to function as a portable and wearable unit, which measures the users' physiological parameters through low-cost sensor modules. The result is transmitted to a Web page (thingspeak) and a SMS API to be accessed in real-time. The block diagram of the system, the flow chart on how the algorithm of the system works and the circuit diagram are shown in Figure 1, 2. and 3 respectively.

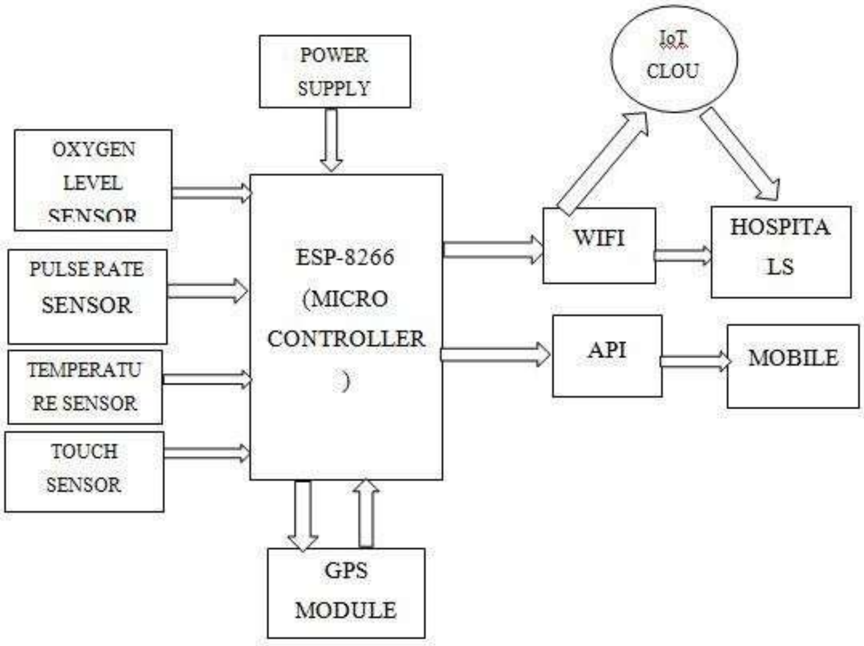

Figure1: Block diagram of the patient health monitoring system

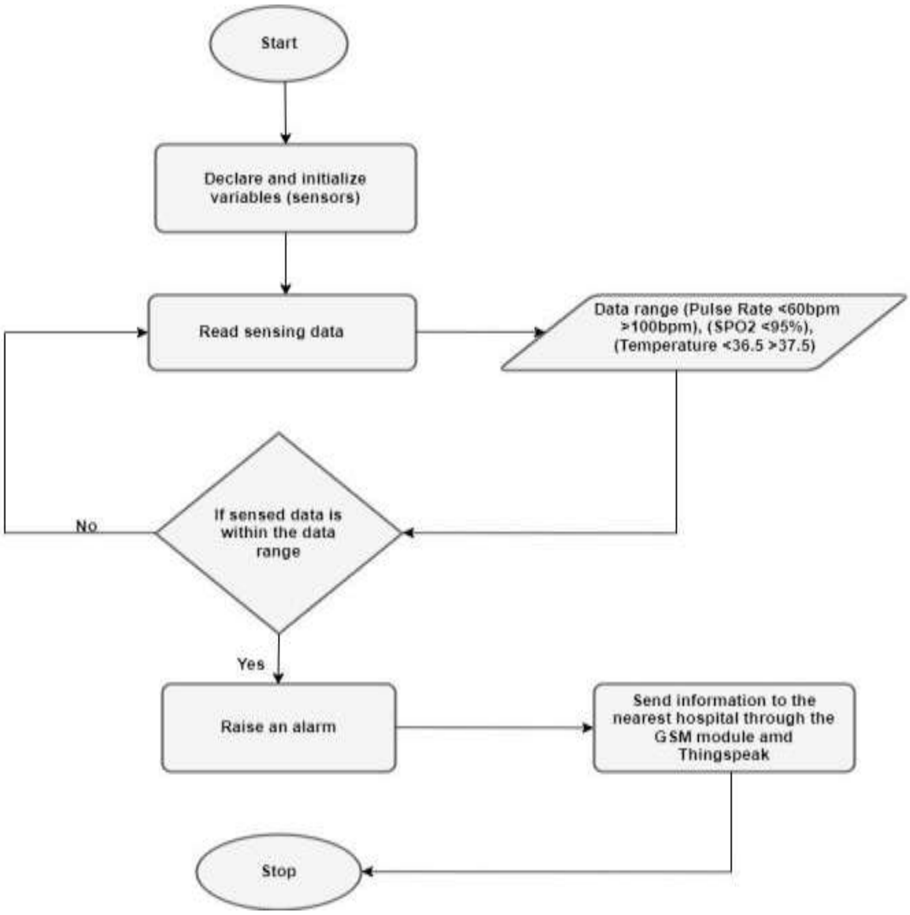

Figure2: The Flowchart of the System.

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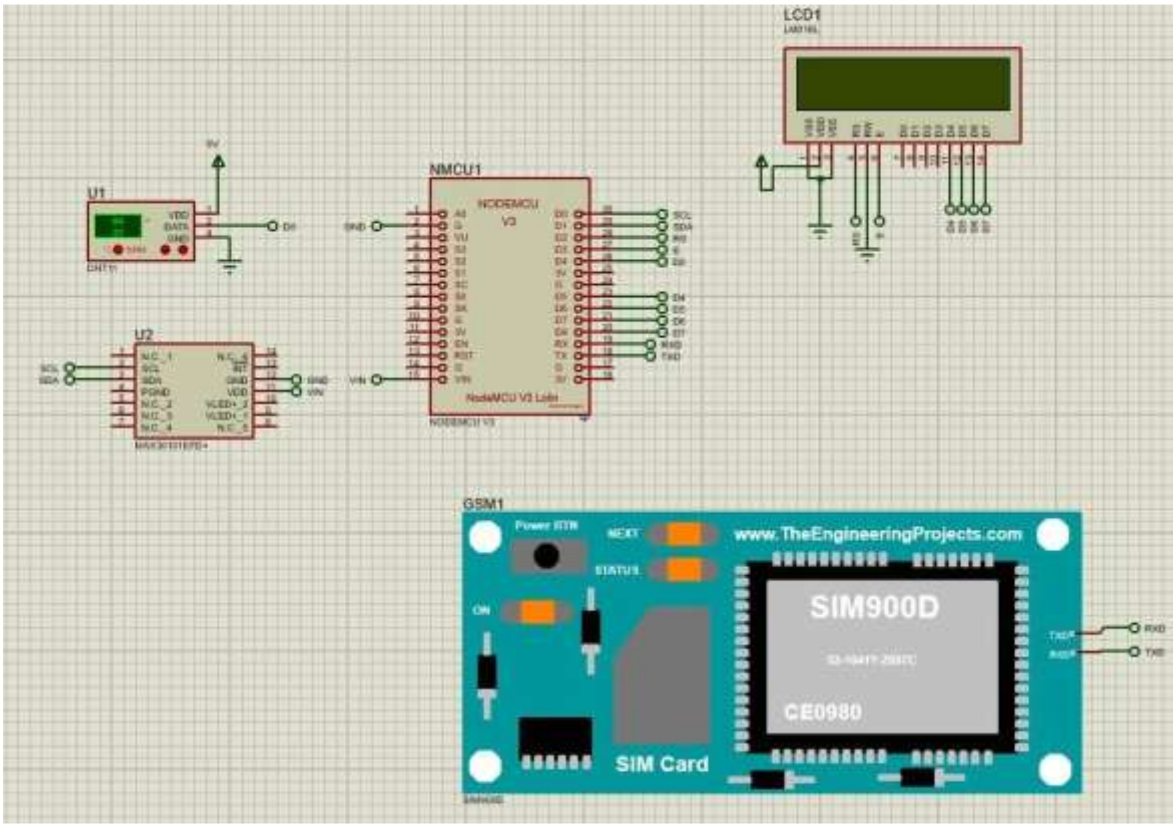


Figure3: Circuit Diagram of the System

3. RESULTS AND DISCUSSION

The design of this work was done using proteus 8.1 design Suite software and the code was written using arduino IDE software. Proteus is a popular software tool used for simulating and designing electronics circuits. It is used for various purposes, including: testing circuit functionality, simulating microcontroller-based systems, and creating virtual prototypes before physical implementation. Proteus is employed in the designing of this system and for simulating the behaviour of the system to examine its functionality. Figure 4 shows the simulated diagram with proteus.

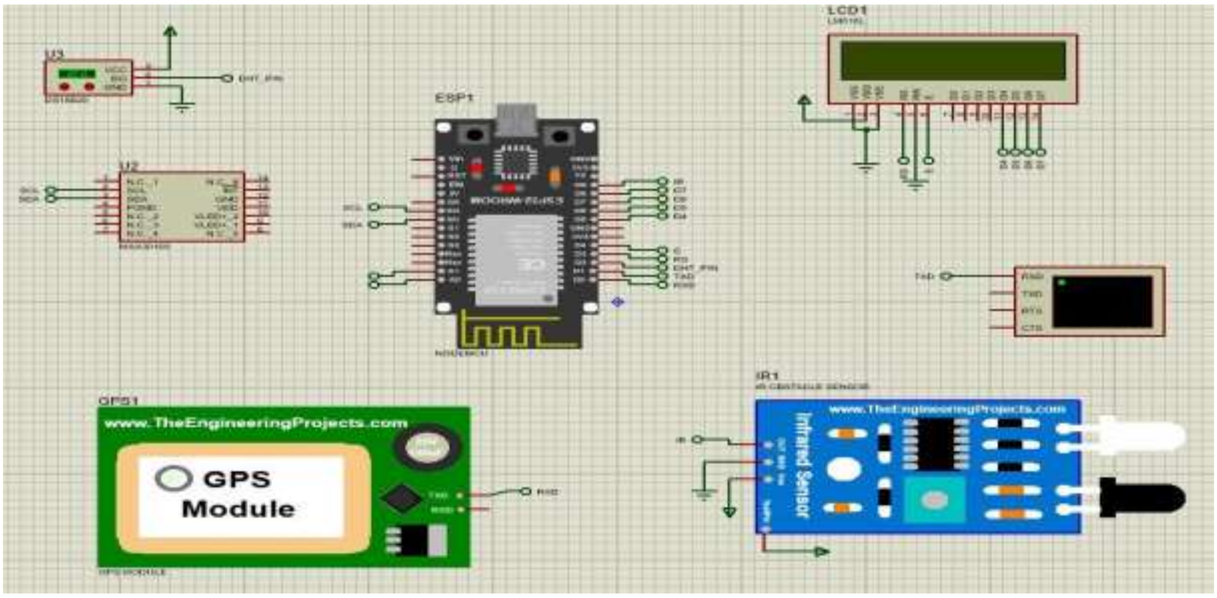


Figure 4: Proteus design of the system during simulation

After completing all of the preliminary design and analysis, the project was implemented on breadboard to observe the behaviour of the sensors and to determine the functionality of the whole system. The implementation of this project involves Implementation of the whole project on the breadboard then, transferring of the code to the hardware (ESP8266NodeMCU).

Each sensor was placed on the breadboard and connected to the microcontroller (ESP8266NodeMCU) one after the other and was tested by uploading the required code for each sensor to achieve respective functionality. Then the LCD was connected to the whole circuit to display the value of the sensors and Batteries were connected with a DC-DC boost converter during this phase to serve as power source that supply 5V to the circuit on breadboard.

After the whole components have been connected and their functionality have been confirmed then the Wi-Fi module on the ESP8266NodeMCU was activated by updating the whole with Wi-Fi connectivity code to send the sensors data value to webserver (ThingSpeak) for visualization and real-time monitoring as shown in Figure 5.

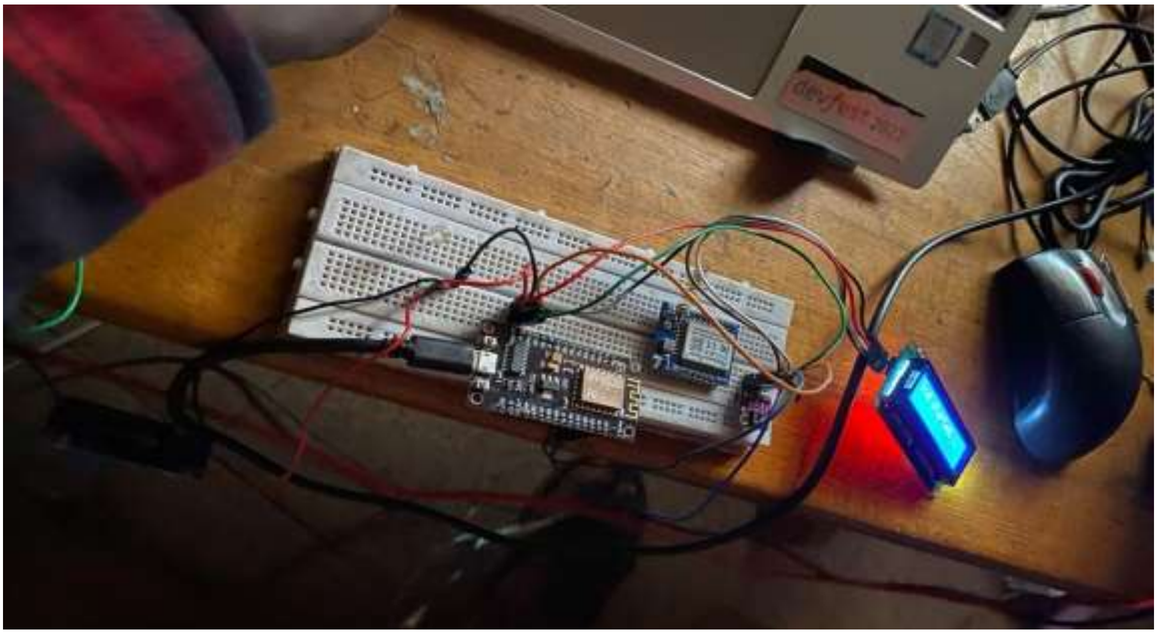


Figure 5: Implementation on the Breadboard

The test for Patient Health Monitoring System using IoT by carrying the whole system close to the body of the patient to measure the physiological vitals of the patient. The temperature was carried out by placing the temperature sensor (DS1B820) on the patient's skin, and the oxygen saturation and heart rate were measured by placing the heart rate sensor (MAX30100) on the finger of the patient.

To test the emergency functionality with the GPS system, four hospitals were set up with longitudes and latitudes of (7.43025,3.92078,7.23897,3.82327,7.23890,3.823349,7.43006,3.89877) respectively the System was further tested in a warm water, the temperature probe was inserted in a warm water of (38°c and 38.5°c) respectively at different location.

At test 1, (38°c), the longitude and latitude of the patient is 7.42076 and 3.86965. The GPS system navigated through the four hospitals that were set up and figured out that the hospital with longitude and latitude 7.43025, 3.92078 is the nearest, the emergency information of the patient was sent to the registered number of the hospital.

At test 2, (38.5°c), the longitude and latitude of the patient is 7.42081 and 3.86983. The GPS system navigated through the four hospitals that were set up and figured out that the hospital with longitude and latitude 7.43006, 3.89877 is the nearest, the emergency information of the patient was sent to the registered number of the hospital.

Table 1 depicts the value of temperature, heart rate, and oxygen saturation that were obtained from the sensors while testing the system. The sensor's data are sent to the web server (ThingSpeak) at 15s intervals for visualization by the health care professional to enhance real-time monitoring of the vital parameters. The result of the data uploaded to the web server (ThingSpeak) is shown in Figure 6 while Figure 7 shows how the system sends Emergency Information to the nearest hospitals at both instances of tests with increased temperature.

Table 1: Body temperature, heart rate, and oxygen saturation that were obtained from the sensors while testing the system.

Tests	Temperature (℃)	SPO2(%)	Heartrate (BPM)	Time(s)
1	36	98	63	15
2	36.5	99	62	30
3	36.3	97	76	45
4	36	97	70	60
5	37	99	68	75
6	36.8	96	78	90
7	36.2	95	65	105
8	37	98	88	120
9	37	96	75	135
10	36.3	97	77	150
11	36	99	67	165
12	38	99	77	170
13	38.5	99	82	169

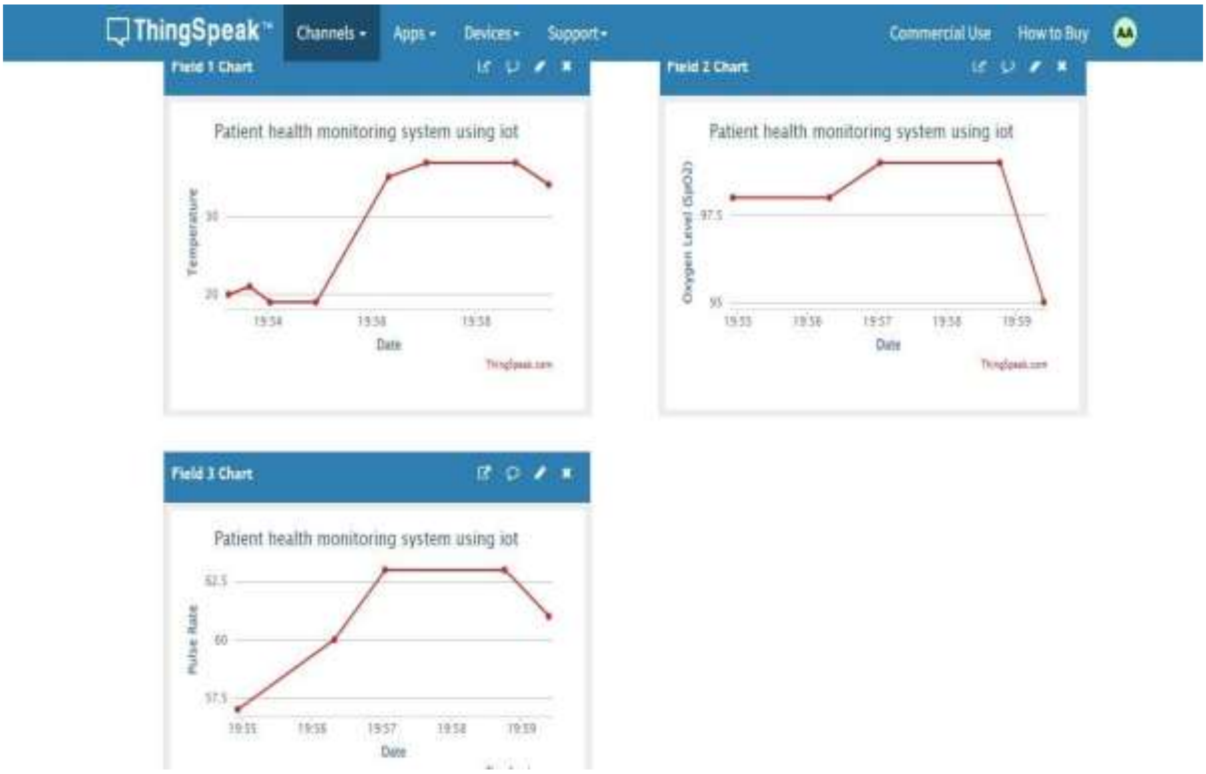


Figure7: Result of the data uploaded to ThingSpeak

Figure 8 shows the temperature data acquired by DS18B20 sensor and the acquired values from the DS18B20 senor is being uploaded to ThingSpeak at interval of 15s. However, the readings from the DS18B20 sensor have good data precision with an average value of 36.545℃ which shows 97% accuracy of the sensor. The error obtained from this sensor is 0.0713.

Figure 9 and 10 shows the SPO2 and heart rate data obtained from MAX30100 respectively and uploading of the acquired values from the sensor to ThingSpeak at interval of 15s. To some extent the sensors data may be proven to be accurate. However, the graph show anomalies of the data sensor. These anomalies may be due to the asynchronous characteristic of the MAX30100 during its operation with other sensors in the system. Figure 11 shows the emergency messages sent to different hospitals at different locations at times when the physiological vitals exceeded the threshold level.

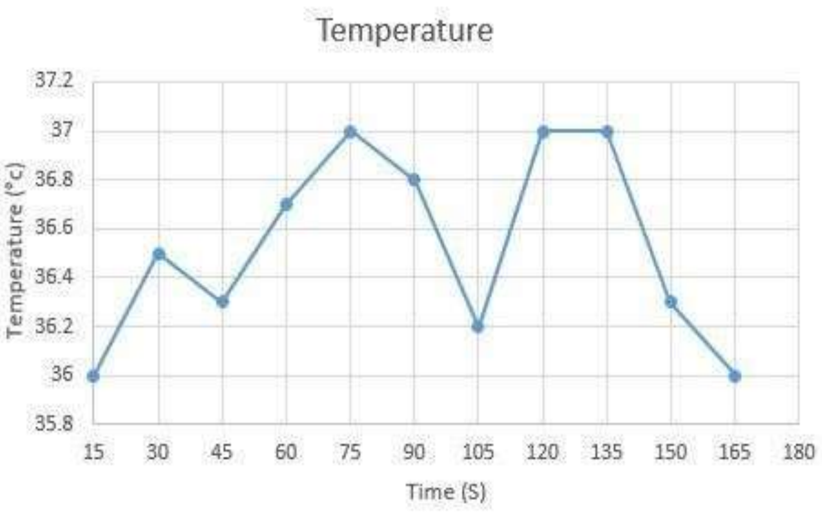


Figure 8: Temperature data uploaded to ThingSpeak at interval of 15s

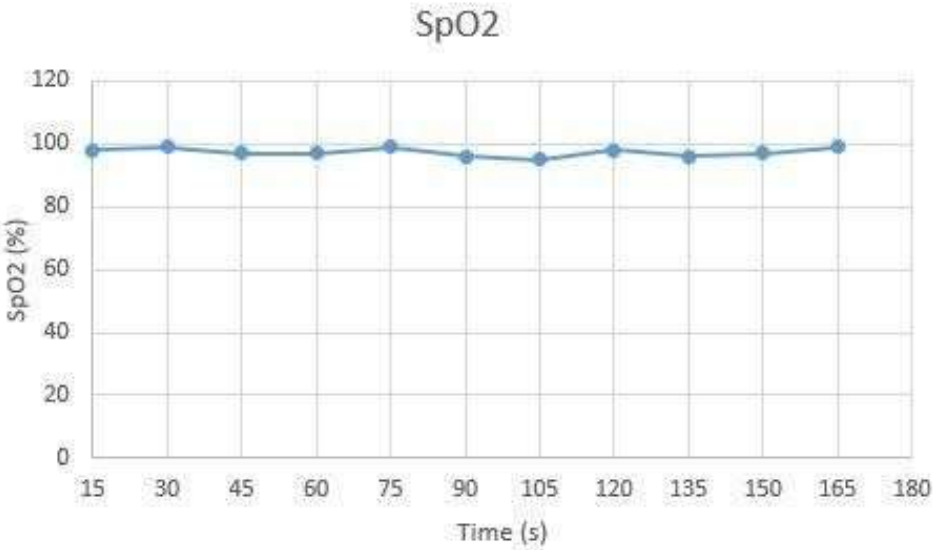


Figure 9: SPO2 data uploaded to ThingSpeak at interval of 15s

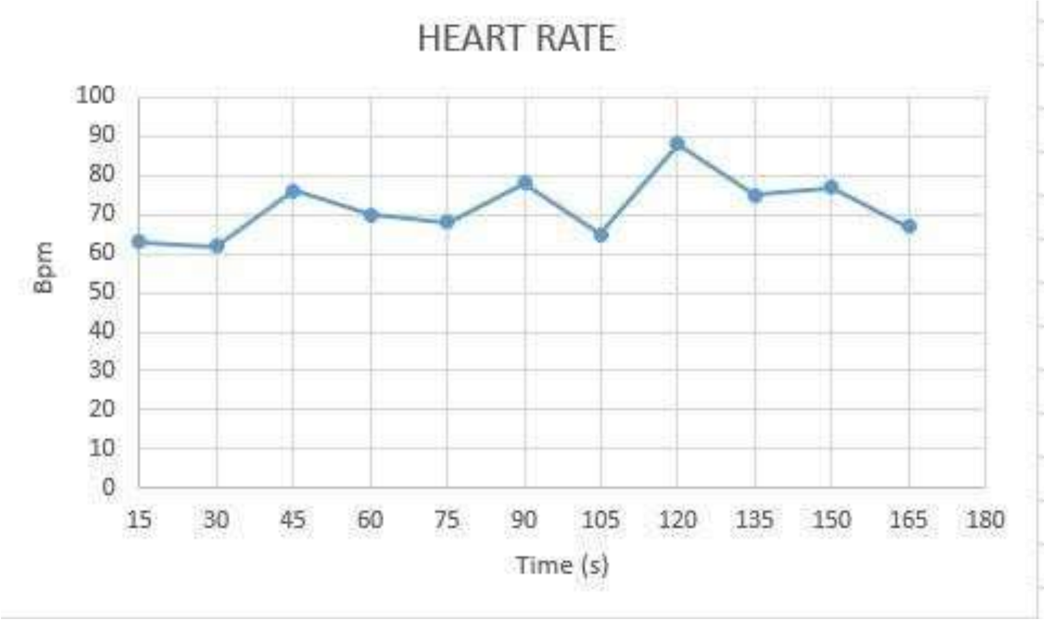
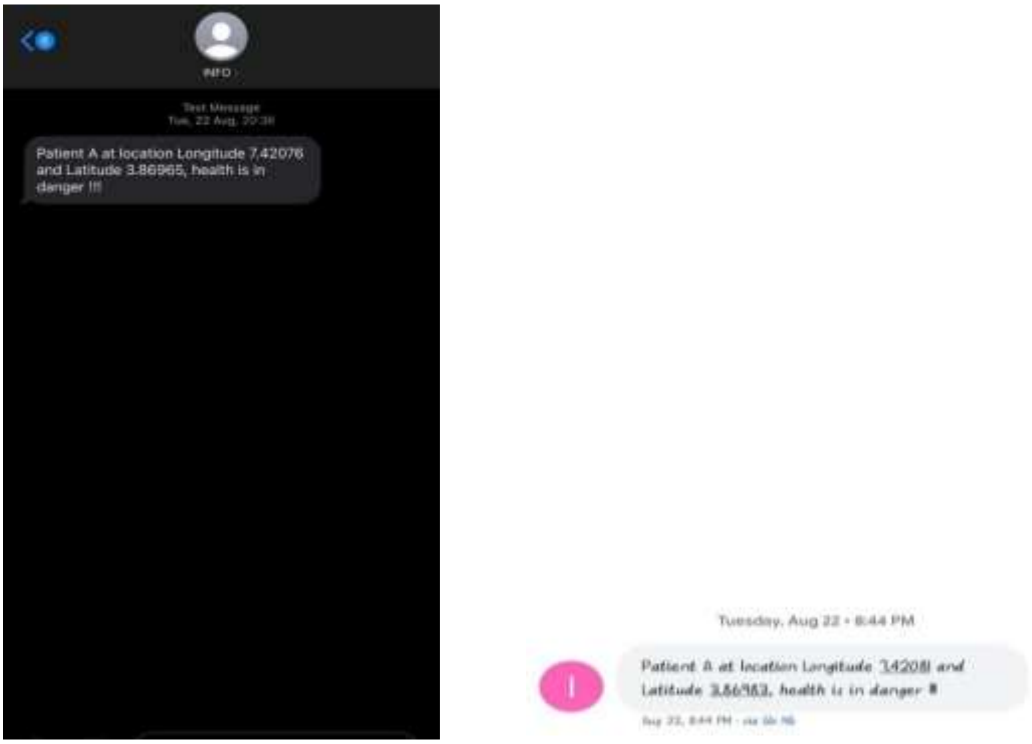


Figure 10: Heart rate data uploaded to ThingSpeak at interval of 15s



Text Message
Tue, 22 Aug, 20:38

Patient A at location Longitude 7.42076 and Latitude 3.86965, health is in danger !!!

Tuesday, Aug 22 • 8:44 PM

Patient A at location Longitude 7.42081 and Latitude 3.86983, health is in danger !!

Figure 11: The Emergency message sent to the nearest Hospital Location

4. CONCLUSION

This research successfully developed and tested a comprehensive IoT-based Patient Health Monitoring System that addresses critical gaps in existing remote monitoring solutions. The developed system demonstrably outperforms other available systems through its integrated, proactive, and location-aware emergency response mechanism. While many existing systems focus primarily on the remote collection and transmission of physiological data to a central server or a pre-registered hospital, this system introduces a critical advancement: dynamic, GPS-enabled emergency dispatch. Unlike conventional systems that may alert a single, fixed medical facility—a significant limitation if the patient is far from that location—this system intelligently identifies and contacts the nearest available hospital in real-time when a patient's vitals exceed predefined thresholds.

This key differentiator ensures that the time between a critical health event and the arrival of first aid is minimized, directly addressing the fatal delay often encountered in emergencies. The system's dual-alert functionality, utilizing both SMS for immediate notification and a web portal (ThingSpeak) for continuous data visualization, provides a robust and redundant communication channel that enhances reliability over systems relying on a single method. Furthermore, the system's hardware implementation using low-cost, widely available components like the ESP8266 microcontroller and standard sensors (DS18B20, MAX30100) demonstrates a cost-effective and scalable approach compared to proprietary or more expensive alternatives. The successful simulation and physical testing, which confirmed the accurate acquisition of temperature, heart rate, and SpO2 data, along with the precise triggering of emergency alerts based on geolocation, validate the system's practical functionality and superiority.

This system outperforms other available patient monitoring systems by transforming a passive data-collection tool into an active, intelligent emergency response ecosystem. It not only enhances the quality of continuous care but also fundamentally improves emergency outcomes by ensuring that help is directed from the closest possible point of care, thereby setting a new benchmark for smart, responsive, and life-saving healthcare technology.

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A Data-Driven Perspective of Stock Market Dynamics: A Case Study of the Nigeria Telecommunication Industry

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Abstract: The Nigerian stock market, despite its vast potential, remains underutilized, hindering the country's economic growth. This underutilization stems from the inability of predictive models to forecast market trends with considerable accuracy, largely due to insufficient data and inadequate modelling techniques. The volatile nature of the stock market exacerbates poor investment decisions, resulting in significant losses thus discouraging potential investors. This research aims to develop a robust stock market prediction model using machine learning algorithms and statistical methods, leveraging evidence-based data from Nigeria's telecommunication companies. By uncovering meaningful patterns and trends, the model will provide valuable insights to inform profitable investment decisions. The study employs a data-driven approach, utilizing historical stock market data to train and test the model. The results demonstrate the model's effectiveness in predicting stock market trends, thereby promoting informed investment decisions. This research contributes to the development of a proven solution for stock market prediction, fostering economic growth, attracting investment, and improving Nigerians' overall stock market performance. By harnessing the potential of Nigeria's stock market, this study uncovers new opportunities for economic growth and prosperity.

Keywords*; Data, Machine-Learning, Predictive-Model, Stock.*

1. INTRODUCTION

Accurate prediction of stock market encourages investment in stock marketing which is vital in an economy [1]. Nigeria stock exchange overtime have witnessed a low participation which stem from poor decision making leading to a huge lost to investors due to the inability of model to make accurate prediction [1, 2]. Considering the facts that stock markets are non-stationary in nature [3], this constant change calls for a careful and sensitive analysis before investment. [4] Existing prediction model with low predictive power due to its development on inadequate data, insubstantial data for training and inadequate modelling techniques are some of the major pitfall this study attempt to address using adequate and evident-based data, leveraging reinforcement learning; [5, 6] a dynamic approach that can be used to adapt to non-stationary environments which can be applicable to stock market. There exists a strong correlation between reductions of investment risk in stock market investments when there is reductions in forecasting error [7].

A scholarly work by [8, 17], examines the inefficiency of models developed based on assumptions (insubstantial data) on the underlying data; and its notes the violations of these assumptions lead to inaccurate predictions afterward. However, the application of evidence-based data in training of model with capability that agent interacts constantly with the environment guarantees a more accurate prediction.

Machine learning (ML) models trained on efficient and evident-based data can counter the common cases of overfitting generally, as verified [9], overfitting occurs when a model is trained on a limited dataset and fails to generalize on a new data [10]. This is particularly problematic for stock market data, which is complex and non-linear, making it easy for models to overfit and gives inaccurate prediction. Nevertheless, the application of dynamic approach in stock market prediction, which can be used for dynamic optimization, where an agent learns through interaction with its environment can solve the problem of overfitting [6,11]. This is evident also as a recent study by [6], used Reinforcement learning (RL) to optimize portfolio allocation and achieved better results than traditional statistical portfolio optimization techniques.

Considering this research as a data science related, many models build solely using the statistical method several limitations have been identified in its application on the Nigeria stock exchange as exposed by the study conducted by [12], which found that statistical models, including Autoregressive Integrated Moving Average (ARIMA) and Generalized Auto Regressive Conditional Heteroskedasticity (GARCH), had limited predictive power for the Nigerian stock market. However, statistical methods cannot be avoided because of its values in stock price prediction such as computation to find out the relationship existing between variables [13].

Also, statistical models may not always have high predictive power because they rely on historical data solely, which may not be a good pointer of future market trends [12]. However, model can further be improved by including additional variables and by using more advanced statistical techniques, hence this research rallies round concrete data to improve prediction accuracy [6].

RL is becoming increasingly important in stock prediction as it can adapt to non-stationary environments, optimize portfolio allocation, and learn from complex market data. This research would utilize evidence-based data to train and validate the model and, leverage the strengths of reinforcement learning to improve accuracy of prediction [14].

In view of the challenges embedded in the stock market predictions using ML model and considering the application of RL in modelling of the stock market as viewed through its potentials, it will be promising in building a stock predictive model with higher accuracy which will restore trust of investors and stockbrokers to used stock predictive model as a tool of guide for investment.

2. METHODOLOGY

This section presents the methods followed in achieving this highly sensitive model in predicting the stock market with higher accuracy.

2.1 Historical Data

Actual dataset gotten from yahoo finance are used to train the model to avoid the anomaly of assumption in training, validating and prediction of a model. The dataset used in training and validating of a stock prediction model is pertinent in determining its accuracy. Hence, this research utilizes concrete dataset of the Nigeria stock market of four competing companies operating locally in Nigeria and offering the same services which, are; MTN Group Limited, Airtel Networks Limited, Globacom Nigeria Limited (Glo), and 9Mobile telecommunication company the major multinational mobile telecommunications companies to mitigate the risk of anomaly of assumption (insubstantial) data in model development. The research focuses on four selected stocks for a period of three to four years and does not account for events that spans beyond these periods.

2.2 Data pre-processing

The dataset of the selected stocks are pre-processed which is necessary to have a well ordered data for analysis in order to avoid conflicting results. Data pre-processing involves cleaning, transforming, and preparing raw data into a format that can be easily analysed. The goal of pre-processing the historic data is to ensure that the data is accurate, complete, consistent, and relevant to the task at hand.

2.3 Data Exploration and Visualization

The pre-processed data will further undergo data exploration and visualization which is critical in any data analysis task, it presents the pictorial view of the data for a better understanding and further analysis. These steps involve understanding and exploring the data to identify patterns, relationships, which gives insights that can be used to guide further analysis.

The steps involved include:

i. Understanding the data: This involves getting a basic understanding of the data, such as; its size, structure, and format.

ii. Descriptive statistics: This involves computation of descriptive statistical measure i.e. mean, median, standard deviation, and other summary statistics to gain insight into the data.

iii. Data visualization: it involves creating visual representations of the data, for instance scatter plots, histograms, and box plots, to identify patterns and relationships between stocks.

iv. Correlation analysis: This has to do with the analyses of the correlation between different variables for the purpose of identifying the relationships and dependencies of the stocks.

2.3 Regression Analysis and ARCH/GARCH Model

Regression analysis is carried out to model the relationship between a dependent variable and one or more independent variables. It is commonly used to estimate the effect of one or more explanatory variables on a particular outcome or response variable.

Regression analysis used a given linear function for predicting continuous values:

$$y = \beta 0 + \beta 1x + \varepsilon \qquad (1)$$

where:

y is the dependent value (continuous variable)

x represents the known independent value

$\beta 0$ is the intercept or the constant term

$\beta 1$ is the slope or the coefficient of the independent variable x

ε is the error term or the random variation in the dependent variable that is not explained by the independent variable

The goal of linear regression is to estimate the values of $\beta 0$ and $\beta 1$ that minimize the sum of the squared errors between the predicted values of y and the actual values of y.

ARCH/GARCH models are used to analyse the volatility of financial time-series data. ARCH stands for Autoregressive Conditional Heteroscedasticity, while GARCH stands for Generalized Autoregressive Conditional Heteroscedasticity. Both models are designed to capture the conditional volatility of a financial asset or a portfolio of assets [15].

2.4 OLS Regression Model

According to [16], OLS regression involves calculating the difference between the predicted values of y and the actual values of y for each data point. The sum of the squared differences is then minimized to find the best estimates of $\beta 0$ and $\beta 1$. The estimates of $\beta 0$ and $\beta 1$ can be used to predict the value of y for a given value of x.

2.5 Reinforced Model

As [14] reported that reinforcement learning (RL) is a machine learning technique in which an agent learns to make decisions by interacting with its surroundings and receiving feedback. The agent's purpose is to maximize a reward signal, eventually determining an optimal policy that maps states to actions and maximizes cumulative rewards over time. In this study, value-based RL approaches are used to improve the predictability of an Ordinary Least

Squares (OLS) model. The RL technique tries to increase prediction accuracy by retraining the model with anticipated values from the OLS model that are supported by evidence-based data.

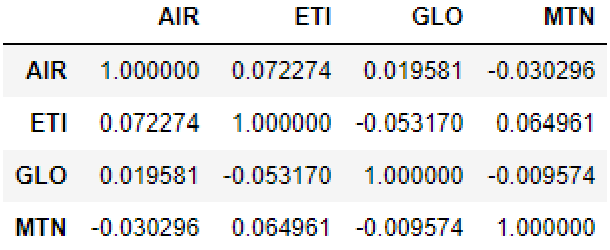
2.6 Model Evaluation

Evaluating a machine learning model is critical for determining its performance on previously unseen data. This approach identifies whether the model is overfitting or under fitting and assesses its generalizability. This study evaluates models using three main metrics: Mean Squared Error (MSE), Root Mean Squared Error (RMSE), and Mean Absolute Error (MAE). These metrics offer a thorough view of the model's performance and forecast accuracy.

3. RESULT AND DISCUSSION

This section presents the findings and discussion of the developed model which will lead our conclusion on the developed model.

Table 1: Correlation Matrix for daily returns



	AIR	ETI	GLO	MTN
AIR	1.000000	0.072274	0.019581	-0.030296
ETI	0.072274	1.000000	-0.053170	0.064961
GLO	0.019581	-0.053170	1.000000	-0.009574
MTN	-0.030296	0.064961	-0.009574	1.000000

Table 1 above, shows the correlation matrix of daily returns for four equities. The findings show weak positive associations between AIR and ETI (0.07), AIR and GLO (0.02), and ETI and MTN (0.06). These low correlation coefficients point to a modest association between the equities. Further investigation may reveal hidden patterns in the data. Furthermore, the presence of multicollinearity among the stocks suggests that each has little influence over the others, indicating a lack of substantial interdependence.

3.1 Regression Analysis and ARCH/GARCH Analysis

ARCH/GARCH

ARCH/GARCH models used to analyze the volatility of financial time-series data. Both ARCH/GARCH models are designed to capture the conditional volatility of the financial asset or a portfolio of assets.

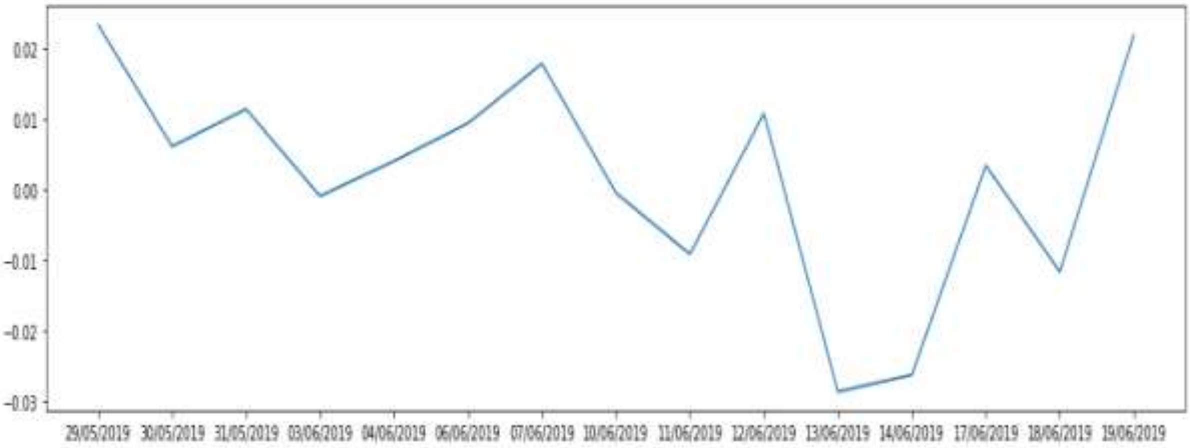


Figure 1: Trend of first 15 returns for AIR

Figure 1 shows the trend plot for the daily returns for Airtel Telecommunications Limited (AIR) within the first 15 days. It can be seen that there is high level of instability within the market, hence this calls for a deeper analysis in order to have higher accuracy in future prediction. Hence, statistical model which are developed solely using historical data without taking into cognizance the volatile nature of stock marketing will not be good for future forecast. This implies its inefficiency predicting the future.

3.2 Regression Analysis

This study used Ordinary Least Squares (OLS) regression analysis to model the relationship between variables, specifically calculating the link between a stock's past and future prices. Using the returns of four related stocks as a training set, the OLS model produced reasonable forecasts for the future returns of the chosen stock, MTN. The findings imply that OLS can be a useful tool for stock prediction, especially when combined with appropriate historical data.

Figure 2 OLS Predicted Returns Vs Actual Returns

Figure 2 shows a trend chart that compares the OLS regression model's daily return projections to the stock's actual daily returns. Notably, the OLS model performs significantly better than ARCH and GARCH predictions. Although phase deviations exist, the true and projected data show comparable trends, demonstrating that the model is effective. The consistency in patterns between actual and expected returns demonstrates the value of employing evidence-based data to train and develop stock predictive models, indicating a significant improvement in statistical modeling.

Thus, a better accuracy metric is needed to be applied to the prediction in order to proffer more insight to the comparison. Figure 3 shows the Mean squared error (MSE), root mean squared error (RMSE), and mean absolute error (MAE) which are all commonly used metrics in evaluating the performance of regression models.

```
Prediction - MSE: 0.0001838614720944296, RMSE: 0.013559552798467567, MAE: 0.00885215900591612
```

Figure 3: OLS Model Standard Error of Mean

While both parameters demonstrate promise accuracy, a more exact comparison requires applying the same process on the reinforced model, allowing for a complete assessment.

3.3 Reinforced Model

The reinforced model which is a build-up from the OLS predicted values as additional attribute which forms that training set and the model was retrained using 4/7th part of the new dataset. Figure 4 reinforced model shows the output chart.

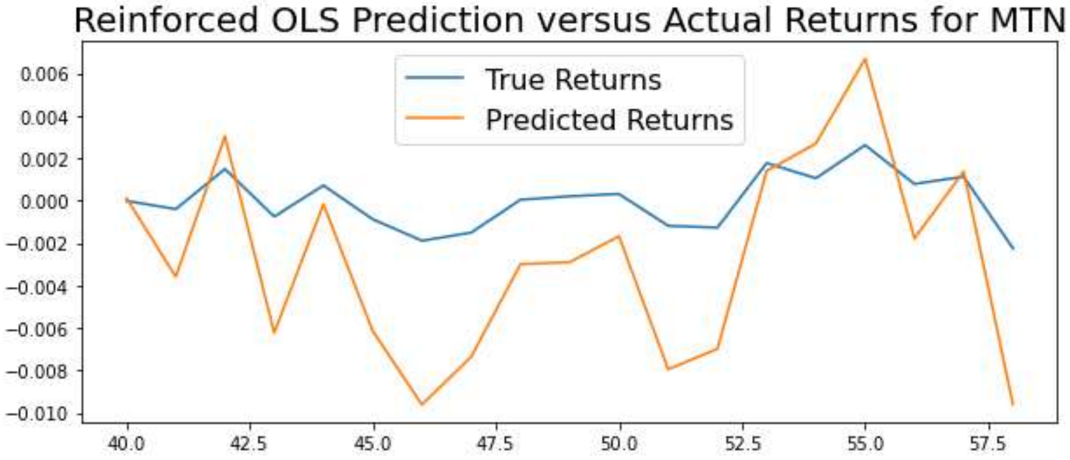


Figure 4: Reinforced Model

The chart depicts the predicted and actual returns for the selected stock, indicating a comparable trend path between the two results. To present a statistically valid argument, we used a more robust evaluation metric. Figure 5 depicts the Standard Error of the Mean and other important accuracy factors. These findings show that the machine learning model, which was derived from the Ordinary Least Squares (OLS) model and retrained with evidence-based data, has greater predictive potential when using reinforcement learning.

```
Reinforced Prediction - MSE: 0.00037786624769936436, RMSE: 0.019438782052879865, MAE: 0.016054463808490467
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Figure 5: Reinforced Model Standard Error of Mean

4. CONCLUSION

In conclusion, this study underscores the significance of evidence-based data in model construction for accurate stock market predictions. Our findings suggest that models trained on well-organized, actual data perform better, increasing trust and confidence in forecasting. We offer a novel method to decision-making for investors and stockbrokers by combining reinforcement learning, statistical tools, and evidence-based data. This can lead to higher stock market investment, lower risk, and, eventually, economic growth. Our findings emphasize the potential of data-driven tactics to alter the stock market and guide investing decisions.

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Digital Financial Inclusion and Rural Consumption Patterns in Nigeria: Implications for Rural Digital Transformation Policy

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Abstract: This study examines the impact of digital financial inclusion (DFI) on rural household consumption patterns in Nigeria, focusing on how digital financial access influences financial well-being and economic behaviour. Utilizing survey data from 2,587 rural households across Nigeria's six geopolitical zones, the study employs descriptive statistics, chi-square tests, and regression models, including an interaction model, to analyse key socioeconomic factors affecting financial inclusion and consumption. The findings reveal significant socioeconomic disparities in digital financial access, with male-headed households, middle-aged individuals, higher-income groups, and the self-employed exhibiting greater financial inclusion. Conversely, larger households, lower-income groups, and female-headed households exhibited great financial exclusion. The chi-square test results show that age, employment status, income, and household headship significantly influence DFI levels, while regression analysis confirms that education and employment status impact financial inclusion positively, whereas household size impacts it negatively. Surprisingly, the results indicate that DFI has a negative effect on financial well-being, suggesting that access alone does not guarantee improved economic outcomes. The interaction model further demonstrates that DFI moderates the relationship between income and consumption, emphasizing the need for financial literacy programs and responsible financial behaviour to maximize the benefits of digital finance. This study shows that inclusive financial policies, enhanced digital literacy, and targeted interventions are critical factors that optimize digital financial inclusion services contribution to improving households' consumption pattern and well-being in rural Nigeria.

Keywords: *Digital Financial Inclusion, Rural Households, Consumption Patterns, Financial Well-being, Socioeconomic Disparities, Financial Literacy,*

1. INTRODUCTION

The integration of digital finance into financial innovation has introduced a transformative dimension to financial inclusion, particularly in developing economies. Financial inclusion refers to the accessibility of diverse financial services to low-income populations, including those in remote rural areas. Globally, financial exclusion remains a significant issue, with over 56% of adults lacking access to formal financial services, and in developing countries, this figure rises to 64% (Ardic, Heimann, & Nataliya, 2011). Rural areas in these regions experience the greatest exclusion from financial services, creating a gap that digital financial inclusion (DFI) seeks to bridge. The introduction of digital technologies in financial services has enhanced financial inclusion by expanding access to banking, payments, credit, and savings opportunities, particularly in countries like Nigeria.

Despite progress in financial inclusion, rural communities in Nigeria remain disproportionately underserved. The Enhancing Financial Innovation & Access (EFInA) survey (2020) indicates that while formal financial inclusion in Nigeria improved from 36% in 2010 to 44% in 2020, exclusion remains twice as high in rural areas (44%) compared to urban areas (20%). The absence of banking infrastructure, combined with socio-economic barriers and the impact of the 2022Naira redesign policy, has underscored the necessity of digital financial solutions. The rapid adoption of fintech solutions, mobile banking, and agent networks presents a critical opportunity to assess the adoption of digital finance in rural communities and its implications for household consumption and well-being.

The increasing penetration of mobile technology and internet connectivity in Nigeria provide a viable platform for enhancing digital financial services in rural areas. However, despite these advancements, challenges such as inadequate financial literacy, security concerns, and cultural resistance to digital transactions persist. While the urban areas have witnessed a surge in fintech adoption, rural dwellers often rely on informal financial systems that may not provide long-term economic stability. Addressing these barriers through targeted digital financial inclusion initiatives can help rural households transition to more secure and efficient financial management systems, thereby improving their overall economic well-being.

While digital financial inclusion has significantly enhanced financial participation in urban areas, rural communities have experienced slower adoption rates, leading to persistent disparities in consumption patterns and overall well-being. The core objective of DFI is to extend financial services to the unbanked, but limited penetration in rural areas undermines this goal. Factors such as low digital literacy, inadequate financial infrastructure, high transaction costs, and internet connectivity challenges continue to hinder rural adoption of digital finance. The 2022Naira redesign policy by the Central Bank of Nigeria (CBN) further exposed vulnerabilities in rural financial access, particularly in cash-dependent sectors. Approximately 60% of Nigeria's population remains unbanked (Ekong & Ekong, 2022), a figure significantly higher than what obtains in comparable economies such as Indonesia (51%), Brazil (30%), and India (20%). Poor access to digital financial services has exacerbated economic inequality and financial exclusion in Nigeria.

Financial inclusion has been linked to higher quality of life, economic resilience, and poverty reduction (Ekong & Ekong, 2022). However, financial exclusion impedes economic mobility, slows business development, and reinforces income inequality. In rural areas, the inability to access formal financial services limits credit availability for small enterprises, disrupts consumption stability, and hampers investment in education and healthcare. Expanding DFI adoption in these communities is crucial for reducing poverty, strengthening local economies, and enhancing financial security. Beyond financial access, rural households often face structural challenges that limit their ability to participate in digital financial ecosystems. Many rural businesses and households rely heavily on cash transactions due to scepticism about digital platforms, unreliable power supply, and concerns over cyber fraud. Moreover, gender disparities in financial inclusion remain prominent, with women in rural areas often having limited access to financial resources due to socio-cultural norms. Addressing these underlying challenges is vital for ensuring that digital financial services are truly inclusive and beneficial to all demographics in rural Nigeria.

This study aligns with the Sustainable Development Goals (SDGs 1, 2, 8, 9, 10, and 12), which emphasize poverty eradication, zero hunger, economic growth, infrastructure development, reduced inequality, and sustainable consumption. Given the interconnection between digital financial inclusion, household consumption, and overall well-being, it is essential to examine how DFI adoption influences rural consumption structures and financial behaviours. By integrating both quantitative and qualitative research methods, the study will provide empirical insights into the effectiveness of digital financial inclusion in transforming rural households economic behaviours. In addition, the study aims to develop an analytical framework for policy formulation that leverages digital financial services to enhance rural economic participation and employment opportunities. The insights derived from this research will provide data-driven policy recommendations to help Nigeria maximize the benefits of DFI for rural socioeconomic development. This study aims to examine the extent to which digital financial inclusion influences rural household consumption patterns and financial well-being in Nigeria. Specifically, the study seeks to (i) assess the level of digital financial inclusion across different rural regions and socio-economic groups, (ii) analyze the impact of digital financial services on consumption diversification and expenditure stability, and (iii) investigate the role of financial literacy and socio-economic factors in moderating the relationship between digital financial inclusion and household financial decision-making. Furthermore, the study aims to (iv) evaluate the barriers that hinder the adoption and effective utilization of digital financial services among rural households and (v) propose policy recommendations to enhance digital financial accessibility, affordability, and usability in rural Nigeria

2. LITERATURE REVIEW

Digital financial inclusion plays a critical role in improving economic stability and consumption behaviours, yet rural households often face significant barriers to accessing and utilizing financial services. Digital financial inclusion refers to the integration of unbanked individuals into the formal financial sector by providing them with access to financial services through digital platforms, such as mobile phones and other electronic devices. It focuses on delivering digital financial services to financially excluded and underserved populations, leveraging technology to enhance accessibility and affordability. By utilizing existing digital technologies, digital financial inclusion ensures that excluded populations can access formal financial services in a cost-effective and sustainable manner Digital financial inclusion is the ongoing effort to offer affordable and accessible financial solutions that integrate low-income individuals into the formal financial ecosystem. It encompasses banking, credit, insurance, and payment services, all facilitated through mobile banking, digital wallets, fintech innovations, and agent banking networks. The overarching goal is to reduce financial exclusion, promote economic participation, and drive inclusive financial growth by extending financial transactions beyond the constraints of traditional banking systems (Ozili, 2021b).

There are four main categories of providers that are important in facilitating digital financial inclusion through digital financial services. The first category comprises full-service banks, which offer a comprehensive range of digital financial solutions, including digital payments, transfers, and value storage, accessible via mobile devices, payment cards, or point-of-sale (POS) terminals. These banks provide an extensive array of digital financial services without limitations. The second category consists of limited-service banks, which specialize in specific digital financial offerings, typically accessible through mobile devices, payment cards, or POS terminals. Unlike full-service banks, their services are more restricted, often catering for a particular region or offering a limited selection of digital financial solutions. The third category includes mobile network operators (MNOs) acting as e-money issuers, while the fourth category encompasses non-bank (non-MNO) e-money issuers, both of which facilitate digital transactions without traditional banking structures.

For digital financial service providers to function efficiently and promote financial inclusion, three essential components must be in place: (i) a digital transactional platform, (ii) an agent network, and (iii) a customer access device. These components work together to ensure seamless financial transactions, enhance accessibility for underserved populations, and create a more inclusive financial ecosystem. This serves as the technological foundation for executing electronic financial transactions. It enables users to conduct a variety of financial activities, including digital payments, money transfers, savings, credit, and insurance services. This platform ensures seamless integration among banks, mobile network operators (MNOs), fintech companies, and other financial service providers. It also incorporates security measures such as encryption, fraud detection, and regulatory compliance to protect user data. Examples of digital transactional platforms include mobile money services like M-Pesa, MTN MoMo, and Airtel Money, as well as fintech applications such as Paystack, Opay, and PayPal. A well-developed digital transactional platform reduces dependence on traditional banking infrastructure, making financial services more accessible to rural and underserved populations.

An agent network acts as a bridge between digital financial service providers and customers, particularly in remote areas with limited banking access. These agents facilitate essential financial transactions such as deposits, withdrawals, bill payments, and customer onboarding for digital services. They also play a crucial role in providing financial literacy thus, helping users understand and navigate digital finance platforms. Agent networks are commonly established through mobile money agents, retail store partnerships, and banking correspondents. In many rural areas, agents serve as trusted intermediaries, increasing confidence in digital financial services. Their presence ensures that even individuals with limited technological proficiency can participate in the digital financial ecosystem.

A customer access device is the tool through which users interact with digital financial services. These devices include mobile phones, POS terminals, smart cards, and computers. Among these, mobile phones particularly basic feature phones with USSD capabilities, are the most widely used access devices in rural areas due to their affordability and ease of use. Secure access through PIN authentication, biometric verification, and encryption enhances the safety of digital financial transactions. Additionally, ensuring interoperability among access devices and financial service providers is crucial for seamless transactions. By leveraging affordable and accessible customer access devices, digital financial service providers can extend their reach to excluded populations, enabling them to send, receive, and store money efficiently.

Household consumption patterns refer to the spending behaviour of individuals and families on goods and services required for daily living. Consumption patterns are influenced by factors such as income levels, access to credit, financial literacy, and economic stability (Modigliani & Brumberg, 1954). Digital financial inclusion has the potential to shape consumption behaviors by providing households with more flexible and secure financial options, enabling better budgeting, savings, and expenditure planning (Beck et al., 2019). Household consumption consists of various expenditures that individuals and families incur to sustain their daily lives. These expenses are influenced by factors such as income level, economic conditions, financial access, and social structures. Understanding the key components of household consumption provides insights into spending patterns and financial decision-making among households. One of the most significant components of household consumption is food and beverages. Food expenses are essential and often constitute the largest share of household budgets, especially in low-income households. Spending in this category includes groceries, dining out, and beverages. Since food is a basic necessity, its demand remains relatively stable despite fluctuations in household income, making it an inelastic component of consumption. Ensuring food security is a crucial aspect of household welfare, influencing nutrition, health, and productivity levels.

Housing and utilities also account for a substantial portion of household consumption. This category includes rent, mortgage payments, electricity, water, gas, and other maintenance costs. Housing expenses are typically fixed costs, meaning they do not fluctuate significantly with short-term changes in income. Access to affordable housing is a critical determinant of household financial stability and overall well-being. The affordability and availability of housing also affect migration patterns, urbanization rates, and the overall quality of life of individuals and families. Another crucial element is transportation, which includes public transit, personal vehicle expenses, fuel costs, and commuting expenditures. The level of transportation spending varies based on urbanization, employment location, and infrastructure availability. In many rural areas, limited access to reliable transportation increases costs and affects household mobility, impacting access to education, healthcare, and employment opportunities. Efficient and affordable transportation is essential for social and economic participation, facilitating movement between homes, workplaces, and essential services.

Healthcare and medical expenses are another vital component, covering hospital visits, medication, insurance premiums, and preventive care. Households with aging or members with chronic illnesses often allocate a higher percentage of their income to healthcare. The availability of health insurance can significantly reduce financial burdens associated with medical emergencies, yet many low-income families lack adequate coverage. Access to quality healthcare services improves life expectancy and overall productivity, making it a significant priority for households. Also, education and childcare represent a critical investment in human capital, with households spending on school fees, tuition, learning materials, and daycare services. In many developing regions, education expenses take up a large portion of household income, particularly for families seeking quality education for their children. Access to affordable education contributes to long-term economic mobility and improved living standards. The quality of education impacts employment opportunities, earning potential, and societal development in the long run.

Expenditure on clothing and personal care covers apparel, footwear, grooming products, and hygiene items. While this category is essential, spending patterns vary depending on income levels and social influences. During economic downturns, households often prioritize essential needs over discretionary spending such as fashion and luxury personal care items. Clothing and personal care play a role in social identity, self-esteem, and cultural expression, making them an important but variable aspect of consumption. Entertainment and recreation spending includes subscriptions to digital platforms, leisure activities, vacations, and sports. As a discretionary expense, it tends to increase when household income rises and decrease during economic hardships. Entertainment and recreational activities contribute to mental well-being and social engagement, making them an important part of household spending. In modern economies, the rise of digital media and online streaming services has changed entertainment consumption patterns.

Savings and investments play a crucial role in long-term financial security and wealth accumulation. Households allocate a portion of their income to emergency funds, retirement savings, and investment portfolios, such as real estate, stocks, or business ventures. A strong savings culture enhances financial resilience, allowing households to better navigate economic uncertainties. Financial literacy and access to savings and investment platforms determine the effectiveness of household financial planning. The increasing reliance on technology has also made communication and digital services a key component of household consumption. Expenses in this category include internet subscriptions, mobile phone services, and digital financial platforms. Digital connectivity has become essential for work, education, and financial transactions, making communication services a fundamental household expenditure. The digital economy has further accelerated the need for seamless connectivity and access to online financial tools.

Households’ consumption patterns also involve allocating resources to miscellaneous and unexpected expenses, which include social obligations, emergency repairs, donations, and unforeseen medical costs. These expenditures vary depending on lifestyle choices, cultural norms, and financial preparedness. Setting aside funds for unexpected expenses enhances household financial stability and reduces the risk of debt accumulation. Managing these unpredictable costs ensures financial security and prevents financial distress in challenging situations. Understanding these key components of household consumption provides valuable insights into economic behaviour, financial priorities, and consumption patterns across different income groups. These components interact dynamically to influence household welfare, financial decision-making, and overall quality of life. By analysing household consumption trends, policymakers and financial institutions can develop targeted interventions to promote financial inclusion, economic stability, and sustainable development.

The integration of digital financial services into household financial planning can lead to improved consumption smoothing, where individuals can better manage income fluctuations. Access to digital savings and credit facilities allows households to invest in essential services such as healthcare, education, and housing, leading to enhanced well-being. However, barriers such as low digital literacy and unreliable internet access can hinder the effectiveness of DFI in rural areas (Aker & Wilson, 2021). Challenges such as lack of digital infrastructure, security concerns, high transaction costs, and socio-cultural resistance remain prevalent in rural communities. Overcoming these barriers requires policy interventions, financial literacy programs, and investments in rural digital infrastructure to ensure widespread and sustainable financial inclusion (Adegbite & Olaniyan, 2020). Gender disparities in financial inclusion also persist, with women in rural communities facing greater challenges in accessing financial services due to cultural and societal norms (Wang & He, 2020). To enhance digital financial inclusion, policymakers must develop robust regulatory frameworks that promote fintech expansion while ensuring consumer protection. Investment in digital infrastructure, particularly in rural areas, is essential for bridging the financial access gap. Additionally, financial literacy programs targeted at rural households can improve the adoption and effective use of digital financial services (Demirgüç-Kunt et al., 2018). Collaboration between government agencies, financial institutions, and fintech firms is crucial to developing innovative solutions that address the unique challenges faced by rural populations.

Financial inclusion means easy access to banking account to receive and make payments; banking products that tailor savings to the pattern of cash flow for poor households; facilities to transfer money with ease, as well as life and non-life insurance facilities (Kama & Adigun, 2013:7). That is, access to financial payments and receipts as well as insurance facilities. In the same vein, strengthening the financial system would include diverse actions by financial institutions, insurance companies, pension institutions, capital market actors, and technology providers to include development of diverse financial products, enhancement of payment processes, development of credit system, encouragement of savings culture among others (Ardic, Heimann, & Nataliya, 2011:21).

Financial inclusion usually refers to the accessibility, the availability, and the usage of financial services for more people, particularly the unbanked and poor (Sarma 2008, 2012; Sarma & Pais 2011). It receives increasing attention from both academia and policymakers these days, as inclusive growth has become one of the important goals for sustainable development (Demirguc-Kunt et al. 2018). Several developing countries, for example China have implemented a series of policies on improving financial inclusion. Policymakers in these nations believe that a more inclusive financial system would benefit economic development in many aspects, such as economic growth (Sarma & Pais 2011), financial efficiency (Beck, Demirguc-Kunt, & Martinez Peria, 2007), financial stability (Morgan & Pontines 2014), and social welfare (Demirgüç-Kunt & Levine 2009). Traditional financial institutions like bank developed microcredit, microfinance and financial inclusion based on manual and field-based operation, a structure that weakened their efficiency in serving the poor (Hart & Prahalad, 2002). Leveraging on ICT, the concept and scope of financial inclusion graduated to digital financial inclusion, a radical innovation that can be a changer for the population at the bottom of the pyramid (Huang et al., 2016). Hart and Prahalad (2002) noted that doing business with the population at the bottom of the pyramid requires radical innovations in technology and business models. Literature on financial inclusion has been quite expansive.

Mallick and Zhang (2019) investigated the effect of financial inclusion on household welfare in China using a household survey panel. The study established the differential impact of financial inclusion across urban and rural areas and income groups. Specific study by Li and Liu (2023) using data from the 2015–2019 China Household Finance Survey (CHFS) posits that DFI significantly raises residents' income, increasing their total annual per capita household income by CNY4200. Wang and He (2020) reported that digital financial services provided by ICT companies have a larger impact on farmers' risk vulnerability than that provided by traditional banks in Rural China. Similarly, Omar and Inaba (2020) in their robust evidence-based study affirmed that financial inclusion significantly reduces poverty rates and income inequality in developing countries. In a study of the impact of digital currency operations on the economy of Nepal, Risal (2018) found that most of the respondents were unaware of digital financial products in the country. Thus, lack of knowledge on these products means that they are inaccessible to the populace. According to Wandeda *et al.* (2023:63), the determinants of financial inclusion include ownership of mobile phone, place of residence (urban or rural), age, level of education, financial decision making, television ownership, religion and gender (Christian/Muslim women), marital status (married/widowed/divorced women). These influence the success or otherwise of financial inclusion programs. Furthermore, Wandeda *et al.* (2023:55), found that the usage of digital finance promotes financial health.

The discussion on the impact of increased access to finance on income inequality and poverty reduction has been ongoing for the past two decades. Existing literature suggests that a well-developed financial system can help reduce income inequality and poverty, while also driving economic growth (Kappel, 2010; Uddin *et al.*, 2014; Abosedra, Shahbaz, & Nawaz, 2016). However, other studies argue that financial development may not always succeed in reducing income disparities and poverty levels. Adeleye, Osabuohien, Bowale, Matthew, and Oduntan (2018) emphasize that rapid financial development, coupled with strong institutions, is necessary to promote inclusive growth. Meanwhile, Migap, Okwanya, and Ojeka (2015) highlight that Nigeria's financial inclusion index remains low compared to other emerging economies, both within and outside Africa. Their study recommends increasing media engagement and financial literacy programs through educational institutions to improve financial inclusion in Nigeria. Nkwede (2015) found a negative relationship between financial inclusion and economic growth in Nigeria, attributing this trend to the exclusion of a large percentage of Nigerian adults from financial services. Given that income, health, and housing are key determinants of well-being, access to financial services is also considered an essential component of human development. Thus, there is a pressing need to design effective financial inclusion policies to ensure broader access to financial services (Chakravarty & Pal, 2013).

Several studies have examined the determinants of financial inclusion across different regions. Zins and Weill (2016) found that gender, income level, age, and education are significant factors influencing financial inclusion in 37 African countries. Similarly, Chikalipah (2017) identified illiteracy as the major obstacle to financial inclusion in Sub-Saharan Africa. Ali (2019) highlights that women in Comoros face financial exclusion in Islamic financial services due to economic disadvantages and financial illiteracy, which contribute to persistent poverty in the country. In terms of financial policies and economic impact, Mitchell and Scott (2019) conclude that the adoption of formal financial inclusion strategies, cashless policies, and increased card-based transactions led to higher public tax revenue in Argentina. Similarly, Ghosh and Bhattacharya (2019) found that financial innovations like 'SureCash' significantly improved financial inclusion in Bangladesh, particularly by reaching more women and low-income earners. In Indonesia, Susilowati and Leonnard (2019) identify income level as the primary determinant of financial service usage, particularly in relation to loan access, which often requires collateral. Other factors influencing financial inclusion include age, gender, educational attainment, and employment type.

3. METHODS AND DATA

This study employs a survey research design to investigate the impact of digital financial inclusion on rural household consumption patterns and well-being in Nigeria. The survey method facilitates extensive data collection from diverse socio-economic groups while enabling direct interaction with respondents to obtain detailed insights into their financial behaviors. This approach is particularly relevant for exploring digital financial adoption and its implications on household expenditure patterns. The research adopts both exploratory and explanatory approaches. The exploratory aspect identifies the extent of digital financial inclusion and associated challenges, while the explanatory aspect establishes causal relationships between digital financial inclusion and household consumption structures. These methods enable a comprehensive understanding of how digital financial services influence consumption decisions in rural Nigeria.

3.1 Sampling and Data Collection

A mixed-methods approach is adopted, integrating both qualitative and quantitative data collection techniques. Primary data were gathered through structured questionnaires administered to rural households, complemented by in-depth interviews (IDIs) with digital financial service providers and policymakers. Additionally, focus group discussions (FGDs) were conducted with household heads and community representatives to explore their perspectives on financial inclusion and consumption behaviours. The study focuses on six geopolitical zones in Nigeria, selecting one state from each zone based on the proportion of rural populations and their level of digital financial service adoption. The selected states are Kogi, Jigawa, Ekiti, Bauchi, Delta, and Osun. A multi-stage sampling technique—incorporating purposive, proportional, cluster, and random sampling—ensures a representative selection of respondents. The study samples 2,587 rural households across these six states, ensuring regional diversity and robust statistical power.

In this study, a structured questionnaire was employed as the primary tool for data collection. The questionnaire was meticulously designed to include both open-ended and multiple-choice questions, as well as a Likert scale format, ensuring a comprehensive evaluation of respondents' experiences with digital financial inclusion and household consumption patterns. Careful attention was given to ensuring that all relevant dimensions of financial inclusion, financial behaviour, and household expenditure were adequately captured in the instrument.

The questionnaire consisted of multiple sections, including socioeconomic characteristics, which collected data on age, gender, household size, employment status, income levels, and digital financial literacy. These variables were crucial in understanding respondents' backgrounds and their financial engagement levels. In addition, specific sections assessed digital financial inclusion in terms of awareness, accessibility, affordability, and usage, allowing for an in-depth evaluation of the extent to which digital financial services were integrated into rural households. Questions on household consumption structures, savings and borrowing behaviours, and the barriers to digital financial adoption were also explored to provide insights into financial decision-making among rural households. A Likert-type scale was adopted for specific survey items to assess respondents' perceptions and experiences. The scale varied across sections depending on the nature of the question. For example, frequency-based questions utilized a scale ranging from "Always" to "Never," while affordability-related items used a scale of "Very Affordable" to "Not Affordable at All", ensuring that responses captured the nuances of digital financial engagement.

To ensure content validity, the questionnaire was reviewed by experts in financial inclusion, economics, and survey research methodology. A pilot test was conducted with a sample of respondents to evaluate clarity, relevance, and the appropriateness of question phrasing before full-scale deployment. Following standard research practices, all measurement scales were adapted from previously validated instruments while being modified to align with the specific context of rural Nigeria. Data collection was conducted through face-to-face surveys with 2,587 rural household heads across six geopolitical zones in Nigeria. The study also incorporated in-depth interviews (IDIs) with financial service providers and policymakers to gain expert insights into financial accessibility and inclusion challenges. Additionally, focus group discussions (FGDs) with community representatives and household heads were carried out to explore perceptions of digital financial services and their influence on consumption patterns.

In testing for the reliability of questions collected with the questionnaire, a Cronbach alpha test was conducted. The result is presented in the table 2 below. The reliability analysis using Cronbach's Alpha reveals varying levels of internal consistency across the different constructs measured in this study. DFI Awareness demonstrates strong reliability with a Cronbach's Alpha value of 0.81, indicating that the questions effectively measure the construct with high internal consistency. This suggests that respondents provided consistent answers regarding their awareness of Digital Financial Inclusion (DFI). However, DFI Accessibility and DFI Usage exhibit moderate and questionable reliability, with alpha values of 0.54 and 0.62, respectively. These values fall below the generally accepted threshold of 0.7, indicating potential inconsistencies in how respondents interpret and respond to the questions on accessibility and usage. This suggested the need for a review of specific items to ensure they align with the construct being measured. Some questions were revised, some reworded, while some were even removed to enhance reliability.

The Consumption Patterns construct, with an alpha value of 0.18, raises significant concerns regarding measurement consistency. The very low reliability score suggests that the questions may not capture a unified concept of consumption patterns among respondents. This could result from ambiguous wording, a lack of clear conceptual focus, or an insufficient number of questions to measure the construct effectively. A thorough review and restructuring of these items were done to improve their reliability.

Table 1: Cronbach alpha Reliability test

Variables	**Cronbach alpha stats**	**Questions**	**No. of Questions**
DFI Awareness	0.81	Q19 – Q26	7
DFI Accessibility	0.54	Q27 – Q38	12
DFI Usage	0.62	Q39 – Q56	16
Consumption Patterns	0.18	Q63 – Q67	5

Source: Author's Computation (2025)

According to Gedik et al. (2015), the interpretation of the Cronbach statistics are as follows:

$0.00 \leq \alpha \leq 0.39$: Scale not reliable

$0.40 \leq \alpha \leq 0.59$: Scale has low reliability

$0.60 \leq \alpha \leq 0.79$: Scale has high reliability

$0.80 \leq \alpha \leq 1$: Scale is definitely reliable

3.3 Model Specification

To examine the impact of digital financial inclusion (DFI) on rural household consumption patterns, this study adopts an extended consumption function model that incorporates income, digital financial inclusion, and other socio-economic factors influencing household spending. The model is specified as follows:

$$ln\, C_{ljt} = \beta_0 + \beta_1 Y_{ljt} + \beta_2 Digital_{ljt} + \xi' X_{ljt} + \theta_t + \mu_{ljt} \qquad (1)$$

Where:

lnC$_{ijt}$ = Log of total household consumption expenditure for household i in region j at time t, representing overall household consumption.

Y$_{ijt}$ = Household income level, which serves as the primary determinant of consumption.

Digital$_{ijt}$ = Digital financial inclusion indicator, capturing access to and usage of digital financial services (e.g., mobile banking, digital payments).

X$_{ijt}$ = Vector of control variables such as education level, household size and employment status.

θ_t = Time-fixed effects, controlling for external macroeconomic factors that may influence household consumption over time.

μ_{ijt} = Error term, capturing unobserved variations affecting consumption behavior.

To further explore how digital financial inclusion affects household consumption stability, an interaction term is introduced in an alternative model:

$$C_{ljt} = \beta_0 + \beta_1 Y_{ljt} + \beta_2 Digital_{ljt} + \beta_3 (Digital \times Y)_{ljt} + \xi' X_{ljt} + \theta_t + \mu_{ljt} \qquad (2)$$

This interaction term (Digital×Y)$_{ijt}$ helps determine whether the effect of income on consumption is amplified by digital financial inclusion, indicating whether households with greater digital financial access experience more stable and diversified consumption patterns.

3.4 Data Analysis Techniques

The data collected were analysed using both descriptive and inferential statistical methods to examine the impact of digital financial inclusion on rural household consumption diversification and stability. Descriptive statistics, including frequency distributions, mean values, and percentages, were used to summarize key socio-economic characteristics such as age, gender, employment status, income levels, and household financial behaviours. These statistics provided an overview of the extent of digital financial inclusion and the variation in household consumption patterns among rural households.

To assess the effect of digital financial inclusion on household consumption diversification, a Consumption Diversity Index (CDI) regression was employed. This index measured how households allocated their spending across different consumption categories such as food, healthcare, education, and durable goods. The regression analysis determined whether access to digital financial services led to greater consumption diversification and improved financial decision-making.

To examine how digital financial inclusion influenced consumption stability and financial resilience, a Moderated Regression Analysis (MRA) was conducted. This model assessed whether income levels and other socio-economic factors (education, employment status and household size) influenced the relationship between digital financial inclusion and household consumption stability. The interaction effects provided insights into whether financial inclusion alone was sufficient to ensure stable consumption patterns or if additional socio-economic conditions played a critical role. The data were analyzed using descriptive and inferential analysis to ensure robust statistical interpretation and accuracy.

4. EMPIRICAL ANALYSIS

4.1 Socioeconomic Profile of Rural Households in Nigeria

The findings in Table 2 reveal that rural households were predominantly middle-aged, with an average age of 43 years (±14 years). Nearly half (46.5%) of the households fell within the 35–54 age range, indicating that most financial decision-makers were in their prime working years. Three in ten (29.9%) households were headed by younger adults aged 18–34 years, a group more likely to embrace digital financial services. However, more than one in five (22.6%) rural households had heads aged 55 years or older, highlighting a significant presence of aging individuals who may be less inclined towards digital finance adoption. An average of 7 persons (±4 persons) per household was recorded with nearly half (48.4%) of the rural households having 4–6 members, while more than one-third (37.1%) had seven or more members, reinforcing the dominance of large family structures. Household size is expected to play a crucial role in financial decision-making. The prevalence of large households suggests higher financial responsibilities, which could impact savings and spending behaviours, especially regarding food, education, and healthcare.

Income disparities among rural households were evident in Table 2, with an average monthly income of ₦93,460 (±₦66,000). Two in five households (41.1%) earned between ₦50,000 and ₦100,000 per month, making this the most common income bracket. However, more than one-quarter (27.6%) of rural households survived on less than ₦50,000 per month, reflecting widespread financial hardship. In contrast, only about 1 in every 10 households (8.9%) had earnings exceeding ₦200,000, emphasizing a sharp income divide. The high standard deviation of ₦66,000 for the most common income bracket suggests significant income inequality, where some households may have access to financial stability while others struggle with economic uncertainty. This disparity may directly impact financial inclusion, as lower-income households often face barriers in adopting digital financial services. These findings underscore the need for targeted financial inclusion policies that improve access to digital financial services for lower-income and larger households, ensuring they can participate fully in the modern financial system.

Table 2: Socio-economic Profile of Rural Households in Nigeria

Variables	Scale	N = 2587	Perc. (100 %)
Age (Mean 43 years± 14 years)	Under 18 years	18	0.7
	18-34 years	776	29.9
	35-54 years	1206	46.5
	55 and above	587	22.6
Household Size (Mean 7 persons ± 4 persons)	1-3 persons	366	14.1
	4-6 persons	1257	48.4
	7-9 persons	532	20.5
	10 or more persons	432	16.6
Monthly Income (Mean ₦93,460 ± ₦66,000)	Less than ₦50,000	715	27.6
	₦50,000 - ₦100,000	1066	41.1
	₦100,001 - ₦200,000	576	22.2
	Above 200,000	230	8.9

Source: Author's Computation (2025)

Table 3 reveals significant gender disparities among sampled respondents, with 7 out of every 10 (70.0%) being male, while only 3 in every 10 (29.7%) were female. This pattern was further reinforced in household headship, where more than 8 in every 10 (85.5%) rural households were headed by men, leaving just 14.2% under female headship. These figures suggest that financial decision-making and economic control predominantly rest with men, which may influence household access to financial services and digital financial inclusion. The lower percentage of female-headed households could signify limited economic opportunities for women or social structures that favour male leadership in financial matters. Employment and income sources further highlight the financial landscape of rural households. Nearly three-quarters (72.2%) of rural dwellers were self-employed, suggesting that most households relied on farming, small-scale businesses, and informal work. Government employment accounted for just 11.4%, while private-sector jobs made up a mere 3.5%, reflecting limited formal employment opportunities in rural areas. Alarmingly, 1 in every 8 rural households (12.6%) were not employed, indicating economic vulnerability for a significant portion of households. Agriculture remained the primary source of income for nearly half (46.4%) of the households, while 3 in every 10 (30.4%) relied on small businesses. Meanwhile, less than 10% earned their income through each of remittances, artisanal work, or private-sector jobs constituting 13.5%, altogether. These findings underscore the prevalence of informal economic activities and highlight the importance of financial interventions tailored to self-employed and agricultural work-based households, ensuring they can leverage digital financial services for improved economic stability and growth.

Table 3: Socio-economic Profile of Rural Households

Variables	**Scale**	**N = 2587**	**Perc. (100 %)**
Gender	Male	1816	70.0
	Female	771	29.7
Household Headship	Male-headed	2219	85.5
	Female-headed	368	14.2
Employment Status	Self-employed	1873	72.2
	Gov. Employee	295	11.4
	Private Sector	92	3.5
	Not employed	327	12.6
Source of Income	Agriculture	1203	46.4
	Small business	789	30.4
	Public sector	165	6.4
	Private sector	70	2.7
	Remittances (Family)	44	1.7
	Artisan (Handwork)	235	9.1
	Other	81	3.1

Source: Author's Computation (2025)

4.2 Access Level of Digital Financial Inclusion among Rural Household

The table 4 presents the distribution of rural household demographics and their financial inclusion levels, as categorized into low, moderate, and high level of inclusion. The Digital Financial Inclusion (DFI) Index was developed to measure the extent of financial inclusion among rural households in Nigeria by assessing their access to and usage of digital financial services. The index incorporates key dimensions of financial inclusion, including awareness, accessibility, affordability, and usage of digital financial services. Each household's DFI score was computed based on a weighted aggregation of these factors, providing a numerical representation of their financial inclusion level. To categorize households into different financial inclusion levels, the computed DFI Index scores were classified into three categories: Low Inclusion (0.0 – 0.3), Moderate Inclusion (0.31 – 0.6), and High Inclusion (0.61 – 1.0). Households with a DFI Index score between 0 and 0.3 were assigned a value of 1 (Low Inclusion), those scoring between 0.31 and 0.6 were assigned a value of 2 (Moderate Inclusion), while households scoring between 0.61 and 1 were classified as High Inclusion (3).

The distribution of DFI levels across various household demographics was analysed using Chi-Square (χ^2) tests, examining the statistical significance of relationships between financial inclusion and key socio-economic factors such as age, gender, household headship, employment status, and income levels. This approach provided insights into patterns and disparities in financial inclusion, highlighting the factors that drive or hinder rural households' access to digital financial services. The DFI Index serves as a valuable tool for policymakers and financial service providers in identifying financially excluded populations and designing interventions to enhance financial inclusion in rural Nigeria.

The results show that age is a significant factor influencing financial inclusion ($\chi^2 = 21.84$, $p = 0.001$). The highest number of respondents fall within the 35–54 years category across all inclusion levels, suggesting that middle-aged individuals are the most engaged with digital financial services. However, older individuals (55 years and above) are disproportionately represented in the Low Inclusion category (263) compared to High Inclusion (178), indicating that older populations face barriers to financial inclusion. Meanwhile, the 18–34 age group exhibits a more balanced distribution, reflecting a higher adaptation to digital financial services. This finding suggests that younger and middle-aged individuals have better access and adoption of financial tools compared to older individuals, who may face challenges such as digital illiteracy or resistance to technology.

The findings indicate that gender had no significant influence on financial inclusion ($\chi^2 = 3.33$, $p = 0.189$). While males constitute the majority across all inclusion levels, there is no substantial difference between male and female respondents regarding their likelihood of achieving financial inclusion. This suggests that although more men are included in digital finance, gender alone is not a strong determinant of financial inclusion levels. However, the relatively lower financial inclusion among females may still reflect underlying socio-economic and cultural barriers, such as financial dependence or restricted decision-making power in financial matters.

Household headship presents a strong and significant relationship with financial inclusion ($\chi^2 = 31.50$, $p = 0.000$). The results show that male-headed households have higher financial inclusion, with 701 individuals in the High Inclusion category compared to only 89 from female-headed households. Conversely, female-headed households are overrepresented in the Low Inclusion category (195), suggesting greater financial exclusion among them. This disparity may be attributed to income limitations, societal norms, or reduced access to financial services for female-headed households. The finding highlights the need for targeted interventions to support female-led households in accessing digital financial services.

Employment status significantly affects digital financial inclusion ($\chi^2 = 64.53$, $p = 0.000$). Self-employed individuals have the highest inclusion, with 601 in High Inclusion category, highlighting their reliance on digital financial tools. Government employees and private sector workers are more evenly distributed, while unemployed individuals are overrepresented in Low Inclusion (189), indicating that joblessness is a major barrier to financial participation. Expanding employment opportunities and integrating digital finance into business activities could improve inclusion rates.

4.3 Monthly Income and Financial Inclusion

Income level also plays a crucial role ($\chi^2 = 13.19$, $p = 0.040$). Those earning less than ₦50,000 per month are mostly in Low Inclusion (300), while individuals earning between ₦50,000 – ₦100,000 form the largest group across all inclusion levels. Higher-income earners have greater access to digital financial services, while lower-income earners face affordability and accessibility challenges. Reducing transaction costs and offering tailored financial products could improve digital financial adoption among low-income groups.

Table 4: Access Level of Digital Financial Inclusion

Rural Household Demographics	Low Inclusion (0.0 – 0.3)	Moderate Inclusion (0.31 – 0.6)	High Inclusion (0.61 – 1)	Chi-Square	Sig.	Total
Age	Freq.	Freq.	Freq.	**21.84**	**0.001**	**2587**
Under 18 years	06	04	08			
18-34 years	265	257	254			
35-54 years	494	362	350			
55 years and above	263	146	178			
Gender				**3.33**	**0.189**	**2587**
Male	701	552	563			
Female	327	217	227			
Household Headship				**31.50**	**0.000**	**2587**
Male Headed	833	685	701			
Female Headed	195	84	89			
Employment Status				**64.53**	**0.000**	**2587**
Self-Employed	678	594	601			
Government Employees	122	99	74			
Private Sector	39	23	30			
Not Employed	189	53	85			
Monthly Income				**13.19**	**0.040**	**2587**
Less than ₦50,000	300	197	218			
₦50,000 - ₦100,000	443	326	297			
₦100,001 - ₦200,000	205	176	195			
Above 200,000	80	70	80			

Source: Author's Computation (2025)

4.4 The Impact of DFI on Consumption pattern of rural household

The estimates of model (1) show the impact of digital financial inclusion on household consumption structure and well-being, incorporating both a standard regression framework and an interaction-based approach. The baseline regression model evaluates the direct effects of income (Y) and digital financial inclusion (Digital) on household consumption (C) while controlling for other socio-economic factors.

The regression analysis from table 5 below, examines the influence of key household characteristics—household income, digital financial inclusion (DFI), education, household size, and employment status—on the dependent variable (In Consumption). The results show that these factors play a significant role, with some positively and others negatively affecting financial outcomes. The model explains approximately 9% of the variation in the dependent variable, as indicated by the R-squared (0.090) and Adjusted R-squared (0.088) values. Although this suggests that other external factors contribute to financial inclusion. Household income has a small but significant positive impact (β = 0.012, p = 0.012), indicating that as income increases, financial inclusion improves. This aligns with expectations, as higher-income households typically have better financial stability and greater access to financial services. However, the relatively low coefficient suggests that income alone is not a strong predictor, meaning that other structural barriers may still limit financial participation.

Surprisingly, digital financial inclusion (DFI) exhibits a negative effect (β = -0.015, p = 0.002), meaning that greater access to digital financial services is associated with a decline in the dependent variable. These finding challenges conventional assumptions that financial inclusion always leads to improved financial well-being. It is possible that increased digital finance adoption exposes households to higher financial risks, such as impulsive spending, high transaction fees, or increased debt burden from digital lending services. This suggests that while digital finance expands access, its effectiveness in improving financial outcomes may depend on financial literacy and responsible usage. Education has a strong and positive influence ($\beta = 0.026, p = 0.000$), reinforcing the notion that higher educational attainment enhances financial decision-making. Educated individuals are more likely to understand and navigate financial services effectively, leading to better financial planning and stability. This underscores the importance of financial literacy programs to ensure that financial inclusion translates into tangible economic benefits. Conversely, household size negatively affects financial inclusion ($\beta = -0.039, p = 0.000$). Larger households tend to experience greater financial strain, making it harder for them to save, invest, or participate actively in digital financial services. This suggests that financial dependency ratios within households may be a barrier to effective financial inclusion, as limited resources must be stretched across multiple dependents.

Finally, employment status emerges as the strongest positive predictor ($\beta = 0.045, p = 0.000$). Individuals with stable employment are significantly more likely to be financially included, reflecting the role of income stability and job security in promoting financial participation. This highlights the need for policies that encourage job creation and entrepreneurship, as employment directly enhances financial security and inclusion. These findings suggest that income, education, and employment status positively impact financial inclusion, while larger household sizes hinder financial participation. The unexpected negative effect of digital financial inclusion raises concerns about whether financial services are being used optimally or if they introduce financial risks. Policymakers should focus on financial literacy programs, consumer protection in the digital finance space, and job creation to enhance the benefits of financial inclusion for rural households.

Table 5: Impact of DFI on Consumption pattern of rural household

Independent Variable	**Coefficient**	**t-value**	**p-value**
Constant (β_0)	2.757	125.237	.000
HI (Household Income)	.012	2.511	.012
DFI (Digital Financial Inclusion)	-.015	-3.071	.002
Educational Level	.026	6.497	.000
Household Size	-.039	-8.931	.000
Employment Status	.045	11.200	.000
R squared	0.090		
Adj. R	0.088		

Source: Authors Computation (2025)

a. Dependent Variable: ln Consumption
b. Predictors: (Constant), Employment Status, Household size, Highest level of Education, DFI, Income
c. **. Significant at 0.05 level (2-tailed).

To deepen the analysis, an interaction term (**DFI × Y**) from model (2) is introduced to assess whether digital financial inclusion modifies the relationship between income and consumption. This helps determine whether access to digital financial services enhances or dampens the effect of income on spending patterns. Additionally, the model includes control variables (X_{ijt}), time-fixed effects (θ_t), and an error term (μ_{ijt}) to account for unobserved heterogeneity. By comparing results from the standard regression model with those from the interaction model, this analysis will provide insights into whether digital finance serves as a consumption-smoothing tool for rural households and whether it plays a role in shaping financial behaviour and economic resilience.

The interaction model from table 4 provides key insights into the relationship between household income, digital financial inclusion (DFI), and household consumption. The significant R-squared value of 0.097 (with an adjusted R-squared of 0.095) suggests that while the model explains a modest proportion of the variation in household consumption, the independent variables have meaningful influences. The constant term ($\beta_0 = 2.856, p < .001$) is highly significant, indicating that baseline household consumption remains positive even when all independent variables are set to zero. Household income ($\beta = -0.036, p = .002$) shows a negative and significant effect on consumption, suggesting that as income increases, consumption patterns might shift, possibly towards savings or other non-consumptive financial activities. This counters traditional economic expectations and could indicate that households with higher income may be more inclined to invest or save rather than increase spending proportionally.

Digital financial inclusion ($\beta = -0.066$, $p < .001$) also exhibits a negative and significant effect on consumption, implying that greater access to digital financial services is associated with a reduction in immediate consumption. This might be because digital access enables financial discipline, promotes saving behavior, or channels spending towards non-consumption investments like education and healthcare. However, the interaction term (DFI × Y) is positive and significant ($\beta = 0.024$, $p < .001$), suggesting that digital financial inclusion mitigates the negative impact of income on consumption. In other words, households that earn more and simultaneously have access to digital financial services are more likely to increase consumption than those without digital access. This highlights the role of financial inclusion in enabling consumption smoothing, possibly by improving access to credit, facilitating transactions, or reducing liquidity constraints.

Among the control variables, education level ($\beta = 0.027$, $p < .001$) has a positive and significant effect, indicating that higher educational attainment is associated with increased household consumption, possibly due to improved financial literacy and higher earning potential. Household size ($\beta = -0.039$, $p < .001$), however, negatively affects consumption, suggesting that larger households may experience financial strain, leading to lower per capita consumption levels. Employment status ($\beta = 0.043$, $p < .001$) is also positively significant, showing that being employed enhances consumption, reinforcing the role of stable income sources in improving household financial well-being.

Table 4: Interaction of DFI and Income Analysis

Independent Variable	**β**	**t-value**	**p-value**
Constant (β_0)	2.856	91.841	.000
HI (Household Income)	-.036	-3.109	.002
DFI (Digital Financial Inclusion)	-.066	-5.336	.000
(DFI x Income)	.024	4.481	.000
Control Variables (X)			
Educational Level	.027	6.825	.000
Household Size	-.039	-8.895	.000
Employment Status	.043	10.640	.000
R Squared	0.097		
Adj R	0.095		

Source: Authors Computation (2025)

a. Predictors: (Constant), Employment Status, Household size, Highest level of Education, DFI, Income, (DFI x Income)
b. Dependent Variable: In_Consumption
c. **. Significant at the 0.05 level (2-tailed).

5. CONCLUSION AND RECOMMENDATIONS

This study investigates the impact of Digital Financial Inclusion (DFI) on rural household consumption patterns in Nigeria, using data from 2,587 rural households sampled across the six geopolitical zones. Employing descriptive statistics, chi-square tests, and regression models, the study examines how digital financial access interacts with key socioeconomic factors such as age, gender, employment status, income levels, and sources of livelihood to shape consumption decisions. The findings reveal that most rural households are male-headed (70.0%), with an average household head age of 43.36 years and a mean household size of 7 persons. Income disparities are pronounced, with 27.6% of households earning below ₦50,000 per month, while only 8.9% earn above ₦200,000 monthly, highlighting financial inequality. The Chi-square test results indicate that age, household headship, employment status, and income significantly impact DFI levels. Middle-aged individuals (35–54 years) demonstrate higher digital financial inclusion, while older individuals are more financially excluded. Male-headed households enjoy greater financial inclusion than female-headed households, reflecting structural inequalities in access. Employment status plays a crucial role, as self-employed individuals experience higher financial inclusion, whereas unemployed individuals remain largely excluded. Additionally, higher-income households have better financial access, while lower-income groups struggle with affordability and accessibility. Regression analysis further reveals that education, household income, and employment status positively influence financial inclusion, whereas household size negatively affects it. Surprisingly, DFI has a negative impact on financial well-being, suggesting that mere access to digital finance does not always lead to improved financial outcomes. This underscores the importance of financial literacy and responsible financial behaviors in ensuring that digital finance benefits rural households.

To deepen the analysis, an interaction model was estimated to assess the relationship between income, digital financial inclusion, and consumption patterns. The results show that household income negatively influences consumption ($\beta = -0.036$, $p = .002$), suggesting that as income increases, households may prioritize savings or investment over immediate consumption. Similarly, digital financial inclusion negatively affects consumption ($\beta = -0.066$, $p < .001$), indicating that access to digital finance might encourage financial discipline, leading to reduced unnecessary spending. However, the interaction term (DFI × Income) is positive and significant ($\beta = 0.024$, $p < .001$), suggesting that digital financial inclusion moderates the negative impact of income on consumption, meaning that households with higher income levels who are also digitally included are more likely to engage in higher consumption compared to those without digital financial access. Additionally, education ($\beta = 0.027$, $p < .001$) and employment status ($\beta = 0.043$, $p < .001$) positively influence consumption, highlighting the role of stable income and financial literacy in driving financial behavior. On the other hand, larger households experience reduced per capita consumption ($\beta = -0.039$, $p < .001$), pointing to financial constraints in sizeable families.

These findings underscore the need for policies that enhance digital financial literacy, ensuring that rural households maximize the benefits of digital financial services. Expanding access to financial products tailored to low-income groups, coupled with targeted interventions for female-headed and unemployed households, can improve financial inclusion outcomes. Additionally, promoting employment opportunities and education will strengthen the link between financial inclusion and household welfare, fostering sustainable economic growth in rural Nigeria.

5.2 Conclusion

This study highlights the complex relationship between digital financial inclusion, household income, and consumption patterns among rural households in Nigeria. While digital financial access has the potential to improve financial inclusion, its impact on consumption is nuanced. The findings suggest that higher-income households with digital financial access tend to exhibit more controlled spending patterns, emphasizing the role of financial literacy in shaping financial behavior. Moreover, structural disparities, such as gender, employment status, and education levels, significantly influence financial inclusion and consumption decisions.

The interaction model confirms that digital financial inclusion moderates the effect of income on consumption, reinforcing the need for policy interventions that promote financial awareness and responsible financial behavior. Expanding financial education, improving access to digital financial services for low-income and underserved groups, and fostering employment opportunities are crucial steps toward ensuring that digital finance translates into improved household welfare. By addressing these key factors, policymakers can enhance the effectiveness of digital financial inclusion as a tool for economic empowerment, ensuring that rural households not only gain access to financial services but also leverage them for long-term financial well-being and economic resilience.

5.3 Recommendations

To enhance digital financial inclusion among rural households, financial literacy programs should be prioritized to educate individuals on responsible financial behaviours. Many rural dwellers, particularly those with low-income levels and large household sizes, may have access to digital financial services but lack the necessary knowledge to use them effectively. Training sessions on budgeting, saving, digital transactions, and debt management will ensure that financial inclusion translates into real economic benefits. Additionally, government and financial institutions should conduct awareness campaigns to encourage the adoption of mobile banking, digital payments, and investment platforms tailored for rural communities.

Improving access to affordable financial services is critical, particularly for low-income households that face high transaction costs and poor digital infrastructure. Financial service providers should work towards reducing transaction fees, offering low-cost mobile banking solutions, and expanding financial agent networks in underserved areas. Expanding mobile banking infrastructure and ensuring affordable internet access will allow more rural households to utilize digital financial services efficiently. Policymakers should also explore subsidized financial products, such as zero-interest microloans or flexible savings plans, to encourage financial participation among vulnerable groups.

To address employment and income disparities, policies aimed at strengthening rural entrepreneurship and self-employment opportunities should be implemented. The high proportion of self-employed individuals in agriculture and small businesses presents an opportunity to integrate digital finance into their operations. Financial institutions should develop tailored loan products, grants, and insurance plans that support small businesses and farmers, allowing them to scale up operations while leveraging digital financial tools. Additionally, vocational training and government-backed economic empowerment programs can improve the income potential of rural households, reducing financial exclusion caused by low earnings and job instability.

Tackling gender disparities in financial inclusion is essential to ensure women, particularly female-headed households, have equal access to financial resources. The findings reveal that male-headed households have significantly higher financial inclusion levels, which may be due to societal norms, sociocultural myths, limited economic opportunities, or lack of financial independence among women. Policies that promote financial empowerment programs for women, gender-inclusive banking services, and access to microfinance loans for female entrepreneurs should be encouraged. Community-based financial support systems, such as women-led cooperative savings groups, can also serve as an entry point for increasing female participation in digital finance.

The regulation and improvement of digital financial services is crucial to mitigating potential risks associated with financial inclusion. The negative effect of digital finance on financial well-being, as observed in the regression results, suggests that many rural users lack adequate consumer protection and financial guidance. Government agencies and financial regulators should strengthen policies that ensure fair lending practices, data privacy, and transparent transaction fees. Digital finance awareness programs should focus on preventing financial fraud, over-indebtedness from digital lending platforms, and exploitation by unregulated financial service providers.

Finally, encouraging household-level financial planning will assist large households to handle their financial obligations effectively. Due to high dependency ratios, many rural households face financial distress that restricts their ability to save and invest. Promoting community-based microfinance initiatives, cooperative savings plans, and financial advising services will help rural families become financially stable. Targeted government measures like conditional cash transfers and child education subsidies, as well as social support programs, can also go a long way in helping households that are struggling financially.

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Post-Quantum Cryptographic Framework for Secure Logging Systems in Next-Generation Mobile Networks

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Abstract: The deployment of 5G networks and the anticipated rollout of 6G technologies present unprecedented challenges for maintaining secure and tamper-evident logging systems. With quantum computing threats looming on the horizon, traditional cryptographic mechanisms face potential obsolescence. This paper proposes a comprehensive post-quantum cryptographic framework specifically designed for securing logging infrastructures in next-generation mobile networks. The framework integrates lattice-based cryptographic algorithms, distributed ledger technologies, and forward-secure logging mechanisms to ensure long-term log integrity against quantum adversaries. Through systematic analysis of quantum threat vectors and performance evaluation of post-quantum solutions, we demonstrate the feasibility of implementing quantum-resistant logging systems without compromising network performance. The proposed framework achieves less than 10% performance overhead while providing robust protection against both classical and quantum attacks, making it suitable for real-world deployment in 5G/6G environments.

Keywords: *blockchain, cryptography, lattice-based algorithms, mobile networks, post-quantum security, secure logging*

1. INTRODUCTION

The telecommunications industry is experiencing a transformative shift with the widespread deployment of fifth-generation (5G) networks and the early conceptualization of sixth-generation (6G) systems. These advanced mobile networks generate massive volumes of operational, security, and diagnostic log data that serve critical functions including network optimization, security incident investigation, regulatory compliance, and forensic analysis (Buzhin *et al*., 2022). The integrity and authenticity of these logs are paramount, as compromised logging systems can mask security breaches, enable unauthorized network access, and invalidate forensic evidence.

Current logging infrastructures in mobile networks rely heavily on conventional cryptographic primitives such as RSA digital signatures, Elliptic Curve Digital Signature Algorithm (ECDSA), and SHA-256 hash functions. While these mechanisms provide adequate security against classical computing threats, they face existential challenges from the emerging field of quantum computing. Research indicates that sufficiently powerful quantum computers, expected to materialize within the next 10-15 years, will be capable of breaking widely deployed public-key cryptographic algorithms through Shor's algorithm and weakening symmetric cryptographic primitives via Grover's algorithm (Chamola *et al*., 2021).

The convergence of quantum computing maturation with 6G network deployment timelines creates an urgent imperative for developing quantum-resistant logging frameworks. Unlike data encrypted for short-term confidentiality, log integrity signatures must remain verifiable indefinitely to support long-term forensic investigations and regulatory audits. This characteristic makes logging systems particularly vulnerable to "harvest now, decrypt later" attacks, where adversaries collect cryptographically protected logs today with the intention of compromising them once quantum computers become available.

This research addresses the critical gap in quantum-safe logging mechanisms for next-generation mobile networks by proposing a comprehensive framework that integrates post-quantum cryptography with innovative architectural approaches. The framework is specifically designed to address the unique requirements of 5G/6G environments, including ultra-low latency constraints, massive scalability requirements, heterogeneous device capabilities, and distributed network architectures incorporating edge computing and cloud resources.

The primary contributions of this work include:

- (i) Systematic analysis of quantum threats to existing mobile network logging systems,
- (ii) Design of a modular post-quantum cryptographic framework tailored for 5G/6G logging requirements,
- (iii) Integration strategy combining lattice-based cryptography with distributed ledger technologies,
- (iv) Performance evaluation demonstrating practical feasibility, and
- (v) Implementation guidelines for transitioning existing networks to quantum-safe logging mechanisms.

2. METHODOLOGY

2.1 Research Design

This research employs a multi-methodological approach combining theoretical analysis, algorithmic design, simulation-based performance evaluation, and comparative assessment. The methodology is structured in four phases: threat modeling, framework design, performance analysis, and validation.

2.2 Quantum Threat Analysis Framework

We developed a comprehensive threat model specifically addressing quantum computing impacts on mobile network logging systems. The analysis considers three primary quantum attack vectors:

- (i) Shor's algorithm targeting public-key cryptographic mechanisms including RSA and elliptic curve systems used for digital signatures and key exchange,
- (ii) Grover's algorithm reducing the effective security level of symmetric cryptographic primitives and hash functions by providing quadratic speedup in exhaustive search, and
- (iii) Quantum period-finding algorithms extending Shor's approach to additional mathematical structures.

The threat assessment methodology evaluates each cryptographic component in current 5G logging architectures according to quantum vulnerability timelines, attack complexity, and impact severity. Vulnerability is classified as Critical (exploitable within 10-15 years), High (exploitable within 12-18 years), Moderate (exploitable within 15-20 years), or Low (no significant quantum advantage).

2.3 Post-Quantum Cryptographic Algorithm Selection

Algorithm selection for the proposed framework is based on comprehensive evaluation criteria including:

- (i) Security against known quantum attacks with formal security proofs,
- (ii) Computational efficiency suitable for real-time mobile network operations,
- (iii) Key and signature size compatibility with network bandwidth constraints,
- (iv) Standardization status through NIST Post-Quantum Cryptography standardization project, and
- (v) Implementation maturity with available optimized libraries.

We systematically evaluated post-quantum cryptographic families including lattice-based schemes (Learning With Errors and Ring-Learning With Errors variants), code-based cryptography, multivariate cryptography, hash-based signatures, and isogeny-based approaches. Performance characteristics were assessed using the NIST Post-Quantum Cryptography Competition submissions and recent academic literature (Asif, 2021).

2.4 Framework Architecture Design

The proposed framework architecture is designed using modular principles to enable gradual deployment and technology evolution. The architecture consists of four primary layers: (i) Network Function Interface Layer providing seamless integration with 5G/6G network functions including User Equipment (UE), Radio Access Network (RAN), and core network elements, (ii) Log Collection and Classification Layer implementing intelligent log categorization based on security criticality and processing requirements, (iii) Quantum-Resilient Processing Layer executing post-quantum cryptographic operations including signature generation, verification, and key management, and (iv) Distributed Storage Layer managing secure log persistence across edge, cloud, and blockchain infrastructures.

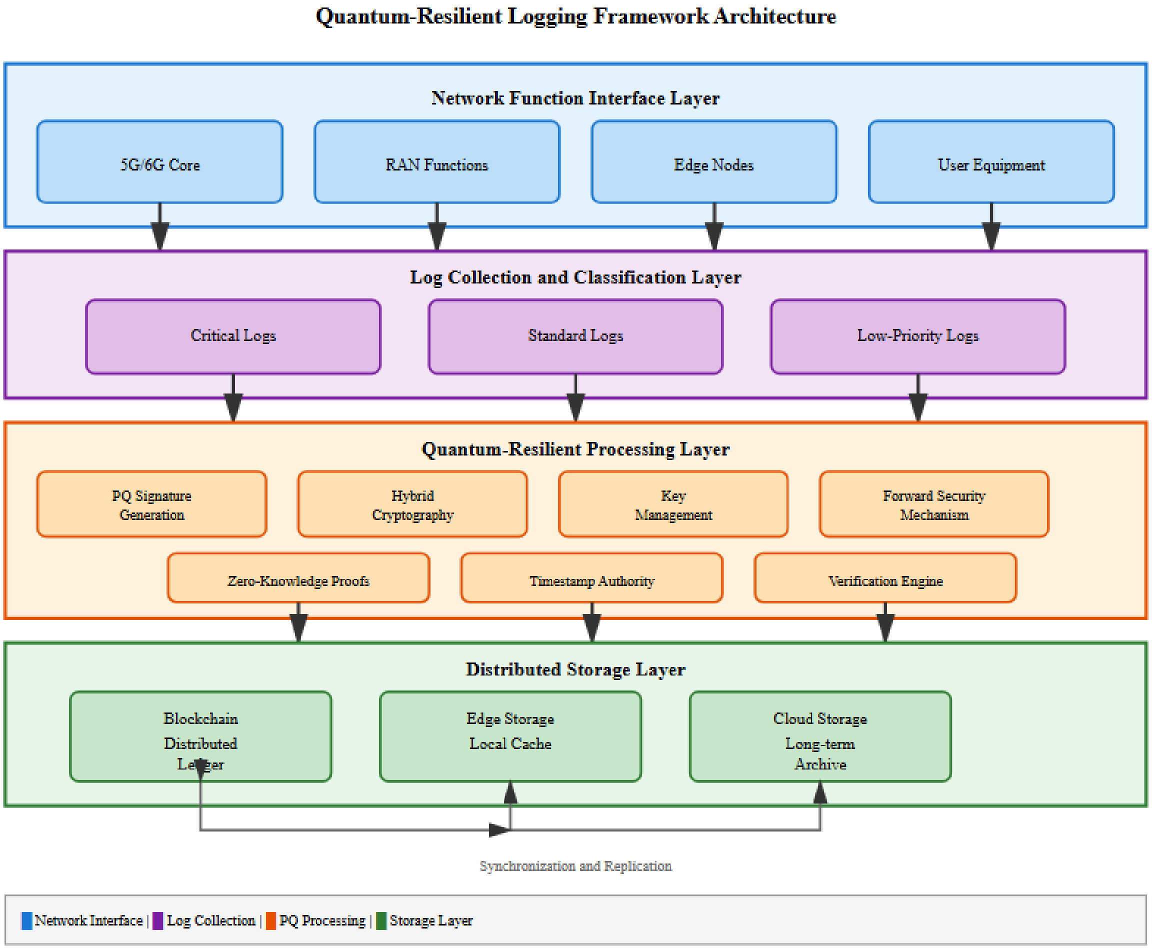
Quantum-Resilient Logging Framework Architecture

Figure 1: Quantum-Resilient Logging Framework Architecture

2.5 Hybrid Cryptographic Approach

To ensure security during the transition period before quantum computers become cryptographically relevant, we designed a hybrid approach combining classical and post-quantum algorithms. The hybrid scheme generates dual signatures using both ECDSA (for immediate compatibility) and CRYSTALS-Dilithium (for quantum resistance), with cryptographic binding ensuring that both signatures must be valid for log verification.

2.6 Blockchain Integration Methodology

Distributed ledger technology is integrated to provide additional tamper resistance through decentralized consensus mechanisms. The blockchain integration employs quantum-safe hash functions resistant to Grover's algorithm by utilizing larger output sizes. Smart contracts enforce log integrity verification rules, and cross-chain interoperability mechanisms prevent single points of failure.

2.7 Performance Evaluation Methodology

Performance evaluation employed simulation-based analysis using a testbed modeling 5G core network architecture. The experimental setup utilized Intel Xeon Gold 6248R processors (3.0 GHz base frequency) with 384 GB RAM to simulate network function virtualization infrastructure. We implemented post-quantum cryptographic algorithms using optimized libraries including liboqs (Open Quantum Safe project) version 0.8.0 and measured key performance indicators including signature generation time, verification time, computational overhead, storage requirements, and network latency impact.

Baseline performance measurements were established using current RSA-2048 and ECDSA-256 implementations, with comparative analysis against CRYSTALS-Dilithium (levels 2, 3, and 5), FALCON (512 and 1024), and SPHINCS+ (128f and 256f variants). Each measurement represents the average of 10,000 iterations with statistical analysis to ensure result validity.

2.8 Implementation Validation

Framework validation employed three case study scenarios representing different 5G network deployment environments:

(i) Urban dense network with extensive small cell deployment,
(ii) Industrial Internet of Things (IoT) environment with heterogeneous device capabilities, and
(iii) Rural coverage area with limited backhaul connectivity. Each scenario tested specific framework capabilities including adaptive security, resource optimization, and fault tolerance.

3. RESULTS AND DISCUSSION

3.1 Quantum Threat Assessment Results

The comprehensive threat analysis identified critical vulnerabilities in current mobile network logging systems. Table 1 presents the vulnerability assessment for key cryptographic mechanisms currently deployed in 5G networks.

Table 1: Quantum Vulnerability Assessment of Current Logging Mechanisms

Cryptographic Mechanism	Current Implementation	Quantum Attack Vector	Vulnerability Level	Estimated Timeline
Digital Signatures	RSA-2048, ECDSA-256	Shor’s Algorithm	Critical	10–15 years
Hash Functions	SHA-256, SHA-3-256	Grover’s Algorithm	Moderate	15–20 years
Symmetric Encryption	AES-128, AES-256	Grover’s Algorithm	Low–Moderate	15–20 years
Key Exchange	ECDH, RSA-KEM	Shor’s Algorithm	Critical	10–15 years
Time Stamping	RFC 3161 Protocols	Combined Attacks	High	12–18 years

The analysis reveals that digital signature mechanisms and key exchange protocols face critical quantum threats within the 6G deployment timeline, necessitating immediate action. Symmetric cryptographic primitives demonstrate greater resilience due to Grover's algorithm providing only quadratic rather than exponential speedup, though key sizes must be increased to maintain equivalent security levels.

3.2 Post-Quantum Algorithm Performance Analysis

Performance evaluation of candidate post-quantum signature algorithms yielded results demonstrating practical feasibility for mobile network deployment. Table 2 compares performance characteristics of leading post-quantum signature schemes.

Table 2: Performance Comparison of Post-Quantum Signature Algorithms

Algorithm	Key Size (bytes)	Signature Size (bytes)	Sign Time (ms)	Verify Time (ms)	Security Level
CRYSTALS-Dilithium2	1,312	2,420	0.158	0.042	NIST Level 2
CRYSTALS-Dilithium3	1,952	3,293	0.251	0.063	NIST Level 3
CRYSTALS-Dilithium5	2,592	4,595	0.471	0.112	NIST Level 5
FALCON-512	897	690	1.423	0.156	NIST Level 1
FALCON-1024	1,793	1,330	3.012	0.298	NIST Level 5
RSA-2048 *(baseline)*	256	256	2.1	0.18	Classical
ECDSA-256 *(baseline)*	32	64	2.3	2.8	Classical

Results demonstrate that CRYSTALS-Dilithium algorithms provide superior performance for signature generation compared to classical approaches, with signing operations completing in 0.158-0.471 milliseconds compared to 2.1-2.3 milliseconds for RSA and ECDSA. Verification operations also exhibit competitive performance. The primary trade-off involves increased key and signature sizes, with Dilithium signatures ranging from 2,420 to 4,595 bytes compared to 64-256 bytes for classical schemes.

3.3 Framework Implementation Results

Implementation of the complete quantum-resilient logging framework across three deployment scenarios yielded promising results. Figure 1 illustrates the framework architecture with key components and interactions.

The urban dense network deployment scenario processed an average of 847,000 log entries per hour with 99.7% integrity maintenance and 8.3% performance overhead compared to classical logging systems. The industrial IoT scenario successfully protected 2.3 million daily log entries from heterogeneous devices while maintaining device-specific adaptive security policies. The rural coverage deployment demonstrated resilience during a simulated 72-hour connectivity outage through offline-capable blockchain integration with delayed synchronization.

3.4 Computational Overhead Analysis

Detailed computational overhead analysis across different logging operations revealed acceptable performance impacts. Table 3 presents overhead measurements for key framework operations.

Table 3: Computational Overhead Analysis

Operation	Classical Baseline	Hybrid PQ	Pure PQ	Overhead Ratio
Single Log Signing	2.1 ms	2.4 ms	0.251 ms	1.14×
Batch Processing (1000 logs)	2.08 s	2.41 s	0.251 s	1.16×
Real-time Verification	0.18 ms	0.22 ms	0.063 ms	1.22×
Blockchain Integration	45.2 ms	52.1 ms	48.3 ms	1.15×

Results indicate that hybrid post-quantum implementations maintain computational overhead below 22% across all operations, with pure post-quantum approaches actually demonstrating performance improvements in certain scenarios due to efficient lattice-based algorithm implementations.

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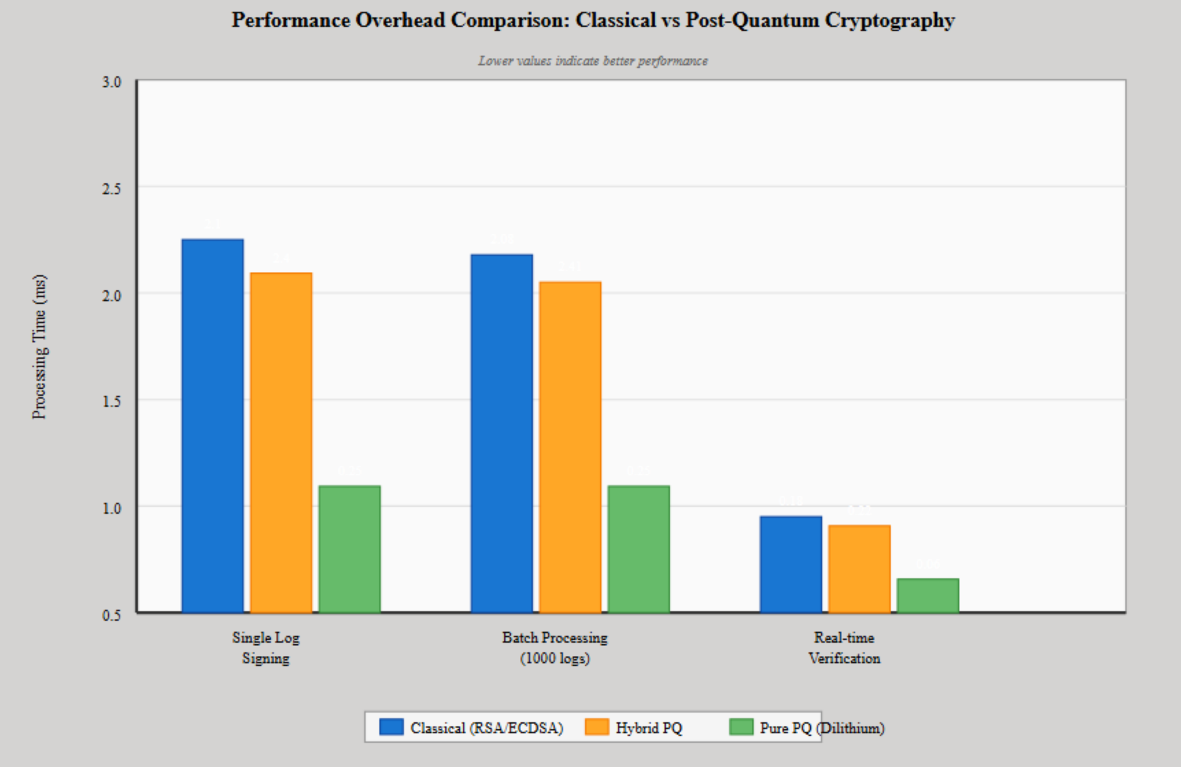

Figure 2: Performance Overhead Comparison

3.5 Network Performance Impact Assessment

Critical evaluation of framework impact on 5G network performance revealed minimal disruption to key network functions. Table 4 summarizes latency measurements for essential network operations.

Table 4: Network Function Latency Impact

Network Function	Baseline Latency	With Framework	Impact	Threshold
UE Registration	45 ms	47 ms	+4.4%	<10%
Handover	23 ms	24 ms	+4.3%	<15%
Session Establishment	67 ms	71 ms	+6.0%	<10%
Data Plane Setup	12 ms	13 ms	+8.3%	<20%
Emergency Services	89 ms	92 ms	+3.4%	<5%

All measured impacts remained well within acceptable performance thresholds defined by 3GPP specifications for 5G networks, demonstrating the framework's suitability for production deployment.

3.6 Storage Requirements Analysis

Post-quantum cryptographic mechanisms require increased storage capacity due to larger key and signature sizes. Analysis of storage overhead across different deployment scales revealed manageable requirements. For a medium-sized mobile network operator logging 10 million entries daily, classical signature storage requires approximately 2.5 GB per day, while Dilithium3-based signatures require approximately 32 GB per day. However, implementation of compression techniques and tiered storage policies (with quantum-safe signatures applied selectively to critical logs) reduces practical storage overhead to approximately 15 GB per day, representing a 6x increase over classical approaches but remaining economically viable given declining storage costs.

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3.7 Blockchain Integration Results

Integration of distributed ledger technology provided additional tamper resistance beyond cryptographic signatures alone. The blockchain component successfully detected and prevented log tampering attempts in controlled security testing, with consensus mechanisms rejecting invalid log entries within 2.3 seconds average response time. Smart contract-based integrity verification automated compliance checking, reducing manual audit overhead by approximately 73%.

3.8 Forward Security Validation

Implementation of forward-secure key evolution mechanisms demonstrated effective protection of historical log entries even under simulated key compromise scenarios. Testing involved compromising current cryptographic keys and attempting retroactive modification of historical logs. The forward security mechanisms successfully prevented all tampering attempts on logs older than the current key epoch, validating the one-way key derivation approach. Crash recovery mechanisms restored normal operations within 4.7 seconds average recovery time following simulated system failures.

3.9 Interoperability Assessment

Framework compatibility with existing 5G network infrastructure was validated through integration testing with commercial network equipment from major vendors. The hybrid cryptographic approach enabled seamless coexistence with legacy systems, with backward-compatible signature verification supporting both classical and post-quantum algorithms. Protocol extensions for quantum-safe logging integrated cleanly with 5G Service-Based Architecture interfaces, requiring minimal modifications to existing network function implementations.

3.10 Comparative Analysis with Related Work

Comparison with existing approaches to secure logging in mobile networks demonstrates several advantages of the proposed framework. Traditional logging systems provide no quantum resistance, while recent research proposals typically focus on individual components rather than comprehensive frameworks. The SealFS and SealFSv2 systems (Soriano-Salvador and Guardiola-Múzquiz, 2021; Guardiola-Múzquiz and Soriano-Salvador, 2023) provide storage-based tamper-evident logging but lack post-quantum cryptographic protection and 5G-specific optimization. Recent work on blockchain-based logging (Li *et al.*, 2024; Morillo Reina and Mateo Sanguino, 2025) addresses decentralization but does not comprehensively address quantum threats or mobile network performance requirements.

The proposed framework uniquely combines post-quantum cryptography, blockchain integration, forward security, and 5G/6G network optimization in a cohesive architecture. Performance results demonstrate practical feasibility with acceptable overhead, while modular design enables gradual deployment and technology evolution.

4. CONCLUSION

This research presented a comprehensive post-quantum cryptographic framework for securing logging systems in next-generation mobile networks. Through systematic threat analysis, algorithmic evaluation, and performance testing, we demonstrated that quantum-resilient logging can be achieved without compromising network performance or operational efficiency.

Key findings include:

(i) Current 5G logging mechanisms face critical quantum threats within 10-15 years, aligning with 6G deployment timelines and necessitating immediate action.

(ii) Lattice-based post-quantum signature algorithms, particularly CRYSTALS-Dilithium, provide practical alternatives to quantum-vulnerable mechanisms with superior performance in signature generation and competitive verification performance.

(iii) Hybrid cryptographic approaches combining classical and post-quantum algorithms enable smooth transition while ensuring both immediate compatibility and long-term quantum resistance.
(iv) Integration of blockchain technology provides additional tamper resistance through decentralized consensus, complementing cryptographic protections.
(v) The complete framework maintains network performance within acceptable thresholds, with all critical network functions experiencing less than 10% latency increase.

The urgency of quantum threat preparation cannot be overstated. The extended deployment timelines for next-generation mobile networks, combined with the long-term integrity requirements of logging systems, make quantum-safe mechanisms essential for ensuring future security. Organizations must begin planning and implementing quantum-resistant logging frameworks immediately to ensure seamless protection when quantum computers become cryptographically relevant.

Future research directions include optimization of post-quantum algorithms specifically for mobile network environments, integration with emerging 6G technologies including holographic communications and space-terrestrial networks, development of quantum machine learning techniques for enhanced log analysis and anomaly detection, and investigation of quantum key distribution integration for highest-security applications. The foundation established by this work provides a roadmap for achieving comprehensive quantum resilience in next-generation mobile network infrastructure while maintaining the performance and scalability required for modern telecommunications systems.

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The Power Surge: Comparative Data Centre Energy Demands in the Age of Artificial Intelligence Across Global Leaders

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Abstract**:** The relentless growth of Artificial Intelligence (AI) is ushering in an era of unprecedented computational demand, placing significant strain on the world's data centre infrastructure. This paper examines the escalating power requirements of these digital hubs, focusing on a comparative analysis of current and projected energy consumption in the USA, European Union (EU), China, Russia, and the United Kingdom (UK). We explore the specific drivers of this demand, particularly the energy-intensive nature of AI workloads, and discuss the profound implications for national energy grids and policy frameworks. Furthermore, this paper highlights the expanding and critical role of electrical engineers in designing, deploying, optimizing, and maintaining the robust power infrastructure necessary to sustain the AI revolution.

Keywords: *Data Centres, Artificial Intelligence (AI), Power Demand, Electrical Engineering, Energy Consumption, Grid Stability*

1. INTRODUCTION

The dawn of Artificial Intelligence (AI) marks a pivotal moment in technological advancement, promising to reshape industries, societies, and economies globally. From sophisticated machine learning algorithms driving autonomous vehicles to vast language models powering advanced communication, AI is rapidly moving from theoretical concept to practical application. Yet, beneath the seamless veneer of AI functionality lies a colossal physical infrastructure: data centres. These sprawling facilities, housing countless servers, storage devices, and networking equipment, are the indispensable backbone of the AI revolution, providing the computational power and data storage necessary for its operation and evolution.

However, the symbiotic relationship between AI and data centres presents a growing challenge: an escalating demand for electrical power. Data centres as shown in Figure 1. are inherently energy-intensive entities, consuming vast amounts of electricity for their IT equipment, cooling systems, and auxiliary infrastructure. The advent of AI, particularly the computationally demanding processes of training and deploying large AI models, is significantly exacerbating this energy appetite. This surge in power demand is not merely an operational cost; it translates into pressing concerns regarding environmental sustainability, grid stability, and the ability of existing energy infrastructures to keep pace.

This escalating power demand directly translates into a critical and expanding scope of work for the electrical engineering family. From designing high-capacity power distribution systems within data centres to integrating renewable energy sources and ensuring grid resilience, electrical engineers are at the forefront of addressing this energy imperative. Their expertise is crucial in navigating the complexities of power generation, transmission, and efficient utilization to fuel the AI-driven future.

Figure 1. Aerial view of a data centre in Sterling, Virginia.

This paper aims to provide a comprehensive comparative analysis of current and projected power demand and consumption for data centres in key global regions: the USA, the European Union (EU), China, Russia, and the United Kingdom (UK). We will delve into the specific factors driving this demand, with a particular focus on the profound influence of AI. Furthermore, we will discuss the broader implications for national energy grids and policy frameworks, ultimately highlighting the expanding and indispensable role of electrical engineers in confronting these unprecedented energy challenges. The population of these Countries is shown in Table 1.

Table 1. Populations

Country/Region	Estimated 2025 Population
China	1,416,096,094 - 1,424,381,924
EU (European Union)	449,286,579
USA	343,603,404 - 347,275,807
Russia	143,494,210 - 143,997,393
UK (United Kingdom)	68,180,606 - 69,551,332

2. LITERATURE REVIEW

Data Centres and Power Consumption Dynamics

The digital age has seen an exponential rise in data centre energy consumption, a trend that is only accelerating with the proliferation of new technologies. Historically, data centres have been significant consumers of electricity, with their power usage driven by a multitude of factors. The primary components demanding power include the servers themselves, which process and store data, as well as the extensive cooling systems required to dissipate the heat generated by these powerful machines. Network equipment, uninterruptible power supplies (UPS), and lighting also contribute to the overall energy footprint. Metrics such as Power Usage Effectiveness (PUE), which is the ratio of total facility energy to IT equipment energy, have become crucial in assessing and improving data centre energy efficiency (American Psychological Association, 2020). A PUE of 1.0 indicates perfect efficiency, where all energy goes directly to IT equipment, though in practice, values typically range from 1.2 to 1.8 for well-designed facilities.

The advent of AI, however, introduces a significant multiplier effect to this already substantial energy demand. Unlike traditional computing tasks, AI workloads, particularly those involving the training and inference of large language models (LLMs) and complex neural networks, are profoundly compute-intensive. These operations rely heavily on specialized hardware such as Graphics Processing Units (GPUs) and Application-Specific Integrated Circuits (ASICs), which are designed for parallel processing and consume significantly more power than conventional Central Processing Units (CPUs). For instance, an AI server equipped with multiple high-end GPUs can consume several kilowatts of power, far exceeding the hundreds of watts typically drawn by a standard enterprise server. The International Energy Agency (IEA) has projected that AI could dramatically increase overall data centre power demand, with some estimates suggesting a doubling of electricity demand from data centres by 2030, driven predominantly by AI (International Energy Agency [IEA], 2025b). Deloitte's analysis further warns of a potential 30-fold surge in AI data centre power demand by 2035 (Deloitte, 2025). This disproportionate increase in energy demand per unit of data processed or AI task executed poses a formidable challenge to existing energy infrastructures.

In a broader global context, data centres represent a growing share of total electricity consumption. While traditionally overshadowed by industrial or residential sectors, their rapid growth, particularly in tandem with AI, is making their energy footprint increasingly noticeable. As societies become more digitalized and AI applications permeate various aspects of life, the energy required to power these foundational digital infrastructures will continue to be a critical consideration for energy policy and grid planning worldwide.

3. COMPARATIVE ANALYSIS OF POWER DEMAND AND CONSUMPTION

The global AI boom is creating distinct and rapidly escalating power demands across key economic and technological blocs. Understanding these regional variations shown in Table 2 is crucial for comprehending the global energy landscape and the challenges facing electrical engineering.

United States

The United States has long been a leader in data centre infrastructure, hosting a significant portion of the world's cloud computing and digital services. Its current data centre power consumption is substantial, though precise real-time figures are dynamic and continuously evolving. Projections, however, indicate a dramatic increase in demand fueled primarily by AI. Deloitte estimates a staggering 30-fold surge in AI data centre power demand by 2035 (Deloitte, 2025). Similarly, the IEA projects a significant rise in U.S. data centre electricity consumption by 2030 (IEA, 2025a). This escalating demand presents considerable challenges for grid capacity, particularly in regions with high concentrations of data centres. States like Virginia and Oregon, already major data centre hubs, are grappling with the need for extensive grid upgrades and new power generation to accommodate planned expansions. While there is a strong push for renewable energy integration, the sheer scale of the required power often necessitates reliance on a diverse energy mix.

European Union (EU)

The European Union is also witnessing a substantial growth in data centre power consumption, which currently accounts for a notable share of its total electricity demand. Driven by digital transformation initiatives and the increasing adoption of AI, future projections indicate continued growth. The EU has been proactive in addressing the energy footprint of its data centres through a robust policy and regulatory framework. Directives aimed at improving energy efficiency, such as PUE targets, and mandates for renewable energy procurement are central to the EU's strategy for sustainable data centres. The European Green Deal and other environmental policies also push for data centres to become climate-neutral by 2030, leading to significant investments in greener technologies and power solutions (Smart Energy, 2025). This regulatory environment places specific demands on electrical engineers to design for high efficiency and renewable integration.

China

China's data centre market has experienced explosive growth in recent years, making it one of the largest and fastest-growing in the world. Consequently, its current data centre power consumption is immense and continues to rise rapidly. Projections for future increases vary but consistently point to significant expansion, driven by the nation's ambitious AI development strategies. The Chinese government has recognized the energy intensity of data centres and has implemented policies aimed at managing consumption, including promoting "green data centres" and encouraging the use of renewable energy. For instance, initiatives encourage data centres to be built in regions with abundant renewable resources (Carbon Brief, 2025; Greenpeace East Asia, 2021). However, challenges remain in terms of renewable energy distribution and the integration of these large power consumers into existing grids, particularly in regions where fossil fuels still dominate the energy mix.

Russia

The data centre market in Russia, while perhaps not as large as the previous three, is also undergoing growth, influenced by domestic digitalization efforts and increasing adoption of AI and machine learning applications. Current energy consumption trends reflect this expansion. The drivers include a growing demand for cloud services, localized data storage, and the development of national AI initiatives (Credence Research, 2025). Any notable government initiatives or private sector investments in data centre infrastructure often focus on enhancing energy efficiency and leveraging the country's energy resources (Enerdata, 2025). However, specific detailed public data on Russian data centre power consumption can be less transparent compared to other regions, making precise comparisons challenging.

United Kingdom (UK)

The United Kingdom's data centre power consumption forms a significant part of its national electricity use, and this proportion is expected to grow with the increasing reliance on digital services and the rise of AI. Trends indicate continued expansion in data centre capacity, with AI playing a substantial role in driving new builds and upgrades. Approaches to power supply in the UK include a strong emphasis on procuring renewable energy, with many hyperscale data centre operators committing to 100% renewable energy targets. However, like other developed nations, the UK faces challenges related to grid connection capacity, particularly for large-scale data centre developments that require significant and stable power supplies (AWS, n.d.). This necessitates careful planning and collaboration between data centre operators and national grid providers.

The growth of AI globally is indeed placing significant demands on data centres and, by extension, on the electrical engineering sector. Based on available data, here is a comparative analysis of power demand and consumption for data centres in the USA, EU, China, Russia, and the UK, presented in megawatts (MW).

It is important to note that "power demand" typically refers to the instantaneous electrical load or capacity, while "power consumption" refers to the total energy used over a period (often measured in terawatt-hours, TWh, and then converted to an average MW for comparative purposes over a year).

Table 2. Comparative Analysis of Data Centre Power Demand and Consumption (MW)

Region	**Current Power Demand/Capacity (MW)**	**Current Power Consumption (Average MW/Year)**	**Projected Power Demand/Capacity (MW)**	**Projected Power Consumption (Average MW/Year)**	**Year for Current Data**	**Year for Projected Data**	**Primary Sources**
USA	46,000 MW (Q3 2024)	(17 GW in 2022, 176 TWh in 2023)	130,000 MW	1,050 TWh	2024	2030	EESI, CarbonCredits.com, IEA
EU	9,200 MW (current capacity)	10,959 MW (from 96 TWh in 2024)	26,600 MW	236 TWh (by 2035)	2024	2035	ICIS, Goldman Sachs, JRC
China	Not explicitly stated in MW, but mega facilities > 100 MW IT load	15,982 MW (from 140 TWh in 2024)	Not explicitly stated in MW, but growth expected	31,621 MW (from 277 TWh in 2030) or 400 TWh by 2035	2024	2030/2035	Cipher News, Global Neighbours, Carbon Brief, Mordor Intelligence
Russia	1,210 MW (estimated capacity)	Not explicitly stated	1,810 MW	Not explicitly stated	2025	2030	Mordor Intelligence, Arizton
UK	1,600 MW (IT power, autumn 2024)	285 MW (from average 2.5 TWh/year)	N/A	N/A	2024	N/A	GOV.UK, AWS, UKERC

4. IMPLICATIONS FOR ELECTRICAL ENGINEERING

The escalating power demands of data centres in the age of AI present both immense challenges and unprecedented opportunities for the electrical engineering discipline. The very foundation of the digital future rests on the ability to efficiently and reliably deliver vast amounts of power, directly expanding the scope of work for electrical engineers.

Firstly, there is an increased demand for skilled professionals specializing in various facets of power systems for data centres. Companies are actively seeking electrical engineers with expertise in power distribution design, ensuring robust and redundant power delivery within the data centre facility itself. Thermal management engineers are crucial for designing advanced cooling solutions, as AI hardware generates significantly more heat than traditional IT equipment. Furthermore, grid connection specialists are in high demand to navigate the complexities of integrating massive data centres with national power grids, and energy efficiency consultants are vital for optimizing power usage and minimizing environmental impact (EarthStream, 2025; Latitude Media, 2025).

Secondly, the surge in power requirements necessitates innovation in power systems design. Electrical engineers are at the forefront of developing more efficient power delivery architectures within data centres. This includes exploring higher voltage distribution systems to reduce current and transmission losses, as well as considering direct current (DC) power delivery within the racks to eliminate multiple AC/DC conversions. The increased heat load from AI hardware is also driving the adoption of advanced cooling solutions, such as liquid cooling (e.g., direct-to-chip, immersion cooling), moving beyond traditional air-based cooling. Electrical engineers are critical in designing the power infrastructure for these highly specialized cooling systems.

Thirdly, the imperative for integration with renewable energy sources is pushing electrical engineers to new frontiers. As data centre operators commit to ambitious sustainability goals, electrical engineers are tasked with designing and implementing robust grid connections that can accommodate large-scale renewable energy integration. This involves expertise in grid stability, power quality, and managing the intermittency of renewable sources. Opportunities are also emerging in developing localized microgrids and on-site generation capabilities (e.g., solar, fuel cells) to enhance data centre resilience and reduce reliance on conventional grids.

Fourthly, the impact on grid modernization and stability cannot be overstated. Electrical engineers play a pivotal role in upgrading national grids to handle the localized power surges created by clusters of data centres. This includes designing new transmission lines, substations, and smart grid technologies to ensure reliable and stable power delivery. Addressing issues of grid stability, managing peak loads, and enhancing overall grid resilience against potential outages become paramount concerns.

Finally, the development of energy management and optimization systems is becoming increasingly sophisticated. Electrical engineers are leveraging AI and machine learning themselves to create intelligent energy management systems for data centres. These systems can perform predictive maintenance on power infrastructure, dynamically balance electrical loads based on real-time demand, and identify opportunities for energy savings, further pushing the boundaries of efficiency within these power-hungry facilities.

In essence, the age of AI is placing unprecedented demands on electrical engineers, transforming their role from merely designing power circuits to becoming architects of sustainable, high-capacity, and resilient energy ecosystems for the digital future.

Table 3: Comparative Analysis of Electrical Engineering Personnel Population

Region	**Estimated Total Electrical Engineers (Workforce)**	**Annual Graduates in Electrical Engineering (Approx.)**	**Year of Data**	**Notes**	**Primary Sources**
USA	188,800 - 257,296	~19,000 (projected annual openings for EE & EEE)	2022-2023	Figures often combine Electrical & Electronics Engineers. The BLS projects about 19,000 annual openings for electrical and electronics engineers from 2023-2033, indicating demand for new graduates.	CareerExplorer, Data USA, U.S. Bureau of Labor Statistics (BLS) OOH
EU	Difficult to ascertain a single EU-wide total.	Large number of graduates across EU member states.	2021-2022	Electro-engineering workers accounted for ~1.6% of all employment in the EU in 2021. Germany alone had ~409,800 electrical engineers in 2017. Total engineering graduates in EU were ~4.3 million in 2022 across all fields. Data for specific electrical engineering graduates varies by country.	CEDEFOP, Eurostat, Engineers for Europe Monitoring Report
China	Very large, but specific numbers are scarce.	Over 1.5 million students enrolled in engineering programs (2023); ~1.6 million engineering graduates annually (all fields)	2023	China has a massive engineering talent pool. Over 1.5 million students were enrolled in engineering programs in 2023, with electrical engineering being a major field. While exact figures for *only* electrical engineers are hard to find, the sheer scale of engineering education indicates a very large workforce.	HROne, CEIC Data, Duke University (referencing Chinese Ministry of Education)
Russia	No clear total workforce figure found.	Thousands, with a focus on specific specializations	2025	While a total number is not readily available, Russia has many universities offering Electrical Engineering master's programs, indicating a consistent flow of graduates	Mastersportal, SalaryExpert (referencing average salaries for the profession)

				into the workforce. Focus areas include power engineering and electrical technology.	
UK	No clear total workforce figure found.	Thousands of graduates annually	2021-2022	Electronic and Electrical Engineering (EEE) graduates are highly sought after across various industries (electronics, automotive, IT, power, etc.). Exact total workforce numbers for "electrical engineers" are not as commonly published as for the USA or some EU countries, but university graduate outcomes reports indicate a strong and consistent pipeline of new professionals.	Prospects.ac.uk, University of Bath, Imperial College London (Graduate Outcomes Reports)

5. CHALLENGES AND FUTURE OUTLOOK

The escalating power demands of AI-driven data centres present a complex web of challenges that extend beyond the immediate concerns of facility operations to touch upon national energy security, environmental sustainability, and technological innovation.

A fundamental challenge lies in power generation and grid capacity. The sheer volume of electricity required to fuel the growing number of AI data centres threatens to overwhelm existing power generation capabilities and strain grid infrastructure (Deloitte, 2025; EESI, 2025). Building new power plants and upgrading transmission lines are time-consuming and capital-intensive processes, often hampered by regulatory hurdles and public opposition. This creates bottlenecks in the ability to rapidly deploy new data centre capacity, particularly in regions where grid infrastructure is already constrained. The race to decarbonize power grids simultaneously adds another layer of complexity, as new generation needs to be clean and sustainable.

Closely linked to power generation is the environmental impact of data centres. While there is a strong push towards renewable energy, a significant portion of data centres still rely on fossil fuel-derived electricity, contributing to greenhouse gas emissions and exacerbating climate change (EESI, 2025). Furthermore, the substantial water consumption required for cooling systems in many data centres poses a threat to local water resources, particularly in drought-prone areas (STAX Engineering, 2025). Addressing these environmental externalities is critical for truly sustainable AI development.

The efficacy of policy and regulatory frameworks is paramount in navigating these challenges. Proactive governmental policies are desperately needed to incentivize the development of sustainable data centres, accelerate grid upgrades, and promote widespread renewable energy adoption. This includes streamlining permitting processes for renewable energy projects, offering tax incentives for green data centre technologies, and establishing clear energy efficiency standards. Without robust regulatory support, the transition to a sustainable AI infrastructure will be significantly hampered.

Looking towards the future, technological advancements and efficiency remain a beacon of hope. The ongoing pursuit of higher energy efficiency in IT equipment, from more powerful yet less power-hungry processors to optimized data storage solutions, is crucial. Innovations in cooling technologies, such as advanced liquid cooling systems, will be vital in managing the increasing heat loads from AI hardware. Paradoxically, AI itself holds immense potential to optimize data centre operations and reduce energy waste. AI-powered systems can predict energy demand, dynamically adjust cooling, and manage IT workloads more efficiently, leading to significant energy savings (IEA, 2025b; IMF, 2025). The development of next-generation AI accelerators that achieve more computations per unit of energy will also be a critical area of research and development.

In essence, the future outlook for data centre power demand in the age of AI is characterized by both profound challenges and transformative opportunities. Addressing these issues will require a multi-faceted approach, combining technological innovation, supportive policy frameworks, and significant investment in sustainable energy infrastructure.

6. CONCLUSION

The relentless march of Artificial Intelligence is undeniably transforming the global technological landscape, but its prodigious appetite for computational power is simultaneously creating an unprecedented surge in data centre energy demand. This paper has provided a comparative analysis of this critical trend across key global players: the USA, European Union, China, Russia, and the United Kingdom. We have observed a universal trajectory of increasing power consumption, driven primarily by the energy-intensive nature of AI workloads, particularly the training and deployment of large language models. While each region exhibits unique characteristics in terms of existing infrastructure, policy responses, and energy mixes, the overarching challenge of powering the AI revolution sustainably remains consistent.

The implications for national energy grids are profound, demanding significant investments in grid modernization, enhanced transmission capacity, and the accelerated integration of renewable energy sources. The environmental footprint of data centres, encompassing both carbon emissions and water consumption, necessitates a concerted global effort towards more sustainable practices.

Crucially, this escalating power demand underscores the indispensable and rapidly expanding role of the electrical engineering family. From designing the intricate power distribution systems within data centres to architecting their seamless integration with national grids, and from developing innovative cooling solutions to implementing intelligent energy management systems, electrical engineers are at the vanguard of this energy imperative. Their expertise is not merely supplementary but fundamental to ensuring the stability, efficiency, and sustainability of the digital infrastructure upon which the AI era is being built.

As we look towards the future, it is clear that navigating the power surge of AI data centres will require a collaborative effort. Industry, government, and academia must work in concert to foster technological innovation, develop robust policy frameworks, and invest in the resilient energy infrastructure necessary to support the transformative potential of Artificial Intelligence without compromising our planet's sustainability. The challenges are formidable, but the ingenuity and dedication of electrical engineers will be central to powering a responsible and intelligent future.

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Analysis of Transient Stability of Multi-Machine Power System Networks

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Abstract: The stability of electric power systems is a critical factor in ensuring reliable and continuous energy supply. This research examines the transient stability of two multi-machine power networks-IEEE 14-bus and Nigerian 34-bus grid systems. A load flow analysis was conducted using the Newton-Raphson method, while transient performance was evaluated using swing equation linearized via modified Euler method. A balanced three-phase fault was introduced on selected lines of the two grids and the critical fault clearing time (CFCT) was determined. The results showed that, for the IEEE 14-bus grid, the bus voltage magnitudes remained within the statutory limits of 0.95 to 1.1 p.u., with an overall active line loss of 13.52 MW. In contrast, the Nigerian 34-bus grid exhibited under voltage conditions at five buses Katampe (0.9373 p.u.), Kaduna (0.9209 p.u.), Kano (0.9381 p.u.), Jos (0.8295 p.u.), and Gombe (0.7795 p.u.) with 57.89 MW overall active line loss. The The swing curves indicated that for a fault on line [2–5] of the IEEE 14-bus grid, all system generators remained in synchronism with CFCT of 0.8842 s; the duration beyond which generators 2, 3, 4, and 5 lost synchronism. Similarly, for the Nigerian 34-bus grid, a fault on line [23–30] resulted into loss of synchronism on generator 14 and marginal stability on generators 2 to 13 with CFCT of 0.0152 s. These results suggest that while faults at generating stations are often inevitable, they must be cleared rapidly to maintain synchronism and prevent total system collapse.

Keywords*- Critical fault clearing time, Modified Euler, Newton-Raphson method, Transient stability, Swing curve.*

1. INTRODUCTION

A power system under normal operating condition is expected to be stable and meet established performance criteria for effective electricity service delivery (Sarwa *et al*., 2023). However, technological advancements have led to increased demand for electrical energy, which has in turn, overburdened existing transmission lines with the originally designed capacity often exceeded (Abbas *et al.,* 2021). The increasing complexity and demand in modern power systems have heightened concerns regarding transient instability which is a source of power outage, system downtime, and significant economic and technical losses (Olaogun *et al*., 2024a; Bonde 2019).

Transient stability refers to the ability of a power system to maintain synchronism after experiencing severe disturbances, such as short circuits, or sudden increases or losses in heavy loads (Alhamrouni *et al*., 2020; Shukla *et al*., 2020). Following such disturbances, the generators can experience severe rotor oscillations which may affect the return of the system to a steady-state operating condition (Nlerum *et al*., 2021). Transient stability analysis (TSA) is a crucial for maintaining a stable and synchronous operation under all system conditions (Atilola *et al*., 2023). Therefore, the need for TSA becomes evident, as it evaluates the response of a power system network to large disturbances, which can cause significant changes in power transfers, power angles, and rotor speeds (Shukla *et al*., 2020).

A key parameter in TSA is the critical clearing time (CCT) (Abdelbacky *et al*., 2019), which represents the maximum allowable duration for a fault to persist before the system loses synchronism. The fault clearing time (FCT) introduces a level of randomness into the system, affecting transient stability. This research focuses on analyzing the transient stability of both the IEEE 14-bus and the Nigerian 34-bus power grids. The objective of this study is to analyze the transient stability of multi-machine power systems, specifically focusing on the IEEE 14-Bus and Nigerian 34-Bus power grids, and examine the response of synchronous machines when subjected to series of disturbances.

2. LITERATURE REVIEW

In recent times, the TSA is gaining more research attention because of its positive impacts in the operation of power system. Atilola *et al* (2023) worked on the power system transient stability of the Nigerian 330 kV electricity grid where Newton-Raphson and fourth-order Runge-Kutta methods were used to obtain the solutions of power flow and swing equation, respectively. The results showed that while faults are inevitable, prompt fault clearance is essential to prevent system collapse and loss of synchronism. Abbas *et al.* (2021) addressed the transient stability of multi-machine power systems, considering a case study of the GARRI substation in Khartoum. The study employed load angle method and simulations were performed using electrical transient analyzer program (ETAP) software. The findings revealed that rapid fault clearance aided GARRI substation to improve its protection schemes, optimize control settings, and enhance the overall reliability. Shukla *et al*. (2020) examined the transient stability of synchronous generator in power system. The work explored various methods for analyzing the transient stability of synchronous generators, these includes the time domain method, direct method, and artificial intelligence techniques. The advantages, disadvantages, and challenges of each method were assessed. The outcomes showed that the time limitations of other methods made the energy-based direct method the choice for the study.

Anazia *et al.* (2023) deployed an eigenvalue approach for power system transient stability assessment. The bus admittances derived were used as inputs to the eigenvalue model with a case study of the Nigerian 330 kV power grid. The results revealed that the test network experienced aperiodic instability and degradation under steady-state and transient settings. Anazia *et al.* (2020) used the Nigerian 330 kV transmission system as a test case to assess the impact of proportional-integral based voltage source converter-high voltage direct current (VSC-HVDC) on transient stability. The system's power flow was modelled and simulated. The generators' dynamic responses with a three-phase fault introduced to some crucial buses and transmission lines were assessed. Evidence from the study indicated that the installation of VSC-HVDC along Ikeja West-Benin transmission line and at the Benin bus increased the system transient stability margin as a whole. Abakar *et al.* (2020) employed ETAP to investigate the multi-machine power system transient stability with a test case of IEEE 10-machine, 30-bus power network. Under various contingency settings, the network's transient stability was examined. Analysis from the work showed the generators connected to the grid experienced changes in the power input during contingency while those that had a very close proximity to the area of the fault experienced a more severe power deviation. Abdelbacky *et al*. (2019) investigated the impact of doubly fed induction generators (DFIGs) on power system transient stability during severe disturbances. Two scenarios were examined: one where DFIG-based wind farms (DFIG-WFs) were integrated in parallel with synchronous generators and another where DFIG-WFs replace synchronous generators entirely. The study shows that replacing synchronous generators with DFIGs offers more significant stability benefits. Based on the reviewed literature, only a limited number of studies have explored the role of FCT and CCT in transient stability analysis. The present study highlights the importance of both FCT and CCT in enhancing the transient stability of power system networks to ensure a stable, safe, and synchronous operation under varying fault conditions.

3. METHODOLOGY

3.1. Power Flow Formulation

Power flow is an essential tool in the design and analysis of power systems. It plays a vital role in power system planning and operation, including power transfer between utilities, economic scheduling, contingency analysis, and transient stability studies (Gupta, 2011; Hadi, 2008; Kothari & Nagrath, 2008). In this study, the power flow is formulated based on a typical power system bus configuration, as illustrated in Figure 1

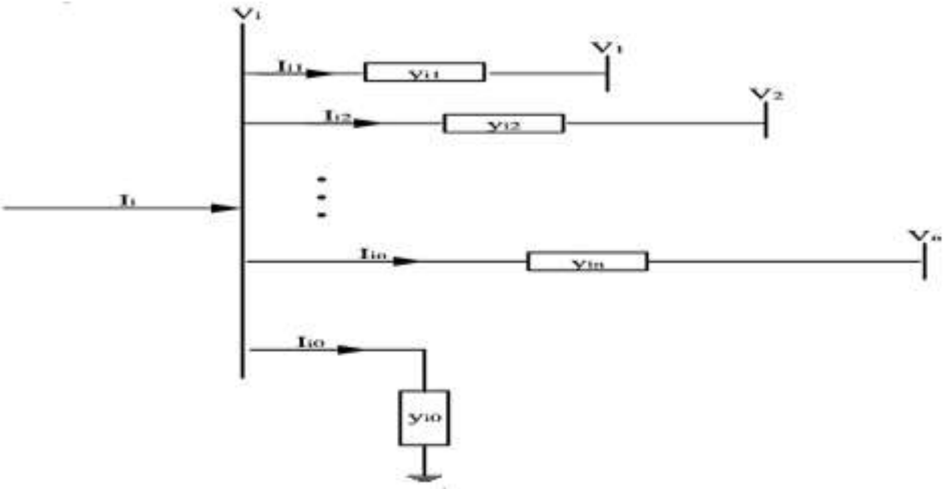

Figure 1: An n-bus structure of power system (Gupta, 2011; Hadi, 2008; Kothari and Nagrath, 2008)

Application of KCL to the bus system in Figure 1 yields equation (1) which modifies into equations (2) and (3) with further application of KVL and algebraic manipulation respectively:

$$I_i = I_{i0} + I_{i1} + I_{i2} + \cdots + I_{in} \tag{1}$$

$$I_i = y_{i0}V_i + y_{i1}(V_i - V_1) + y_{i2}(V_i - V_2) + \cdots + y_{in}(V_i - V_n) \tag{2}$$

$$I_i = (y_{i0} + y_{i1} + y_{i2} + \cdots + y_{in})V_i - y_{i1}V_1 - y_{i2}V_2 - \cdots - y_{in}V_n \tag{3}$$

Where I_i is the current injected into bus *i*

I_{i0} is the current flowing from bus *i* to ground

I_{i1} is the current flowing from bus *i* to bus 1

I_{i2} is the current flowing from bus *i* to bus 2

I_{in} is the current flowing from bus *i* to bus n

V_i is voltage at bus *i*

V_1 is the voltage at bus 1

V_2 is the voltage at bus 2

V_n is the voltage at bus n

y_{i0} is the admittance of transmission line between bus i and ground

y_{i1} is the admittance of transmission line between bus i and bus 1

y_{i2} is admittance of transmission line between bus i and bus 2

y_{in} is admittance of transmission line between bus i and bus n

Further simplification of equation (3) with definition given by equation (4) results in equation (5) with a modification expressed by equations (6) and (7):

$$\begin{cases} Y_{ii} = y_{i0} + y_{i1} + y_{i2} + \cdots + y_{in} \\ Y_{i1} = -y_{i1} \\ Y_{i2} = -y_{i2} \\ \vdots \quad \vdots \quad \vdots \\ Y_{in} = -y_{in} \end{cases} \tag{4}$$

$$I_i = Y_{ii}V_i + Y_{i1}V_1 + Y_{i2}V_2 + \cdots + Y_{in}V_n \qquad (5)$$

$$I_i = \sum_{j=1}^{n} Y_{ij}V_j \qquad (6)$$

$$I_i = \sum_{j=1}^{n} |Y_{ij}||V_j|\angle\theta_{ij} + \delta_j \qquad (7)$$

Where I_i, V_i, y_{ij}, Y_{ij}, V_j,$|Y_{ij}|$, $|V_j|$, θ_{ij} and δ_j respectively denote the supplied current at bus *i*, the voltage at bus *i*, the admittance of line *i-j*, the element of bus admittance derived from admittance of line *i-j*, the voltage of bus *j*, the magnitude of admittance of line *i-j*, the magnitude of voltage at bus *j*, the angle of admittance of line *i-j*, and the angle of voltage at bus *j*.

Expansion of equation (6) for *i* equals to 1 to n produces equation (8) with Y_{bus} given by the matrix of equation (9):

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ Y_{n1} & Y_{2n} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{bmatrix} \qquad (8)$$

$$Y_{bus} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ Y_{n1} & Y_{2n} & \cdots & Y_{nn} \end{bmatrix} \qquad (9)$$

The power supplied at bus *i* takes an expression of equation (10) which produces equations (11) and (12) after substitution of equation (7) and decomposition into real and imaginary components:

$$P_i - jQ_i = V_i^* I_i \qquad (10)$$

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|cos(\theta_{ij}+\delta_{ij}) \qquad (11)$$

$$Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}|sin(\theta_{ij}+\delta_{ij}) \qquad (12)$$

With $\delta_{ij} = \delta_j - \delta_i$ (13)

Where P_i and Q_i respectively represent bus *i* active and reactive powers.

Equations (11) and (12) are the static power flow expressions that govern the steady state response of a power system. They are non-linear equations solved via numerical iterative method. These equations were implemented in this study using the Newton-Raphson method because of its faster convergence rate, accuracy, and reliability in comparison to other iterative methods (Gupta, 2011; Hadi, 2008; Kothari and Nagrath, 2008). The Newton-Raphson-based power flow equations arising from the linearization of equations (11) and (12) are expressed by equation (14):

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \qquad (14)$$

Where J_1, J_2, J_3, and J_4 are the elements of the Jacobin matrix, ΔP, ΔQ, $\Delta\delta$ and $\Delta|V|$ are respectively active power, reactive power, bus voltage angle, and bus voltage magnitude mismatches.

ΔP, ΔQ, $\Delta\delta$, $\Delta|V|$, J_1, J_2, J_3, and J_4 are expressed by equations (15) to (22):

$$\Delta P = \begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \end{bmatrix} \tag{15}$$

$$\Delta Q = \begin{bmatrix} \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} \tag{16}$$

$$\Delta \delta = \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_n^{(k)} \end{bmatrix} \tag{17}$$

$$\Delta |V| = \begin{bmatrix} \Delta \left|V_2^{(k)}\right| \\ \vdots \\ \Delta \left|V_n^{(k)}\right| \end{bmatrix} \tag{18}$$

$$J_1 = \begin{bmatrix} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} \end{bmatrix} \tag{19}$$

$$J_2 = \begin{bmatrix} \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \end{bmatrix} \tag{20}$$

$$J_3 = \begin{bmatrix} \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} \end{bmatrix} \tag{21}$$

$$J_4 = \begin{bmatrix} \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{bmatrix} \tag{22}$$

The active and reactive powers mismatch at the kth iteration and new estimates of the bus voltage angle and magnitude are expressed respectively by equations (23) and (26):

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)} \tag{23}$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)} \tag{24}$$

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta \delta_i^{(k)} \tag{25}$$

$$V_i^{(k+1)} = \left|V_i^{(k)}\right| + \Delta \left|V_i^{(k)}\right| \tag{26}$$

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The voltage and reactive power constraints imposed at bus i are expressed by equations (27) and (28) respectively:

$$V_{imin} \leq V_i \leq V_{imax} \tag{27}$$

$$Q_{imin} \leq Q_i \leq Q_{imax} \tag{28}$$

Where V_{imin}, V_{imax}, Q_{imin}, and Q_{imax} respectively denote minimum voltage magnitude, maximum voltage magnitude, minimum reactive power supply, and maximum reactive power supply at bus i.

3.2. Swing Equation Formulation

According to Newton's second law, the motion of the rotor of a generating unit comprising a three-phase synchronous generator and its prime mover is described by equation (23) (Glover and Sarma, 2002; Kothari & Nagrath, 2008):

$$J \propto_m (t) = T_m(t) - T_e(t) = T_a(t) \tag{23}$$

Where $\propto_m$, T_m, T_e, and T_n denote rotor angular acceleration in ${}^{rad}/_{s^2}$, mechanical torque of the prime mover minus retarding torque resulting from mechanical losses in Nm, electrical torque responsible for the generator's total three-phase electrical power output plus electrical losses in Nm and net accelerating torque in Nm respectively.

The angular acceleration of the rotor is expressed by equation (24) (Glover & Sarma, 2002; Kothari & Nagrath, 2008):

$$\propto_m (t) = \frac{d\omega_m}{dt} = \frac{d^2\theta_m(t)}{dt^2} \tag{24}$$

$$\text{With } \omega_m(t) = \frac{d\theta_m(t)}{dt} \tag{25}$$

Where ω_m and θ_m respectively denote the angular velocity of the rotor in ${}^{rad}/_{s}$ and the angular position of the rotor about a stationary axis.

The operation of the generator requires that both T_m and T_e are positive while at steady-state, T_m is the same as T_e, leading to T_a and $\propto_m$ being zero and consequently resulting in a constant velocity of the rotor termed synchronous speed. T_a is positive when T_m exceeds T_e, making $\propto_m$ to be positive and therefore, leads to an increased speed of the rotor. Equally, the speed of the rotor decreases when T_m is lower than T_e. Since the angular position of the rotor is conveniently measured about a synchronously rotating reference axis unlike a stationary axis, $\theta_m(t)$ is, hence, expressed as equation (26) (Glover & Sarma, 2002; Kothari & Nagrath, 2008):

$$\theta_m(t) = \omega_{msyn}t + \delta_m(t) \tag{26}$$

Where ω_{msyn} and δ_m are respectively defined as the rotor's synchronous angular velocity in ${}^{rad}/_{s}$ and the angular position of the rotor about a synchronously rotating reference.

The use of equations (24) and (26) in (23), produces equation (27):

$$J\frac{d^2\theta_m(t)}{dt^2} = J\frac{d^2\delta_m(t)}{dt^2} = T_m(t) - T_e(t) = T_a(t) \tag{27}$$

Multiplication of equation (27) by $\omega_m(t)$ and dividing by S_{rated} yields the generator's three-phase volt-ampere rating expressed by equation (28) which is a per-unit power quantity (Glover & Sarma, 2002; Kothari & Nagrath, 2008):

$$\frac{J}{S_{rated}}\frac{d^2\delta_m(t)}{dt^2}\omega_m(t)=\frac{(T_m(t)-T_e(t))}{S_{rated}}\omega_m(t)=\frac{P_m(t)-P_e(t)}{S_{rated}}=P_{mp.u.}(t)-P_{ep.u.}(t)=P_{ap.u.}(t) \tag{28}$$

Where $P_{mp.u.}$ and $P_{ep.u.}$ denote the prime mover's mechanical power mover minus the per unit mechanical losses and the generator's electrical power output plus the per unit electrical losses.

Combining equation (28) with a normalized inertia constant, H defined as equation (29) results in equation (30) (Glover & Sarma, 2002; Kothari & Nagrath, 2008):

$$H=\frac{J\omega_{msyn}^2}{S_{rated}}joules/_{VA}\ or\ per\ unit-seconds \tag{29}$$

$$2H\frac{\omega_m(t)}{\omega_{msyn}^2}\frac{d^2\delta_m(t)}{dt^2}=P_{mp.u.}(t)-P_{ep.u.}(t)=P_{ap.u.}(t) \tag{30}$$

Considering that the per-unit angular velocity of the rotor is defined as equation (31) and substituted into equation (30), equation (32) is obtained (Glover & Sarma, 2002; Kothari & Nagrath, 2008):

$$\omega_{p.u}(t)=\frac{\omega_m(t)}{\omega_{msyn}^2} \tag{31}$$

$$\frac{2H\omega_{p.u.}(t)}{\omega_{msyn}}\frac{d^2\delta_m(t)}{dt^2}=P_{mp.u.}(t)-P_{ep.u.}(t)=P_{ap.u.}(t) \tag{32}$$

Electrical angular acceleration α, electrical radian frequency ω, power angle δ of a synchronous generator with P number of poles, synchronous electrical radian frequency ω_{syn}, and per-unit electrical frequency $\omega_{p.u}(t)$ are respectively expressed as equation (33) to (37) (Glover & Sarma, 2002; Kothari & Nagrath, 2008):

$$\alpha(t)=\frac{P}{2}\alpha_m(t) \tag{33}$$

$$\omega(t)=\frac{P}{2}\omega_m(t) \tag{34}$$

$$\delta(t)=\frac{P}{2}\delta_m(t) \tag{35}$$

$$\omega_{syn}=\frac{P}{2}\omega_{msyn} \tag{36}$$

$$\omega_{p.u}(t)=\frac{\omega(t)}{\omega_{syn}}=\frac{\frac{2}{P}\omega(t)}{\frac{2}{P}\omega_{syn}}=\frac{\omega_m(t)}{\omega_{myn}} \tag{37}$$

The use of equations (35) and (36) in equation (32) results in equation (38) referred to as the per-unit swing equation.

$$\frac{2H}{\omega_{syn}}\omega_{p.u.}(t)\frac{d^2\delta(t)}{dt^2}=P_{mp.u.}(t)-P_{ep.u.}(t)=P_{ap.u.}(t) \tag{38}$$

Equation (38) is very crucial in the analysis of rotor dynamics for transient stability studies. It is a second-order ordinary differential equation in which an assumption of lossless machine and negligible damper winding torque have eliminated the damping term (proportional to $\frac{d\delta}{dt}$) (Kothari and Nagrath, 2009). The electrical power P_e in equation (38) depends on the sine of the angle δ and it is mathematically expressed as equations (39) and (40) (Kothari & Nagrath, 2008):

$$P_e=P_{max}sin\delta \tag{39}$$

$$P_e = \frac{|E||V|}{X_d} sin\delta \tag{40}$$

With $P_{max} = \frac{|E||V|}{X_d}$ (41)

Where P_{max} is the maximum electrical power

$|E|$ is the electromotive force of the generator

$|V|$ is the terminal voltage of the generator

X_d is the direct axis reactance

Using equations (39) and (40) in equation (38), equations (42) and (43) are obtained respectively:

$$\frac{2H\omega_{p.u.}(t)}{\omega_{syn}}\frac{d^2\delta(t)}{dt^2} = P_{mp.u.}(t) - P_{maxp.u.}sin\delta(t) \tag{42}$$

$$\frac{2H\omega_{p.u.}(t)}{\omega_{syn}}\frac{d^2\delta(t)}{dt^2} = P_{mp.u.}(t) - \frac{|E||V|}{X_d}sin\delta(t) \tag{43}$$

Assumption of ω_{syn} as $2\pi f$ and $\omega_{p.u.}(t)$ as unity for ease of analysis results in the swing equation expressed by equations (42) and (43) to be respectively modified as equations (44) and (45) respectively:

$$\frac{H}{\pi f}\frac{d^2\delta(t)}{dt^2} = P_{mp.u.}(t) - P_{maxp.u.}sin\delta(t) \tag{44}$$

$$\frac{H}{\pi f}\frac{d^2\delta(t)}{dt^2} = P_{mp.u.}(t) - \frac{|E||V|}{X_d}sin\delta(t) \tag{45}$$

3.3. Swing Equation Linearization

Transient stability analysis requires that the swing equation be linearized via a numerical iterative procedure since the exact solution is unavailable in practice. Euler, modified Euler, classical Runge-Kutta, and point-to-point methods are the common numerical techniques available for swing equation linearization (Kothari & Nagrath, 2008; Ogboh *et al.*, 2019) However, for this study, the modified Euler method (MEM) was adopted because of its simplicity and directness. MEM provides more accurate approximations of non-linear systems or functions through re-evaluation of the gradient of the line segment (Dobrushkin, 2024; Samsudin *et al.*, 2021). MEM application for linearization of swing equation requires the transformation of equation (38) modified as equations (44) and (45) which are all second-order non-linear differential equations into two first-order linear differential equations expressed by the state variable forms given by equations (46) and (47) for ease of analysis.

$$\frac{d\delta}{dt} = \Delta\omega \tag{46}$$

$$\frac{d\Delta\omega}{dt} = \frac{\pi f}{H}P_a \tag{47}$$

Application of MEM to equations (46) and (47) produces equations (48) to (53):

$$\delta_{i+1}^{p} = \delta_i + \left.\frac{d\delta}{dt}\right|_{\Delta\omega_i}\Delta t \tag{48}$$

$$\Delta\omega_{i+1}^{p} = \Delta\omega_i + \left.\frac{d\Delta\omega}{dt}\right|_{\delta_i}\Delta t \tag{49}$$

$$\left.\frac{d\delta}{dt}\right|_{\Delta\omega_{i+1}^{p}} = \Delta\omega_{i+1}^{p} \tag{50}$$

$$\left.\frac{d\Delta\omega}{dt}\right|_{\delta_{i+1}^{p}} = \frac{\pi f}{H}\left.P_a\right|_{\delta_{i+1}^{p}} \tag{51}$$

$$\delta_{i+1}^{c} = \delta_i + \left(\frac{\left.\frac{d\delta}{dt}\right|_{\Delta\omega_i} + \left.\frac{d\delta}{dt}\right|_{\Delta\omega_{i+1}^{p}}}{2}\right)\Delta\mathrm{t} \tag{52}$$

$$\Delta\omega_{i+1}^{c} = \Delta\omega_i + \left(\frac{\left.\frac{d\Delta\omega}{dt}\right|_{\delta_i} + \left.\frac{d\Delta\omega}{dt}\right|_{\delta_{i+1}^{p}}}{2}\right)\Delta\mathrm{t} \tag{53}$$

Where p is the predicted value of the involved parameters at the specified iteration and c is the corrected value of the involved parameters at the specified iteration, which is obtained from the average of the two derivatives as indicated in equations (52) and (53) respectively.

3.4. Test Networks

The IEEE 14-bus and the Nigerian 330 kV, 34-bus power grids were considered as test cases in this study with one line-diagrams respectively presented in Figures 2 and 3. The network data of the two grid systems are presented in Appendices 1 to 6.

4. RESULT AND DISCUSSION

4.1 Load Flow and Transient Stability Results for IEEE 5-Machine,14-Bus Power Network

4.1.1 Load Flow Results of IEEE 14-Bus Network

The results of the IEEE 14-bus network load flow study, conducted prior to the transient stability analysis, are presented in Figures 4. These figures show the system voltage profile and the total active line losses, respectively. The figure illustrates that all buses in the IEEE 14-bus network maintained voltage magnitudes within the acceptable tolerance range of 0.95 to 1.1 p.u., indicating that no bus violated the specified voltage limits. Based on the load flow results, transient stability analysis was performed on bus 2 [2-5].

4.2.2 Transient Stability Analysis Results of IEEE 14-Bus Network for Three-Phase Fault on Bus 2, Line [2-5]

The swing curves of the generators in the IEEE 14-bus power network, following the introduction of a three-phase short-circuit fault on Bus 2, Line [2-5], cleared at different times, are presented in Figures 5 to 7. The results in Figure 5 show that when the fault on bus 2, line [2-5] was cleared at 0.8841 s, the network remained stable. In this case, the rotor angle differences between generators 2 and 5 increased over time, reached a peak, and then began to oscillate, indicating no loss of synchronism. However, as shown in Figure 6, when the FCT was increased to 0.8842 s, the rotor angle differences between generators 2 and 5 with respect to the reference generator started to decrease continuously, signalling that the four generators had lost synchronism and the system had become unstable. Further extending the FCT to 0.8845 s, as shown in Figure 7, resulted in continued instability for generators 2 to 5. The simulation results indicated that the Critical Fault Clearing Time (CFCT) for generators 2 to 5 was 0.8841 s.

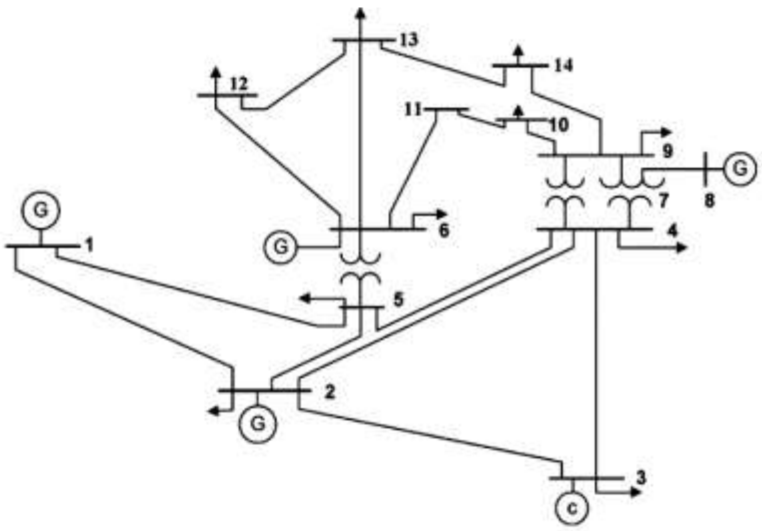

Figure 2: IEEE 5-machine, 14-bus power network (Olaogun *et al*., 2024b)

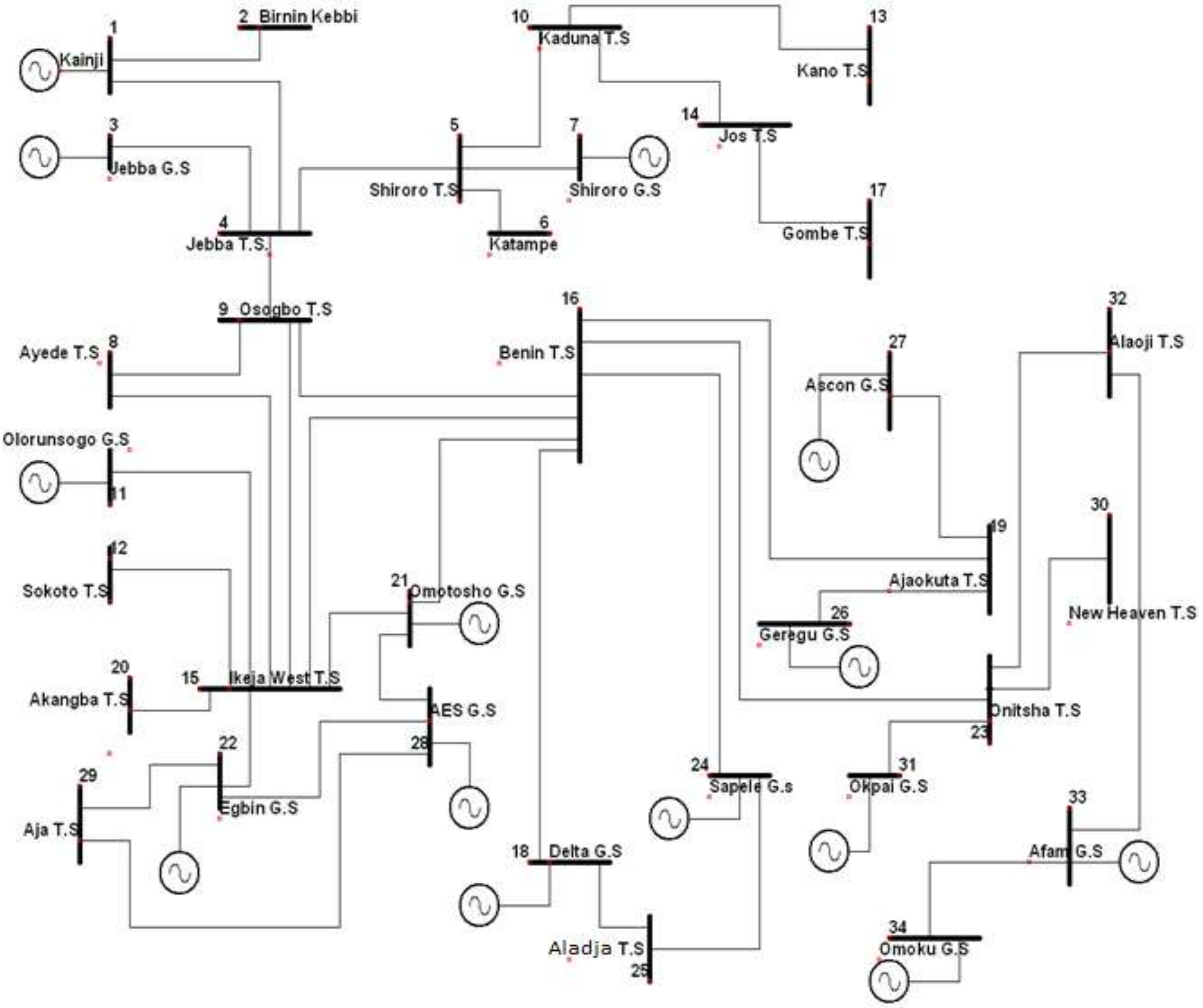

Figure 3: Nigerian 14-machine, 34-bus power network (Olaogun *et al.,* 2024a)

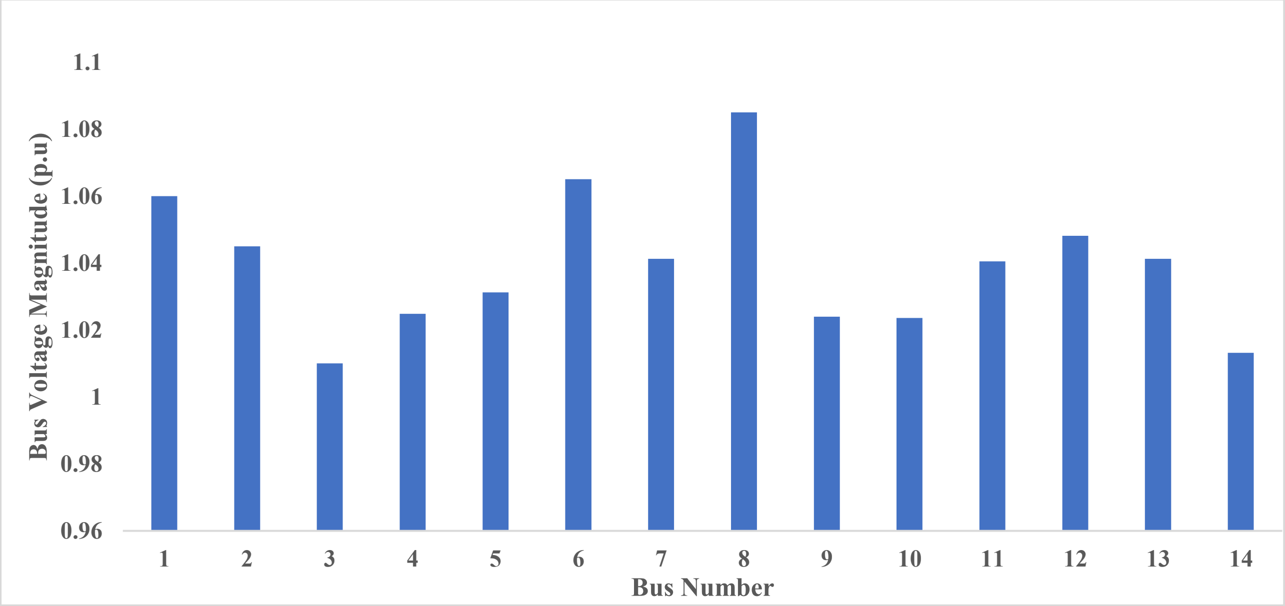

Figure 4: Voltage Magnitudes of the IEEE 14-bus network

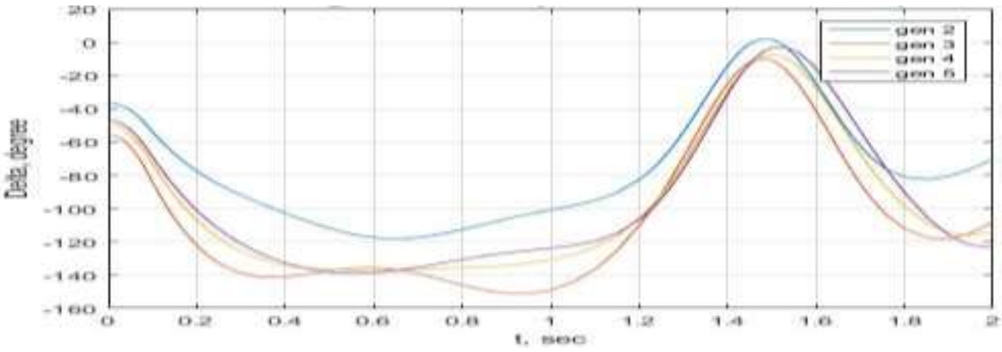

Figure 5: Swing curve of three-phase fault on bus 2, line [2-5] of the IEEE 14-bus power network and cleared at 0.8841 s.

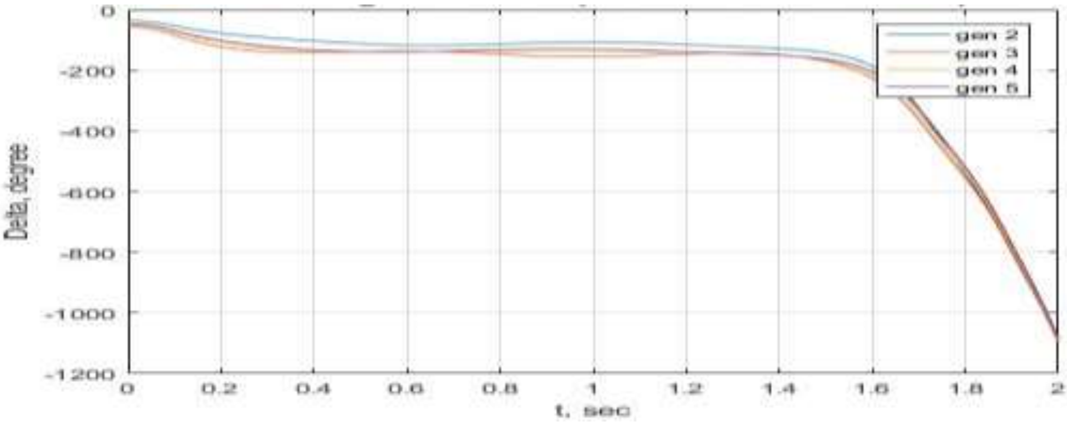

Figure 6: Swing curve of three-phase fault on bus 2, line [2-5] of the IEEE 14-bus power network and cleared at 0.8842 s

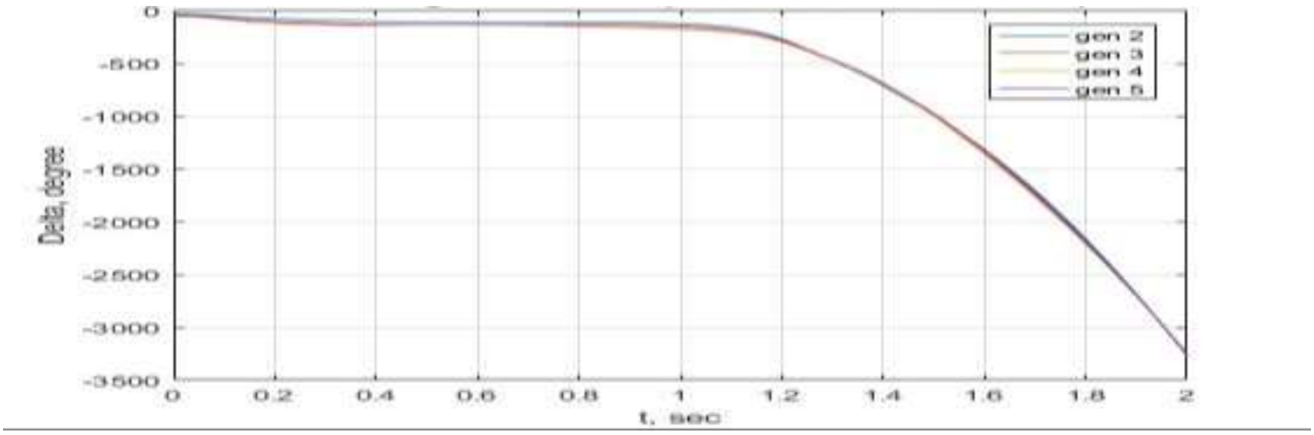

Figure 7: Swing curve of three phase fault on bus 2, line [2-5] of the IEEE 14-bus power network and cleared at 0.8845 s.

4.3 Load Flow and Transient Stability Analysis Results Nigerian 14-Machine, 34-Bus Power Network

4.3.1 Load Flow Results for Nigerian 34-Bus Network

The results of the Nigerian 34-bus network load flow prior to transient stability analysis, are presented in Figures 8, which shows the system voltage profile. From Figure 8, it was observed that five buses violated the voltage limits of 0.95 to 1.05 p.u. These buses-Katampe (bus 6), Kaduna T.S. (bus 10), Kano T.S. (bus 13), Jos T.S. (bus 14), and Gombe T.S. (bus 17)-had voltage magnitudes of 0.9373, 0.9209, 0.9381, 0.8295, and 0.7795 p.u., respectively, falling outside the desired voltage range for normal system operation. However, for the transient stability analysis of the system, bus 30 was selected as it is not among the buses with voltage violations.

4.3.2. Transient Stability Analysis Results of Nigerian 34-Bus Network

4.3.2.1. Transient Stability Analysis Results of Nigerian 34-Bus Network for Three-Phase Fault on Bus 30, Line [23-30]

The swing curves of the generators in the Nigerian 34-bus power network, following the introduction of a three-phase short-circuit fault on Bus 30, Line [23-30], and cleared at different FCTs are presented in Figures 9 to 11. From Figure 9, it was observed that the system remained stable with a FCT of 0.0151 s. However, when the FCT was increased to 0.0152 s, Generator 14 lost synchronism, while Generators 2 to 13 exhibited marginal stability, meaning they did not completely lose synchronism in response to the fault, as shown in Figure 10. When the FCT margin was increased to 0.0155 s, persistent instability was observed in Generator 14, while Generators 2 to 13 continued to exhibit marginal stability, as shown in Figure 11. The analysis of the results revealed that the Critical Fault Clearing Time (CFCT) for Generator 14 was 0.0151 s.

4.4. General Discussion of the Results

This research focused on the transient stability assessment of two different power grid models: the IEEE 14-bus grid and the Nigerian 330 kV, 34-bus grid. Prior to the transient stability analysis, a load flow study was conducted on each grid to evaluate their steady-state performance. The load flow results indicated that all buses in the IEEE 14-bus grid operated within the specified voltage limits of 0.95 to 1.1 p.u. In contrast, five buses in the Nigerian 34-bus grid—Katampe (Bus 6), Kaduna T.S. (Bus 10), Kano T.S. (Bus 13), Jos T.S. (Bus 14), and Gombe T.S. (Bus 17)—had voltage magnitudes of 0.9373, 0.9209, 0.9381, 0.8295, and 0.7795, respectively, which were outside the statutory voltage range of 0.95 to 1.05 p.u.

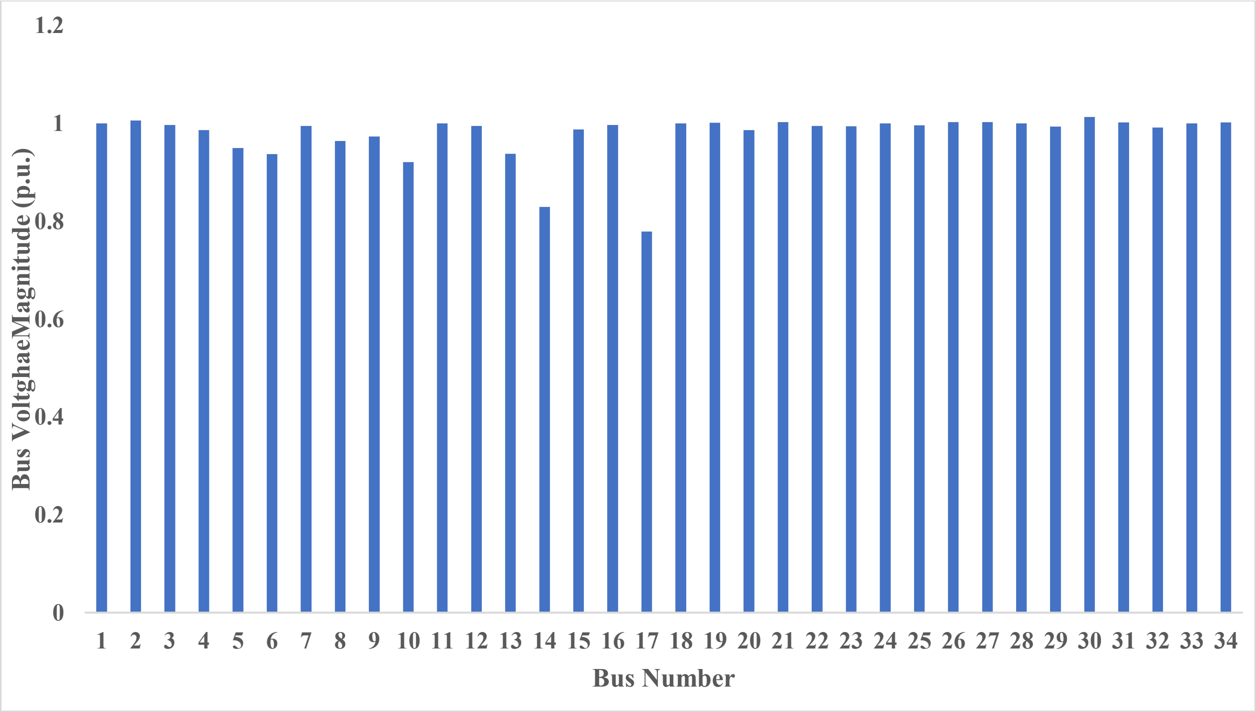

Figure 8: Voltage Magnitude of the Nigerian 34-bus power network

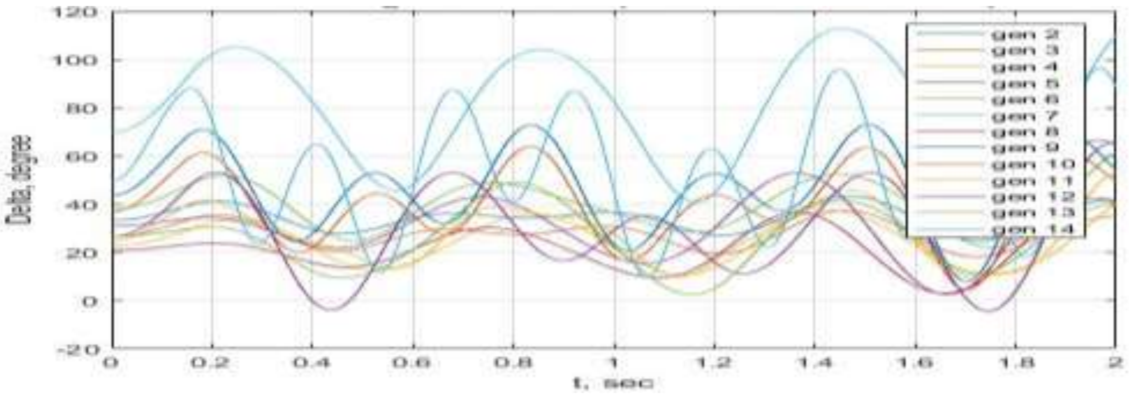

Figure 9: Swing curve of three-phase fault on bus 30, line [23-30] of the Nigerian 34-bus power network and cleared at 0.0151 s

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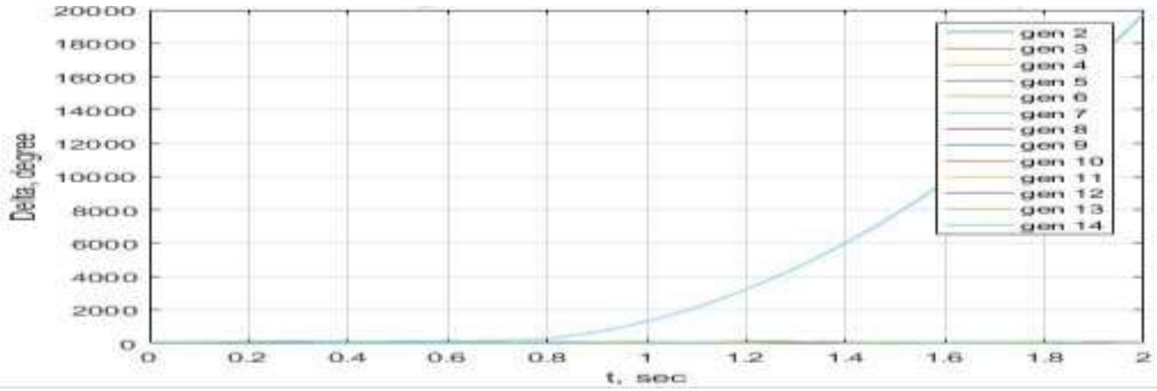

Figure 10: Swing curve of three-phase fault on bus 30, line [23-30] of the Nigerian 34-power network and cleared at 0.0152 s

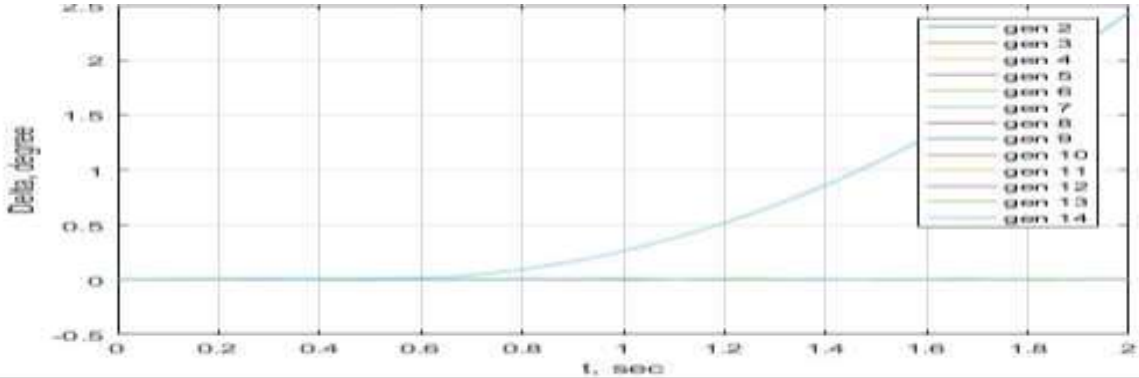

Figure 11: Swing curve of three-phase fault on bus 30, line [23-30] of the Nigerian 34-power network and cleared at 0.0155 s

After evaluating the steady-state conditions of the IEEE 14-bus and Nigerian 34-bus power grids, transient stability analysis was conducted on selected buses from both grids under various operating conditions. For the IEEE 14-bus grid, a three-phase short-circuit fault introduced on Bus 2, Line [2-5] and cleared at 0.8841 s showed that the system remained stable. However, when the fault clearing time (FCT) was increased to 0.8842 s, the system became unstable and this instability persisted until 0.8845 s. The undulating characteristics of the rotor angle-time relationship indicated system instability, causing generators 2 to 5 to lose synchronism, with instability sustained until a FCT of 0.8845 sSimilarly, on the Nigerian 330 kV, 34-bus grid, when transient stability analysis was conducted through the introduction of a balanced three-phase fault on bus 30, line [23-30] of the system, the result revealed that generator 14 lost synchronism when the FCT was beyond 0.0151s while generators 2 to 13 experienced marginal stability. The findings of the transient stability analysis in this study align with those of Atisola *et al.,*(2024) and Balapure and Chavhan (2021), the two authors emphasized that both fault clearing time (FCT) and critical clearing time (CCT) are critical factors in determining whether a system maintains stability or loses synchronism during major disturbances such as faults. These observations are consistent with the results of the present study, which further underscores the importance of critical clearing time in maintaining the stability of the power networks. The study established that Critical fault clearing time is a key determinant of the point at which a power system network loses stability.

5. CONCLUSION

This research explores the transient stability of multi-machine power systems using two models: the IEEE 14-bus system and the Nigerian 34-bus, 330 kV transmission grid. A load flow analysis revealed that while the IEEE grid maintained acceptable voltage levels, however, five buses in the Nigerian grid fell below the recommended voltage range. The study then performed transient stability simulations under three-phase fault conditions at selected buses. For both IEEE system and Nigeria 34 bus system, it was found that increasing the fault clearing time beyond certain thresholds resulted in the loss of synchronism among generators, highlighting the importance of critical clearing time (CCT). These results align with prior research and emphasize the role of FCT and CCT for maintaining a stable and safe synchronous operation under all system conditions. The study concludes that timely fault clearing is essential for effective fault management strategies and reliable operation of modern power systems networks.

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APPENDICES

Table 1: Bus Parameters for IEEE 14-Bus Test System

Bus No	Bus Type	Pd (MW)	Qd (MVAr)	Vm (p.u.)	Va (p.u.)	Vmax (p.u.)	Vmin (p.u.)
1	3	0	0	1.06	0	1.1	0.95
2	2	21.7	12.7	1.045	-4.98	1.1	0.95
3	2	94.2	19	1.01	-12.72	1.1	0.95
4	1	47.8	-3.9	1.019	-10.33	1.1	0.95
5	1	7.6	1.6	1.02	-8.78	1.1	0.95
6	1	11.2	7.5	1.07	-14.22	1.1	0.95
7	1	0	0	1.062	-13.37	1.1	0.95
8	1	0	0	1.09	-13.36	1.1	0.95
9	1	29.5	16.6	1.056	-14.94	1.1	0.95
10	1	9	5.8	1.051	-15.1	1.1	0.95
11	1	3.5	1.8	1.057	-14.79	1.1	0.95
12	1	6.1	1.6	1.055	-15.07	1.1	0.95
13	1	13.5	5.8	1.05	-15.16	1.1	0.95
14	1	14.9	5	1.036	-16.04	1.1	0.95

Table 2: Generator Parameters for IEEE 14-Bus Test System

Bus No	Pg (MW)	Qg (MVAr)	Qmax (MVAr)	Qmin (MVAr)	Vg (p.u.)	Pmax (MW)	Pmin (MVAr)	X (p.u)	H
1	232.4	-16.9	10	0	1.06	332.4	0	0.3	5.148
2	40	42.4	50	-40	1.045	140	0	0.19	6.54
3	0	23.4	40	0	1.01	100	0	0.185	6.54
6	0	12.2	24	-6	1.07	100	0	0.232	5.06
8	0	17.4	24	-6	1.09	100	0	0.232	5.06

Table 3: Branch Parameters for IEEE 14-Bus Test System

From Bus	To Bus	R (p.u.)	X (p.u.)	B (p.u.)
1	2	0.01938	0.05917	0.0528
1	5	0.05403	0.22304	0.0492
2	3	0.04699	0.19797	0.0438
2	4	0.05811	0.17632	0.034
2	5	0.05695	0.17388	0.0346
3	4	0.06701	0.17103	0.0128
4	5	0.01335	0.04211	0
4	7	0	0.20912	0
4	9	0	0.55618	0
5	6	0	0.25202	0
6	11	0.09498	0.1989	0
6	12	0.12291	0.25581	0
6	13	0.06615	0.13027	0
7	8	0	0.17615	0
7	9	0	0.11001	0
9	10	0.03181	0.0845	0
9	14	0.12711	0.27038	0
10	11	0.08205	0.19207	0
12	13	0.22092	0.19988	0
13	14	0.17093	0.34802	0

Table 4: Bus Parameters of the Nigeria 34-Bus, 330 kV Power System Network

Bus No	Bus Type	Pd (MW)	Qd (MVAr)	Vm (p.u.)	Vmax (p.u.)	Vmin (p.u.)
1	3	00.00	00.00	1.06	1.05	0.95
2	1	40.00	- 10.00	1.0	1.05	0.95
3	2	00.00	00.00	1.04	1.05	0.95
4	1	140.00	30.00	1.0	1.05	0.95
5	1	90.00	30.00	1.0	1.05	0.95
6	1	160.00	70.00	1.04	1.05	0.95
7	2	00.00	00.00	1.0	1.05	0.95
8	1	130.00	70.00	1.0	1.05	0.95
9	1	300.00	90.00	1.0	1.05	0.95
10	1	210.00	40.00	1.02	1.05	0.95
11	2	00.00	00.00	1.0	1.05	0.95
12	1	50.00	-20.00	1.0	1.05	0.95
13	1	100.00	-30.00	1.0	1.05	0.95
14	1	120.00	60.00	1.0	1.05	0.95
15	1	500.00	50.00	1.0	1.05	0.95
16	1	250.00	43.00	1.0	1.05	0.95
17	1	70.00	38.00	1.0	1.05	0.95
18	2	00.00	00.00	1.03	1.05	0.95
19	1	200.00	55.00	1.0	1.05	0.95
20	1	150.00	35.00	1.0	1.05	0.95
21	2	00.00	00.00	1.02	1.05	0.95
22	2	00.00	00.00	1.05	1.05	0.95
23	1	300.00	45.00	1.0	1.05	0.95
24	2	00.00	00.00	1.04	1.05	0.95
25	1	100.00	58.00	1.0	1.05	0.95
26	2	00.00	00.00	1.01	1.05	0.95
27	2	00.00	00.00	1.03	1.05	0.95

28	2	00.00	00.00	1.02	1.05	0.95
29	1	120.00	80.00	1.0	1.05	0.95
30	1	130.00	-78.00	1.0	1.05	0.95
31	2	00.00	00.00	1.03	1.05	0.95
32	1	200.00	67.00	1.0	1.05	0.95
33	2	00.00	00.00	1.04	1.05	0.95
34	2	00.00	00.00	1.02	1.05	0.95

Table 5: Generator Parameters of the Nigeria 34-Bus, 330 kV Power System Network

Bus No	Pg (MW)	Qg (MVAr)	Qmax (MVAr)	Qmin (MVAr)	Vg (p.u.)	R (p.u.)	X (p.u.)	H
1	00.00	00.00	0	0	1.05	0.0020	0.0901	9.920
3	300.00	40.00	110	0	1.04	0.0080	0.3000	3.390
7	400.00	60.00	140	0	1.0	0.0240	0.3000	3.240
11	150.00	50.00	114	0	1.0	0.0036	0.2200	4.000
18	280.00	45.00	100	0	1.03	0.0020	0.1240	12.400
21	240.00	55.00	104	0	1.02	0.0036	0.2200	4.000
22	700.00	68.00	108	0	1.05	0.0040	0.3080	3.090
24	180.00	00.00	132	0	1.04	0.0030	0.1060	12.690
26	190.00	-35.00	126	0	1.01	0.0061	0.3400	1.245
27	150.00	51.00	100	0	1.03	0.0036	0.3000	1.242
28	130.00	80.00	150	0	1.02	0.0051	0.2100	1.249
31	150.00	00.00	100	0	1.03	0.0061	0.3000	4.000
33	200.00	59.00	140	0	1.04	0.0010	0.0610	28.050
34	300.00	65.00	125	0	1.02	0.0051	0.1900	1.350

Table 6: Branch Parameters of the Nigeria 34-Bus, 330 kV Power System Network

From Bus	To Bus	R (p.u.)	X (p.u.)	B (p.u.)
1	2	0.0121836	0.0916336	1.21
1	4	0.0015918	0.0119716	0.31
3	4	0.0001572	0.0094178	0.00
4	5	0.0047827	0.0360219	0.09
4	9	0.0020565	0.0154692	0.07
5	6	0.0018864	0.0141884	0.36
5	7	0.0003144	0.0188355	0.00
5	10	0.0018864	0.0141884	0.37
8	9	0.0053843	0.0404961	0.33
8	15	0.0053343	0.0405651	0.45
9	15	0.0065432	0.0426547	0.55
9	16	0.0098648	0.0741936	0.98
10	13	0.0090394	0.0679862	0.52
10	14	0.0077425	0.0582316	0.77
11	15	0.0020643	0.0103951	0.31
12	15	0.0040534	0.0305160	0.41
14	17	0.0104150	0.0783319	0.01
15	16	0.0110045	0.0827653	0.09
15	20	0.0003527	0.0026574	0.05

15	21	0.0055023	0.0413829	0.35
15	22	0.0012184	0.0091634	0.20
16	18	0.0063843	0.0404961	0.15
16	19	0.0038336	0.0288242	0.76
16	21	0.0055023	0.0413829	0.55
16	23	0.0053843	0.0404961	0.38
16	24	0.0009826	0.0073898	0.19
18	25	0.0010218	0.0076553	0.10
19	26	0.0005109	0.0038427	0.38
19	27	0.0006105	0.0038427	0.40
22	28	0.0005109	0.0036458	0.30
22	29	0.0002749	0.0020654	0.20
23	30	0.0037730	0.0283768	0.37
23	31	0.004913	0.0036949	0.09
23	32	0.00605225	0.0455212	0.02
24	25	0.0024760	0.0186223	0.24
28	29	0.0034640	0.0206114	0.30
32	33	0.0009825	0.0073898	0.09
33	34	0.0005109	0.0038427	0.30

Power Quality and Efficiency: An Electrical Engineer's Guide to Phase Load Balancing in Industry

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***Abstract**:* The escalating demand for electrical power, particularly in the industrial sector driven by automation, digitalization, and the advent of energy-intensive technologies, necessitates a heightened focus on power quality and distribution efficiency.[1] A critical aspect often overlooked is phase-to-phase load balancing within three-phase power systems. Imbalanced loads lead to significant energy losses, equipment degradation, reduced system capacity, and increased operational costs.[2] This paper explores the fundamental principles, benefits, challenges, and technological solutions associated with achieving optimal phase-to-phase load balance in industrial settings. It highlights the growing importance of this practice in ensuring efficient power distribution and reliable load demand management amidst rising consumption trends, with a particular emphasis on the role of smart technologies and potential influence of artificial intelligence (AI) in future solutions.

Keywords: *Load Balancing, Three-Phase Power, Industrial Power Distribution, Energy Efficiency, Unbalanced Loads, Power Quality*

1. INTRODUCTION

The global economy's reliance on industrial output, coupled with the rapid adoption of advanced manufacturing techniques and the burgeoning energy demands of technologies like AI-driven automation, has placed unprecedented stress on electrical power distribution systems. Industries, ranging from heavy manufacturing to data centres and advanced robotics, require not only large quantities of electricity but also a stable and high-quality power supply. In three-phase alternating current (AC) systems, which are standard for industrial power distribution, the ideal scenario involves an equal distribution of load across all three phases (R, Y, B or L1, L2, L3).[3] However, in reality, various factors lead to unbalanced loads, where the current or voltage in each phase is unequal.[4]

The consequences of such imbalances are far-reaching and detrimental.[5] They range from increased energy losses within the distribution network and connected equipment, premature failure of motors and transformers due to overheating, reduced overall system capacity, to significant power quality issues that can disrupt sensitive industrial processes (Aforenergy, 2025; PowMr, n.d.) as shown in Figure 1. As electricity consumption continues to climb globally, the imperative for efficient power distribution becomes ever more critical, making phase-to-phase load balancing not just a best practice, but a fundamental requirement for operational efficiency, cost reduction, and grid stability.

Figure 1. Burnt Electrical Breaker as a result of supply unbalance (Shutterstock)

This paper aims to delve into the intricate aspects of phase-to-phase load balancing, examining its importance in the context of rising industrial power consumption and demand. We will explore the causes and effects of unbalanced loads, outline the significant benefits of achieving balance, discuss current and emerging technologies for identification and mitigation, and consider the future role of advanced analytics and Artificial Intelligence (AI) in optimizing power distribution and load management.

2. UNDERSTANDING UNBALANCED LOADS: CAUSES AND CONSEQUENCES

In an ideal three-phase power system, the voltage magnitudes are equal, and the phase angles are displaced by exactly 120 degrees from one another. Consequently, when a balanced three-phase load is connected, the currents in each phase are also equal in magnitude and displaced by 120 degrees. However, several factors contribute to load imbalance in real-world industrial environments:

Causes of Unbalanced Loads:

i. **Uneven Distribution of Single-Phase Loads:** This is the most common cause. While industrial facilities use many three-phase motors and equipment, they also have numerous single-phase loads (e.g., lighting, heating, control systems, small machinery). If these single-phase loads are not meticulously distributed across the three phases during design and operation, imbalances inevitably arise (Aforenergy, 2025; ResearchGate, 2024).

ii. **Asymmetrical Power Consumption:** Even with careful initial distribution, the dynamic nature of industrial operations means that loads are constantly switching on and off. If large single-phase or even three-phase loads with varying characteristics cycle on and off irregularly, they can pull disproportionate power from one phase, creating transient or chronic imbalances (Aforenergy, 2025).[6]

iii. **Faulty Wiring or Connections:** Loose connections, damaged cables, or incorrect wiring can introduce varying impedances across phases, leading to current and voltage imbalances (PowMr, n.d.).[7]

iv. **Asymmetrical System Impedances:** Variations in the impedance of the power distribution components themselves, such as different cable lengths, wire sizes, or transformer winding variations, can contribute to inherent system unbalance (PowMr, n.d.).

v. **Faulty or Aging Equipment:** Degradation of windings in motors or transformers, or issues with reactive power compensation devices, can lead to uneven current draw (Aforenergy, 2025).

vi. **Harmonics and Non-Linear Loads:** Modern industrial facilities increasingly use non-linear loads like variable frequency drives (VFDs), rectifiers, and switch-mode power supplies.[8] These devices draw non-sinusoidal currents, which can introduce harmonic currents that propagate through the system and exacerbate phase imbalances (PowMr, n.d.).[9]

vii. **Renewable Energy Integration:** Improperly sized or installed solar inverters in grid-tied setups can feed power disproportionately into one phase, causing or worsening unbalance (Aforenergy, 2025).

Consequences of Unbalanced Loads:

The presence of unbalanced loads can lead to a cascade of negative effects throughout the power system and on connected equipment:[10]

i. **Increased Energy Losses (I²R Losses):** Unbalanced currents lead to higher neutral current in a three-phase, four-wire system. Even in three-wire systems, uneven phase currents result in higher RMS current, which significantly increases power losses (I²R losses) in transformers, cables, and other distribution components. This translates directly into wasted energy and higher electricity bills (ResearchGate, 2024; ZHENGXI, n.d.).[11]

ii. **Reduced Equipment Lifespan and Damage:**
   a. **Motors:** Induction motors, which are ubiquitous in industries, are particularly susceptible.[12] Unbalanced voltages cause unbalanced currents in the motor windings, leading to increased heating (particularly in the rotor), reduced efficiency, vibrations, and premature insulation degradation.[13] A small voltage imbalance can lead to a much larger current imbalance in motors (Aforenergy, 2025; ZHENGXI, n.d.).
   b. **Transformers:** Unbalanced loads cause excessive heat in transformer windings and can reduce their effective capacity, potentially leading to derating or failure (ResearchGate, 2024; ZHENGXI, n.d.).[14]
   c. **Cables and Switchgear:** Overloaded phases experience higher temperatures, accelerating insulation degradation and increasing the risk of faults or failures.

iii. **Reduced System Capacity:** An unbalanced system effectively reduces the available capacity of feeders and transformers, as the overall system capacity is limited by the most heavily loaded phase. This means less usable power is available for expansion or new loads (Shinenergy, n.d.).

iv. **Voltage Fluctuations and Power Quality Issues:** Unbalanced loads can cause voltage drops on overloaded phases and voltage rises on underloaded phases, leading to voltage unbalance at the load points.[15] This affects the performance of sensitive electronic equipment, can cause flickering lights, and disrupt automated processes (Aforenergy, 2025; Pebblex, 2023).[16]

v. **Increased Neutral Current:** In a three-phase, four-wire system, if the phase currents are unequal, a significant current will flow through the neutral conductor. This can lead to overheating of the neutral conductor, voltage drops in the neutral, and potential safety hazards (ResearchGate, 2024).[17]

vi. **Higher Operating and Maintenance Costs:** All the aforementioned consequences translate directly into increased operational costs (higher energy bills, penalties from utilities for poor power factor) and higher maintenance costs (frequent repairs, premature equipment replacement, and downtime) (Pebblex, 2023).

3. BENEFITS OF PHASE-TO-PHASE LOAD BALANCING

Proactive management and correction of phase-to-phase load imbalances as shown in figure 2 yield significant operational, financial, and environmental benefits for industrial facilities:

i. **Enhanced Energy Efficiency and Reduced Consumption:**
   a. When loads are balanced, current flows more evenly, minimizing unnecessary I²R losses in conductors and transformers.[19] This direct reduction in resistive losses translates into lower energy consumption and, consequently, lower electricity bills (Pebblex, 2023; Shinenergy, n.d.).
   b. Motors and other equipment operate closer to their optimal design parameters when supplied with balanced voltages, leading to improved efficiency and reduced waste.

ii. **Increased Usable System Capacity:**
   a. By distributing the load evenly, the strain on any single phase is reduced, preventing localized overloading.[20] This maximizes the utilization of the upstream electrical infrastructure, including feeders, transformers, and switchgear.
   b. A balanced system means the entire electrical infrastructure can operate closer to its rated capacity without risking overloads, potentially delaying costly upgrades or expansions (Shinenergy, n.d.).

iii. **Extended Equipment Lifespan and Reduced Maintenance Costs:**
   a. Balanced loads minimize stress on electrical components, particularly motors, transformers, and cabling.[21] This reduces overheating and mechanical vibrations, which are primary causes of premature wear and failure.[22]

   b. Longer equipment lifespan means fewer breakdowns, less frequent need for maintenance, and reduced replacement costs, directly improving the return on investment for capital equipment (Aforenergy, 2025; Pebblex, 2023; Shinenergy, n.d.).

iv. **Improved Power Quality and System Reliability:**
   a. Load balancing helps to stabilize voltage levels across all phases, reducing voltage fluctuations and unbalance.[23] This is critical for the reliable operation of sensitive electronic equipment, programmable logic controllers (PLCs), and automated systems (Aforenergy, 2025).[24]
   b. By preventing overloads and reducing stress on components, the overall reliability of the electrical system is enhanced, leading to fewer unplanned outages and disruptions to production.

v. **Reduced Neutral Current:**
   a. In four-wire systems, balancing the phase currents significantly reduces the current flowing through the neutral conductor. This prevents neutral conductor overheating, reduces neutral-to-ground voltage, and minimizes potential safety hazards and data transmission issues caused by electromagnetic interference (ResearchGate, 2024).

vi. **Compliance and Safety:**
   a. Maintaining balanced loads helps ensure compliance with national electrical codes and utility standards, which often specify limits for voltage and current unbalance (ResearchGate, 2024).
   b. Reducing the risk of overloads and overheating enhances the overall electrical safety of the industrial facility, protecting personnel and property.

vii. **Improved Power Factor:**
   a. While not always a direct outcome, an unbalanced system can lead to a poorer power factor.[25] Balancing loads can help maintain a healthier power factor, avoiding penalties from utility providers (Sunbird DCIM, n.d.).[26]

Figure 2. Balanced Circuit Breaker (Shutterstock)

4. TECHNOLOGIES AND METHODOLOGIES FOR LOAD BALANCING

Achieving and maintaining optimal phase-to-phase load balance in industrial environments requires a combination of systematic approaches, monitoring tools, and advanced technologies.[27]

i. **Load Assessment and Manual Redistribution**
   The foundational step involves a thorough load assessment or audit. This includes:

a. **Identifying all single-phase and three-phase loads:** Documenting their location, typical operating patterns, and power requirements.
b. **Metering and Monitoring:** Using power quality analyzers, smart meters, and current transformers to measure real-time current and voltage on each phase at key distribution points (e.g., main switchgear, sub-panels, large motor control centers). Shown in figure 3.
c. Analyzing historical data: Identifying trends, peak demands, and periods of significant imbalance.28

Based on this assessment, manual load redistribution can be performed. This involves physically reassigning single-phase loads from heavily loaded phases to less loaded ones. This is often done during scheduled maintenance or facility upgrades (BeattieDukeLow Electrical, 2023).

Figure 4. Three Piguhase Balanced three phase Meter (Dreamstime)

ii. Intelligent Monitoring and Management Systems:

Modern industrial facilities increasingly leverage supervisory control and data acquisition (SCADA) systems, energy management systems (EMS), and data center infrastructure management (DCIM) software for power quality monitoring.29

a. These systems collect real-time data from sensors and meters across the power distribution network.[30]
b. They can provide alerts when phase current or voltage unbalance exceeds predefined thresholds (Sunbird DCIM, n.d.).
c. Some advanced systems can offer recommendations for load redistribution or even trigger automated actions.

iii. Load Balancing Devices and Technologies

Several devices are designed to actively or passively mitigate load imbalances:

a. **Automatic Phase Selectors/Switches:** These devices automatically shift single-phase loads from an overloaded phase to a less loaded phase to maintain balance. They are particularly useful for critical single-phase loads in three-phase systems (IRJMETS, n.d.).
b. **Static Var Compensators (SVCs) and Static Synchronous Compensators (STATCOMs):** These are power electronic-based devices that can rapidly inject or absorb reactive power to regulate voltage and can also be configured to compensate for phase current imbalances, particularly in large industrial applications (AAST.edu, n.d.).[31] While expensive, they offer fast and dynamic compensation.
c. **Active Power Filters (APFs):** These devices can inject compensating currents into the system to cancel out harmonic currents and also correct current imbalances caused by non-linear loads.[32]

d. **Three-Phase Split-Phase Automatic Voltage Stabilizers:** These devices can independently adjust the voltage of each phase to correct voltage unbalance, which can indirectly help in current balancing by providing more stable conditions for loads (ZHENGXI, n.d.).[33]
e. **Capacitor Banks:** Strategically placed and controlled capacitor banks shown in figure 5, can compensate for reactive power imbalances across phases, improving the power factor and sometimes contributing to better current balance.[34]

Figure 5. Three Phase balance Capacitor Bank (Shutterstock)

f. **Special Transformers:** Transformers like Scott or Steinmetz transformers can be used in specific applications to manage or convert phase configurations, helping to balance the load seen by the upstream three-phase grid from mixed single and three-phase loads (AAST.edu, n.d.).

iv. Advanced Algorithms and Artificial Intelligence (AI)

The increasing complexity of industrial power systems and the dynamic nature of loads are driving the adoption of more sophisticated, data-driven approaches:

a. **Optimization Algorithms:** Genetic algorithms (GAs), particle swarm optimization (PSO), and other metaheuristic algorithms can be used to determine optimal load redistribution strategies to minimize unbalance and power losses (AAST.edu, n.d.).[35]
b. **Machine Learning (ML) and Predictive Analytics:**
    i. ML algorithms can analyze historical power consumption data to identify patterns of imbalance and predict future imbalances.[36]
    ii. This predictive capability allows for proactive adjustments rather than reactive responses.
    iii. AI-driven load balancing systems can dynamically allocate resources, anticipate needs, and reassign loads among servers or industrial processes in real-time, especially critical in data centres or highly automated factories (ResearchGate, 2025; Hitachi Energy, 2025).[37]
    iv. AI can learn the load profiles of different equipment and optimize their operational schedules to maintain overall system balance.
c. **IoT Integration:** Internet of Things (IoT) sensors deployed throughout the industrial facility can provide real-time, granular data on current, voltage, temperature, and power factor at various points, feeding into AI/ML models for continuous monitoring and optimization (IRJMETS, n.d.).[38]

The integration of these technologies, from fundamental load assessment to advanced AI-driven dynamic balancing, represents the future of efficient and reliable industrial power distribution.

5. CHALLENGES AND FUTURE OUTLOOK

While the benefits of phase-to-phase load balancing are clear, implementing and maintaining optimal balance in complex industrial environments is not without challenges. However, the future outlook points towards increasingly sophisticated and automated solutions.

Challenges:

i. **Dynamic Nature of Loads:** Industrial loads are not static. Machines start and stop, production lines change, and energy consumption fluctuates. This dynamic behavior makes it difficult to maintain perfect balance continuously with manual methods.
ii. **Complexity of Industrial Networks:** Large industrial facilities often have extensive and intricate power distribution networks with multiple feeders, sub-panels, and diverse loads. Identifying the root causes of imbalance and determining optimal corrective actions can be complex.
iii. **Cost of Implementation:** Investing in advanced monitoring equipment, active balancing devices (like STATCOMs or APFs), or intelligent energy management systems can require significant upfront capital expenditure.
iv. **Integration and Interoperability:** Integrating various monitoring devices, control systems, and software platforms from different vendors can pose technical challenges.
v. **Legacy Infrastructure:** Many older industrial plants operate with legacy electrical infrastructure not designed with modern balancing technologies in mind, making upgrades more complex and costly.
vi. **Harmonic Distortion:** The increasing prevalence of non-linear loads in industries can complicate load balancing efforts, as harmonic currents contribute to unbalance and require specialized mitigation techniques in addition to fundamental frequency balancing (PowMr, n.d.).
vii. **Skill Gap:** There is a need for highly skilled electrical engineers and technicians who understand power quality issues, can interpret complex data, and are proficient in deploying and managing advanced balancing technologies.

Future Outlook:

The growing demand for electricity and the imperative for energy efficiency are driving rapid advancements in load balancing technologies:

i. **AI and Machine Learning will become mainstream:** AI's ability to analyze vast datasets, predict load fluctuations, and make real-time, dynamic adjustments will be transformative. AI-driven systems could not only optimize load distribution but also learn from system behavior to proactively prevent imbalances.[39] Hitachi Energy (2025) highlights that AI workloads themselves cause rapid and unpredictable power fluctuations, necessitating AI-driven solutions to manage grid stability. Research already suggests AI-driven load balancing could save up to a third of energy in data centers (ResearchGate, 2025).
ii. **Proactive and Predictive Maintenance:** AI and IoT integration will enable more predictive maintenance of power system components. By monitoring subtle shifts in current and voltage patterns, potential equipment failures due to unbalance can be identified before they lead to costly outages.[40]
iii. **Grid-Interactive Industrial Facilities:** Industrial facilities will increasingly become active participants in the smart grid.[41] Through sophisticated load balancing and demand-side management, they could provide flexibility to the grid, shifting consumption to off-peak hours or adjusting loads in response to grid signals, particularly for large consumers like data centers (Hitachi Energy, 2025).
iv. **Advanced Power Electronics:** Continued innovation in power electronic devices (e.g., faster, more efficient, and cost-effective active filters and compensators) will enable more precise and dynamic control over power flow and unbalance mitigation.
v. **Standardization and Interoperability:** Efforts towards greater standardization of communication protocols (e.g., IEC 61850) will facilitate the seamless integration of diverse devices and systems for comprehensive load management.

vi. **Renewable Energy Integration Optimization:** As more industries adopt on-site renewable energy generation (solar, wind), balancing technologies will evolve to manage the intermittency and potential unbalance introduced by these sources more effectively.

6. CONCLUSION

The contemporary industrial landscape, characterized by escalating power consumption and an increasing reliance on energy-intensive technologies, underscores the critical importance of efficient power distribution. Phase-to-phase load balancing within three-phase electrical systems is not merely a technical detail but a fundamental prerequisite for achieving optimal operational efficiency, minimizing costs, and ensuring the reliability of industrial processes. Unbalanced loads, stemming from various factors including uneven single-phase load distribution, system impedances, and non-linear devices, lead to significant energy losses, premature equipment degradation, reduced system capacity, and compromised power quality.

This paper has illuminated the substantial benefits derived from achieving load balance, including enhanced energy efficiency, prolonged equipment lifespan, increased usable system capacity, improved power quality, and reduced operational and maintenance costs. These advantages are paramount for industries striving to remain competitive and sustainable in an increasingly energy-constrained world.

Moreover, we have explored a spectrum of technologies and methodologies essential for effective load balancing, ranging from meticulous manual load assessment and redistribution to sophisticated active power electronic compensators. The growing integration of intelligent monitoring systems, IoT sensors, and advanced algorithms, particularly those leveraging Artificial Intelligence and Machine Learning, represents the frontier of dynamic load management. These innovations promise to transform reactive problem-solving into proactive optimization, enabling real-time adjustments and predictive maintenance.[42]

While challenges such as the dynamic nature of industrial loads, the complexity of existing infrastructure, and implementation costs persist, the future outlook for load balancing is optimistic.[43] The continued development of AI-driven solutions, advanced power electronics, and integrated smart grid technologies will empower electrical engineers to design and manage highly efficient, resilient, and self-optimizing industrial power systems. As industries continue to expand their power consumption, the role of electrical engineering in ensuring efficient power distribution and load demand balance will be more critical than ever before, driving both economic growth and environmental sustainability.

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Exploring Polylactide as a Petroplastic Substitute for a Greener Environment in Load-Bearing Applications

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Abstract: In the wake of the global campaign for a green environment, petroplastics have been identified as one of the foremost threats to a sustainable environment. Besides the problem of ingestion of microplastics by aquatic life, their non-biodegradable nature has immensely contributed to flooding and other environmental hazards. This study examined the mechanical properties of polylactic acid (PLA) – a bioplastic – with a view to using it as a substitute for petroplastics, specifically in load-bearing capacity. The pellets of the bioplastics were pre-dried, heated to a molten state at 210 °C, mould-pressed into cylindrical samples of varying slenderness ratio (λ), and then subjected to a uniaxially loaded compression test. Mechanical properties at the yield, maximum stress and fracture points were extracted from the stress-strain curve, and the result is presented in this study. The modulus of elasticity of PLA was found to be about 40.86% higher than that of major load-bearing petroplastics like Polyvinyl Chloride (PVC). PLA was also found to be 81.77% and 22.12% higher in strength at yield and at break, respectively. Ductility of PLA was, however, 97.89% lower than that of the usual petroplastics. The ANOVA results reveal that λ significantly influenced all the properties examined, with a minimum p-value of 4.10×10^{-2}, indicating statistical significance. Future studies could investigate the potential of incorporating hydrophobic fillers into PLA to enhance ductility while controlling its biodegradation rate.

Keywords: *Biodegradation profile, End-of-Life, environmental hazards, mechanical properties, wind turbine blade*

1. INTRODUCTION

Petroplastics have been heavily criticised by Environmental Scientists, Urban and Regional Planners, Waste Management Specialists, and Climate Change Analysts. Some of the concerns raised are plastic pollution in oceans and waterways; harmful effects on marine life and ecosystems; contribution to climate change through the product lifecycle; waste management issues and lack of biodegradability; chemical leaching and contamination of soil and water; impact on human health, which includes cancer and reproductive issues; and so on [1]–[7]. The main issue with petroplastics is the absence of polar bonds within the polymer, making it difficult for enzymes to break the intermolecular forces in them [8]. The obvious consequence of this is non-biodegradability. Urban and regional planners have attributed the consequence of non-biodegradability to flooding and other environmental hazards as non-degradable plastics accumulate, clogging both natural and built drainage infrastructure [6], [9].

Besides the impacts of petroplastics on the physical environment, the damage they cause to marine life is untold. Aquatic animals ingest plastics as microplastics, leading to fatal issues like disruption of the endocrine system, dyspepsia and damage to digestive tissue, pericardial oedema and caudal deformities, alterations in sex hormones and so on [10]. Presently, several marine animals are *reservoirs* of microplastics and heavy metals. Interestingly, most of the load-bearing structures requiring lightweight materials are petroleum-based products whose end-of-life (EoL) status poses grave danger to the environment because of biodegradability issues.

Polyvinyl Chloride (PVC), Polyethylene Terephthalate (PET), Acrylonitrile Butadiene Styrene (ABS), Polystyrene (PS), Polypropylene (PP), Polyethylene (PE), Polyamide (PA – Nylon), and many more that are used as load-bearing structures and insulation materials are non-biodegradable plastics, making their EoL non-benign [11]. In spite of their adverse effects on the environment, petroplastics are generally considered load-bearing and insulation materials in electrical engineering because they are good at resisting electrical charge, since their valence electrons are not free to move. Hence, they are efficient at stopping electric current from leaking, thereby keeping power systems safe. Apart from their poor electrical conductivity, polymers also possess lower thermal conductivity than metals and metal alloys. In addition to their desirable thermal and electrical properties for certain applications, the fact that they are 60 – 75% lighter than ceramics, and are not prone to breakages, has positioned them as much-desired materials in electrical transmission and distribution. Polymers' applications are not limited to insulation in electrical engineering; they find application in the construction of Wind Turbine Blades (WTB), components that have been chorused as an instrument for the generation of clean energy (Figure 1) [12].

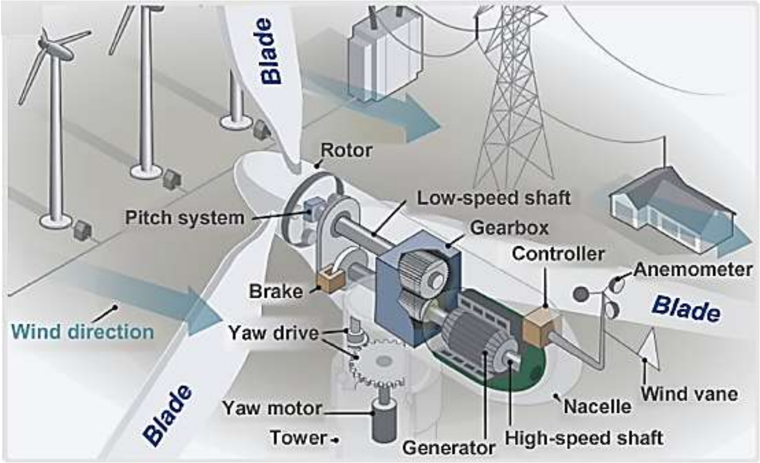

Figure 5: Wind turbine in energy generation [12].

Remarkably, it has been predicted that by 2050, about 698 kt of EoL WTB materials would have been generated in Germany. If such a huge volume cannot be managed successfully, the claim that wind power is a clean energy alternative becomes doubtful [12]. Interestingly, the volume of waste WTB materials in Germany is small compared to what would be generated across the globe by 2050 (Figure 2) [13]. Apart from the waste generated from WBT, massive quantities of plastic waste, primarily unrecycled, persist for centuries in the environment and landfills, causing toxic pollution, with millions of tons annually discharged into the ocean [11].

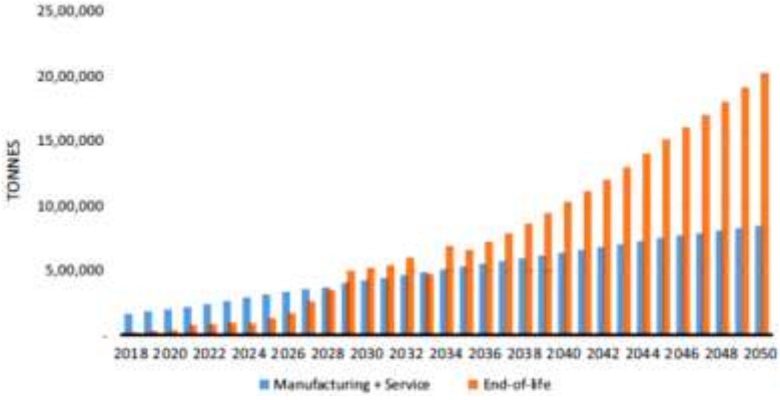

Figure 6: Wind turbine blade EoL material projection up to 2050 across the globe [13]

As the search for substitutes for petroplastics intensifies, polylactic acid (PLA), a thermoplastic polymer belonging to the α-hydroxy acid family, readily comes to mind because of its biomechanical properties that combine mechanical strength and biodegradability [14]–[16]. Being a bioplastic, its clinically admired bio-properties, with relatively high mechanical properties, have made it a subject of various applications. It has been processed via various processing techniques for soft and hard tissue engineering applications [15], [17]–[19]. Aside from its bio-mechanical properties, its EoL does not pose environmental problems, unlike petroleum-based polymers. Although other bioplastics offer a wide range of biomechanical properties, PLA stands out in a way because of the balance it has attained in combining several properties that are necessary for structural applications while maintaining environmental benignity; for instance, the biodegradation products of PLA are CO_2 and H_2O, enhancing green environment. These promising properties have made it a subject of many applications [14], [20], resulting in numerous configurations through various processing techniques [21]–[24]. The question that is left unanswered is whether it is structurally strong enough to replace the load-bearing petroplastics that are currently in use in many applications. It was this question that this study sought to explore.

2. MATERIALS AND METHODS

AutoCAD software was used to make a CAD model (Figure 1a). G-codes were generated from the CAD models and were keyed into a CNC milling machine – model XM 1060 – situated at the Mechanical Engineering workshop, Covenant University, Ota, Nigeria. A mild steel blank (Figure 1b) was fed into the CNC machine to obtain the mould (Figure 1c) used for the production of all the samples.

PLA of overall lactide purity ≥ 99.5% was used in this study. The pellets were put in the oven to pre-dry them to avoid the usual effects of moisture presence in polymers [25], [26]. They were left in the oven for 6 hours at 50 ºC and thereafter heated in a crucible to 210 ºC to obtain molten PLA. The molten PLA was mould-pressed [27] to obtain various solid cylinders of varying heights according to Equation 1, where l_n is the length of the *n*th term of a sample, while α is the first term or the starting length (Table 1). c represents the positive common difference in the lengths of any two successive samples, while n is the *n*th term. Ten samples with different slenderness ratios (λ) were produced in triplicate using the melt casting method. λ was calculated using Equation 2. The diameter, *d,* being constant (i.e., 13.28 mm), $\alpha = 9.40$ mm and $c = 4$mm. The solid cylinders were produced in triplicate for each sample configuration.

$$l_n = \alpha + c(n-1) \quad (1)$$

$$\lambda = \frac{l_n}{0.25d} \quad (2)$$

Table 1: Determined lengths, calculated slenderness ratio and measured masses of the samples

***l* (mm)**	9.4	13.4	17.4	21.4	25.4	29.4	33.4	37.4	41.4	45.4
λ	2.83	4.04	5.24	6.45	7.65	8.86	10.06	11.27	12.47	13.67
Mass (g)	1.63	2.28	3.03	3.64	4.29	5.07	5.73	6.43	7.07	7.71

The masses of the samples were measured and recorded (Table 1) before they were subjected to a compression test [28] using an Instron universal testing machine (model number 3369) equipped with Bluehill software, and situated at the Centre for Energy Research and Development (CERD) at Obafemi Awolowo University, Ile-Ife in Nigeria. The mechanical properties were recorded from three points on the stress-strain curves, namely: yield, ultimate compressive strength and breaking points.

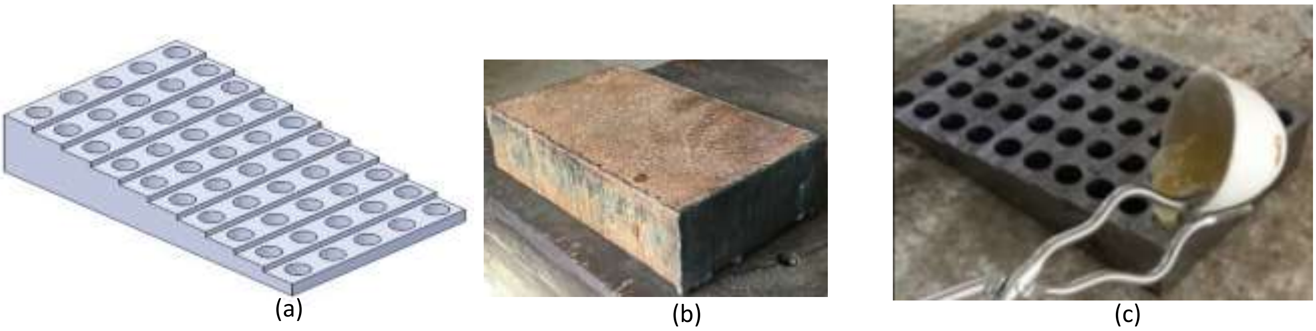
(a) (b) (c)

Figure 7: Development of the mould for sample production: (a) CAD model; (b) mild steel blank fed into CNC milling machine; and (c) the produced mould

3. RESULTS AND DISCUSSION

This study exhaustively captures the mechanical behaviour of PLA under uniaxial compressive load. Figures 4 – 8 depict the mean (μ) values of all the properties considered. These Figures give insight into how changes in the sample size can produce different values of mechanical properties when under compressive loads. All the values presented are the mean values of the mechanical properties of each sample size, compressively loaded in triplicate. In addition, the mechanical values were presented as a function of the slenderness ratio, λ, *pari passu* with their corresponding sample sizes.

Figure 4 presents the measured masses of the samples side-by-side with their compressive moduli of elasticity. It was observed that a direct proportional linearity relationship was maintained between the slenderness ratio and the mass, in spite of the fact that the samples were not degassed. It implies that the process employed in the production of the samples trapped little or no air, keeping voids to a minimum. Sample size clearly impacted the E_c of the samples; the moduli of elasticity, as shown in Figure 4, range between 0.51 – 3.04 GPa. These values compare favourably with the moduli of elasticity of many petroplastics (Table 2) currently used as load-bearing materials.

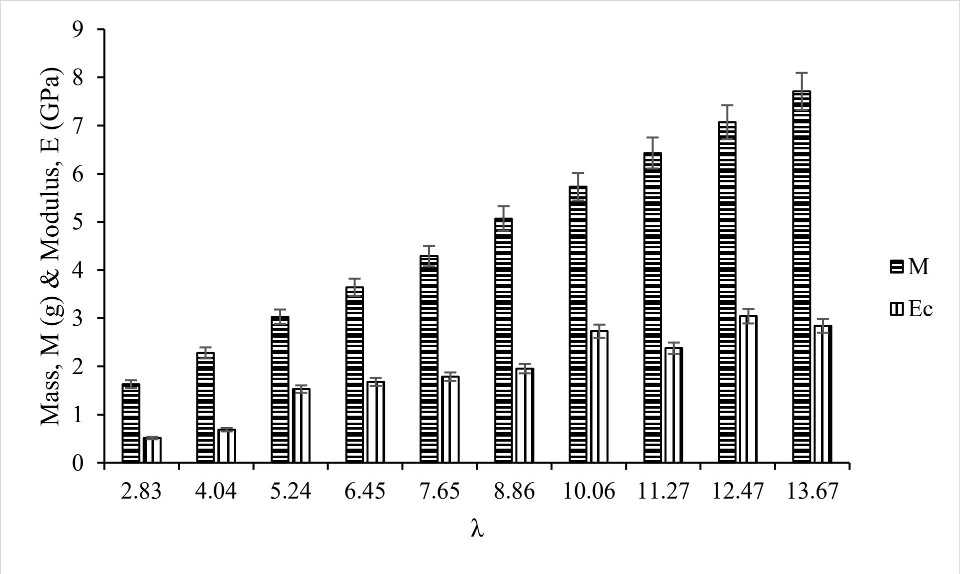

Figure 8: Mass and compressive modulus at different slenderness ratios

Table 2: Compressive modulus of common petroplastics for load-bearing applications

Petroplastics	PVC	PET	ABS	PS	PP	PE	PA (Nylon)
E_c (GPa)	2.8 - 3.5	2.8 - 3.5	2.5	2.5 - 3.0	1.1 - 1.6	0.5 - 1.3	1.8 - 3.2

Figure 5 shows the loads at yield, maximum stress and breaking points, while Figure 6 displays the sample values of the yield strength, ultimate compressive strength, and stress at break. These values amplify the impact of load on the atomic bond within PLA when loaded in uniaxial compression. At λ=8.86, the yield strength was seen to exceed the ultimate compressive strength. This possibility can be linked to the effect of chipping off of samples during testing due to the brittle nature of PLA [24]. A material will generally experience elastic deformation before deforming plastically, as seen in other samples. Hence, the values in Figure 6 would normally be distinct for ductile materials at yield, maximum strength and fracture, unlike what Figure 6 portrays. The fact that these values are close shows that PLA is a brittle material and can fail suddenly or catastrophically under load, except when reinforced with fibres or ductile additives.

Figure 7 is one of the consequences of the events captured by Figure 6. The values of ductility for the samples stand in contrast with the values of the usual ductile materials like metals and metal alloys. These values indicate the brittle nature of PLA. Ductility also declined with growing sample size, which implies that PLA, though environmentally friendly, may not be suitable for large load-bearing structures if used unreinforced. This possibly explains the reason why investigation of the load-bearing capacity of its unreinforced form has been limited to scaffolds for tissue engineering applications [19], [23], [29], [30]. In Figure 8, the amount of energy absorbed by the samples from the points they were loaded till they fractured were indicated. These values are characteristic of brittle materials, as ductile materials would absorb a greater amount of energy before they eventually fracture. These values again reiterate the fact that PLA must be reinforced with ductile additives for better performance as load-bearing materials.

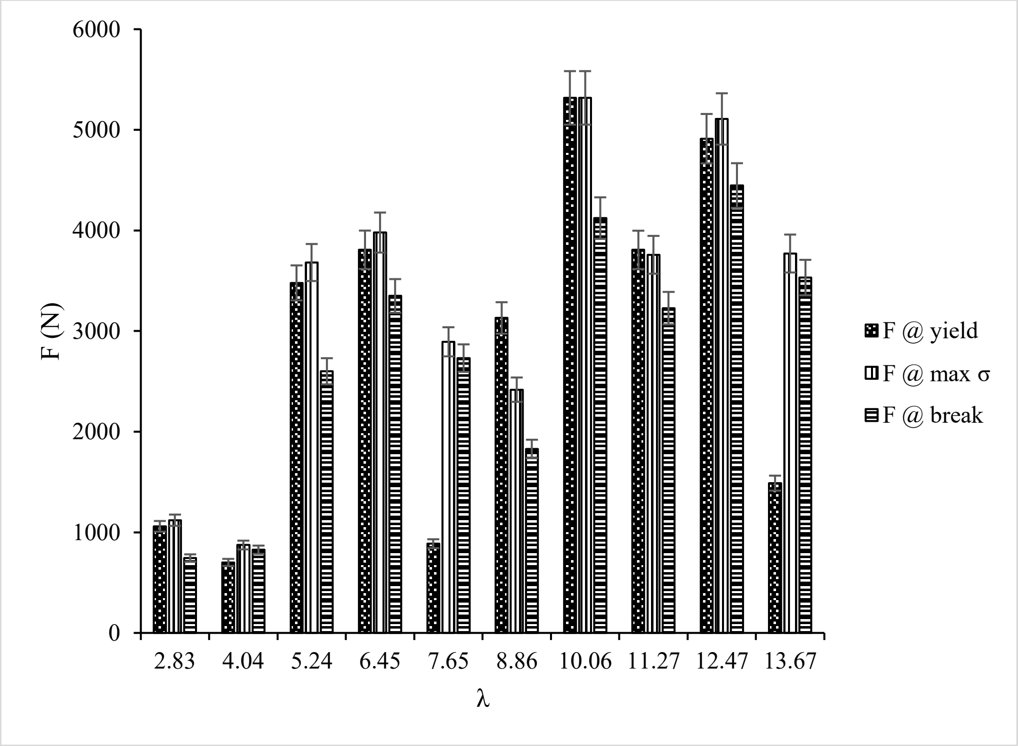

Figure 9: Load at the characteristic points on the stress-strain curve

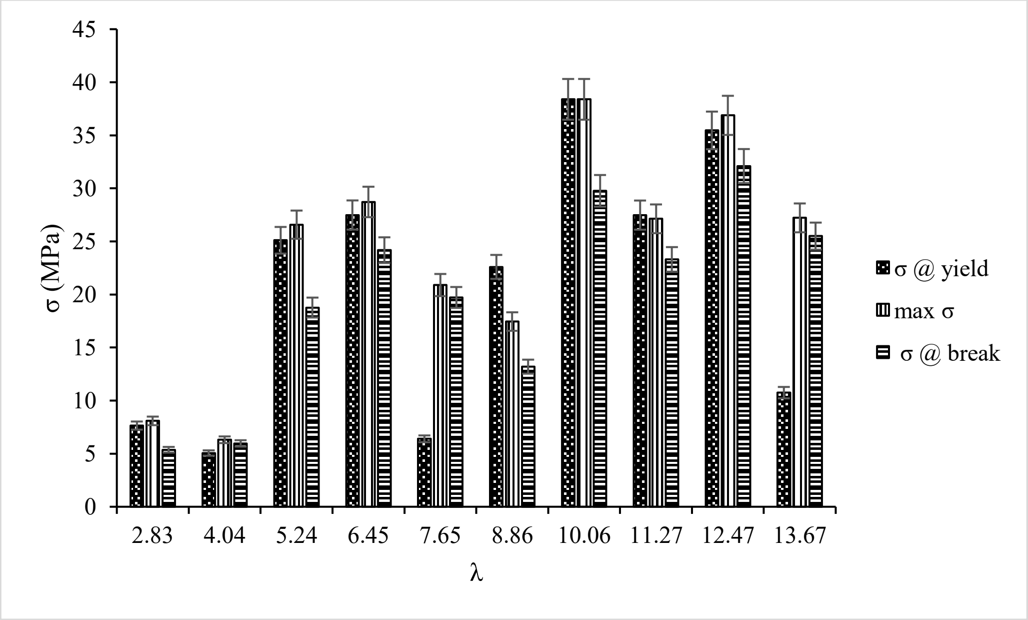

Figure 10: Stress at the characteristic points on the stress-strain curve

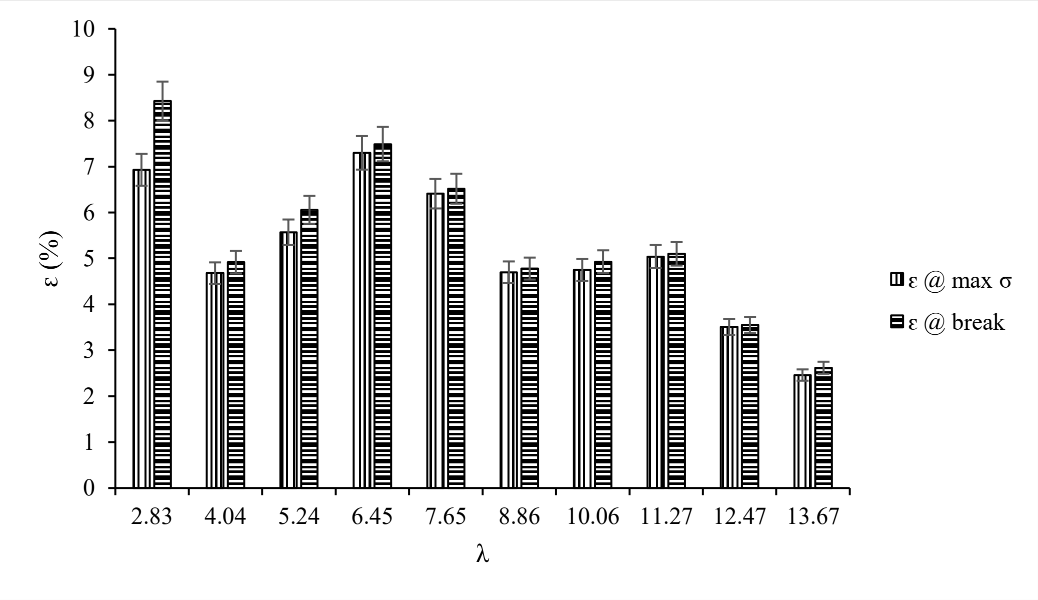

Figure 11: Ductility at the characteristic points on the stress-strain curve

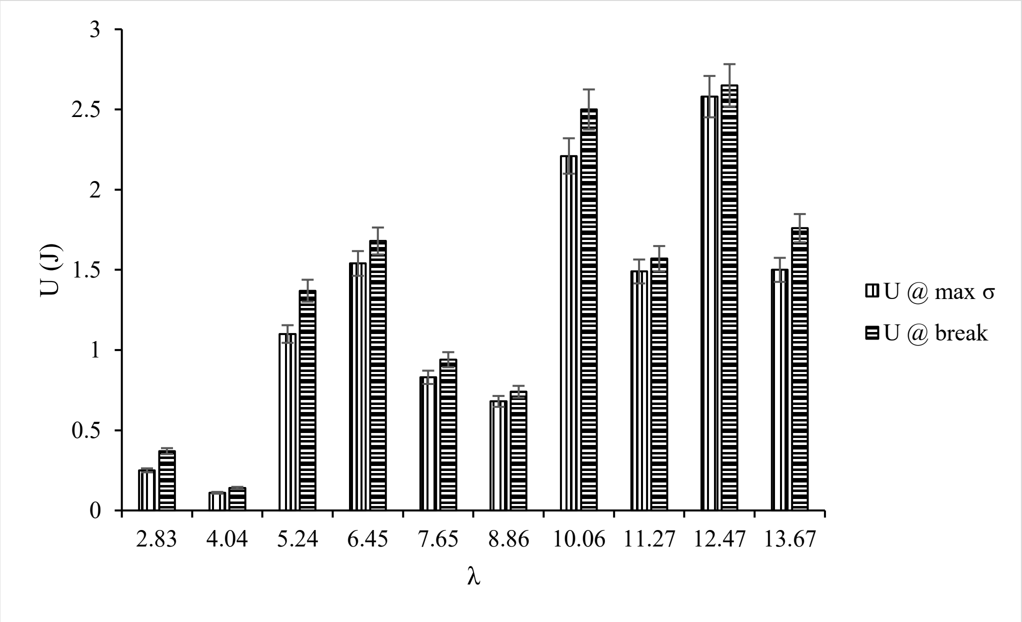

Figure 12: Energy at the characteristic points on the stress-strain curve

3.1 Analysis of variance on the mechanical properties

Tables 3-5 present the Analysis of Variance (ANOVA) on the mechanical properties at the three points that were considered on the stress-strain curve. The summary of ANOVA on the properties obtained at the maximum compressive strength is detailed in Table 3, while Table 4 shows the ANOVA on the properties obtained at the breaking point. Table 5 gives a comprehensive summary of the ANOVA on the properties at the yield point. These analyses show the extent of dependence of the mechanical properties of PLA on the sample size, namely, the slenderness ratio (λ). The summary of the sum of squares (SS), mean of squares (MS), statistically significant differences between groups (BG), statistically significant differences within group (WG), F, P-value and F critical are all presented to expatiate on the level of statistical significance of the results. These values show that the sample size significantly impacted the mechanical performance of PLA. All the mechanical properties, without exception, that were considered showed strong dependence on λ.

Table 3: Summary of ANOVA on the level of significance of slenderness ratio's effect on the mechanical properties of PLA at maximum compressive stress

Properties	SS-BG	SS-WG	MS-BG	MS-WG	F	P-value	F crit
Maximum Compressive stress (MPa)	1203.146	1160.104	1203.146	64.45024	18.6678	4.12×10^{-4}	4.4139
Compressive strain at Maximum Compressive stress (%)	48.64404	139.7976	48.64404	7.766532	6.2633	2.22×10^{-2}	4.4139
Energy at Maximum Compressive stress (J)	246.7009	125.4794	246.7009	6.971076	35.3892	1.25×10^{-5}	4.4139
Compressive load at Maximum Compressive stress (N)	53907106	19959664	53907106	1108870	48.6144	1.64×10^{-6}	4.4139
Compressive extension at Maximum Compressive stress (mm)	242.6942	121.4005	242.6942	6.744471	35.9842	1.13×10^{-5}	4.4139

Table 4: Summary of ANOVA on the level of significance of slenderness ratio effect on the mechanical properties of PLA at break

Properties	SS-BG	SS-WG	MS-BG	MS-WG	F	P-value	F crit
Compressive stress at Break (Standard) (MPa)	665.1732	878.3523	665.1732	48.79735	13.6313	1.67×10^{-3}	4.4139
Compressive load at Break (Standard) (N)	37332392	14554129	37332392	808562.7	46.1713	2.31×10^{-6}	4.4139
Compressive strain at Break (Standard) (%)	39.59337	147.0668	39.59337	8.170379	4.8460	4.10×10^{-2}	4.4139
Compressive extension at Break (Standard) (mm)	239.0914	121.2265	239.0914	6.734807	35.5009	1.23×10^{-5}	4.4139
Energy at Break (Standard) (J)	236.6946	126.0417	236.6946	7.002319	33.8023	1.65×10^{-5}	4.4139

Table 5: Summary of ANOVA on the level of significance of slenderness ratio's effect on the mechanical properties of PLA at yield

Properties	SS-BG	SS-WG	MS-BG	MS-WG	F	P-value	F crit
Compressive stress at Yield (Zero Slope) (MPa)	767.136	1484.368	767.136	82.46491	9.3026	6.89×10^{-3}	4.4139
Compressive load at Yield (Zero Slope) (N)	40628692	26180820	40628692	1454490	27.9333	5.03×10^{-5}	4.4139
Modulus (E) (MPa)	18150616	6718480	18150616	373248.9	48.6287	1.63×10^{-6}	4.4139

4. CONCLUSIONS

The possibility of replacing petroplastics with bioplastics that have load-bearing capacity was explored in this work. The compressive mechanical properties of a uniaxially loaded cylindrical sample were examined. The results provide the relationship between the slenderness ratio of melt-cast, mould-pressed PLA samples and the mechanical properties, such as the modulus of elasticity, ductility, strength, etc. The results obtained from the experiment show that:

i. PLA, if properly reworked, can favourably replace petroplastics as a load-bearing material. This bold move is expected to allay the fear of Environmental Scientists, Urban and Regional Planners, Waste Management Specialists, and other environmental enthusiasts on the issue of environmental degradation.
ii. The values presented can be used to relate the sample size of PLA processed via melt casting and some other fused deposition modelling (FDM) and injection moulding, to its mechanical properties on the compressive stress-strain curve.
iii. The focus of material engineers and scientists should be on ensuring a more ductile PLA by developing fibre-reinforced composites, as this will position the material for greater performance in a load-bearing capacity.

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Performance Enhancement of the Nigerian Power Transmission Grid Using STATCOM

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Abstract: One of the critical challenges bedevilling the Nigerian electricity grid is operational inefficiency that has hindered the system from attaining its full potential. This research proposes the use of static synchronous compensator (STATCOM) for performance enhancement of the Nigerian 330 kV, 34-bus electricity grid. The system's steady state performance was modelled using Newton-Raphson based load flow algorithm. Simulations were done using MATLAB R2020a environment. The system's voltage profile and total active power loss before and after enhancement was applied were determined. The results showed that prior to the installation of STATCOM on the Nigerian 34-bus grid, the voltage magnitudes of Katampe (0.9373 p.u.), Kaduna (0.9209 p.u.), Kano (0.9381 p.u.), Jos (0.8295 p.u.), and Gombe (0.7795 p.u.) infringed the statutory voltage magnitude limit of 0.95 to 1.05 p.u. However, through the compensation offered by the STATCOM installed on the grid, these voltage magnitudes were enhanced to 0.9650, 0.9550, 0.9789, 0.9630, and 0.9550 p.u., respectively; bringing the voltage magnitudes of all system buses within acceptable operational limits. Furthermore, the system's total active power losses decreased which was 57.887 MW before compensation reduces by 3.91% to 55.623 MW after compensation; indicating an enhancement in overall active line flow of the system. This research showed that the deployment of a fast compensating device such as STATCOM can help ameliorate the performance ineffectiveness of the Nigerian electric power transmission network which has been overstretched beyond designed capacity due to ever-growing demand.

Keywords: *Newton-Raphson load flow, Nigerian electricity grid, Operational inefficiency, STATCOM, Total active power loss***,** *Voltage profile.*

1. INTRODUCTION

Recent advancements in power systems highlight the effectiveness of Flexible Alternating Current Transmission System (FACTS) controllers in enhancing system performance, offering superior controllability and rapid response compared to traditional methods (Relic *et al.*, 2025; Olaogun *et al.*, 2024a). Conventional or traditional approaches such the use of Mechanical switches, creation of more generation plants and transmission lines, capacitor banks among others were initially employed in the past for power system enhancement (Nguyen, 2020). However, these methods often faced with challenges, which include but not limited to delayed responses, high maintenance costs, significant capital investments, right of way, environmental impacts, and wear and tear on mechanical components (Olaogun *et al.,* 2024b).

These limitations necessitate the introduction of FACTS controllers in power systems (Onah.*et al*., 2020). FACTS devices, which are based on solid-state and power electronics technology, enable rapid control of operating conditions offers benefits such as increased system stability, loadability, and power transfer capacity without necessitating additional generators or new transmission lines. The device maximises the effective use or utilization of existing transmission facilities, enhance system security and reliability, and provide the flexibility needed for integrating new generation sources, potentially deferring the need for new transmission infrastructure (Barua *et al.,* 2021). Since their introduction in 1995, FACTS devices have proven capable of addressing key issues such as power flow management, voltage regulation, and stability improvements in both steady state and transient conditions (Rani and Popuri, 2020).

The integration of FACTS devices has also been associated with improved energy efficiency during fault conditions (Barua *et al.,* 2021; Khan *et al.,* 2017). They help maintain system stability, reduce power factor fluctuations, and rapidly compensate for active and reactive power demands in electrical networks (Behzadpoor *et al.,* 2022; Yadav *et al*., 2015). According to the Institute of Electrical and Electronics Engineers, FACTS encompasses solid-state and static controllers that enhance power transfer capabilities in AC transmission systems (Udo and Aminu, 2019). The widespread acceptance of FACTS technology is attributed to its rapid response, cost-effectiveness, and its ability to enhance system reliability, security, and efficiency (Adebisi *et al*., 2018; Jokojeje *et al.,* 2015b).

X-raying some existing literature revealed that the FACTS family which includes several notable controllers such as Unified Power Flow Controller (UPFC), Static Synchronous Series Capacitor (SSSC), Thyristor Controlled Series Capacitor (TCSC), Static Var Compensator (SVC), and Static Synchronous Compensator (STATCOM) are widely employed for power system enhancement globally (Relic *et al* 2025; Deebom *et al*., 2024; Singh *et al*., 2024; Behzadpoor *et al.,* 2022; Goel and Gupta 2022; Anichebe and Ekwue, 2020; Mai *et al*., 2018; Noaman *et al*., 2017; Sheetal and Heeman, 2016;).

Among these FACTS family, a device like STATCOM stands out for its effectiveness in voltage regulation and reactive power compensation (Ali and Yadav 2024). This capability is crucial in maintaining system reliability and performance, especially during fault conditions. Its versatility enables tailored solutions to specific challenges in power systems, enhancing the choice of these technologies especially as energy demands rise and systems become increasingly complex, such as in smart grids, renewable energy integration, and decentralized generation, Nevertheless, each controller possesses unique characteristics that make it particularly well suited for specific applications within modern power networks (Singh *et al*.,2024).

There has been so many efforts put towards performance enhancement of the Nigerian electricity grids with some promising outcomes using different techniques, however, the growing population, rapid industrialization, and advancing technology continue to place increasing pressure on energy delivery system, this underscores the need for continuous performance monitoring and system enhancement, otherwise, the system may suffer collapse, once the operational limit becomes violated.(Alayande *et al*., 2024; Fawzy *et al*., 2024; Kumar *et al*., 2024; Deeboom *et al*., 2024; Salleh *et al*., 2024a; Salleh *et al*;., 2024b; Fombu *et al.,* 2024; Vishwanathan *et al.,* 2024; Ahmed *et al* 2023, Nakka *et al* 2023; Liaqat *et al*., 2023; Moe and Myint 2022, Anichebe and Ekwe 2020; Adebisi *et al*., 2018; Jokojeje *et al*., 2015)

For this research, the goal is to use STATCOM for performance enhancement of the Nigerian 330 kV, 34-bus power network where the existing transmission system is being over-burdened than the initial designed capacity due to the ever-growing demand for electrical energy (Deebom *et al.,* 2024; Shrivastava *et al*., 2021; Adebisi *el al.,* 2018), furthermore, to improve the utilization of existing infrastructure within the power system, leading to more efficient and reliable operation thereby avoiding the need for new generation units or additional transmission lines (Sarwar et al., 2023).

2. STATIC SYNCHRONOUS COMPENSATOR

According to Alhamrouni *et al*. (2020), STATCOM is described by IEEE as self-commutated switching power converter supplied from an appropriate electric energy source and operated to produce a set of adjustable multiphase voltage, which may be coupled to an AC power system for the purpose of exchanging independently controllable real and reactive power. STATCOM is a shunt controller usually deployed to compensate reactive power in electricity grids in a way that the device's output is being adjusted to manage various aspects of the grid systems. STATCOM, at the system fundamental frequency, produces three sets of balanced sinusoidal voltages with amplitude and phase adjustment (Sharan *et al*., 2019). Essentially, STATCOM comprises a coupling transformer, a DC capacitor and a voltage source converter (VSC) as delineated in Figure 1. It is used for voltage support in power network when a voltage drop occurs. According to Gadupudia and Rao (2021), STATCOM has the following operation characteristics of Fast response to provide reactive power and hence manage voltage disturbances, low maintenance, good harmonic performance, low noise generation and low associated magnetic fields.

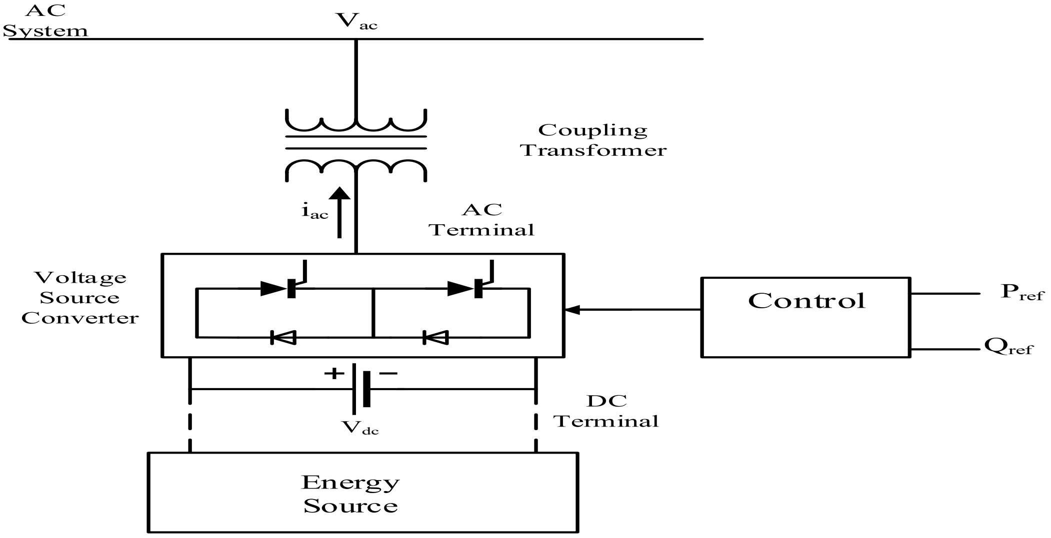


Figure 1: Structure of a STATCOM (Gadupudia and Rao, 2021)

3. METHODOLOGY

3.1. The Power Flow Formulation

In load flow analysis, loads and sources are defined in terms of power while power network components such as branches, transformers, and circuits are represented as impedances (Weedy, 2012). Power flow studies, often referred to as load flow studies, serve as the backbone of power system analysis and design. These studies are essential for operations, planning, economic scheduling, and power exchange between utilities, in addition, power flow analysis is also crucial for various other assessments, including transient stability and contingency studies (Kothari and Nagrath, 2009; Hadi, 2007). Power flow studies provide a systematic mathematical framework for determining bus voltages, active and reactive power flows through branches, phase angles, and load or generator characteristics under steady-state conditions. This analysis is a vital mathematical tool for obtaining detailed insights into the performance of power systems (Gupta, 2011; Glover and Sarma, 2001).

Consider a typical power system bus arrangement in Figure 2, which serves as the basis for the power flow analysis. Applying Kirchhoff's Current Law (KCL) to the n-bus arrangement in Figure 2 leads to equations that describe the resultant current and the complex apparent power delivered at bus i. Application of KCL to the bus system in Figure 2 yields equation (1) to (4) (Gupta, 2011; Kothari and Nagrath, 2008; Hadi, 2007, Glover and Sarma, 2001):

$$I_i = y_{i0}V_i + y_{i1}(V_i - V_1) + y_{i2}(V_i - V_2) + \cdots + y_{in}(V_i - V_n) \tag{1}$$

$$I_i = (y_{i0} + y_{i1} + y_{i2} + \cdots + y_{in})V_i - y_{i1}V_1 - y_{i2}V_2 - \cdots - y_{in}V_n \tag{2}$$

$$I_i = V_i \textstyle\sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij}V_j \qquad j \neq i \tag{3}$$

$$I_i = \textstyle\sum_{j=1}^{n} Y_{ij}V_j \tag{4}$$

where I_i, V_i, y_{ij}, Y_{ij} and V_j respectively denote supplied current at bus *i*, voltage at bus *i*, admittance of line *i-j*, element of bus admittance derived from admittance of line *i-j* and voltage of bus *j*.

The use of polar form of Y_{ij} and V_j in equation (4), produced equation (5):

$$I_i = \textstyle\sum_{j=1}^{n} |Y_{ij}||V_j|\angle\theta_{ij} + \delta_j \tag{5}$$

where $|Y_{ij}|$, $|V_j|$, θ_{ij} and δ_j denote magnitude of admittance of line *i-j*, magnitude of voltage at bus j, angle of admittance of line *i-j* and angle of voltage at bus j.

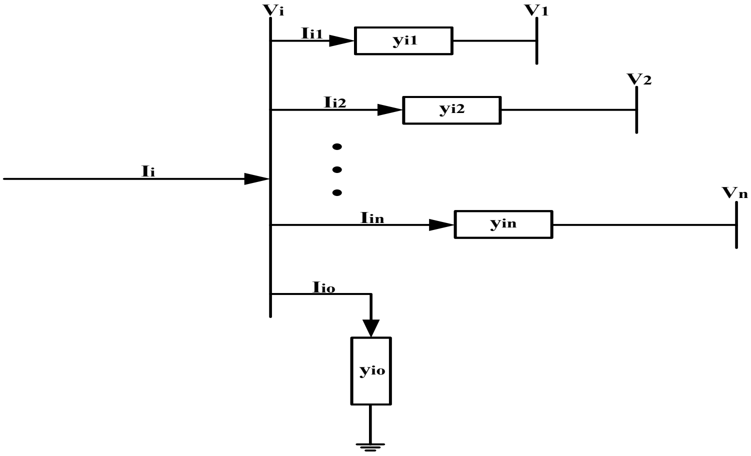


Figure 2: A typical power system n-bus arrangement (Gupta, 2011; Kothari and Nagrath, 2008; Hadi, 2008 Glover and Sarma, 2001)

The supplied power at bus i takes an expression of equation (6):

$$P_i - jQ_i = V_i^* I_i \tag{6}$$

Where P_i and Q_i respectively represent bus i active and reactive powers.

Substitution of equation (5) into equation (6) and decoupling into real and imaginary components produced equations (7) and (8):

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| cos(\theta_{ij} + \delta_{ij}) \tag{7}$$

$$Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}| sin(\theta_{ij} + \delta_{ij}) \tag{8}$$

with $\delta_{ij} = \delta_j - \delta_i$ (9)

Equations (7) and (8) are the static power flow expressions which govern the steady state response of a power system. They are non-linear equations solved via numerical iterative method. These equations were implemented in this study using Newton-Raphson method because of its faster convergence rate, accuracy, and reliability in comparison to other iterative methods (Gupta, 2011; Kothari and Nagrath, 2008; Hadi, 2007; Glover and Sarma, 2001). The Newton- Raphson based power equations arising from the linearization of equations (7) and (8) are expressed by equation (10):

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \tag{10}$$

where J_1, J_2, J_3 and J_4 are the elements of the Jacobin matrix, ΔP, ΔQ, $\Delta \delta$ and $\Delta |V|$ are respectively active power, reactive power, bus voltage angle and bus voltage magnitude mismatches.

The ΔP, ΔQ, $\Delta \delta$, $\Delta |V|$, J_1, J_2, J_3 and J_4 are expressed by equations (11) to (18):

$$\Delta P = \begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \end{bmatrix} \tag{11}$$

$$\Delta Q = \begin{bmatrix} \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} \tag{12}$$

$$\Delta \delta = \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_n^{(k)} \end{bmatrix} \tag{13}$$

$$\Delta |V| = \begin{bmatrix} \Delta \left|V_2^{(k)}\right| \\ \vdots \\ \Delta \left|V_n^{(k)}\right| \end{bmatrix} \tag{14}$$

$$J_1 = \begin{bmatrix} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} \end{bmatrix} \tag{15}$$

$$J_2 = \begin{bmatrix} \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \end{bmatrix} \tag{16}$$

$$J_3 = \begin{bmatrix} \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} \end{bmatrix} \tag{17}$$

$$J_4 = \begin{bmatrix} \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{bmatrix} \tag{18}$$

The active and reactive powers mismatches at kth iteration and new estimates of the bus voltage angle and magnitude are expressed respectively by equations (19) and (22):

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)} \tag{19}$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)} \tag{20}$$

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta \delta_i^{(k)} \tag{21}$$

$$V_i^{(k+1)} = \left|V_i^{(k)}\right| + \Delta \left|V_i^{(k)}\right| \tag{22}$$

The voltage and reactive power constraints imposed at bus *i* are expressed by equations (23) and (24) respectively:

$$V_{imin} \leq V_i \leq V_{imax} \tag{23}$$

$$Q_{imin} \leq Q_i \leq Q_{imax} \tag{24}$$

where V_{imin}, V_{imax}, Q_{imin} and Q_{imax} respectively denotes minimum voltage magnitude, maximum voltage magnitude, minimum reactive power supply and maximum reactive power supply at bus *i*.

3.2. Power Flow Model of STATCOM for Performance Improvement

The power flow equations describing the compensating capability of STATCOM as voltage source converter in this study are derived based on the architecture in Figure 3. The equations guiding the operation of STATCOM are expressed by equations (25) to (29) with matrix in equation (30) giving the linearized Newton-Raphson model of STATCOM applying these equations.

$$E_{vR} = V_{vR}(cos\delta_{vR} + jsin\delta_{vR}). \tag{25}$$

$$P_{vR} = V_{vR}^2 G_{vR} + V_{vR}V_k[G_{vR}cos(\delta_{vR} - \theta_k) + B_{vR}sin(\delta_{vR} - \theta_k)] \tag{26}$$

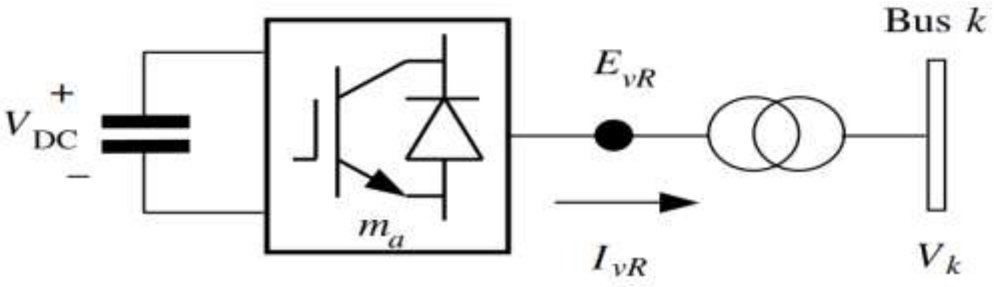
$$Q_{vR} = -V_{vR}^2 B_{vR} + V_{vR}V_k[G_{vR}sin(\delta_{vR} - \theta_k) + B_{vR}cos(\delta_{vR} - \theta_k)] \tag{27}$$

$$P_k = V_k^2 G_{vR} + V_k V_{vR}[G_{vR}cos(\theta_k - \delta_{vR}) + B_{vR}sin(\theta_k - \delta_{vR})] \tag{28}$$

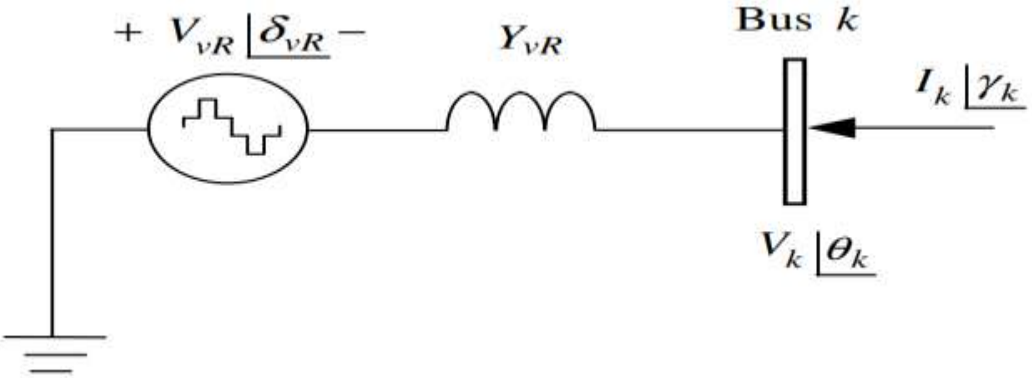
$$Q_k = -V_k^2 B_{vR} + V_k V_{vR}[G_{vR}sin(\theta_k - \delta_{vR}) + B_{vR}cos(\theta_k - \delta_{vR})] \tag{29}$$

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \\ \Delta P_{vR} \\ \Delta Q_{vR} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial |V_k|}|V_k| & \frac{\partial P_k}{\partial \delta_{vR}} & \frac{\partial P_k}{\partial |V_{vR}|}|V_{vR}| \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial |V_k|}|V_k| & \frac{\partial Q_k}{\partial \delta_{vR}} & \frac{\partial Q_k}{\partial |V_{vR}|}|V_{vR}| \\ \frac{\partial P_{vR}}{\partial \theta_k} & \frac{\partial P_{vR}}{\partial |V_k|}|V_k| & \frac{\partial P_{vR}}{\partial \delta_{vR}} & \frac{\partial P_{vR}}{\partial |V_{vR}|}|V_{vR}| \\ \frac{\partial Q_{vR}}{\partial \theta_k} & \frac{\partial Q_{vR}}{\partial |V_k|}|V_k| & \frac{\partial Q_{vR}}{\partial \delta_{vR}} & \frac{\partial Q_{vR}}{\partial |V_{vR}|}|V_{vR}| \end{bmatrix} \begin{bmatrix} \Delta\theta_k \\ \frac{\Delta|V_k|}{|V_k|} \\ \Delta\delta_{vR} \\ \frac{\Delta|V_{vR}|}{|V_{vR}|} \end{bmatrix} \tag{30}$$

where E_{vR}, V_{vR}, δ_{vR}, P_{vR}, Q_{vR}, P_k, Q_k and V_k respectively denote variable voltage source, controllable voltage magnitude, source phase angle, active power supplied by the shunt converter, reactive power supplied by the shunt converter, active power at bus *k*, reactive power at bus *k* and voltage at bus *k*.



(a)



(b)

Figure 3: STATCOM architecture (a) Schematic diagram (b) Thevenin's equivalent circuit (Onah et al 2020)

3.3. Choice of Simulation Software

For the implementation of load flow and transient stability analysis in this study, MATLAB software was utilized. This powerful tool is widely used in engineering and scientific research and offers numerous features beneficial for power system studies, includes; Robust features for simulating complex power system dynamics, the ability to create adaptable models tailored to specific system configurations, support for designing and testing control strategies, tools for analyzing results and visualizing system performance, compatibility with additional software and tools for enhanced functionality, access to a wealth of community knowledge and documentation.

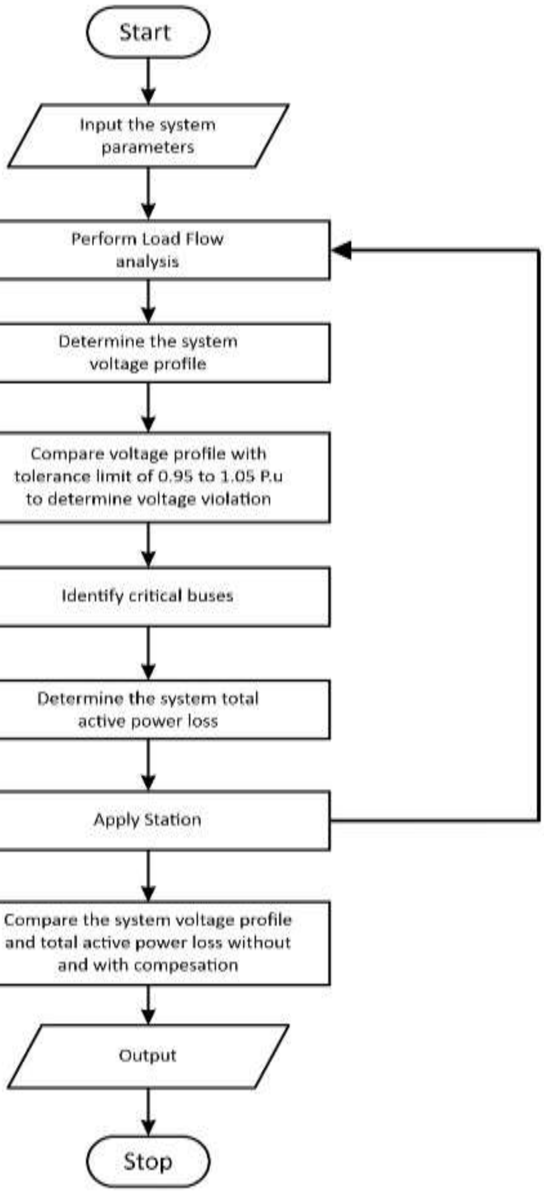


Figure 4: The flowchart for Simulation Procedure

3.4. Test Network

The study considered a test case based on the 14-machine, 34-bus model of the Nigerian 330 kV power network. A one-line diagram of the system is shown in Figure 2, with relevant data provided in Tables 1-3.

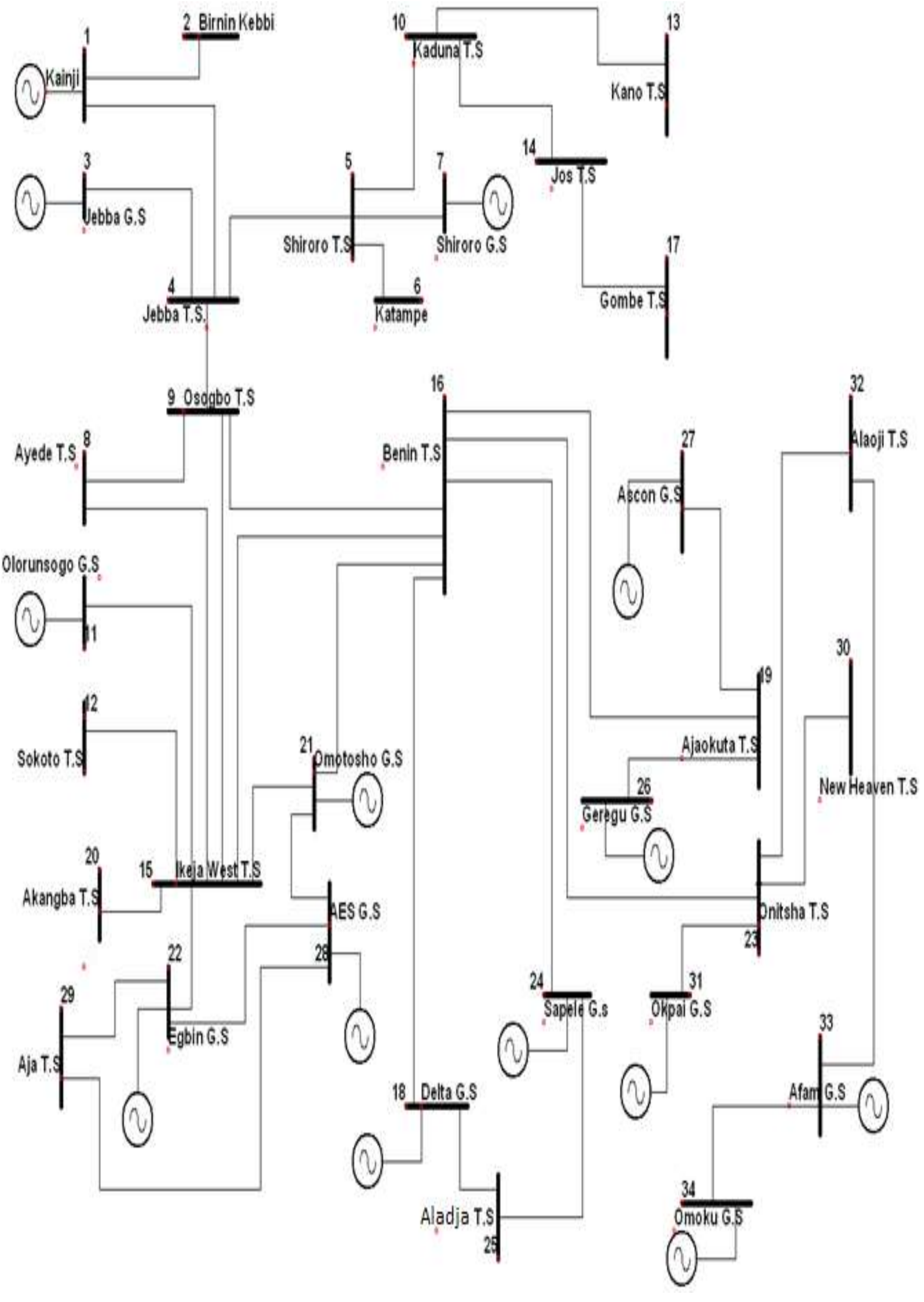


Figure 5: Nigerian 14-machine, 34-bus power network. (Olaogun *et al.*, 2024)

Table 1: Bus Parameters of the Nigeria 34-Bus, 330 kV Power System Network

Bus No	Bus Type	Pd (MW)	Qd (MVAr)	Vm (p.u.)	Vmax (p.u.)	Vmin (p.u.)
1	3	00.00	00.00	1.06	1.05	0.95
2	1	40.00	- 10.00	1.0	1.05	0.95
3	2	00.00	00.00	1.04	1.05	0.95
4	1	140.00	30.00	1.0	1.05	0.95
5	1	90.00	30.00	1.0	1.05	0.95
6	1	160.00	70.00	1.04	1.05	0.95
7	2	00.00	00.00	1.0	1.05	0.95
8	1	130.00	70.00	1.0	1.05	0.95
9	1	300.00	90.00	1.0	1.05	0.95
10	1	210.00	40.00	1.02	1.05	0.95
11	2	00.00	00.00	1.0	1.05	0.95
12	1	50.00	-20.00	1.0	1.05	0.95
13	1	100.00	-30.00	1.0	1.05	0.95
14	1	120.00	60.00	1.0	1.05	0.95
15	1	500.00	50.00	1.0	1.05	0.95
16	1	250.00	43.00	1.0	1.05	0.95
17	1	70.00	38.00	1.0	1.05	0.95
18	2	00.00	00.00	1.03	1.05	0.95
19	1	200.00	55.00	1.0	1.05	0.95
20	1	150.00	35.00	1.0	1.05	0.95
21	2	00.00	00.00	1.02	1.05	0.95
22	2	00.00	00.00	1.05	1.05	0.95
23	1	300.00	45.00	1.0	1.05	0.95
24	2	00.00	00.00	1.04	1.05	0.95
25	1	100.00	58.00	1.0	1.05	0.95
26	2	00.00	00.00	1.01	1.05	0.95
27	2	00.00	00.00	1.03	1.05	0.95
28	2	00.00	00.00	1.02	1.05	0.95
29	1	120.00	80.00	1.0	1.05	0.95
30	1	130.00	-78.00	1.0	1.05	0.95
31	2	00.00	00.00	1.03	1.05	0.95
32	1	200.00	67.00	1.0	1.05	0.95
33	2	00.00	00.00	1.04	1.05	0.95
34	2	00.00	00.00	1.02	1.05	0.95

Table 2: Generator Parameters of the Nigeria 34-Bus, 330 kV Power System Network

Bus No	Pg (MW)	Qg (MVAr)	Qmax (MVAr)	Qmin (MVAr)	Vg (p.u.)	R (p.u.)	X (p.u.)	H
1	00.00	00.00	0	0	1.05	0.0020	0.0901	9.920
3	300.00	40.00	110	0	1.04	0.0080	0.3000	3.390
7	400.00	60.00	140	0	1.0	0.0240	0.3000	3.240
11	150.00	50.00	114	0	1.0	0.0036	0.2200	4.000
18	280.00	45.00	100	0	1.03	0.0020	0.1240	12.400
21	240.00	55.00	104	0	1.02	0.0036	0.2200	4.000
22	700.00	68.00	108	0	1.05	0.0040	0.3080	3.090
24	180.00	00.00	132	0	1.04	0.0030	0.1060	12.690
26	190.00	-35.00	126	0	1.01	0.0061	0.3400	1.245
27	150.00	51.00	100	0	1.03	0.0036	0.3000	1.242
28	130.00	80.00	150	0	1.02	0.0051	0.2100	1.249

31	150.00	00.00	100	0	1.03	0.0061	0.3000	4.000
33	200.00	59.00	140	0	1.04	0.0010	0.0610	28.050
34	300.00	65.00	125	0	1.02	0.0051	0.1900	1.350

Table 3: Branch Parameters of the Nigeria 34-Bus, 330 kV Power System Network

From Bus	To Bus	R (p.u.)	X (p.u.)	B (p.u.)
1	2	0.0121836	0.0916336	1.21
1	4	0.0015918	0.0119716	0.31
3	4	0.0001572	0.0094178	0.00
4	5	0.0047827	0.0360219	0.09
4	9	0.0020565	0.0154692	0.07
5	6	0.0018864	0.0141884	0.36
5	7	0.0003144	0.0188355	0.00
5	10	0.0018864	0.0141884	0.37
8	9	0.0053843	0.0404961	0.33
8	15	0.0053343	0.0405651	0.45
9	15	0.0065432	0.0426547	0.55
9	16	0.0098648	0.0741936	0.98
10	13	0.0090394	0.0679862	0.52
10	14	0.0077425	0.0582316	0.77
11	15	0.0020643	0.0103951	0.31
12	15	0.0040534	0.0305160	0.41
14	17	0.0104150	0.0783319	0.01
15	16	0.0110045	0.0827653	0.09
15	20	0.0003527	0.0026574	0.05
15	21	0.0055023	0.0413829	0.35
15	22	0.0012184	0.0091634	0.20
16	18	0.0063843	0.0404961	0.15
16	19	0.0038336	0.0288242	0.76
16	21	0.0055023	0.0413829	0.55
16	23	0.0053843	0.0404961	0.38
16	24	0.0009826	0.0073898	0.19
18	25	0.0010218	0.0076553	0.10
19	26	0.0005109	0.0038427	0.38
19	27	0.0006105	0.0038427	0.40
22	28	0.0005109	0.0036458	0.30
22	29	0.0002749	0.0020654	0.20
23	30	0.0037730	0.0283768	0.37
23	31	0.004913	0.0036949	0.09
23	32	0.00605225	0.0455212	0.02
24	25	0.0024760	0.0186223	0.24
28	29	0.0034640	0.0206114	0.30
32	33	0.0009825	0.0073898	0.09
33	34	0.0005109	0.0038427	0.30

4. RESULTS AND DISCUSSION

4.1. Nigerian 34-Bus Network Load Flow Results

The results of Nigerian 34-bus network load flow study before enhancement are indicated in Figure 6 and 7. Figure 6 depicts the system's voltage profile while the total active line losses are respectively given by Figure 7. It was observed from Figure 6 that five buses violated voltage statutory limit of 0.95 to 1.05 p.u. These buses are Katampe (6), Kaduna T.S (10), Kano T.S (13), Jos T.S (14) and Gombe T.S (17) with voltage magnitudes of 0.9373, 0.9209, 0.9381, 0.8295 and 0.7795 respectively falling out of the desired voltage range for normal operation of the network. However, application of STATCOM to the system enhanced the voltage magnitudes on Katampe, Kaduna T.S, Kano T.S, Jos and Gombe to 0.9650, 0.9550, 0.97890, 0.9630 and 0.9550 p.u. respectively, representing an increase of 2.9, 3.71, 4.089, 16.11 and 22.5% respectively. The system total active power losses before compensation as observed from Figures 7 was 57.887 MW and was reduced to 55.623 MW, after compensation was applied; representing 4.07 % reduction respectively in the network total active line losses. The voltage magnitudes on these constrained buses were improved and fell within the statutory voltage limit for effective operation of the system through the compensation provided by STATCOM.

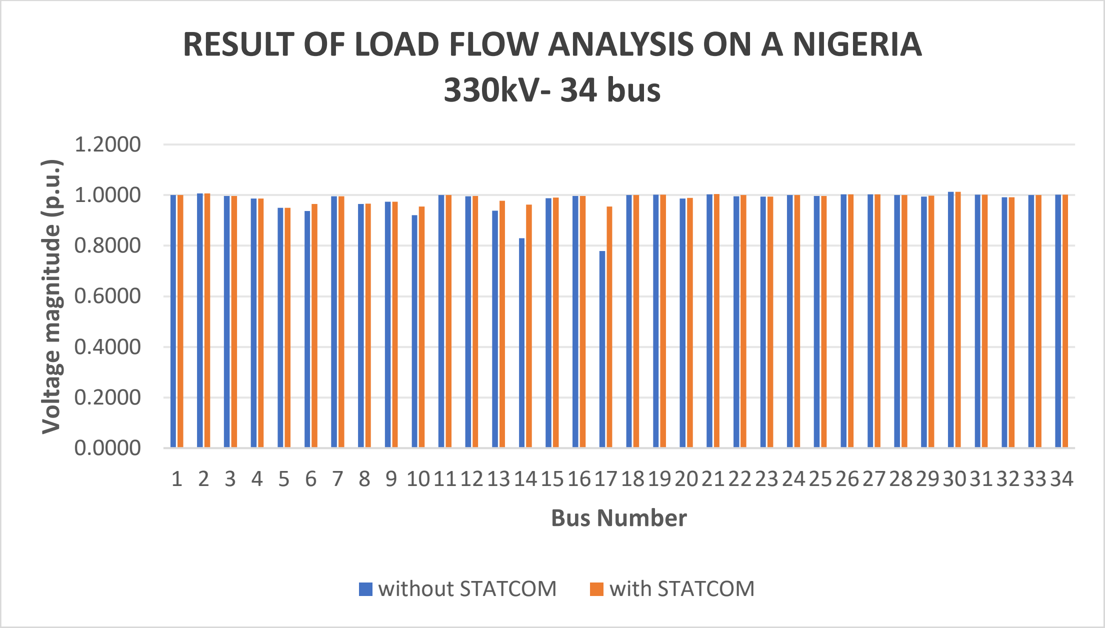


Figure 6: Voltage magnitudes of the Nigeria 34-bus power network

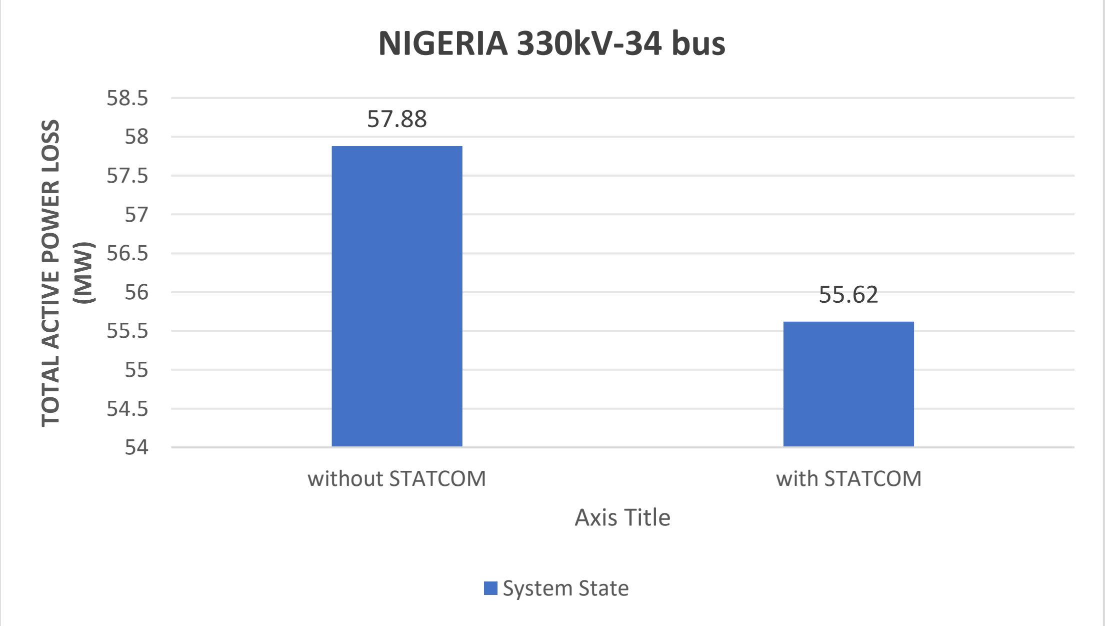


Figure 7: Total active power loss of the Nigeria 34-bus power network

4.2. General Discussion of the Results

This research focused on assessing the Nigerian 330 kV, 34-bus power grid both with and without compensation. Load flow analysis was conducted to evaluate the grid's steady-state performance before and after the introduction of compensation. The results indicated that five buses in the Nigerian 34-bus grid—Katampe (6), Kaduna T.S (10), Kano T.S (13), Jos T.S (14), and Gombe T.S (17)—had voltage magnitudes of 0.9373, 0.9209, 0.9381, 0.8295, and 0.7795, respectively, which fell outside the statutory voltage limits of 0.95 to 1.05 p.u. The installation of a STATCOM on the grid significantly improved the voltage magnitudes at these buses, raising them to 0.9650, 0.9550, 0.9789, 0.9630, and 0.9550 p.u., respectively. This represents percentage increases of 2.90%, 3.71%, 4.09%, 16.11%, and 22.51% in voltage levels with the application of STATCOM.

Before the STATCOM was incorporated, the total active line losses in the Nigerian 34-bus grid amounted to 57.887 MW. After the installation, these losses decreased to 55.623 MW, indicating an improvement of 3.91% in the grid's active line loss. The overall enhancement in the steady-state performance of the Nigerian 34-bus power grid can be attributed to the effective compensating capabilities of the STATCOM. This device successfully injected reactive power into the network, addressing deficiencies at various points, thereby improving voltages and minimizing both total active and reactive power losses.

5. CONCLUSION

This research examined the performance enhancement of power system networks with STATCOM, a FACTS controller, with the Nigerian 330 kV 34-bus electricity grid serving as the test network. The load flow results revealed that five buses—Katampe (6), Kaduna T.S (10), Kano T.S (13), Jos T.S (14), and Gombe T.S (17)—initially exhibited voltage magnitudes below the acceptable limit of 0.95 to 1.05 p.u. However, with the implementation of STATCOM, these voltage magnitudes improved to 0.9650, 0.9550, 0.9789, 0.9630, and 0.9550 p.u., reflecting increases of 2.90%, 3.71%, 4.09%, 16.11%, and 22.51%, respectively. The total active power loss also decreased from 57.887 MW to 55.623 MW with the inclusion of STATCOM, resulting in a 3.91% reduction in total active power loss. The results underscore that deploying quick-acting compensating devices like STATCOM can lead to enhanced and cost-effective performance in power systems. Similarly, the implementation of STATCOM in the Nigerian electricity grid could not only improve the system voltage profile but also increase the power transfer capability.

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AI-Driven Secured Unit Commitment in Microgrids with Renewable Energy Sources

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Abstract: The escalating global energy crisis and rising electricity costs demand efficient energy management in microgrid systems. While renewable energy sources such as Solar Photovoltaic (PV) and Pumped Hydro Energy Storage Systems (PHESS) offer cleaner alternatives to fossil fuels, their intermittent nature poses challenges for reliable power supply. This study presents an optimized unit commitment framework for a secured hybrid microgrid integrating Solar PV, PHESS, utility grid supply, and a diesel generator. To address the complexity of energy source variability and load fluctuations, computational intelligence techniques; Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA), and hybrid models (PSO-GA and PSO-SA) were implemented in Python. An electronic synchronizer was incorporated to enhance system stability and power flow coordination. Simulation results revealed that the hybrid PSO-SA algorithm achieved the lowest operational cost (₦1,246,765.58) and CO_2 emissions (₦10,695.87), outperforming the other techniques. The analysis demonstrated the effectiveness of Solar PV and PHESS in reducing dependence on diesel generators and public utility supply. Load dispatch patterns highlighted the algorithms' ability to adaptively balance supply and demand across varying timeframes. This work underscores the potential of computational intelligence in optimizing microgrid performance, with implications for sustainable and cost-effective energy management. Future research will focus on parameter optimization and advanced hybridization to further enhance system efficiency.

Keywords: *Microgrid Energy Management, Unit Commitment Optimization, Computational Intelligence, Hybrid Renewable Energy Systems, PSO-SA Algorithm, Solar PV and PHESS Integration*

1. INTRODUCTION

1.1 Background of the Study

The global increase in energy demand, coupled with persistent power shortages and rising electricity costs, has intensified the need for efficient and sustainable energy management strategies. Conventional power generation methods, heavily reliant on fossil fuels, significantly contribute to greenhouse gas emissions such as carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and hydrocarbons thereby exacerbating environmental degradation and accelerating climate change (Kalu et al., 2024). In response to these concerns, microgrid systems that integrate renewable energy technologies such as Solar Photovoltaic (PV) and Pumped Hydro Energy Storage Systems (PHESS) alongside conventional energy sources like diesel generators and utility supply have gained prominence (Gao et al., 2021). Microgrids provide a decentralized approach to power generation, offering enhanced energy accessibility, reliability, and resilience while reducing dependence on centralized grid systems. However, managing unit commitment in such hybrid energy environments is a complex task due to the variability and intermittency inherent in renewable energy sources and the stochastic nature of load demand (Bilal et al., 2024). Efficient scheduling of energy resources is critical to achieving cost optimization, minimizing pollutant emissions, and maintaining system stability. Traditional optimization techniques often lack the computational robustness required to address these multi-objective challenges effectively. Consequently, advanced computational intelligence (CI) techniques including Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA), and their hybrid variants (PSO-GA and PSO-SA) have emerged as promising tools for addressing the unit commitment problem in modern microgrids (Xing & Jia, 2023). In hybrid microgrid systems, the absence of proper synchronization among diverse energy sources can result in power flow inconsistencies, increased fuel usage, and elevated emissions. The integration of an electronic synchronizer plays a pivotal role in maintaining system stability by ensuring seamless coordination, reducing transient switching effects, and enhancing power flow management (Punitha et al., 2024). This study aims to develop a secured unit commitment framework that leverages CI-based optimization techniques to reduce operational costs and greenhouse gas emissions while ensuring reliable and stable microgrid operation. It contributes to the broader objective of smart energy management by promoting the efficient utilization of renewable energy resources and environmentally sustainable solutions (International Energy Agency [IEA], 2024). The dominance of thermal power in conventional electricity generation is rapidly declining in favor of renewable energy, which accounted for 81% of newly installed global power capacity in 2021 and is projected to reach 40% of total electricity generation by 2030 (Chen et al., 2023). This paradigm shift introduces increased complexity to power systems due to the geographically distributed nature and diverse temporal characteristics of renewable sources. Existing scheduling techniques often struggle to coordinate these heterogeneous systems effectively, resulting in renewable energy curtailment, grid congestion, and supply reliability issues. The challenge lies in the need for multi-scale optimization across long-term planning, short-term scheduling, and real-time operation to manage the dynamic output profiles of solar, wind, hydro, and storage systems efficiently. In the African context, particularly in Nigeria, the deployment of microgrids, mini-hydro plants, and solar home systems offers a viable path toward energy security, economic development, and environmental sustainability. Investments in these technologies are essential for improving living standards, fostering academic and research activities, and mitigating the effects of climate change (Adeyinka & Ainah, 2024; Akindele, 2024). Despite their promise, the integration of multiple energy sources in microgrids presents operational and optimization challenges, as highlighted by Basit et al. (2020), Yu et al. (2023), and Ibrahim (2024). To overcome issues of intermittent power supply, energy storage technologies such as PHESS are employed to store excess energy during periods of low demand and discharge it during peak loads. Additionally, the integration of solar PV, diesel generators, and public grid supply is leveraged to ensure a balanced, reliable, and efficient energy mix (Jafarizadeh, 2024; De Carne et al., 2024). To enhance the scheduling efficiency of these systems, a range of metaheuristic optimization algorithms including Ant Colony Optimization (ACO), SA, PSO, GA, and their hybrid models; have been proposed in the literature, with the goal of achieving optimal dispatch strategies in terms of cost, reliability, and environmental impact (Gupta & Srivastava, 2020).

1.2 Aim and Objectives

The primary aim of this study is to develop an optimized unit commitment framework for a secured hybrid microgrid system integrating Solar Photovoltaic (PV), Pumped Hydro Energy Storage System (PHESS), utility grid supply, and a diesel generator. The proposed framework employs advanced computational intelligence techniques namely Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA), and their hybrid variants (PSO-GA and PSO-SA) to minimize operational costs and pollutant emissions while maintaining system reliability and stability through the integration of an electronic synchronizer.

To achieve this aim, the study pursues the following specific objectives:

i. To formulate a unit commitment optimization model for a microgrid system comprising Solar PV, PHESS, utility supply, and diesel generation sources.
ii. To incorporate an electronic synchronizer within the microgrid framework to enhance system stability, mitigate switching transients, and improve power flow coordination.
iii. To implement and simulate the developed model using computational intelligence techniques (GA, PSO, SA, PSO-GA, and PSO-SA) for solving the unit commitment problem.
iv. To assess and compare the performance of the optimization algorithms based on operational cost reduction, emission minimization, and algorithmic convergence behavior.
v. To identify the most effective computational intelligence approach that achieves an optimal trade-off between cost efficiency, environmental sustainability, and system reliability within a microgrid context.

2. LITERATURE REVIEW

2.1 Fundamental Concept of Unit Commitment

Unit Commitment (UC) in power systems is defined as the strategic planning of power plant operations to meet fluctuating demand while effectively managing costs and maintaining necessary reserves (Abdou &Tkiouat, 2018; Yang &Wu, 2021). To enhance UC planning and address the inherent uncertainties of renewable energy, particularly in grid operations, Salman & Kusaf (2021) investigated the application of machine learning for improved wind power forecasting.

2.2 Hybrid Power System Modeling and Cost Analysis

This section provides a comprehensive modeling and cost analysis of a hybrid power system, which integrates a micro pumped hydro energy storage (PHES) system, solar photovoltaic (PV), diesel generators, and a public utility supply. The mathematical models for each component, encompassing their operational characteristics and associated quadratic cost functions, are detailed. The seamless operation of this integrated system is ensured through the incorporation of an electronic synchronizer. Furthermore, the environmental impact of the system is assessed by quantifying pollutant emissions, thereby laying the groundwork for the application of computational intelligence techniques to optimize the system's overall performance, balancing economic efficiency, operational reliability, and environmental sustainability.

Researchers are extensively exploring unit commitment (UC) optimization in hybrid energy systems, particularly focusing on efficient renewable integration. Lu *et al*. (2025) address bidding and revenue, while Eriksson *et al*. (2019), Lofti & Nikkah (2024), and Kant *et al*. (2024) investigate various optimization algorithms. However, these studies consistently acknowledge the need for further research on managing uncertainties from renewable sources and demand response. Wang et al. (2018) and Hou et al. (2023) introduced novel methodologies, advocating for more validation. Sun et al. (2023) further contributes to this growing field of UC optimization.

Syama *et al*. (2020)'s hybrid optimization for UC-CEED needed more detailed analysis of computational complexity and robustness. Pelusi *et al*. (2020)'s Improved Moth-Flame Optimization (IMFO) effectiveness was problem-dependent. Anyaka *et al*. (2020)'s PSO application for UC lacked comprehensive evaluation. Moretti *et al*. (2020)'s robust optimization model for day-ahead scheduling faced computational efficiency challenges. Marcelino *et al*. (2020)'s MESH hybrid algorithm for hydro-power UC lacked comprehensive scalability analysis. Rendroyoko *et al*. (2020)'s hybrid optimization for microgrids was limited by a single case study.

Ranganathan *et al*. (2021)'s SAFA for UC lacked comprehensive analysis of its advantages and limitations. Bakirtzis *et al*. (2021)'s demand response framework for renewables neglected real-world challenges. Das *et al*. (2021)'s microgrid scheduling optimization lacked robustness and scalability analysis. Jia *et al*. (2021)'s cooperative game theory approach for multi-microgrids had potential computational burden. Tian *et al*. (2021)'s hybrid power generation system optimization for a remote village lacked generalizability and comparative analysis. Sayed *et al*. (2021)'s hybrid MPSO-EO for UC lacked explicit discussion of computational complexity.

Montero et al. (2022) reviewed UC, providing a broad overview without in-depth comparative analysis. Fateh *et al*. (2022) reviewed optimization for Virtual Power Plants (VPPs) with renewables, lacking consideration for heat load and tool explanations. Bolurian *et al*. (2022)'s microgrid scheduling model lacked comprehensive performance analysis and uncertainty consideration. Aldosari *et al*. (2022)'s KHA-based multi-objective optimization model for microgrids had potentially limited generalizability. Ang et al. (2022)'s multi-objective optimization for hybrid renewable energy systems faced challenges in achieving high penetration. deMars *et al*. (2022)'s Guided A* search for UC needed further validation. Garlik (2022)'s AI-based method for energy sustainability in cities had limited applicability. Hosseini-Firouz et al. (2022)'s UC model with wind uncertainty relied on a deterministic approach. Zuniga et al. (2022)'s robust UC model had potential computational complexity and data requirements.

Aharwar *et al*. (2023) reviewed the UC problem but provided a general overview. Cordera *et al*. (2023)'s multistage stochastic dynamic programming for UC was limited by a small-scale system. Abuelrub *et al*. (2023)'s modified AVOA for UC with wind lacked other uncertainty considerations. Hayat et al. (2023)'s hybrid PSO-VNS-SA for scheduling had a single objective focus. Islam & Roy (2023) reviewed intelligent techniques in renewable energy systems, but lacked discussion on challenges. Suhail *et al*. (2023)'s hybrid HMFPSO for transmission line parameter estimation lacked explicit discussion of limitations. Zhang *et al*. (2023)'s integrated energy system UC model with P2G and CVaR had limited scope and high data requirements.

Ji (2024)'s two-layer optimization model for hybrid renewable energy systems needed comprehensive validation. Xiao *et al*. (2024)'s robust optimization for wind-solar storage systems did not fully discuss computational complexity. Mena *et al*. (2024)'s multi-objective UC model for wind and BESS had potential BESS capacity constraints and computational complexity. Feng *et al*. (2024)'s framework for renewable-thermal-storage generation bases lacked detailed computational scalability analysis. Kamboj *et al.* (2024)'s Chaotic Zebra Optimization Algorithm (CZOA) for UC lacked comprehensive analysis of complexity and scalability. Manoharan *et al*. (2024)'s MIPSO for microgrids lacked detailed discussion of limitations. Singh *et al*. (2024)'s multi-objective UC model for renewable-integrated power systems needed more comprehensive consideration of other renewables. Ramasamy *et al*. (2024)'s hybrid BWO and THDCNN for UC needed more comprehensive evaluation and further investigation into computational challenges. Xu *et al*. (2024)'s multi-objective optimization model for hybrid energy storage systems had potential challenges in handling real-world complexity. Pourahmadi & Kazempour (2024)'s SVM-based method for accelerating UC was limited by deterministic focus and scalability issues. Qin *et al*. (2024)'s hybrid HSA-DELF lacked evaluation on larger, more complex real-world problems. Widayanti *et al*. (2024) reviewed trends in metaheuristic optimization for dynamic UC. Al-Kubragyi & Ali (2025)'s hybrid MFO-PSO for UC lacked evaluation on larger systems and sensitivity analysis. González-Niño *et al*. (2025) conducted a bibliometric analysis of microgrid energy management. Dev *et al*. (2025) presented a systematic literature review of microgrid technology. Singh *et al*. (2025) reviewed load frequency control and solar energy integration challenges in India.

Ejuh Che *et al*. (2025) provided a comprehensive review detailing the challenges and mitigation strategies for VRE integration into grid-connected systems. Their work synthesized existing research, highlighted successful country case studies, and proposed a seven-point conceptual framework emphasizing advanced energy storage and smart grid infrastructure to manage VRE variability. However, as a review, it primarily presents a structured overview rather than original experimental data or novel methodologies.

Concurrently, Singh *et al*. (2025) introduced a hybrid demand-side management (DSM) approach for optimizing microgrid load profiles. This method combines load shifting, load curtailment, and smart charging for plug-in hybrid electric vehicles (PHEVs), validated by Differential Evolution (DE) optimization. The authors demonstrated its effectiveness in reducing both generation costs and emissions, addressing critical economic and environmental concerns. Acknowledged limitations include the focus on a specific microgrid scenario, which may affect generalizability, and the need for further analysis on the scalability and robustness of this hybrid DSM approach in larger, more complex power systems.

Paul *et al*. (2025) proposed a multi-objective optimization framework for grid-connected microgrids, employing quantum particle swarm optimization (QPSO) to minimize operational costs and environmental emissions. Their research showed QPSO's significant effectiveness in achieving cost and emission reductions, outperforming traditional methods and offering a robust framework for real-world applications. However, the study indicated a need for more comprehensive analysis regarding QPSO's computational complexity and scalability for very large-scale microgrid systems, along with a detailed comparative analysis against other advanced optimization algorithms to fully ascertain its practical implementation value.

2.3 Research Gap

This work addresses several critical research gaps identified in the existing literature concerning hybrid energy systems and microgrid optimization.

Firstly, a significant gap exists in the comparative analysis of multiple optimization techniques. Many studies, such as Anyaka *et al*. (2020) and as highlighted by Montero *et al*. (2022), have lacked an in-depth comparison of different algorithms. This research directly addresses this by conducting a comprehensive comparative analysis of Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA), and their hybrids, PSO-GA and PSO-SA.

Secondly, there's a recognized need for more practical case studies and real-world applicability. Previous research, including Rendroyoko *et al*. (2020) and Tian *et al*. (2021), was often limited by single-case study applications or lacked practical implementation. This study utilizes the University of Jos as a practical case study, adding significant real-world relevance to the findings.

Furthermore, few studies have explicitly focused on the integration of an electronic synchronizer for system stability. This research uniquely incorporates this aspect to enhance system stability, reduce switching transients, and improve power flow management. The study also provides a detailed analysis of hybrid optimization techniques, building upon the work of others like Syama *et al*. (2020) and Al-Kubragyi & Ali (2025), by thoroughly examining the performance of hybrid PSO-SA and PSO-GA approaches within a microgrid setting.

Lastly, this study places a strong emphasis on cost minimization and emission reduction in a hybrid microgrid, a crucial aspect of modern energy management. It also directly addresses renewable energy intermittency through the strategic use of Pumped Hydro Energy Storage Systems (PHESS), the electronic synchronizer, and multiple power sources, providing a 24-hour operational analysis to demonstrate how intermittency is managed.

In summary, this research offers a practical, comparative analysis of various optimization techniques in a real-world microgrid context, focusing on cost, emissions, and system stability. This directly fills several gaps in existing literature, particularly regarding the need for comprehensive comparisons, practical applicability, and the integration of crucial stabilizing technologies.

3. MATERIALS AND METHOD

3.1 Multi-Objective Optimization for Unit Commitment

The understanding of UC, particularly its role in balancing power generation with varying demand and considering costs and reserve requirements, has been significantly advanced by researchers like Abdou & Tkiouat (2018**)** and Yang &Wu (2022). Further insights into the formulation of the UC optimization problem are provided by Salman & Kusaf (2021). The multi-objective optimization of unit commitment for cost minimization has been addressed by Wood *et al*. (2013), while Bhattacharya and Chattopadhyay (2010) and Rosli *et al*. (2022) have focused on economic cost and emission reduction in hybrid power systems. The crucial role of a synchronizer in the economics of power systems has been analysed by Kundur (1994) and is further emphasized by IEEE Std. 1547 (2022).

This multi-objective optimization (MOO) integrates three key aspects:

i. Cost minimization: Encompassing fuel cost, utility cost, storage cost, and solar PV savings.
ii. Pollutant emission minimization: Targeting reductions in CO2, CO, SO2, NOx, and HC emissions.
iii. Electronic synchronizer equation: Ensuring precise frequency, voltage, and phase matching for grid stability.

The hybrid system under consideration operates over a 24-hour period and comprises the following components:

i. Diesel Generator (DG)
ii. Utility Supply (US)
iii. Pumped Hydro Energy Storage System (PHESS)
iv. Solar PV (SPV) Plant

a) Multi-Objective Function

Multi-objective optimization seeks trade-off solutions for conflicting objectives, not a single optimal one (Equation 1).

$$\text{MOO} = w_1 C_{total} + w_2 E_{total} + w_3 S_{sync} \tag{1}$$

Where, $\mathrm{w_1, w_2, w_3} = \text{weight for cost, emission} \wedge \text{synchronization}$

$\mathrm{C_{total}} = \text{total operational cost}$
$\mathrm{E_{total}} = \text{total emissions}$
$\mathrm{S_{sync}} = \text{synchronization penalty functio}$

i. Cost Function

The cost functionC_{total} calculates the total energy cost over 24 hours by summing the costs of Diesel Generator (DG), Utility Supply (US), Pumped Hydro Energy Storage System (PHESS), and subtracting the savings from Solar Photovoltaic (SPV) generation as in equation (2)

$$C_{total} = \sum_{i=1}^{24}\left(C_{DG,t} + C_{US,t} + C_{PHESS,t} - C_{SPV,t}\right) \tag{2}$$

Where,

$$C_{DG,t} = a_{DG}P_{DG,t}^2 + b_{DG}P_{DG,t} + C_{DG} + C_{DG}^{start}U_{DG,t}(Diesel\ generator\ cost)$$

$$C_{US,t} = \lambda_{US,t}P_{US,t}(Utility\ supply\ cost)$$

$$C_{PHESS,t} = \lambda_{US,t}P_{PHESS,t}^{charge} + P_{PHESS,t}^{O \wedge M}(PHESS\ charging \wedge maintenance\ cost)$$

$$C_{SPV,t} = C_{SPV,t}P_{SPV,t}(Solar\ PV\ savings)$$

i. Emission Function

The emission function calculates the total emissions over 24 hours by summing the emissions from Diesel Generator (DG), Utility Supply (US), and subtracting the emissions avoided by Solar Photovoltaic (SPV) and Pumped Hydro Energy Storage System (PHESS) for various pollutants such as CO_2, SO_2, NO_x, and HC as in equation (3)

$$\sum_{i=1}^{24} \sum_{p\epsilon(CO_2 CO,SO_2,NO_x HC} \left(E_{DG,t}^P + E_{US,t}^P - E_{SPV,t}^P - E_{PHESS,t}^P\right) \quad (3)$$

Where,

$$E_{DG,t}^P = \alpha_{DG}^P P_{DG,t}^2 + \beta_{DG}^P P_{DG,t} + \gamma_{DG}^P(Diesel\ generator\ emission)$$

$$E_{US,t}^P = \lambda_{US}^P P_{US,t}(Grid - based\ emissions)$$

$$E_{SPV,t}^P = \lambda_{US}^P P_{SPV,t}(Avoided\ emissions\ due|solarPV)$$

$$E_{PHESS,t}^P = \lambda_{US}^P P_{PHESS,t}^{discharge}(Avoided\ emission\ due|PHESS)$$

ii. Synchronization Function

The synchronization function ensures system stability by summing the deviations in frequency (Δf), voltage (ΔV), and phase angle (Δθ) over 24 hours, weighted by constants k_f, k_v, and k_θ as in equation (4)

$$S_{sync} = \sum_{i=1}^{24}\left(k_f|\Delta f_t| + k_v|\Delta V_t| + k_\theta|\Delta\theta_t|\right) \quad (4)$$

Where,

$k_f, k_v, k_\theta = Synchronization\ penalty\ coefficients$
$\Delta f_t = f_{ref,t} - f_{source,t}(Frequency\ \ deviation)$
$\Delta V_t = V_{ref,t} - V_{source,t}(Voltage\ \ deviation)$
$\Delta\theta_t = \theta_{ref.t} - \theta_{source,t}(Phase\ angle\ \ deviation)$

The synchronizer adjusts power sources using a PID controller is as shown in equation (5)

$$\Delta P_{source,t} = K_p.\Delta f_t + K_i\int_0^t \Delta f_t dt + K_d\frac{d}{dt}\Delta f_t \quad (5)$$

Where, K_p, K_i, K_d $are\ PID\ gains$

Sources are committed as shown in equation (6) when:

$$|\Delta f_t| \leq \epsilon_f, |\Delta V_t| \leq \epsilon_v, |\Delta\theta_t| \leq \epsilon_\theta \quad (6)$$

iii) Constraints

Constraints ensure that the system operates within feasible and safe limits. The power balance constraint ensures that total generation equals demand, while generator, utility, and storage limits restrict power output and input within specified ranges to maintain system stability and efficiency as in equations (7) to (11).

i. Power balance

$$P_{DG,t} + P_{US,t} + P_{SPV,t} + P_{PHESS,t}^{discharge} = P_{demand.t}P_{PHESS,t}^{charge} \tag{7}$$

ii. Generator limits

$$P_{DG}^{min} \leq P_{DG,t} \leq P_{DG}^{max} \tag{8}$$

iii. Utility limits

$$P_{US}^{min} \leq P_{US,t} \leq P_{US}^{max} \tag{9}$$

iv. Storage limits

$$0 \leq P_{PHESS,t}^{charge} \leq P_{PHESS}^{max} \tag{10}$$

$$0 \leq P_{PHESS}^{discharge} \leq P_{PHESS}^{min} \tag{11}$$

3.3 Materials Used

This study utilized Python Anaconda with libraries like Pandas, Matplotlib, Pyplot, geneticalgorithm, pyswarm, scip, linprog, Nump, multiprocessing, and Scipy for modeling and optimization. Key materials included a line diagram of the University of Jos microgrid, demand response and meteorological data, and an RTO Unit Commitment Test System GAMs Program. Figure 1 further illustrates the microgrid's simplified single-line diagram, depicting power flow from a 33kV source through a transformer to 11kV, connecting public supply, solar PV, diesel generator, PHESS, and various load units.

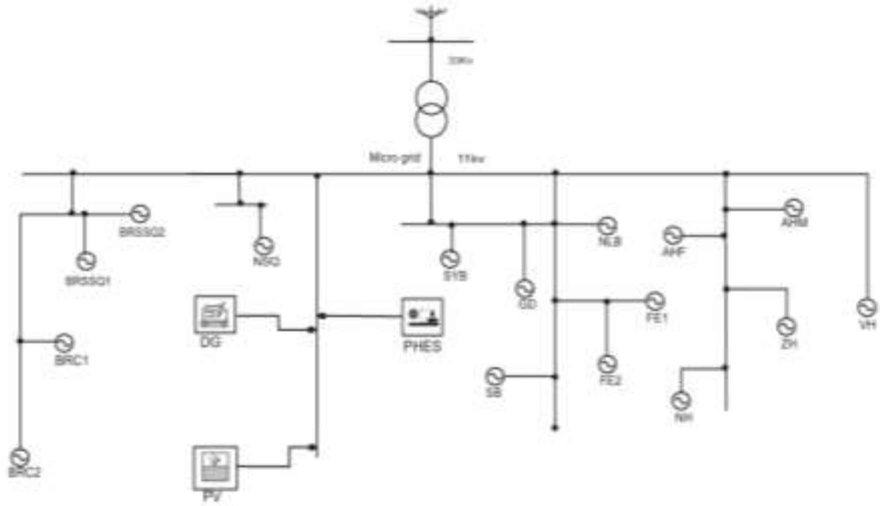

Figure 1: Hybrid Energy System

LEGEND

DG -Diesel Generator; PV -Solar PV ; PHES- Pump Hydro Energy Storage; BRC1 -Bauchi Road Campus 1 ; BRC2- Bauchi Road Campus 2 ; BRSSQ1- Bauchi Road Senior Staff Quarters 1; BRSSQ2 -Bauchi Road Senior Staff Quarters 2; NSQ- Naraguta Staff Quarters; SYB -Skye Bank ; SB- Senate Building; NLB -Naraguta Library; FE1 -Faculty of Education 1; FE 2 -Faculty of Education 2 ; AHF -Abuja Hostel Female; AHM -Abuja Hostel Male ; NH- Naraguta Hostel ; VH- Village Hostel ; ZH -Zion Hostel ; GD- Geology Department

3.4 Methodology

The study employed a comprehensive methodology for analyzing hybrid microgrid operation. This involved data collection and preprocessing (24-hour load demand, solar irradiance, cost data for diesel, utility, and PHESS; defining cost functions per Equations 12 -15), unit commitment model development, and optimization algorithm selection and implementation (PSO, SA, GA, and hybrid approaches). The process concluded with simulation, data output generation, result analysis, and presentation of findings.

Diesel Generator Cost: CDG = 0.002 x PDG^2 + 0.5 X PDG + 1 (12)

Utility Supply Cost: CUS = 0.15 X PUS (13)

PHESS Cost: CPHESS = 0.1 x $PHESS_{Charge}$+ 0.05 (14)

Solar PV Cost (Savings): CSPV = -0.12 x PSPV (negative due to cost reduction) (15)

4. RESULTS AND DISCUSSION

This section presents the simulation results and analysis of a hybrid microgrid's 24-hour power dispatch optimization, aiming to minimize operational costs and ensure reliable supply from solar PV, PHESS, diesel generators, and public utility. Simulations were run in Python (Anaconda Spyder) using Particle Swarm Optimization (PSO), Simulated Annealing (SA), Genetic Algorithm (GA), and hybrid PSO-SA and PSO-GA. The chapter comprehensively examines optimized dispatch schedules, cost distributions, and performance comparisons among these techniques, using tables and graphs to illustrate effective, cost-effective, and sustainable energy management.

4.1 Algorithm Parameters

The optimization algorithms were configured with the following parameters:

i. Particle Swarm Optimization (PSO): Swarm size = 30; Maximum Iterations = 100; Inertia weight (w) = 0.7; Cognitive parameter (C1) = 1.5; Social parameter (C2) = 1.5.
ii. Genetic Algorithm (GA): Population Size = 50–100; Crossover Probability = 0.8–0.9; Mutation Probability = 0.01–0.05; Selection Mechanism = Tournament Selection; Number of Generations = 20–50.
iii. Simulated Annealing (SA): Initial temperature = 1000; Cooling rate = 0.95.

4.2 Results of the HPSO-SA

Table 1 presents the 24-hour power output from four generation sources, along with the optimized CO_2 emission cost and synchronization penalty. Figures 2 shows graph of the individual power outputs of the four sources, specifically using the Hybrid PSO-SA optimization.

Table 1. Output of four sources of power generation for 24-hour period, best CO_2 emission cost, and best synchronization penalty.

Hour	P (Solar)	P(phess)	P (diesel)	P (public)	Cost
24 -1	0.000000	340.330000	0.000000	0.000000	21781.120000
1-2	0.000000	311.010001	0.000000	0.000000	19904.641363
2-3	0.000000	314.525681	0.000000	17.995584	22800.378484
3-4	0.000000	408.657703	0.000000	140.052278	42960.385718
4-5	37.073244	492.118550	0.000000	126.215789	48423.414726
5-6	563.228092	359.727863	0.000000	22.470659	53170.624757
6-7	1000.000000	204.121614	0.000000	0.000000	61065.397303
7-8	452.081256	493.310651	0.000000	334.957209	93485.762966
8-9	768.144454	199.605769	12.700865	157.779104	72809.176757
9-10	801.417899	146.583641	1.197427	92.021676	59132.141416
10-11	476.934769	413.105231	0.000000	0.000000	49331.604155
11-12	0.000000	780.820000	0.000000	0.000000	49972.480000
12-13	336.575172	428.525093	0.000000	0.000000	43581.479161
13-14	0.000000	340.016679	0.273751	532.190389	89359.483134
14-15	672.038618	218.752311	0.000000	0.000000	46648.930678
15-16	0.000000	635.638847	0.000000	298.399927	77757.651376
16-17	0.000000	663.539557	0.000000	254.029652	72999.298717
17-18	0.000000	649.322383	0.000000	260.157081	73754.945697
18-19	0.000000	730.200434	0.000000	208.988398	72230.267505
19-20	0.000000	848.310000	0.000000	0.000000	54291.840000
20-21	0.000000	79.844467	4.263959	545.770111	71496.713645
21-22	0.000000	542.947637	0.000000	20.239272	37950.452333
22-23	0.000000	413.250000	0.000000	0.000000	26448.000000
23-24	0.000000	167.956528	0.005100	173.385541	31653.670879

Table 2. The cost analysis for the hybrid energy system includes contributions from solar, PHESS, diesel, and public power supply sources, best emission cost and synchronization penalty. Below is the summary of cost components, emission, and synchronization performance and percentage contributions for each energy source within the microgrid system, providing insight into the economic distribution of energy generation.

Table 2. Cost Analysis of Power Generation Sources. Emission and Synchronization Penalty

Power Source	Total Cost (₦)	Percentage Contribution (%)
Solar PV (Savings)	352,335.60	30.77
PHESS	636,244.35	55.55
Diesel Fuel	25,453.68	2.22
Public Power Supply	130,825.44	11.43
Total Cost	1, 144, 859.07	100
Best CO_2 Emission Cost	10,695.87	-
Synchronization Penalty	0	-

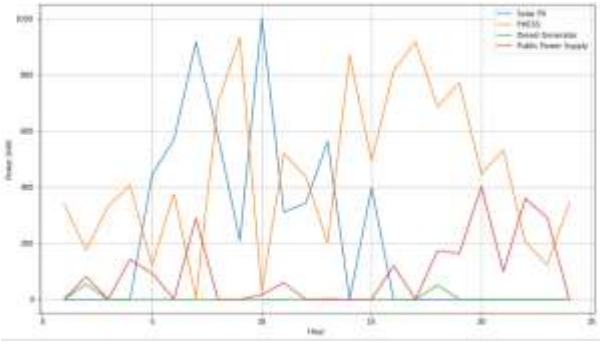

Figure 2. Load dispatch of the four sources of power within the next 24 hours (HPSO-SA)

4.3 Results of the HPSO-GA

Table 3: Output of the Four Sources of Power Generation for 24-Hour Period, best CO_2 emission cost and best synchronization penalty. Figures 3 display of the four sources of power output using Hybrid PSO-GA.

Table 3 Output of four sources of power generation for 24-hour period, best CO_2 emission cost, and best synchronization penalty.

Hour	P (Solar)	P(phess)	P (diesel)	P (public)	Cost
24 -1	0.000000	202.438384	0.000000	137.795545	29587.593258
1-2	0.000000	0.000000	311.010000	0.000000	62202.000000
2-3	0.000000	202.292633	0.000000	130.084747	28924.278095
3-4	0.000000	455.523268	0.000000	98.380735	46153.179846
4-5	0.000000	341.942705	0.000000	313.412016	59549.053551
5-6	122.474331	812.453906	6.695782	0.000000	62600.955207
6-7	274.743603	136.772348	0.000000	792.540034	117109.942269
7-8	320.663957	558.126273	5.291536	386.390234	108395.087055
8-9	647.107418	492.812627	0.000000	0.000000	62601.208836
9-10	657.739901	201.195908	0.000000	183.651915	67854.007795
10-11	789.575388	24.631107	0.000000	75.001106	49308.541154
11-12	780.281205	0.424063	0.053494	0.000000	37552.573988
12-13	26.981030	494.626377	0.000000	239.163663	65979.746713
13-14	479.283954	384.696507	0.000000	11.710157	55922,043363
14-15	890.400000	0.000000	0.000000	0.000000	42739.200001
15-16	0.000000	932.770000	0.000000	0.000000	59697.280000
16-17	0.000000	917.520000	0.000000	0.000000	58721.280000
17-18	0.000000	745.723821	0.000000	163.198849	67732.856186
18-19	0.000000	751.311076	0.000000	189.433724	72790.755642
19-20	0.000000	494.018892	0.000000	346.402585	81074.042208
20-21	0.000000	212.978630	0.000000	417.688067	64499.896985
21-22	0.000000	544.632932	0.000000	0.000000	54183.575304
22-23	0.000000	198.222996	0.000000	218.171028	42010.819091
23-24	0.000000	341.250000	0.000000	0.000000	21840.000000

Cost Analysis and Distribution

Table 4. The cost analysis for the hybrid energy system includes contributions from solar, PHESS, diesel, and public power supply sources, best emission cost and synchronization penalty. Below is the summary of cost components, emission, and synchronization performance and percentage contributions for each energy source within the microgrid system, providing insight into the economic distribution of energy generation.

Table 4. Cost Analysis of Power Generation Sources, Emission and Synchronization Penalty

Power Source	Total Cost (₦)	Percentage Contribution (%)
Solar PV (Savings)	258,591.09	20.13
PHESS	648,648.65	50.49
Diesel fuel	54,884.38	4.27
Public Power Supply	322,251.18	25.11
Total Cost	₦1,284,375.30	100%
Best CO_2 Emission Cost	13,096.83	-
Synchronization Penalty	0	-

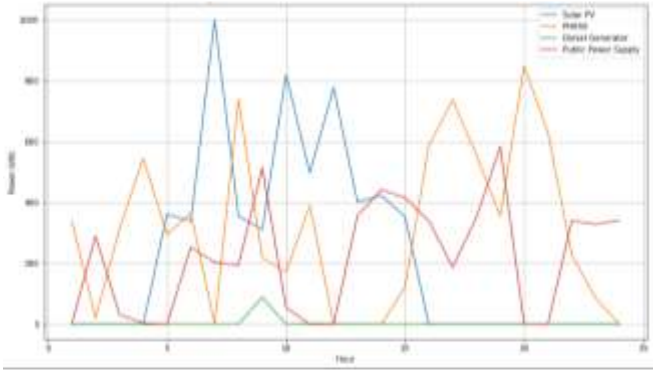

Figure 3. Load dispatches of the four sources of power within the next 24 hours (PSO-GA)

4.4 PSO Results.

Table 5: Output of the Four Sources of Power Generation for 24-Hour Period, best CO_2 emission cost and best synchronization penalty. Figures 4, display of the four sources of power output using Hybrid PSO.

Table 5 Output of four sources of power generation for 24-hour period, best CO_2 emission cost, and best synchronization penalty.

Hour	P (Solar)	P(phess)	P (diesel)	P (public)	Cost
24 -1	0.000000	336.524773	0.267714	3.481700	22064.745573
1-2	0.000000	0.000000	311.010000	0.000000	62202.000000
2-3	0.000000	26.031695	0.038843	305.939759	38386.865362
3-4	0.000000	254.837516	0.000000	293.869543	51576.887205
4-5	182.404315	150.838381	0.000000	322.072554	57151.64028
5-6	479.001862	466.008779	0.000000	0.000000	52817.292417
6-7	183.122151	641.109011	0.042575	379.846269	95410.912791
7-8	988.17318	292.123371	0.035832	0.000000	66138.321580
8-9	214.574862	925.435110	0.000000	0.000000	69521.709149
9-10	671.226407	369.993593	0.000000	0.000000	55898.457652
10-11	282.799808	77.536012	0.000000	529.843497	82257.232754
11-12	567.730131	213.089687	0.000000	0.000000	40888.968070
12-13	382.834101	278.722876	0.000000	103.541932	48640.423292
13-14	365.670385	360.30028	0.000000	142.353414	57781.536962
14-15	529.455478	354.837967	5.995405	0.000000	49433.723360
15-16	0.000000	497.483882	435.309254	0.000000	118923.723360
16-17	0.000000	917.520000	0.000000	0.000000	58721.280000
17-18	0.000000	908.465429	0.034567	0.000000	58148.704702
18-19	0.000000	496.806795	0.000000	441.313579	85402.890722
19-20	0.000000	794.036132	0.000000	53.979245	57590.44690
20-21	0.000000	493.725024	0.000000	136.199499	47946.864954
21-22	0.000000	42.938619	0.02228	520.959001	65307.748652
22-23	0.000000	413.250000	0.000000	0.000000	26448.000000
23-24	0.000000	341.250000	0.000000	0.000000	21840.000000

Table 6. The cost analysis for the hybrid energy system includes contributions from solar, PHESS, diesel, and public power supply sources, best emission cost and synchronization penalty. Below is the summary of cost components, emission, and synchronization performance and percentage contributions for each energy source within the microgrid system, providing insight into the economic distribution of energy generation resulting from the Particle Swarm Optimization (PSO) algorithm.

Table 6. Cost Analysis of Power Generation Sources, Emission and Synchronization Penalty

Power Source	Total Cost (₦)	Percentage Contribution (%)
Solar PV (Savings)	237290.172	16.73
PHESS	529534.541	37.31
Diesel	48298.479	3.40
Public Power Supply	603404.257	42.55
Total Cost	₦1,418,527.45	100%
Best CO_2 Emission cost	14,442.32	-
Synchronization Penalty	0	-

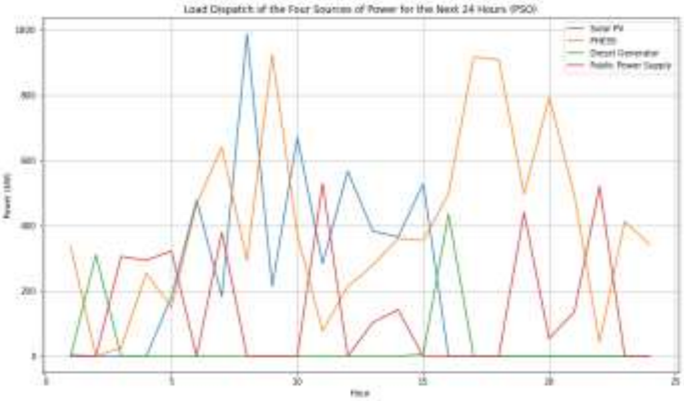

Figure 4. Load dispatch of the four sources of power within the next 24 hours (PSO)

4.5 Results of GA

Table 7: Output of the Four Sources of Power Generation for 24-Hour Period, best CO_2 emission cost and best synchronization penalty. Figures 5, display of the four sources of power output using Hybrid GA.

Table 7. Output of four sources of power generation for 24-hour period, best CO_2 emission cost, and best synchronization penalty.

Hour	P (Solar)	P(phess)	P (diesel)	P (public)	Cost
24 -1	0.000000	86.176624	0.000000	207.783741	76818.987982
1-2	0.000000	290.158474	0.000000	160.589744	177579.129195
2-3	0.000000	272.185389	0.000000	98.922829	68388.822025
3-4	0.000000	185.857584	382.585762	0.000000	108145.384197
4-5	110.152787	368.049186	18.467940	119.648433	85985.535387
5-6	302.401758	425.891685	235.286129	0.000000	107399.149871
6-7	111.712551	536.935450	268.849443	185.153506	217183.430712
7-8	724.937428	161.003157	0.000000	417.439200	118243.687366
8-9	203.649085	300.234019	204.832503	419.057442	132390.478474
9-10	182.276935	626.730184	214.236735	77.821710	160891.540040
10-11	342.817187	287.035362	237.646191	99.224868	170945.318651
11-12	281.567915	190.428731	231.660271	14.627850	136325.327600
12-13	428.147133	0.000000	179.196247	124.893654	104240.516577
13-14	77.790772	265.700996	38.668482	413.647280	151102.660523
14-15	498.598431	238.282352	13.793279	123.019381	73418.333415
15-16	0.000000	721.023669	0.000000	179.013549	100359.921882
16-17	0.000000	91.391632	175.930955	574.225033	185914.639592
17-18	0.000000	520.260545	289.214114	92.884153	108426.783788
18-19	0.000000	730.0203205	140.878195	70.4884153	85972.940760
19-20	0.000000	328.530205	489.137465	44.015575	137508.539900
20-21	0.000000	351.496959	49.901161	269.680866	105996.727168
21-22	0.000000	59.079135	71.441899	387.993984	110073.704574
22-23	0.000000	335.637487	0.000000	50.712595	54466.229268
23-24	0.000000	188.042265	49.557335	86.296071	49656.029210

Cost Analysis and Distribution

Table 8. The cost analysis for the hybrid energy system includes contributions from solar, PHESS, diesel, and public power supply sources, best emission cost and synchronization penalty. Below is the summary of cost components, emission, and synchronization performance and percentage contributions for each energy source within the microgrid system, providing insight into the economic distribution of energy generation as determined in GA

Table 8. Cost Analysis of Power Generation Sources, Emission and Synchronization Penalty

Power Source	**Total Cost (₦)**	**Percentage Contribution (%)**
Solar PV (Savings)	156674.495	8.68
PHESS	483849.692	26.80
Diesel fuel	658254.821	36.47
Public Power Supply	506056.832	28.05
Total Cost	**₦1,804,835.84**	100
Best CO_2 Emission Cost	15184.37	-
Synchronization Penalty	0	-

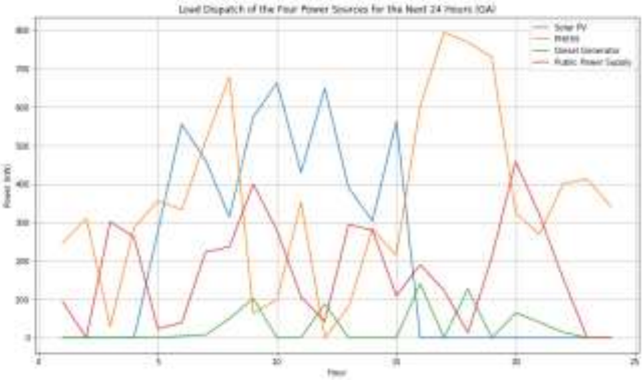

Figure 5 Load dispatches of the four sources of power within the next 24 hours (GA)

4.6 RESULTS of SA

Table 9 Output of the Four Sources of Power Generation for 24-Hour Period, best CO_2 emission cost and best synchronization penalty. Figure 6. display of the four sources of power output using SA.

Table 9. Output of four sources of power generation for 24-hour period, best CO_2 emission cost, and best synchronization penalty.

Hour	**P (Solar)**	**P(phess)**	**P (diesel)**	**P (public)**	**Cost**
24 -1	0.000000	50.288244	0.000000	290.618950	38669.915665
1-2	0.000000	0.000000	7.759912	300.660601	40220.740898
2-3	0.000000	42.027688	0.000000	284.222254	42556.500363
3-4	0.000000	546.634655	0.000000	0.000000	37059.963020
4-5	244.597356	409.325730	0.000000	0.000000	39424.432972
5-6	305.725829	641.376827	0.572861	0.000000	58503.046732
6-7	40.089307	775.539375	0.000000	388.803623	98527.547013
7-8	697.043943	272.802676	312.801150	0.000000	115795.480452
8-9	234.999690	201.744669	471.985980	227.847036	149273.108618
9-10	390.258567	420.070450	235.350750	0.000000	97587.303175
10-11	0.000000	0.000000	711.979087	179.561472	165443.752998
11-12	536.567292	0.000000	52.682792	191.857844	59602.656834
12-13	0.000000	761.463999	0.000000	0.000000	52369.697127
13-14	764.793718	91.134128	0.000000	0.000000	55414.836953

14-15	301.175841	188.535765	356.731819	42.192710	104696.083479
15-16	0.000000	64.175185	308.912791	558.717392	133900.488747
16-17	0.000000	271.627980	69.295010	578.493439	102558.835317
17-18	0.000000	453.721553	0.000000	453.398299	84826.123251
18-19	0.000000	820.760146	0.000000	117.625810	67027.791179
19-20	0.000000	527.134100	0.000000	326.243914	77953.866052
20-21	0.000000	150.198911	0.140190	479.968765	67027.791179
21-22	0.000000	75.011929	51.479322	437.956778	68139.470333
22-23	0.000000	127.730213	59.466498	217.890196	54377.948814
23-24	0.000000	324.368075	0.000000	16.401074	23208.536157

Cost Analysis and Distribution

The cost analysis for the hybrid energy system includes contributions from solar, PHESS, diesel, and public power supply sources, best emission cost and synchronization penalty. Below is the summary of cost components, emission, and synchronization performance and percentage contributions for each energy source within the microgrid system, providing insight into the economic distribution of energy generation as determined in SA

Table 10 Cost of Power, Emission and Synchronization Penalty

Power Source	**Total Cost (₦)**	**Percentage Contribution (%)**
Solar PV (Savings)	168,732.07	**9.48**
PHESS	461,163.03	25.92
Diesel fuel	537,831.63	30.23
Public Power Supply	611,095.22	34.37
Total Cost	₦1,778,821.95	100
Best CO2 Emission Cost	14,076.46	-
Synchronization Penalty	0	-

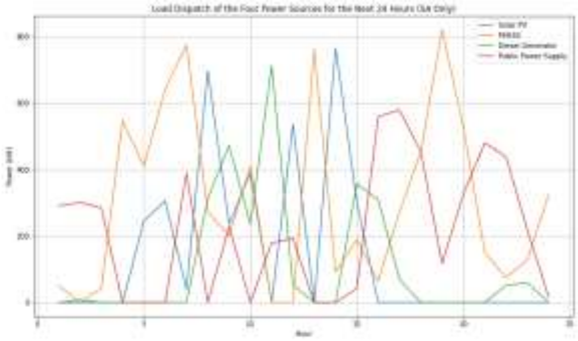

Figure 6 Load dispatches of the four sources of power within the next 24 hours (SA)

Table 11 compared the performance of different power source generation methods, showing their total generation costs, CO_2 emissions costs, and synchronization penalty costs.

Table 11: Cost of Power, Emission and Synchronization Penalty

Power Source Generation Method	Total cost of Generation (₦)	Best CO₂ Emissions Cost (₦)	Best Synchronization penalty
HPSO-SA	1,246,765.58	10,695.87	0
HPSO-GA	1,33,9047.98	13,096.83	0
PSO	1,418,786.74	14,442.32	0
GA	1,445,289.88	15,184.37	0
SA	1,834,763.01	14,076.46	0

Table 11 showed the superior cost-effectiveness of HPSO-SA compared to other optimization methods within the micro-grid system. The simulation results demonstrated that the hybrid PSO-SA algorithm achieved the most effective power dispatch for the hybrid microgrid, yielding the lowest operational cost (₦1,246,765.58) and CO_2 emissions (₦10,695.87) compared to HPSO-GA, PSO, and GA. This superiority stems from its ability to effectively balance the strengths of Particle Swarm Optimization's global search and Simulated Annealing's ability to avoid local optima. The analysis highlighted the critical role of Solar PV and PHESS in reducing dependency on costly and polluting diesel generators and the public utility, while also revealing an optimal operating range for cost-effectiveness. Load dispatch graphs illustrated the algorithms' capability to manage diurnal solar patterns, fluctuating PHESS contributions, minimal diesel usage, and strategic utility supply, ultimately showcasing the potential for sustainable and cost-efficient microgrid operation.

5. CONCLUSIONS

This study successfully modeled and optimized the unit commitment for a hybrid microgrid. The simulation provided detailed hourly power dispatch schedules for all energy sources (Solar PV, PHESS, diesel, utility), demonstrating the model's operational decision-making capability. The electronic synchronizer's requirements were effectively integrated, indicated by a zero-synchronization penalty in optimized schedules.

The research successfully implemented and compared GA, PSO, PSO-GA, and PSO-SA, providing detailed dispatch schedules and cost analyses for each. Hybrid PSO-SA emerged as the most effective algorithm, achieving the lowest operational cost (₦1,246,765.58) and CO_2 emissions. Its ability to maintain system reliability with a zero-synchronization penalty further solidified its superior performance for this microgrid setting.

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APPENDIX

```
Created on Tue Apr 1 03:35:29 2025

@author: GWAIVANGMIN BARNABAS I

"""

import numpy as np

import pandas as pd

import matplotlib.pyplot as plt

from pyswarm import pso

from scipy.optimize import dual_annealing


# Power Source Limits (kW)

P_DG_max, P_DG_min = 1000, 50

P_US_max, P_US_min = 800, 0

P_PHESS_max = 500


# Load demand data (kW)

load_demand = np.array([

    340.330, 311.010, 332.010, 548.710, 655.410, 945.010, 1204.120, 1280.330,

    1139.920, 1041.220, 890.040, 780.820, 765.100, 868.800, 890.400, 932.770,

    917.520, 908.500, 938.770, 848.310, 629.920, 563.960, 413.250, 341.250

])


# Solar irradiance data (W/m²)

solar_irradiance = np.array([

    0, 0, 0, 0, 109, 385, 543, 708, 773, 745, 742, 662, 635, 449, 223, 0, 0, 0, 0, 0, 0, 0, 0, 0

])


# Solar PV efficiency factor (kW per W/m²)
```

```
solar_efficiency = 0.1

def solar_pv_generation(irradiance):
    return irradiance * solar_efficiency

# Compute solar PV output
solar_pv_output = solar_pv_generation(solar_irradiance)

# Cost function
def cost_function(schedule):
    total_cost = 0
    for t in range(24):
        P_DG, P_US, P_PHESS_charge, P_PHESS_discharge, P_SPV = schedule[t]
        C_DG = 0.002 * P_DG**2 + 0.5 * P_DG + 1
        C_US = 0.15 * P_US
        C_PHESS = 0.1 * P_PHESS_charge + 0.05
        C_SPV = -0.12 * P_SPV  # Solar savings
        total_cost += (C_DG + C_US + C_PHESS - C_SPV)
    return total_cost

# Objective function for PSO-SA
def objective_function(x):
    schedule = np.array(x).reshape(24, 5).tolist()
    total_cost = cost_function(schedule)
    penalty = 0
    for t in range(24):
        P_DG, P_US, P_PHESS_charge, P_PHESS_discharge, P_SPV = schedule[t]
        demand_met = P_DG + P_US + P_PHESS_discharge + P_SPV - P_PHESS_charge
        if demand_met < load_demand[t]:
            penalty += (load_demand[t] - demand_met) * 1000  # High penalty for unmet demand
    return total_cost + penalty

# PSO Optimization
def pso_optimization():
    num_variables = 24 * 5
    lb = [P_DG_min, P_US_min, 0, 0, 0] * 24
```

```
    ub = [P_DG_max, P_US_max, P_PHESS_max, P_PHESS_max, 100] * 24

    xopt, fopt = pso(objective_function, lb, ub, swarmsize=20, maxiter=50, debug=True) #added debug
    best_schedule = np.array(xopt).reshape(24, 5)

    return best_schedule, fopt

# Simulated Annealing Optimization
def sa_optimization(initial_solution):
    bounds = [(P_DG_min, P_DG_max), (P_US_min, P_US_max), (0, P_PHESS_max), (0, P_PHESS_max), (0, 100)] * 24

    cost_history = []  # Store cost history

    def callback(x, f, context):
        cost_history.append(f)

    result_sa = dual_annealing(objective_function, bounds, x0=initial_solution.flatten(), maxiter=1000, callback=callback)
    best_schedule = np.array(result_sa.x).reshape(24, 5)

    return best_schedule, result_sa.fun, cost_history #Added cost_history

# Run PSO first
best_PSO, cost_PSO = pso_optimization()

# Use PSO result as initial solution for SA
best_SA, best_cost, cost_history = sa_optimization(best_PSO) #added cost_history

# Convert to DataFrame
df_dispatch = pd.DataFrame(best_SA, columns=["Diesel", "Public", "PHESS_Charge", "PHESS_Discharge", "Solar"])
df_dispatch.index.name = "Hour"
df_dispatch.index += 1

# Print results
print("\nOptimized Load Dispatch for 24 Hours:")
```

```
print(df_dispatch)
print(f"\nOptimized Total Cost: {best_cost:.2f} N")

# Plot results
plt.figure(figsize=(10, 6))
for col in df_dispatch.columns:
   plt.plot(df_dispatch.index, df_dispatch[col], label=col, marker="o")
plt.xlabel("Hour")
plt.ylabel("Power (kW)")
plt.title("Optimized Power Dispatch (PSO-SA)")
plt.legend()
plt.grid(True)
plt.show()

# Plot Cost vs. Iteration
plt.figure(figsize=(10, 6))
plt.plot(cost_history)
plt.xlabel("Iteration")
plt.ylabel("Cost")
plt.title("Cost vs. Iteration (SA)")
plt.grid(True)
plt.show()

# Calculate total power for each source and overall total
total_DG = np.sum(best_SA[:, 0])
total_US = np.sum(best_SA[:, 1])
total_PHESS_charge = np.sum(best_SA[:, 2])
total_PHESS_discharge = np.sum(best_SA[:, 3])
total_Solar = np.sum(best_SA[:, 4])
overall_total = total_DG + total_US + total_Solar + total_PHESS_discharge - total_PHESS_charge

# Print total power results
print("\nTotal Power for Each Source (kW):")
print(f"Diesel Generator (DG): {total_DG:.2f}")
print(f"Utility Supply (US): {total_US:.2f}")
print(f"PHESS Charge: {total_PHESS_charge:.2f}")
```

```
print(f"PHESS Discharge: {total_PHESS_discharge:.2f}")
print(f"Solar PV: {total_Solar:.2f}")
print(f"Overall Total Power: {overall_total:.2f}")
```

The Case for a Cloud First and Unified Government Platform in Nigeria – Lessons from the UK's Digital Transformation

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Abstract: This paper makes a case for Nigeria's transition to a cloud-first and unified government digital platform by drawing strategic and operational lessons from the United Kingdom's digital transformation journey. The study explores how the UK's Cloud First policy, hybrid hosting architecture, cybersecurity frameworks, and single-service portal (GOV.UK) offer a viable model for modernising Nigeria's fragmented digital public infrastructure. Using institutional theory and policy analysis as a conceptual lens, the paper evaluates Nigeria's systemic challenges, including duplication of IT investments, weak cybersecurity enforcement, and lack of interoperability, and proposes policy and technical recommendations for a sustainable digital transformation. The study concludes that while technology is essential, institutional readiness, coordinated policy enforcement, and inclusive digital governance are critical to success.

Keywords: Cloud First, e-Government, Digital Transformation, Nigeria, Unified Government Platform, UK G-Cloud

1. INTRODUCTION

When I consider the sweeping changes the digital age imposes on public administration, I recognise that governments must rethink how they deliver services, safeguard national security, and nurture innovation. In my view, a Cloud First policy coupled with unified digital platforms has become the cornerstone of this transformation in many developed nations. Nigeria, as Africa's largest economy and most populous country, has even more to gain from such a shift. Observing the United Kingdom's journey from its 2013 Cloud First mandate to the creation of the Government Digital Service (GDS), I see a practical, well-tested roadmap we can adapt to our own context [1,2]. The UK's consolidation of services under the single GOV.UK portal demonstrates the power of centralised access to boost efficiency and public trust [1, 3]. By contrast, Nigeria's e-Government strategy documents highlight persistent gaps: inter-agency silos and fragmented IT systems continue to impede collaboration across ministries, departments, and agencies [4]. By highlighting these differences, adopting and customising the UK's approach could greatly help modernise governance in Nigeria and rebuild public trust in digital services.

2. METHODOLOGY

This study uses a mixed-methods, desk-based comparative policy analysis of the UK's Cloud First strategy and Nigeria's digital-government context. I began with a structured literature review (2012–2025) covering peer-reviewed articles, UK government guidance (Cabinet Office/GDS, NCSC, CCS), World Bank diagnostics, and credible grey literature, applying inclusion criteria of English language, public-sector digital policy, and relevance to cloud adoption, security, procurement, and inclusion. Documents were thematically coded across five lenses, governance and enterprise architecture, hosting strategy, security/zero trust, procurement, and accessibility and supplemented by targeted keyword searches such as "interoperability" and "vendor lock-in." Evidence was triangulated with spend dashboards and civil-society procurement reports, with limited non-attributive key-informant checks. Quality was assessed for authority, recency, and corroboration, and findings were mapped using a light theory-of-change approach. Ethical safeguards included proper attribution, exclusion of confidential data, and careful treatment of security details. Limitations, notably uneven Nigerian data quality, were mitigated through triangulation and transparent reporting.

2.1 Understanding the Cloud First Approach

Looking back at the UK's Cloud First mandate, I now recognise it as more than a policy directive; it represented a fundamental rethinking of how government systems could be built for speed, resilience, and value [2]. The decision to reorient procurement and infrastructure planning toward cloud-based solutions wasn't just about reducing capital expenditure; it was about embracing a future-ready architecture that supports responsive and citizen-centred services.

In exploring public cloud adoption, I was particularly drawn to the agility and resource efficiency it provides. The use of platforms like AWS, Azure, and Google Cloud enabled government agencies to dynamically scale services in response to shifting demand, notably during COVID-19 [5]. During this distressing period, I came to see the cloud as a tool for resilience: one that empowers governments to act quickly and serve reliably under pressure.

However, this transformation didn't entail a wholesale abandonment of traditional infrastructure. The UK's use of hybrid and private cloud models revealed a critical lesson for me: that flexibility is essential, sensitive workloads in justice or defence demand low latency, high compliance, and greater control [6]. The hybrid approach validated the idea that cloud adoption must be tailored to context, not imposed as a monolith.

Crown Hosting shifted my perspective on readiness. Initially, I viewed cloud migration as a binary decision: either on or off. But the UK's provision of secure co-location facilities through Crown Hosting offered a middle path for departments not yet prepared to go fully cloud native [7]. This insight helped me appreciate the importance of transitional infrastructure to reduce disruption, de-risk transformation, and build institutional confidence over time.

As I reflect more broadly, it becomes evident that the UK's Cloud First approach embodies not just a technical evolution but a cultural one, encouraging innovation, mitigating waste, and fostering digital trust [2, 3]. For countries like Nigeria, the key takeaway is that a cloud-first agenda must be backed by clear policy, phased support systems, and a commitment to reimagining public service delivery in the digital age.

2.2 Why Cloud First Matters for Nigeria

Nigeria's digital landscape shows that Cloud First is far more than a technical preference; it offers a deliberate break from years of fragmented IT investments and siloed ministry systems documented in diagnostic work [4]. By shifting to a unified, cloud-based foundation, the government can convert chronic inefficiencies into strategic savings and redirect funds to frontline services.

Cloud architecture also embodies resilience. Pandemics, flooding and civil unrest show how brittle legacy infrastructure can be, whereas cloud platforms scale elastically and replicate data across regions so essential services remain available when they are needed most (NCSC, 2021a). Just as important, centralised cloud systems embed audit trails and access controls, improving transparency and reducing opportunities for manipulation.

In contemplating the academic evidence, I find myself aligning with Weill and Ross's argument that a well-governed enterprise architecture is the launchpad for genuine agility [8]. Yet Avgerou's cautionary note lingers: without strong institutions and vigilant oversight, even the most promising technology can stall in bureaucratic inertia [9]. For Nigeria, Cloud First must therefore travel hand-in-hand with policy reform, capacity building and a cultural shift that prizes transparency and accountability.

2.3. Hosting Strategies for A Digital Government

A striking feature of the UK's strategy is the requirement that departments consider cloud solutions first, shifting the default and nudging culture [2]. Alongside this, hybrid support acknowledges that 'legacy' can also mean 'mission-critical'. Crown Hosting offers a strategic bridge for certain systems not yet ready for public cloud [7]. The Home Office and wider central government have publicly described journeys that combine legacy modernisation with Zero Trust and internet-first principles [10, 6].

The requirement for certified environments through frameworks like G-Cloud/GPA ensures providers meet strict security and compliance expectations, designing trust into the ecosystem [11, 7]. The UK's move away from the historic PSN model to internet-first, identity-centric security reinforces modern assumptions about connectivity and risk [6].

Data residency policies also matter; keeping sensitive data within jurisdiction is both a compliance and strategic sovereignty issue [6].

Finally, systematic legacy modernisation such as replatforming, refactoring or retiring systems offers a practical roadmap for sustainable change [3, 5].

3. NIGERIA'S CHALLENGES

Looking closely at Nigeria's digital infrastructure, diagnostic work highlights persistent fragmentation across ministries, departments and agencies [4]. Without unified oversight and enforceable enterprise architecture, digital investments operate in silos, leading to inefficiency and missed opportunities.

Budget leakages and duplicated projects have been documented by civic-tech monitors and investigative journalists, underscoring the cost of opaque procurement and weak coordination [12, 13, 14]. The Federal Government's mandatory IT Project Clearance process has reported substantial savings over ₦591.2bn cumulatively by May 2024 illustrating what central oversight can achieve [15].

Disconnected systems also harm public outcomes. Fragmented health records and a lack of interoperability standards impede coordinated care and compromise patient safety; broader data silos reduce the state's ability to aggregate data and evaluate policy [4].

International partners warn that over-reliance on fragmented and externally hosted systems can undermine digital sovereignty and resilience, recommending stronger domestic digital ecosystems and data governance [16].

3.1 Security and Compliance in Cloud Adoption

The UK's approach is guided by the National Cyber Security Centre, and this illustrates how security must be embedded, not appended, with Zero Trust principles ('authenticate and authorise everywhere') now mainstream in public guidance [6, 18]. Continuous monitoring, encryption in transit/at rest, and identity-centric controls are treated as baseline expectations [17].

By contrast, Nigeria's legal frameworks (for example, the Cybercrime Act and the National Cybersecurity Policy and Strategy) have seen uneven implementation, with persistent capability and coordination gaps [19, 20]. This gap between policy and practice heightens exposure and erodes trust, reinforcing the need for a well-resourced, cross-sector cybersecurity capability.

3.2 Procurement and the G-Cloud Model

The UK's G-Cloud model simplifies and safeguards procurement via a transparent, pre-approved catalogue, improving speed and visibility while reducing scope for opaque deals [11]. It has also widened supplier participation: SMEs account for the vast majority of listed suppliers and continue to win a material share of spend [11, 21, 22]. Recent CCS and independent spend dashboards evidence both the volume transacted and the participation of smaller providers [7, 23].

For Nigeria, civic reports have repeatedly flagged non-transparent procurement and weak open-contracting data publication, reinforcing the case for a Nigerian Digital Marketplace with open standards and SME pathways [13, 24].

3.3 The Role of Gov.Uk Domains and Unified Identity

Consistent use of the .GOV.UK domain is a deliberate trust signal that also enables central security controls and incident response (CDDO, 2024). UK guidance sets out naming, eligibility and security obligations, emphasising that domains are 'critical digital assets' (CDDO, 2024). By comparison, incoherent government domain use in Nigeria creates avoidable confusion and weakens citizen confidence; instituting a mandatory ".GOV.NG" policy and unified identity would improve assurance and reduce phishing risk (World Bank, 2019).

3.4 Inter-Governmental Connectivity and Zero Trust Models

The UK's move from Public Services Network (PSN) to internet-first, API-driven integration under Zero Trust reframes trust around identity, device health and context, not network location [5]. GDS and the Home Office publish practical standards for APIs and zero-trust-aligned designs [10]. For Nigeria, secure inter-agency APIs and policy-backed data-sharing frameworks are essential to reduce duplication, close fraud loopholes and improve service continuity [4].

3.5 Accessibility, Open Standards, and Inclusion

In the UK, public sector services must meet WCAG 2.2 AA as a minimum standard under the Public Sector Bodies (Websites and Mobile Applications) Accessibility Regulations 2018 and related guidance [26, 27, 28]. Accessibility and open standards are treated as enablers of inclusion and interoperability, not optional extras [29]. Diagnostic work on Nigeria indicates wide gaps in usability and inclusion that are consistent with low adherence to common standards and limited mobile-first design (World Bank, 2019). Enforcing WCAG and open standards, supporting multiple devices/languages and investing in digital skills would materially expand equitable access.

4 ROLES OF GOVERNMENT STAKEHOLDERS IN IMPLEMENTATION

Federal leadership must set policy, fund delivery and enforce accountability, while states and LGAs adapt to local contexts. Structured collaboration with the private sector through transparent marketplaces and capability partnerships can accelerate safe adoption [7, 4]. A National Digital Transformation Office and inter-governmental taskforces would provide coherence and scale.

5 CONCLUSION

The UK's experience shows what is possible when strategy, security, accessibility and user-centred design are embedded end-to-end. For Nigeria, the window is open: Cloud First anchored in Zero Trust, open standards, unified identity and transparent procurement can deliver resilient and inclusive public value, provided policy ambition is matched by disciplined execution [4, 15, 6].

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