Power system operation enhancement modelling using MATLAB/Simulink

*Tobiloba Emmanuel Somefun*n[1*], *Olaoye Daniel Ayodeji*[2], *and Omowunmi Mary Longe*[1]

[1]Department of Electrical and Electronic Engineering Science, University of Johannesburg, Johannesburg 2006, South Africa
[2]Department of Electrical and Electronics Engineering, Covenant University, Ota, Nigeria

Abstract. This paper focuses on enhancing power system operations at the injection substation through the integration of renewable energy, modelled and simulated using MATLAB/Simulink. The study explores the incorporation of photovoltaic (PV) systems and energy storage solutions (ESS) to improve the substation's operational efficiency and reliability. By simulating different scenarios, including PV integration and ESS operations, the results show a significant improvement in voltage stability, with an average voltage profile enhancement of 13.33% across all feeders. Additionally, the energy storage system scenario demonstrated the capability to continue supplying power to the feeders even after the 33 kV grid supply was cut off, further proving its effectiveness in ensuring grid stability during disruptions. These findings suggest that renewable energy integration, coupled with advanced control mechanisms, holds great potential for broader application in enhancing the reliability and sustainability of power systems.

Keywords. Renewable energy, injection substation, MATLAB/Simulink

1 Introduction

Electricity is crucial for the development of any country, where it supports industrial, agricultural, health, and educational sectors [1]. Despite abundant fossil and renewable energy resources, Nigeria still struggles with an unreliable power supply. As of 2021, only 59.5% of Nigerians had access to electricity, according to World Bank data [2], [3]. The national grid faces issues such as inefficient power plants, insufficient renewable energy, deteriorating transmission lines, poorly maintained distribution facilities, lack of proper communication infrastructure, illegal connections, and outdated meters [4-7].

There are 6,056 MW of available power out of Nigeria's 10,396 MW of total installed generation capacity. Among these are hydropower (1,938.4 MW) and thermal generation (8,457.6 MW installed) [8-11]. Despite privatisation and reform efforts, the energy sector has seen minimal progress due to political challenges. Considering Nigeria's population of over 200 million, the actual demand should be closer to 200,000 MW [12]. The country's energy

* Corresponding author: 224200942@student.uj.ac.za

sector is transitioning, driven by industrialisation, urbanisation, and population growth, necessitating a re-evaluation of its energy mix.

The global energy landscape is shifting towards sustainability and resilience due to limited conventional energy supplies and the urgent need to address climate change. Nigeria, amid rapid economic growth, is at the forefront of this transition, facing both opportunities and challenges in integrating renewable energy sources. Reducing reliance on fossil fuels is crucial for advancing these renewable initiatives. [13].

While there is no quick fix for Nigeria's power supply issues, incremental improvements can lead to significant outcomes. This study aims to enhance power system operations in injection substations through renewable energy integration. Many injection substations in Nigeria face operational inefficiencies and grid instability, affecting their ability to provide reliable electricity. Issues such as voltage swings, frequency changes, and inadequate load control contribute to these challenges.

A core challenge is the seamless integration of renewable energy into the substation's operations. Despite Nigeria's abundant renewable energy potential, technical limitations and inadequate grid management hinder the effective harnessing of these resources. The intermittent nature of renewable energy further complicates consistent power output, leading to reliability issues. The substation requires robust control systems optimised for renewable integration, utilising advanced modelling and simulation tools like MATLAB/Simulink. This study focuses on improving the availability and stability of the power supply at the injection substation, addressing critical issues to create a more reliable and sustainable power system. The remainder of this paper is organised as follows: Section 2 offers a comprehensive literature review on renewable energy integration and power system enhancements, with a focus on photovoltaic systems and MATLAB/Simulink simulations. Section 3 outlines the methodology, detailing the modelling and simulation of the substation using MATLAB/Simulink. Section 4 presents and analyses the simulation results, assessing the impact of renewable energy integration on substation performance. Finally, Section 5 summarises the key findings and provides recommendations for future research.

2 Literature review

The integration of renewable energy sources into power systems has been a key focus in addressing energy sustainability and system reliability issues [14], [15]. Numerous studies have explored the technical and operational challenges associated with renewable energy integration, particularly in developing nations like Nigeria, where the power infrastructure is often underdeveloped [2]. This section centres on the review of relevant literature on renewable energy integration, power system enhancement through MATLAB/Simulink, and the role of photovoltaic (PV) systems in improving power stability.

Nigeria's power system is characterised by frequent instability and supply shortfalls, despite the country's abundant energy resources. The national grid faces severe challenges, including inefficient power generation, inadequate transmission infrastructure, and poorly maintained distribution networks [16]. Adebayo et al. in reference [17] pointed out that the absence of a comprehensive energy policy and limited investment in grid infrastructure exacerbate the country's power supply issues. These challenges necessitate a transition to more resilient and sustainable systems, integrating renewable energy resources to support peak loads and enhance grid stability.

2.1 Renewable energy resources

Renewable energy resources are essential for sustainable energy systems, as they offer an environmentally friendly alternative to fossil fuels. These resources include solar, wind, hydropower, biomass, and geothermal energy, each contributing to reducing greenhouse gas emissions and diversifying the energy mix. Solar energy has gained prominence due to its vast potential and declining photovoltaic (PV) technology costs. PV systems convert sunlight directly into electricity, making them an attractive option for both large-scale power generation and decentralised applications. Hence, in this study, PV is considered.

The integration of renewable energy into power systems has been widely researched due to its potential to diversify energy sources and reduce dependency on fossil fuels. In developed countries, renewable energy systems such as wind, solar, and hydropower have been successfully integrated into national grids, improving both environmental sustainability and energy security. According to Etukudoh et al., renewable energy integration poses unique challenges, such as intermittent generation and voltage fluctuations, requiring advanced control and management systems [14]. These issues are particularly pronounced in developing countries where grid infrastructure is less robust.

In Nigeria, the potential for renewable energy, particularly solar energy, is immense due to the country's high solar irradiation levels [18]. However, the integration of renewable energy into the national grid has been slow, primarily due to technical limitations and the absence of appropriate regulatory frameworks. An analysis by authors in [19] emphasised that without advanced control algorithms and grid management systems, the integration of renewable energy would remain inefficient.

MATLAB/Simulink is a powerful simulation tool that has been extensively used in power system studies for modelling, control, and optimization of renewable energy integration. Several researchers have employed Simulink to simulate the dynamic behaviour of power systems under various renewable energy integration scenarios. For instance, Patel et al. used MATLAB/Simulink to model a microgrid with integrated PV and wind systems, demonstrating its effectiveness in predicting system stability and control responses [20].

In the context of Nigeria's power infrastructure, Araoye et al. modelled the integration of renewable energy sources at substation levels using MATLAB/Simulink, concluding that the tool is crucial for identifying operational bottlenecks and optimizing grid performance [21]. MATLAB/Simulink's ability to simulate different operating conditions and renewable energy scenarios makes it an indispensable tool for this study.

Photovoltaic systems have gained widespread adoption as a clean, renewable energy source capable of improving the stability and efficiency of power systems. Several studies have highlighted the benefits of PV integration in addressing power supply deficits and enhancing voltage stability, particularly in regions with high solar potential. According to Moghadam et al., PV systems, when integrated with energy storage systems, can significantly mitigate the variability in power supply caused by intermittent solar generation [22].

For developing nations like Nigeria, PV systems offer a practical solution to the country's energy challenges. The work of Amole et al., demonstrated that PV integration at the distribution substation level can enhance voltage profiles and reduce the load on thermal generation units [23]. However, they also identified that effective PV integration requires robust control systems capable of managing power flow and ensuring system stability under varying conditions.

2.1.1 Photovoltaic systems

Photovoltaic (PV) systems are a widely adopted technology that converts sunlight directly into electricity through the photovoltaic effect. These systems use semiconducting materials, typically silicon, to create an electric current when exposed to sunlight. PV cells are interconnected to form solar panels, which can be installed on rooftops, in solar farms, or integrated into building materials. The visual representation of a PV system is shown in Fig. 1.

PV systems have several advantages, making them attractive renewable energy source. They harness an abundant and free energy source, the Sun, and produce zero greenhouse gas emissions during operation, contributing to environmental sustainability. Additionally, PV systems incur minimal operating and maintenance costs after installation. Their scalability allows for usage in various sizes, from small residential setups to large-scale commercial installations. Although the initial costs of PV systems are high, technological advancements have led to a steady price decrease. PV systems typically have a life expectancy of 25-30 years, with a low carbon footprint over their lifecycle [24], [25].

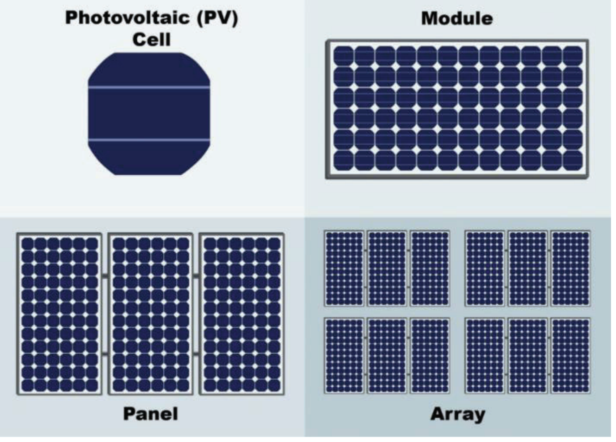

Fig. 1. PV Cell, Modules, and Array

2.1.2 Nickel Metal Hydride (NiMH) Batteries

Nickel Metal Hydride (NiMH) batteries are rechargeable batteries that use nickel oxide hydroxide and a hydrogen-absorbing alloy as electrodes. They are commonly used in applications requiring long battery life and moderate power capacity.

NiMH batteries offer several benefits, including a higher energy density than Nickel Cadmium (NiCd) batteries, making them more efficient. They are also environmentally safer, containing fewer toxic metals than other battery types. NiMH batteries have a good cycle life and can be recharged hundreds of times. The initial cost of NiMH batteries is moderate, and their capacity typically ranges from 1.2V cells with capacities between 600mAh and 10,000mAh [26]. These batteries have a 2-5 years life expectancy or 500-1000 charge cycles, balancing performance and sustainability [27].

2.1.3 Solid Oxide Fuel Cells (SOFC)

Solid Oxide Fuel Cells (SOFC) are fuel cells that use a solid oxide or ceramic electrolyte to produce electricity. Operating at high temperatures (around 800-1000°C), SOFCs can utilise a variety of fuels, including natural gas, biogas, and hydrogen. SOFCs are known for their high efficiency, achieving 50-60% electrical efficiencies and up to 85% in combined heat and power (CHP) applications [28]. They are also fuel-flexible and capable of using various fuels to generate electricity. The low emissions of SOFCs make them environmentally friendly compared to traditional combustion-based power generation methods. Despite their high initial costs, SOFCs offer substantial benefits in terms of efficiency and environmental impact. The capacity of SOFCs ranges from a few kilowatts for residential use to several megawatts for commercial and industrial applications. Typically, SOFCs have a life expectancy of 5-10 years, though ongoing research aims to extend this lifespan [29].

PV systems, NiMH batteries, and SOFCs offer unique advantages and are suited for different applications. PV systems provide a renewable, low-emission source of electricity with minimal operating costs. NiMH batteries balance energy density and environmental safety for moderate power applications. SOFCs, with their high efficiency and fuel flexibility, are ideal for continuous power generation in various settings. Understanding these technologies' operational characteristics, advantages, and costs is crucial for their effective integration into power systems, enhancing reliability, efficiency, and sustainability. Table 1 shows a comparative analysis of these technologies.

Table 1. Comparison of Some Renewable Energy Sources

Attribute	**Photovoltaic (PV)**	**Nickel Metal Hydride (NiMH)**	**Solid Oxide Fuel Cell (SOFC)**
Renewability	Renewable	Not renewable	Depends on fuel source
Environment Impact	Low operational emissions	Moderate, better than NiCd	Low operational emissions
Initial Cost	High	Moderate	High
Operating Cost	Low	Low	Moderate yo high
Capacity	Varies from few watts to MWs	Varies from 600 mAh to 10,000 mAh	Varies from kWs to MWs
SOC	Not applicable	Applicable	Not applicable
Life Expectancy	25 – 30 years	25 years	5 – 10 years
Cycle Life	High	Moderate (500 – 1000 cycles)	Not applicable (continuous operation)

The reviewed literature underscores the importance of integrating renewable energy sources, particularly PV systems, into power systems to improve reliability and sustainability. While developed countries have made significant strides in renewable energy integration, developing nations like Nigeria still face considerable challenges due to outdated infrastructure and inadequate grid management systems. MATLAB/Simulink has been proven to be a useful tool in modelling and simulating renewable energy integration into power systems. However, control systems need to be optimized to handle the variability and intermittent nature of PV generation.

This study builds on existing research by focusing on the integration of PV systems into the injection substation and using MATLAB/Simulink to simulate operational improvements and grid stability.

3 Methodology

This section is organised into several subheadings, covering load flow analysis using MATLAB/Simulink, the integration of renewable energy sources, and a detailed case study exploring multiple scenarios. By utilizing these advanced simulation tools, we optimise power system performance and ensure the smooth integration of renewable energy at injection substations.

3.1 Load Flow Studies using MATLAB/Simulink

The load flow analysis helps to understand the voltage profiles and overall system performance under various operating conditions. Given an n-bus system with 4n variables, 2n of which are known or specified, and 2n power flow equations of the form:

$$f(g,h)=0 \quad (1)$$

Where $g = 2n$ unknown variables, $h = 2n$ input data, known controlled fixed variables. Consider a typical bus of a power system network shown in Fig. 2.

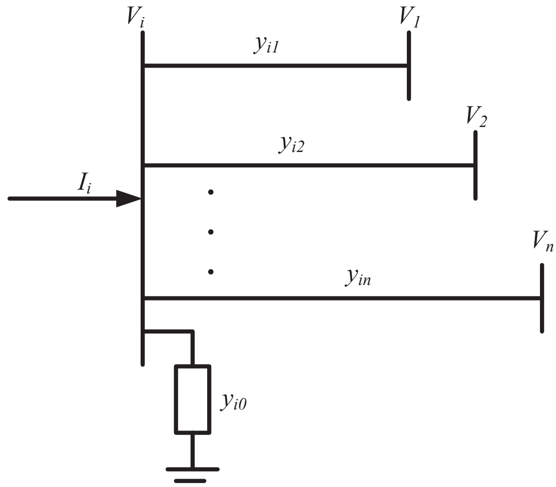

Fig. 2. A Power System Typical Bus

Pi-models is used represent the transmission lines with their admittances in per-unit on a shared MVA base. The overall nodal current equation that describes the operation of the power system network shown in Fig. 2 is as follows:

$$I_{bus}=Y_{bus}V_{bus} \quad (2)$$

Alternatively, on any bus i,

$$I_i=\sum_{j=1}^{n}Y_{ij}V_j \quad (3)$$

From Fig. 2, the total nodal current entering the i_{th} bus of n-bus system is given by:

$$I_i=Y_{i1}V_1+Y_{i2}+\ldots+Y_{ii}V_i+\ldots+Y_{in}V_n=\sum_{j=1}^{n}Y_{ik}V_k \quad (4)$$

Where $Y_{ik} =$ admittance of the line between buses i and k, and $V_k =$ the voltage at the bus k

The complex power injected into the i_{th} bus is

$$S_i=P_i+jQ_i=V_j\times I_{ij}^{*} \quad (5)$$

Taking the complex conjugate of the above equation gives the complex conjugate power as:

$$S_i^{*}=P_i-jQ_i=I_iV_i^{*} \quad (6)$$

Substituting the value of I_i from equation (4) into equation (6) gives:

$$S_i^{*}=P_i-jQ_i=V_i^{*}\sum_{i=1}^{n}Y_{ik}V_k \quad (7)$$

where $i = 1,2,3 \; . \; . \; . \; . \; ., n$

$$V_i^* = |V_i| < -\delta_i = |V_i| e^{-j\delta_i} \tag{8}$$

Therefore,

$$P_i - jQ_i = |V_i| \sum_{k=1}^{n} Y_{ik} |V_k| e^{-j(\theta_{ik}+\delta_i-\delta_k)} \tag{9}$$

$$P_i - jQ_i = \sum_{k=1}^{n} |V_i||V_{ik}||V_k| \left[\cos(\theta_{ik}+\delta_i-\delta_k) - j\sin(\theta_{ik}+\delta_i-\delta_k)\right] \tag{10}$$

Splitting equation (10) into real and imaginary parts results in the power-flow equations given by:

$$P_i = \Re e \left\{ \sum_{\substack{j=1 \\ j\neq i}}^{n} V_i \times V_j \times Y_{ij} \right\} \tag{11}$$

$$Q_i = -\Im m \left\{ \sum_{\substack{j=1 \\ j\neq i}}^{n} V_i \times V_j \times Y_{ij} \right\} \tag{12}$$

The developed model algorithm is presented in the flowchart shown in Fig. 3.

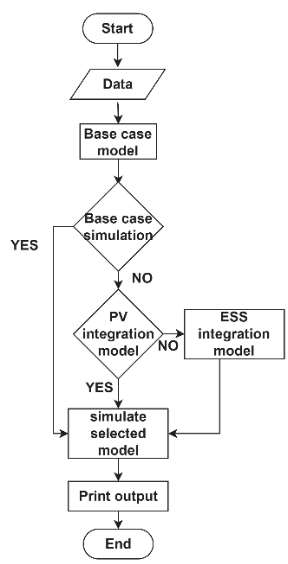

Fig. 3. Flowchart of the modelled algorithm

3.2 Case Study

The primary objective of this case study is to evaluate the impact of integrating renewable energy sources, specifically photovoltaic (PV) systems, Nickel Metal Hydride (NiMH) batteries, and Solid Oxide Fuel Cells (SOFC), for the voltage stability and efficiency of the injection substation. By examining these, the study proposes enhancing power system operations in the context of renewable energy integration. The case study is structured to analyse various scenarios, including a base case, the base case with PV integration, and the base case with the combined integration of PV and energy storage systems (ESS).

3.3 Base Case (Scenario 1)

The base case scenario focuses on the current operational state of the injection substation. This scenario involves a detailed load flow analysis using MATLAB/Simulink, incorporating the coincidental loads, feeder lengths, and the electrical properties of the transmission lines, such as resistance and inductance. Regarding substation configuration, the injection substation is equipped with a 15MVA 33/11kV transformer, which steps down the voltage for distribution to various feeders. Multiple feeder lines distribute electricity to residential, commercial, and industrial consumers. The lengths of these feeders vary, impacting voltage drops and power losses. Additionally, protective devices such as circuit breakers and other equipment ensure the safe and reliable operation of the substation, as shown in Fig. 4.

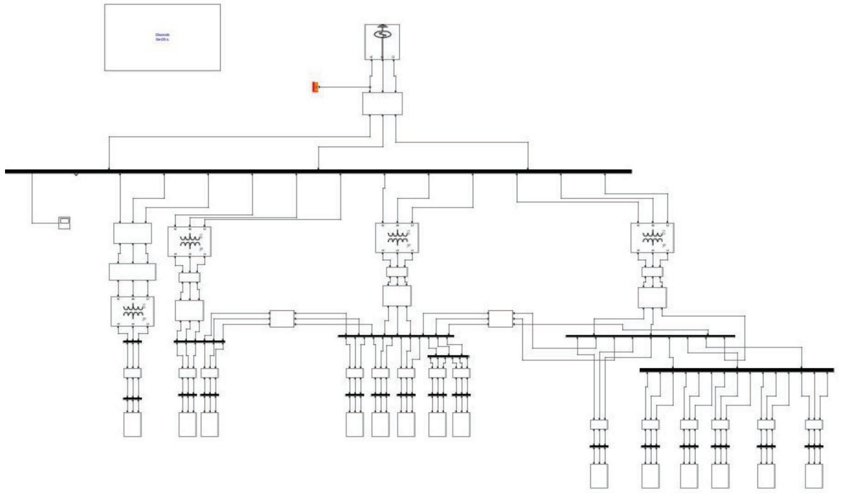

Fig. 4. Base Case Model

The load flow study in the base case scenario aims to determine the voltage, current, and power characteristics within the injection substation under normal operating conditions. The analysis identifies areas of potential improvement by examining the voltage profiles and power losses along the feeders, determining if there are any significant voltage drops or overloading issues.

3.4 Photovoltaic System Integration Scenario for Voltage Stability (Scenario 2)

In Scenario 2, Photovoltaic (PV) systems integration is evaluated to enhance voltage stability at the injection substation. This scenario builds upon the base case by incorporating a PV model, specifically integrated at bus 33 as shown in Fig. 5. The PV system in this model is rated at 100 kW, effectively augmenting the substation's power capacity.

The primary goal in this second scenario is to assess how the addition of PV systems influences the voltage stability and overall performance of the substation. The load flow analysis for Scenario 2 involves incorporating the PV system into the existing Simulink model of the substation. The simulation considers the interaction between the PV system and the existing substation infrastructure, focusing on how the additional power generation affects voltage levels, reduces power losses, and enhances overall system stability.

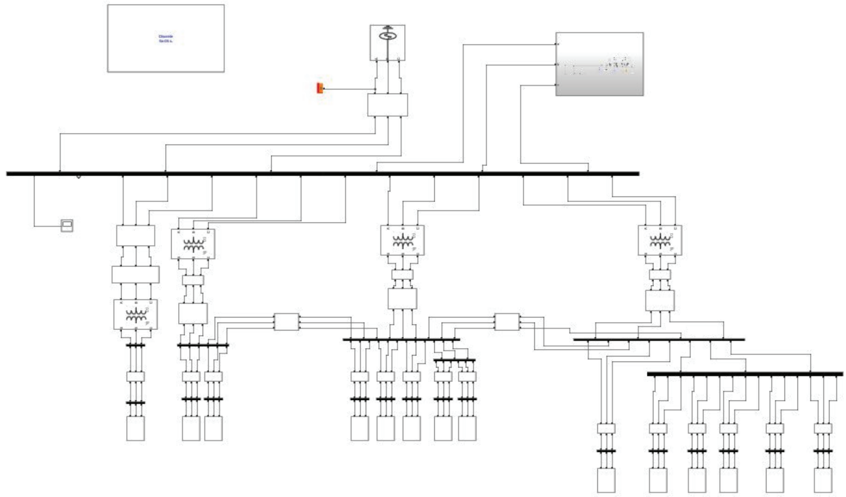

Fig. 5. Scenario 2 with PV Integration at 33 kV Bus

3.5 Energy Storage Systems for Island Mode (Scenario 3)

In Scenario 3, the integration of Energy Storage Systems (ESS) is explored to provide reliability and continuity of supply, specifically for island mode operation at the injection substation. This scenario builds upon the scenarios 1 and 2 as shown in Fig. 6 by incorporating Nickel Metal Hydride (NiMH) batteries and Solid Oxide Fuel Cells (SOFC) to ensure that the substation can maintain power supply even when there is no input from the 33 kV bus.

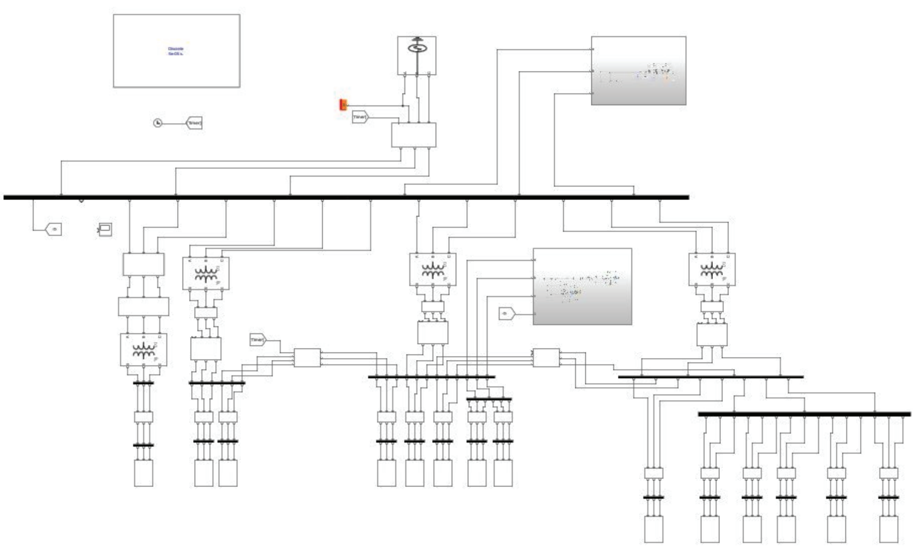

Fig. 6. Scenario 3 with PV Integration at 33 kV Bus and ESS at 11 kV

For this scenario, the ESS is strategically integrated at bus 11 kV. This setup ensures that the batteries can provide substantial energy storage and deliver power for an extended period. The integration of NiMH and SOFC energy storage technologies aims to offer a reliable backup power solution that can sustain the substation's operations for up to 2 hours without supply from the 33 kV bus. The primary objective in this scenario is to evaluate the performance and reliability of the substation when operating in island mode, solely relying on the ESS. Island mode operation is crucial for maintaining the stability and functionality of the substation during outages or disruptions in the main power supply. The combined use of NiMH batteries and SOFC provides immediate and sustained power support, ensuring critical loads can operate without interruption.

The load flow analysis for Scenario 3 involves simulating the transition to island mode and the subsequent performance of the substation while relying on the ESS.
The benefits of integrating advanced energy storage solutions become evident by analysing the results from this scenario. The NiMH batteries offer high energy density and fast response times, while the SOFC provides a steady and reliable power output. Together, these technologies enhance the resilience of the substation, ensuring that it can maintain operations during power disruptions. This scenario highlights the critical role of ESS in modern power systems, particularly in enhancing grid stability and reliability during unforeseen events. Scenario 3 demonstrates the potential of energy storage systems to provide essential backup power, ensuring continuous and reliable operation of the injection substation in island mode. This analysis supports the case for incorporating advanced ESS technologies into power grid infrastructure, further promoting the integration of renewable energy sources and enhancing overall system resilience.

4 Results and Discussion

This section presents the simulated results for the injection substation, considering the integration of PV renewable energy sources and energy storage solutions (Nickel Metal Hydride and Solid Oxide Fuel Cells). The results are presented in three scenarios: the first presents the results for the base case model, the second presents the effect of PV integration, and the third is for the islanded mode through ESS. The following assumptions are considered:

i. Coincidental Loads: The injection substation is assumed to operate under coincidental load conditions. This means that the peak load demand on the substation occurs simultaneously across different feeders, ensuring that the load profile reflects the worst-case scenario for system analysis.
ii. Transformers on Soak: It is assumed that no transformer within the substation is on soak. Transformers on soak mode are typically in a state of low-load or no-load operation to absorb excess reactive power. Excluding this condition ensures a more straightforward analysis of the system's load-bearing capacity and performance.
iii. 33 kV Incomer as Swing Bus: The 33 kV incomer to the substation is considered a single entity and is used as the swing bus for the simulation. The swing bus is the reference point in power flow studies, providing a stable voltage and absorbing any active and reactive power imbalances in the system.
iv. Feeder Losses Relative to Feeder Length: The losses in each feeder are directly proportional to the feeder length. This assumption simplifies the calculation of distribution losses by correlating more extended feeders with higher resistive and inductive losses, impacting overall efficiency and voltage regulation.
v. Uniform Cable Resistance and Inductance: All 33 kV cables are assumed to have the same resistance and inductance values as the 11 kV cables. This uniformity in cable characteristics standardises the parameters for simulation, making it easier to model and analyse the electrical behaviour of the substation's network under various loading conditions.

4.1 Base Case (Scenario 1)

Table 2 represents the load flow voltages per feeder for the base case scenario at the injection substation. Each bar corresponds to a different feeder, showing each point's per-unit (PU) voltage level. Fourteen feeders were used in this analysis.

Table 2. Voltage Profile

Feeders	Voltages PU
1	0.7934
2	0.8968
3	0.8170
4	0.8290
5	0.8295
6	0.8292
7	0.8296
8	0.9314
9	0.7576
10	0.8848
11	0.3655
12	0.8285
13	0.9084
14	0.8708

A red dashed horizontal line is drawn at 0.95 PU to indicate the acceptable lower voltage limit for the system's operational standards. Many feeders, including 1st (0.7934 PU), 2nd (0.8968 PU), 3rd (0.8170 PU), 4th (0.8290 PU), 5th (0.8295 PU), 6th (0.8292 PU), 7th (0.8296 PU), 9th (0.7576 PU), 10th (0.8848 PU), 11th (0.3655 PU), 12th (0.8285 PU), and 13th (0.8708 PU) have voltage levels below the acceptable limit of 0.95 PU. The 11th feeder shows a significantly low voltage level at 0.3655 PU, indicating a severe voltage drop and highlighting a critical area that requires attention. The 8th feeder (0.9314 PU) and the 13th feeder (0.9084 PU) have voltages closer to the 0.95 PU limit but still fall below it, indicating these feeders are also experiencing significant voltage drops. The base case chart demonstrates that the voltages across most feeders at the injection substation are below the acceptable limit of 0.95 PU. This voltage drop is primarily due to the high load demand on the substation, which stresses the power system and reduces voltage levels across the feeders as shown in Fig. 7.

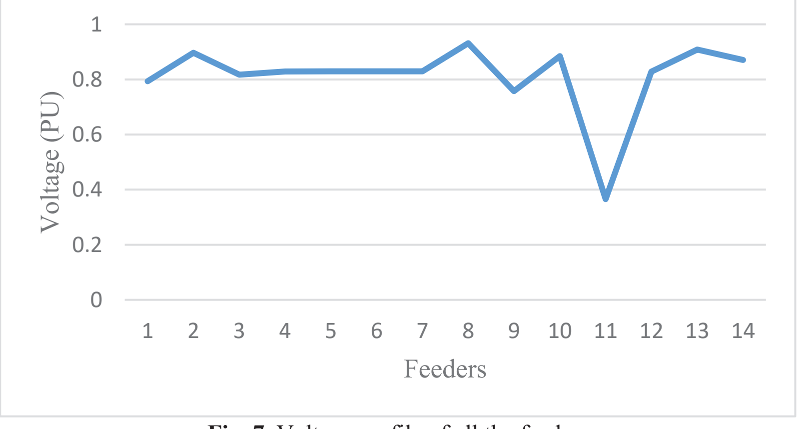

Fig. 7. Voltage profile of all the feeders

4.2 Scenario 2 with PV Integration at 33 kV Bus

Table 3 and Fig. 8 compare the base case voltages (Voltages PU) and the enhanced voltages (Enhanced Voltage PU) for each feeder at the injection substation. Each feeder is represented by two bars: one for the base case voltage and one for the enhanced voltage.

Table 3. Enhanced Voltage Profile

Feeders	Voltages PU	Enhanced Voltage PU
1	0.7934	0.8706
2	0.8968	0.9640
3	0.8170	0.9398
4	0.8290	0.9503
5	0.8295	0.9507
6	0.8292	0.9505
7	0.8296	0.9508
8	0.9314	0.9939
9	0.7576	0.8396
10	0.8848	0.9529
11	0.3655	0.5360
12	0.8285	0.9015
13	0.9084	0.9748
14	0.8708	0.9400

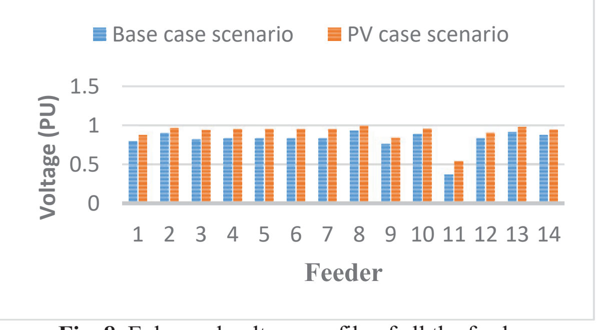

Fig. 8. Enhanced voltage profile of all the feeders

The graph illustrates a comparison of voltage profiles for various feeders before and after enhancement measures were implemented. The x-axis represents different feeders, while the y-axis shows the voltage in per unit (PU). Across all feeders, the enhanced voltages are consistently higher than the original voltages. This indicates that the measures taken to enhance the voltages were effective, resulting in 13.33% improved average voltage levels throughout the grid. The 11^{th} feeder demonstrates the most substantial improvement (46.65%), with its voltage rising from 0.3655 PU to 0.5360 PU. This significant enhancement suggests that the 11^{th} feeder had the most room for improvement and benefitted greatly from the enhancement measures. Feeders such as the 2^{nd}, 5^{th}, 6^{th}, 7^{th}, 8^{th}, 10^{th}, and 13^{th} exhibit enhanced voltages clustered around the 0.95 to 0.99 PU range. These feeders were relatively stable initially, and the enhancements have brought their voltages closer to optimal levels, indicating effective fine-tuning. The uniform rise in voltage levels across all feeders suggests that the enhancement strategy applied was consistently effective and by increase the PV rating can further improve the feeders' voltage profile. This indicates a systematic approach to voltage improvement, ensuring better voltage regulation and stability across the entire network. This consistent enhancement across the grid leads to improved reliability and performance, reducing the risk of under-voltage conditions and enhancing the overall efficiency of the power distribution system using PV integration.

4.3 Scenario 3 Energy Storage Systems for Island Mode

In Scenario 3, the integration of Energy Storage Systems (ESS) is explored to provide reliability and continuity of supply, specifically for island mode operation at the injection substation. The simulation is run for 2 seconds with a very low step size of 5e-6 to obtain precise and detailed results. The simulation is configured such that at the 1-second mark, the 33 kV feeder experiences a supply interruption as shown in Fig. 9.

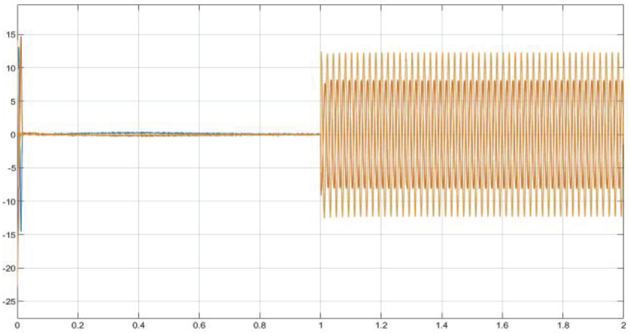

Fig. 9. Islanded Mode Voltage

At this point, the ESS begins discharging its stored energy to the 11 kV feeders while the photovoltaic (PV) source continues to supply power to a dedicated feeder i.e. the 8^{th} feeder). The primary objective of this scenario is to evaluate the capability of the injection substation to operate in island mode during a supply interruption and to assess the role of ESS and PV systems in maintaining voltage levels and reliability. Observations from the simulation indicate that the voltage level measured at one of the feeders was lower than the required voltage level, primarily due to the high load demand at the injection substation. This suggests that although the ESS and PV systems provide substantial support, they may only be sufficient to meet the entire load if they experience some voltage drop. Effective demand management is, therefore, crucial to maintaining voltage levels within acceptable limits. This could involve load shedding or shifting non-critical loads to ensure that critical loads receive adequate power.

The voltage remains relatively stable during the first second and close to zero. This indicates that the system is in a steady-state condition before any disturbance or load is applied. No significant fluctuations suggest that the grid maintains its voltage without any load or external influence. At the 1-second mark, a trigger event occurs where the 33 kV feeder supply is cut off, and the ESS voltage starts discharging to support the 11 kV feeders. The voltage has an immediate response, as indicated by the sharp increase and oscillations starting at 1 second.

After the trigger event, the voltage exhibits high-frequency oscillations. These fluctuations indicate the dynamic response of the grid voltage to the sudden load change. The voltage oscillations range between -1.5 kV and 1.5kV, showing significant variation as the islanded mode attempts to stabilize the voltage levels under the new load conditions as shown in Figs. 10, 11, and 12. The oscillations indicate the transient behaviour of the power system, which includes the charging and discharging cycles of the grid voltage as it supplies power to the substation. The voltage scope demonstrates the dynamic response of the grid voltage when the 33 kV feeder supply is interrupted. The initial steady-state period followed by high-frequency oscillations indicates the grid's active role in providing voltage support and maintaining system stability.

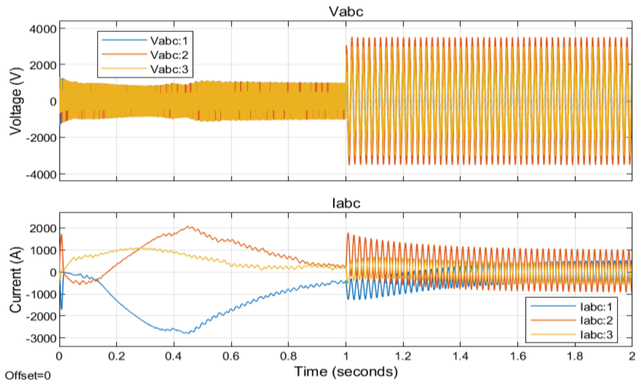

Fig. 10. Nikel Metal Hydride scope

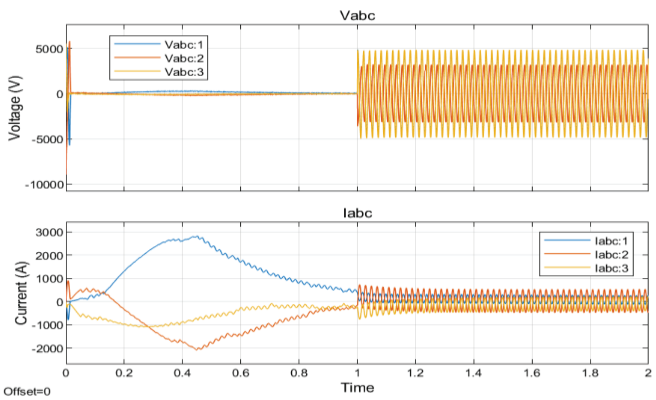

Fig. 11. Solid oxide fuel cell scope

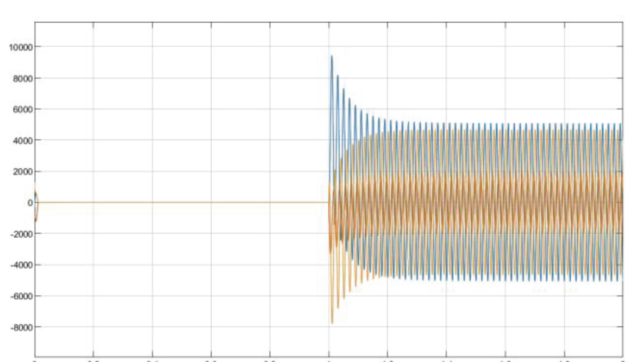

Fig. 12. Current drawn by dedicated feeder

The simulation successfully demonstrates the feasibility of operating the injection substation in island mode for a limited duration. With proper demand management, the substation can sustain island mode operation with desired based on the capacity ESS or additional renewable energy sources, further enhancing grid resilience and reliability.

5 Conclusion

Integrating renewable energy sources and energy storage systems (ESS) into the injection substation has demonstrated significant potential for enhancing power system stability and reliability. The conducted simulations highlight the critical role of demand response (DR) strategies in managing the dynamic and often unpredictable nature of renewable energy inputs. In the base case scenario, the voltage levels across various feeders were below acceptable limits, indicating the substation's struggle to meet the high load demand. Incorporating photovoltaic (PV) systems in the enhanced scenario showed improved voltage profiles, though specific feeders still experienced voltage drops due to persistent high demand. The introduction of ESS in Scenario 3 further supplied power to the feeders during island mode operations. Despite the 33 kV feeder supply being cut off, the ESS and the PV system-maintained power supply to the 11 kV feeders and the dedicated feeder, respectively. However, it was noted that voltage levels dropped slightly under heavy load conditions, underscoring the importance of effective load management strategies. In all, presenting injection substation as a case study for the integration of renewable energy has broader implications regarding Nigeria's electrical grid. Through the demonstration of the viability and advantages of integrating renewable energy at a strategically located distribution point, this study has the potential to replicate the same across the country. Promoting the replication of renewable energy projects might diversify the energy mix, accelerate the nation's shift to cleaner energy sources, and increase Nigeria's power grid's resilience to external disruptions.

Fundings

This research was funded by the National Research Foundation, South Africa, with grant reference SRUG2205025715.

References

[1] W. Strielkowski, L. Civín, E. Tarkhanova, M. Tvaronavičienė, and Y. Petrenko, Renewable energy in the sustainable development of electrical power sector: A review, *Energies*, 14, 8240, (2021).
[2] O. A. Somoye, Energy crisis and renewable energy potentials in Nigeria: A review, *Renew. Sustain. Energy Rev.*, 188, 113794, (2023).
[3] E. R. Okoroafor, E. Baik, and C. Dikeh, A Roadmap to Universal Energy Access in Nigeria, *Adv. Sci. Technol.*, 142, 91–113, (2024).
[4] H. N. Amadi and L. Ekeng, A Critical Analysis of Voltage Collapse in a Fragile Grid: The Nigeria Experience, *Int. J. Eng. Res. Dev.*, 20, 47–56, (2024).
[5] N. C. Ole, The Nigerian electricity regulatory framework: hotspots and challenges for off-grid renewable electricity development, *J. Energy Nat. Resour. Law*, 38, 367–390, (2020).
[6] T. Somefun, C. Awosope, A. Abdulkareem, J. Ojo, E. Amuta, and T. Sanni, Cost implications analysis of grid supplied electricity and solar source of electricity in Nigeria, *TELKOMNIKA (Telecommunication Comput. Electron. Control.*, 18, 3258–3265, (2020).
[7] O. O. Babayomi *et al.*, A review of renewable off-grid mini-grids in Sub-Saharan

Africa, *Front. Energy Res.*, 10, 1089025, (2023).

[8] O. Bamisile, Q. Huang, P. Ayambire, P. O. K. Anane, S. Abbasoglu, and W. Hu, Analysis of solar pv and wind power penetration into nigeria electricity system, in *2020 IEEE/IAS 56th Industrial and Commercial Power Systems Technical Conference (I&CPS)*, IEEE, 2020, 1–5.

[9] O. Bamisile *et al.*, An approach for sustainable energy planning towards 100% electrification of Nigeria by 2030, *Energy*, 197, 117172, (2020).

[10] A. Samuel and O. Tt, Power Generation In Nigeria: The Past, Present And The Future, *vol*.

[11] C. I. Igwe, A review of power generation in Nigeria: Limitations and recommendations..

[12] Y. N. Chanchangi, F. Adu, A. Ghosh, S. Sundaram, and T. K. Mallick, Nigeria's energy review: Focusing on solar energy potential and penetration, *Environ. Dev. Sustain.*, 25, 5755–5796, (2023).

[13] J. L. Holechek, H. M. E. Geli, M. N. Sawalhah, and R. Valdez, A global assessment: can renewable energy replace fossil fuels by 2050?, *Sustainability*, 14, 4792, (2022).

[14] E. A. Etukudoh, A. Fabuyide, K. I. Ibekwe, S. Sonko, and V. I. Ilojianya, Electrical engineering in renewable energy systems: a review of design and integration challenges, *Eng. Sci. \& Technol. J.*, 5, 231–244, (2024).

[15] Q. Hassan, S. Algburi, A. Z. Sameen, H. M. Salman, and M. Jaszczur, A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications, *Results Eng.*, 101621, (2023).

[16] T. Somefun, A. Abdulkareem, O. Popoola, C. Somefun, and T. Ajewole, Strategic DG placement and sizing in developing nations' power systems using ISNT and modified forward-backward sweep, *Eng. Res. Express*, 6, 35342, (2024).

[17] A. V. Adebayo and P. K. Ainah, Addressing Nigeria's Electricity Challenges: Past, Present, And Future Strategies, 5, 1–16, (2024), doi: https://doi.org/10.5281/zenodo.12633012.

[18] M. I. Yahuza and M. B. Suleiman, Assessment of Solar Energy Potentials of North-Eastern Region of Nigeria, *J. Syst. Eval. Divers. Eng.*, (2024).

[19] M. Khalid, Smart grids and renewable energy systems: Perspectives and grid integration challenges, *Energy Strateg. Rev.*, 51, 101299, (2024), doi: https://doi.org/10.1016/j.esr.2024.101299.

[20] S. Patel, A. Ghosh, and P. K. Ray, Optimum control of power flow management in PV, wind, and battery-integrated hybrid microgrid systems by implementing in real-time digital simulator-based platform, *Soft Comput.*, 27, 10863–10891, (2023).

[21] T. O. Araoye, E. C. Ashigwuike, S. V. Egoigwe, F. U. Ilo, A. C. Adeyemi, and R. S. Lawal, Modeling, simulation, and optimization of biogas-diesel hybrid microgrid renewable energy system for electrification in rural area, *IET Renew. Power Gener.*, 15, 2302–2314, (2021).

[22] M. Moghadam and N. Ghaffarzadeh, Suppressing solar PV output fluctuations by designing an efficient hybrid energy storage system controller, *Unconv. Resour.*, 4, 100077, (2024).

[23] A. O. Amole, S. Oladipo, O. E. Olabode, K. A. Makinde, and P. Gbadega, Analysis of grid/solar photovoltaic power generation for improved village energy supply: A case of Ikose in Oyo State Nigeria, *Renew. Energy Focus*, 44, 186–211, (2023).

[24] H. Tian, F. Mancilla-David, K. Ellis, E. Muljadi, and P. Jenkins, A cell-to-module-to-array detailed model for photovoltaic panels, *Sol. energy*, 86, 2695–2706, (2012).

[25] N. A. Ludin *et al.*, Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: A review, *Renew. Sustain. Energy Rev.*, 96, 11–28, (2018).

[26] M. D. Fleischauer, M. R. Kupsta, and A. D. Johnson, Improved conflat cell for repeatable electrochemical testing to 400° C, *J. Electrochem. Soc.*, 166, A398, (2019).
[27] Z. Yang, H. Huang, and F. Lin, Sustainable electric vehicle batteries for a sustainable world: perspectives on battery cathodes, environment, supply chain, manufacturing, life cycle, and policy, *Adv. Energy Mater.*, 12, 2200383, (2022).
[28] R. J. Braun and P. Kazempoor, Application of SOFCs in combined heat, cooling and power systems, (2013).
[29] C. Strazza, A. Del Borghi, P. Costamagna, M. Gallo, E. Brignole, and P. Girdinio, Life Cycle Assessment and Life Cycle Costing of a SOFC system for distributed power generation, *Energy Convers. Manag.*, 100, 64–77, (2015).