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ASSESSING THE IMPACT OF SOLAR ENERGY TECHNOLOGIES ON THE EFFECTIVENESS OF AC POWER SYSTEM

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Abstract
The introduction of solar energy technologies in conventional Alternating Current (AC) power systems globally is gradually changing the over dependence on fossil fuel. In Nigeria, the grid is characterized by limited spinning reserves, weak transmission lines, and consistence frequency excursions. The integration of solar photovoltaic (PV) present both operational challenges and efficiency opportunities. This study assessed the impact of solar energy technologies on the stability and efficiency of the National AC grid power system. It evaluated key stability indicators, such as frequency response, voltage regulation and system inertia, under varying solar penetration levels. Power flow and dynamic simulations were conducted on a representative model of the Nigerian transmission network to analyse intermittency effects and reduced synchronous generation displacement. Results indicated that while moderate solar penetration improves overall system efficiency by reducing transmission losses and fuel dependency, high levels of inverter-based generation without adequate grid support mechanisms may degrade frequency stability and voltage profiles. The study demonstrated that integrating grid-forming inverters, battery energy storage systems, and advanced reactive power compensation significantly enhances system resilience and operational reliability. The findings provided strategic insights for optimizing solar integration, which supported Nigeria energy diversification goals in maintaining grid stability and efficiency.

Keywords: Battery energy storage systems, photovoltaic cells, renewable energy, alternating current, grid power system.

Introduction

Photovoltaic generation of power is caused by electromagnetic radiation separating positive and negative charge carriers in absorbing material, Qubeissi *et al*. (2020). According to Freris *et al*. (2008), Cloud cover can significantly reduce the net radiation and cause relatively fast variations in intensity, in some cases significant variations from minute to minute or even over seconds. Photovoltaic (PV) energy is the most easily scalable type of renewable energy generation, Phuangpornpitaka *et al*. (2013). Different technologies, such as the ones based on energy storage, can be used to support the integration of Renewable Energy Systems (RES), they usually demand a huge investment., Alazemi *et al.* (2024).

The worldwide transition toward low carbon energy systems has accelerated the deployment of renewable energy technologies within conventional Alternating Current (AC) power networks. Driven by climate change mitigation goals, declining technology costs, and energy security concerns, countries are integrating solar Photovoltaic (PV), wind, and small hydropower resources into existing grids that were originally designed for centralized, synchronous generation. While renewable energy offers environmental and economic benefits, its large-scale integration introduces technical challenges

related to frequency stability, voltage regulation, power quality, and overall system efficiency. Battery Energy Storage System (BESS) has the ability to mitigate renewable Distribution Energy Resources (DER) variability and improve Transmission and Distribution utilization, Henderson *et al.* (2017). Energy storage can smooth out the fluctuations of wind and solar power and improve the load availability, Wang *et al.* (2008).

In Nigeria, the power system is characterized by limited generation capacity, aging infrastructure, weak transmission corridors, and inadequate spinning reserves. The Nigerian AC grid operates with relatively low system inertia due to frequent generator outages and constrained dispatch flexibility. As renewable energy deployment increases particularly grid-connected and embedded solar PV installations concerns arise regarding intermittency, reduced synchronous inertia, bidirectional power flows, and the potential for voltage and frequency instability. These issues are especially critical in a network already prone to disturbances and system collapses. Sustainable development includes the use of renewable energy, energy security, energy pricing, energy policy, renewable energy applications and smart grid technologies, Qubeissi *et al*. (2020).

Nigeria's renewable expansion is supported by national policy frameworks such as the Federal Ministry of Power and targets outlined in the Renewable Energy Master Plan, which aim to diversify the energy mix, reduce reliance on fossil fuels, and improve electricity access. However, achieving these objectives requires a careful technical assessment of how renewable energy technologies affect grid performance metrics, including transient stability, small-signal stability, voltage profiles, system losses, and overall operational efficiency. Sinsel *et al.* (2022) comment that variable renewables such as solar photovoltaics and wind power are key technologies for achieving the decarbonization of the power sector.

Unlike conventional synchronous generators, inverter based renewable sources contribute little or no inherent rotational inertia, thereby weakening frequency response during disturbances. Additionally, variability in solar irradiance and wind speed can cause rapid power fluctuations, increasing the burden on existing control systems. On the other hand, distributed renewable generation can reduce transmission congestion, minimize losses, and enhance local voltage support when properly coordinated. Sinsel *et al.* (2022) suggested that sufficient power quality is the dominant performance requirement for end consumers. The power quality category comprises the requirements for uninterrupted power supply and stable conditions of voltage and current, as well as safe conditions in case of outages.

Zangeneh *et al.* (2024) proposed an intelligent multi-input/output Fuzzy Logic Control (FLC) to manage the Hybrid Renewable Energy System (HRES) operation (as shown in Fig. 1) that included a PV panel, a lithium-ion battery box and access to the power grid. The proposed controller ensures that the battery was charged by solar energy or the power grid and discharged in special weather conditions. The vigorous expansion of renewable energy as a substitute for fossil energy is the predominant route of action to achieve worldwide carbon neutrality, Liu *et al.* (2022). Managing energy in microgrids is a complex and challenging endeavor due to the uncertainties linked to renewable energy resources, fluctuating demand, and a variety of devices, Hematian *et al*. (2024).

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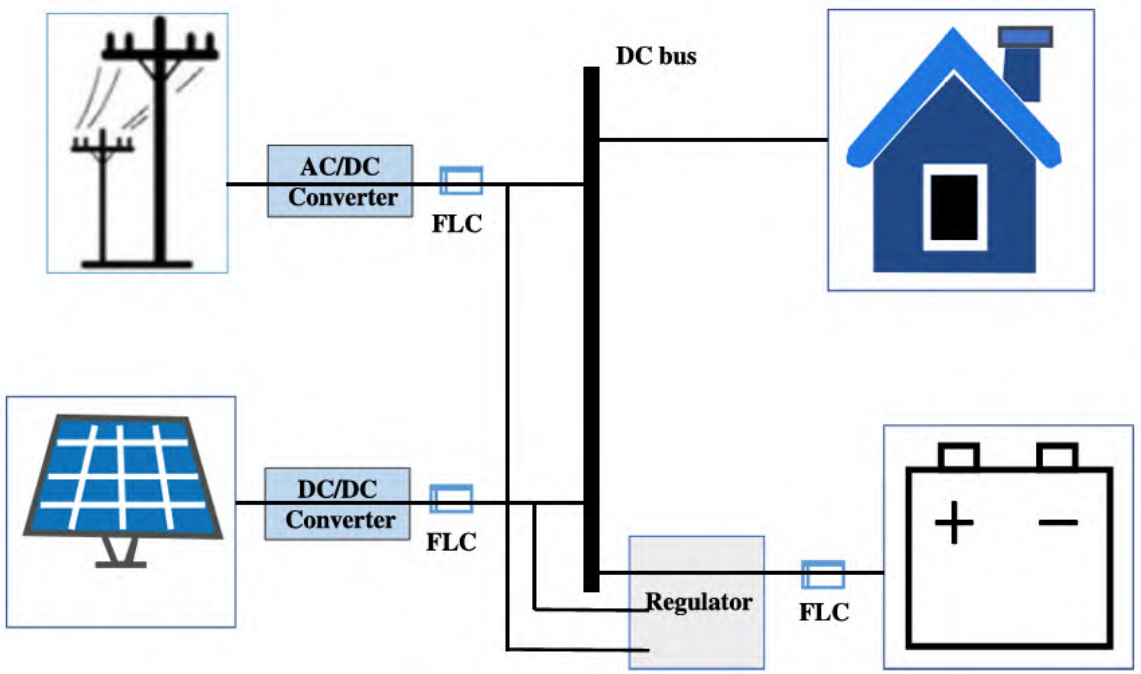


Figure 1: The studied hybrid power system
Source: Zangeneh *et al.* (2022)

This study therefore investigates the impact of renewable energy technologies on the stability and efficiency of Nigeria's AC grid power system. By evaluating system behaviour under varying levels of renewable penetration and analysing key stability indicators, the research provides insights into the technical requirements for reliable integration. The findings are intended to support policymakers, grid operators, and power system planners in developing strategies that balance sustainability goals with operational reliability and grid efficiency.

Materials and Methods

This study modelled the Nigerian 132 kV transmission network to evaluate the technical impact of solar Photovoltaic (PV) integration under different penetration levels. Steady-state and dynamic analyses were performed to assess voltage profile, frequency stability, and transmission losses.

The Newton–Raphson method was used to compute bus voltages and line flows. The active power equation at bus *i* is:

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

Equation 1

Where:
Vi and Vj are bus voltages,
Gij and Bij are elements of the admittance, and
θij is the voltage angle difference.
Transmission losses were estimated as:

$$P_{loss} = \sum G_{ij}(V_i^2 + V_j^2 - 2V_iV_j \cos\theta_{ij})$$

Equation 2

Solar PV Modelling

Solar output was modelled as a function of irradiance and temperature:

$$P_{PV} = \eta AG\,[1 - \beta(T_c - T_{ref})] \quad \text{Equation 3}$$

Where:
H is the PV efficiency,
A is panel area,
G is the solar irradiance, and
β is the temperature coefficient.

Frequency Stability Assessment

The swing equation was used to analyze system inertia and frequency response:

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e \quad \text{Equation 4}$$

The rate of change of frequency

$$\frac{df}{dt} = \frac{P_{imbalance}}{2H_{sys}f_0} \quad \text{Equation 5}$$

Where: H_{sys} is the equivalent system inertia and f_o is 50Hz

Battery Energy Storage Systems (BESS)

Battery state of charge dynamic was modelled as:

$$SOC(t) = SOC(t-1) + \frac{\eta_c P_{charge} - P_{discharge}/\eta_d}{E_{rated}} \quad \text{Equation 6}$$

Results and Discussion

The analysis revealed that integrating renewable energy technologies particularly solar PV into the Nigerian AC grid had both stabilizing and destabilizing tendencies depending on penetration level and grid management strategies. Case simulations of high renewable penetration scenarios showed improved voltage profile in localized areas with solar generation during peak daylight hours. However, without adequate ancillary services and real time balancing, the intermittency of solar energy contributed to increased frequency fluctuations and occasional voltage swings on weak network segments as in Figure 2. This trend aligns with observed instability episodes recorded by the Nigerian grid Engineers during periods of rapid load variation and insufficient spinning reserves.

A key finding was that distributed solar generation improved local reliability, but when scaled without proper control mechanisms (e.g., inverter-based support, reactive power compensation), it can stressed transmission corridors and complicate system protection coordination as in Figure 2. This underscores the need for adaptive grid controls and forecasting tools in the Nigerian context.

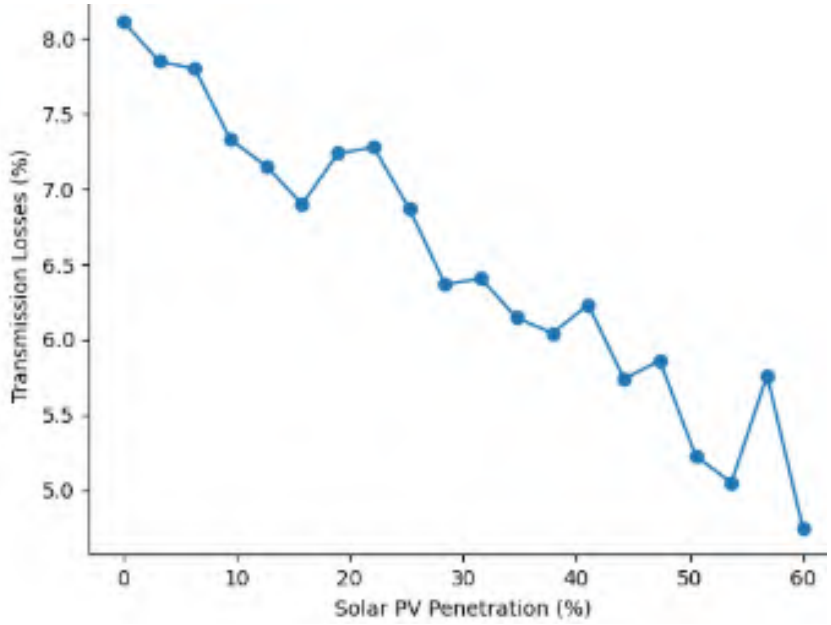


Figure 2: AC transmission losses on solar system integration reduction

Furthermore, findings from load flow studies suggested that distributed renewables reduce congestion and enhance power quality in select zones, particularly around Lagos and Kaduna, where localized PV systems alleviated stress on long-distance power transfers from centralized stations. Despite efficiency gains, the study highlights persistent challenges unique to the Nigerian grid which are:

- Frequent outages and aging of transmission infrastructure diminish the effectiveness of renewable integration.
- Low short-circuit capacity in several regions magnifies the impacts of renewable variability, necessitating advanced grid-forming inverters and energy storage support.
- Inconsistent renewable policies and limited incentives have slowed investment in grid-enhancing technologies such as smart inverters and grid-scale storage systems.

Solar technologies contributed positively to efficiency and localized reliability, without systemic upgrades and regulatory frameworks, they can exacerbate grid instability under high penetration scenarios. The study's outcomes advocated for strategic deployment of renewables coupled with grid modernization which are:

- Control systems and enhanced forecasting to reduce intermittency impacts.
- Support frequency regulation and energy storage integration to buffer variability.
- Market mechanisms that reward solar generators for ancillary service provision and flexible grid codes.
- Investment in grid infrastructure to strengthen weak sections and improve network resilience.

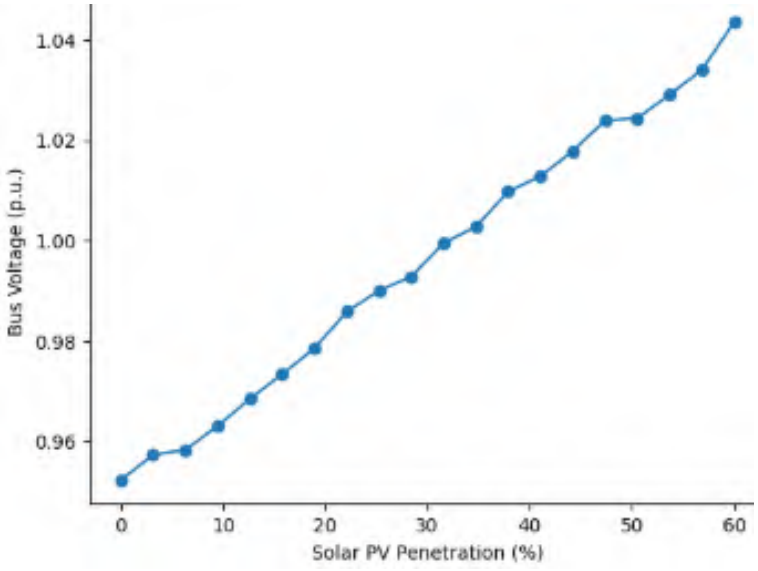


Figure 3: The effect of solar PV penetration on AC power system voltage profile

The results indicated measurable gains in overall system efficiency with renewable integration. Modelled operational cost analyses demonstrated that fuel consumption in thermal plants declined by approximately from 15% to 20% when solar supply displaced peak load demand. This reduction reflected lower generation costs and decreased transmission losses from reduced power flow distances, particularly in regions with high solar potential like the northern states.

Conclusion

The integration of solar energy technologies into Nigeria's AC grid demonstrated cleared potential to enhanced system efficiency, reduced fuel dependency, and improved localized reliability. However, the inherent variability of solar generation introduced new stability challenges, particularly in regions with weak grid infrastructure and limited ancillary support. Effective solar integration in Nigeria will therefore require coordinated grid modernization, including advanced control systems, energy storage solutions, and strengthened transmission networks. With strategic planning and supportive policies, solar energy can play a pivotal role in achieving a more resilient, efficient, and sustainable Nigerian power system.

Contributions to Knowledge

It expands knowledge on how solar PV affect frequency stability, voltage regulation, power quality, and system inertia in AC grids. It analyses how renewable integration influences transmission losses, generation efficiency, and overall system performance. It contributes improved methods, simulations, or mathematical models for assessing renewable penetration levels and their technical implications. It proposes solutions such as energy storage systems, flexible generation, smart inverters, and grid code enhancements to maintain reliability. It offers insights that guide engineers, planners, and policy makers in transitioning from conventional fossil fuel-based systems to more sustainable and resilient AC power systems.

Recommendations

To maximize the benefits of renewable energy integration while safeguarding grid stability in Nigeria, the following measures are recommended: Upgrade aging transmission and distribution networks to improve grid strength, short-circuit capacity, and voltage stability, particularly in weak northern corridors. Integrate grid scale battery energy storage to manage renewable intermittency, support frequency regulation, and provide spinning reserve replacement. Adopt smart inverters, real-time monitoring systems, and improved forecasting tools to enhance system flexibility and operational response. Update Nigerian grid codes to require renewable plants to provide ancillary services such as reactive power and frequency support, while creating incentives for private investment in grid-support technologies. Encourage properly regulated embedded and rooftop solar systems to reduce transmission congestion and improve local reliability without compromising protection coordination.

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