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Research Article

Enhancing Renewable Energy-Grid Integration by Optimally Placed FACTS Devices: The Nigeria Case Study

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Abstract

Integrating renewable energy sources into existing power grids presents considerable challenges, especially with the intermittency of wind and solar power. This issue is particularly acute in developing countries like Nigeria, where grid infrastructure is often weak, significantly limiting the potential for RE penetration. This study explores strategies to enhance RE integration in Nigeria by employing Flexible Alternating Current Transmission System (FACTS) devices. By leveraging the reactive-power sensitivity index through modal analysis, the optimal location for the FACTS device can be determined. Analysis of the Nigerian power grid demonstrates that the deployment of FACTS devices, specifically Static Synchronous Compensators (STATCOMs), can increase the penetration limit of RE by 40%. This enhancement allows for the integration of an additional 152 MW of wind energy without compromising system stability. The findings underscore the potential of FACTS devices to improve voltage profiles and overall grid stability, thereby facilitating a higher integration of renewable energy sources into weak grids without necessitating substantial changes to the existing power system architecture. This solution can help Nigeria and other countries with similar infrastructure challenges to overcome their renewable energy integration hurdles and transition towards a more sustainable, reliable, and resilient energy mix, paving the way for a cleaner and greener future.

Keywords

FACTS Devices, Renewable Energy, DFIG-Wind Energy, Penetration Limit, Power System Analysis

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1. Introduction

The global shift towards renewable energy (RE) sources, prompted by climate change concerns and fossil fuel depletion, has gained momentum. Projections indicate a 30% increase in worldwide energy consumption by the year 2040 [1]. Wind and solar power, among other renewable technologies, provide sustainable alternatives to traditional fossil fuel-based generation. However, integrating these intermittent energy sources into existing electrical grids presents significant technical hurdles [2], necessitating robust planning, coordination, and investment in grid management and control systems to ensure stability and reliability. Maintaining grid stability and reliability while accommodating the variable nature of renewable energy generation is a key challenge. The impact of RE integration varies depending on penetration level, grid condition, and geographical location. As correctly noted by Mararakanye [3], the effects of RE on the grid vary depending on the context. Consequently, findings from one power system may not universally apply to others. Saleem *et al.* [4] showcased how grid strength can limit RE integration, highlighting that weak grids pose greater challenges than stronger ones. Therefore, power systems in many developing countries, often weakened due to their longitudinal nature [5], face more stringent limitations on RE penetration.

Nigeria boasts abundant renewable energy sources like wind and solar, as highlighted in numerous studies [6-9]. However, limited attention has been given to how grid conditions may restrict renewable energy penetration. While Li *et al.* [10] proposed a fault control mechanism to enable up to 90% wind energy integration, whether the grid remains stable for such integration remains uncertain. Ozioko *et al.* [11] found a 10% penetration limit for DFIG-based wind farms on the Nigerian grid, noting no improvement in voltage profile due to PQ-controlled integration. Adetokun *et al.* [12] suggested using large-scale solar photovoltaic energy to enhance the grid's voltage profile based on load flow analysis, but further dynamic simulation and power loss investigations are needed to confirm system stability under large integration.

This study investigates enhancing renewable energy grid integration by strategically positioning FACTS devices within the Nigerian power system. Placing FACTS devices at strategic points strengthens the grid, thereby boosting the penetration capacity of renewable energy. Through strategic placement in the grid infrastructure, FACTS devices enhance grid flexibility, facilitating improved integration of renewable energy sources.

Numerous studies have explored the implementation of FACTS devices to enhance the Nigerian power system [13-22]. However, none have examined extending the renewable energy penetration limit, a focus of this paper. Addressing these gaps, the utilization of STATCOM and DFIG-based wind farms was investigated. Our interest is in STATCOM due to its efficient dynamic performance [23] and in wind power due to its abundance in Nigeria with high potential for large-scale electricity generation.

The remainder of this paper is structured as follows: Section II presents an overview of the Nigerian grid's status, providing essential context regarding its weaknesses. Section III outlines the methodology used for conducting investigations, along with pertinent theoretical underpinnings. In Section IV, the findings are presented and discussed. Finally, Section V concludes the paper, summarizing its key points.

2. The State of Power Supply in Nigeria

Nigeria, the most populous nation in Africa and the continent's largest economy [24], has struggled to provide reliable electricity to its citizens. To address this, the government reformed the power sector, allowing private companies to generate and distribute electricity while maintaining state control over transmission [24]. The power sector is structured into generation companies (GENCOs), transmission company of Nigeria (TCN), and distribution companies (DISCOs), with the Nigerian Electricity Regulatory Commission (NERC) overseeing their interactions [24].

Despite an installed capacity of 10,396 MW and an available capacity of 6,056 MW [24], Nigeria faces a significant shortfall in meeting its projected electricity demand of 12,800 MW [24]. The transmission network, spanning approximately 20,000 km of transmission lines and high-voltage substations [24], is plagued by technical challenges, limiting its capacity to 5,300 MW [24, 25]. This leads to poor voltage profiles, transmission losses, and frequent grid collapses [7]. The discussion can be synthesized with Figure 1.

Nigeria's power transmission system transmits bulk electricity from generating stations to distribution substations at high voltages – 330kV for primary transmission and 132kV for secondary transmission – using a 3-phase system. The electricity is then transformed and delivered to consumers at various distribution voltages, including 33kV, 11kV, and 415V, to meet their specific power requirements. However, the transmission network is severely strained, struggling to keep up with demand. As a result, transformers and conductors are overloaded, 132/33 kV substations are inadequate, and injection points are insufficient to support growing demand. Furthermore, rural electrification efforts have put additional pressure on the 33 kV and 11 kV systems, leading to poor voltage profiles and reduced reliability. As the transmission line capacity falls short of available capacity and demand, even with sufficient generation, transmission constraints hinder efficient power delivery to load centers. Moreover, these lengthy lines incur high losses, impeding effective power distribution. As a result, the weak grid struggles to withstand minor disturbances and experiences frequent collapses.

The power network has a control center at Osogbo, known as the National Control Center (NCC), which employs a Supervisory Control and Data Acquisition (SCADA) system. The primary control technique used is mostly load shedding. Consequently, utilities carry out excessive load shedding, leaving a significant portion of the population living in darkness. According to the World Bank's 2020 report, only 60% of Nigerians access electricity [7]. Nigeria is working towards reducing its dependence on fossil fuels by incorporating a mix of renewable energy sources such as wind and solar. Although there is currently no wind energy in the grid, there is a 10 MW wind farm under construction in Kastina State. Additionally, privately owned micrograms that utilize solar photovoltaic systems are operational [7] but are not yet connected to the national grid. Research indicates that there is significant wind energy potential, with more proposals currently in development. As these renewable energy sources scale up to grid-scale production, they will eventually feed into the grid, offering hope for improved electricity access and a more stable power sector.

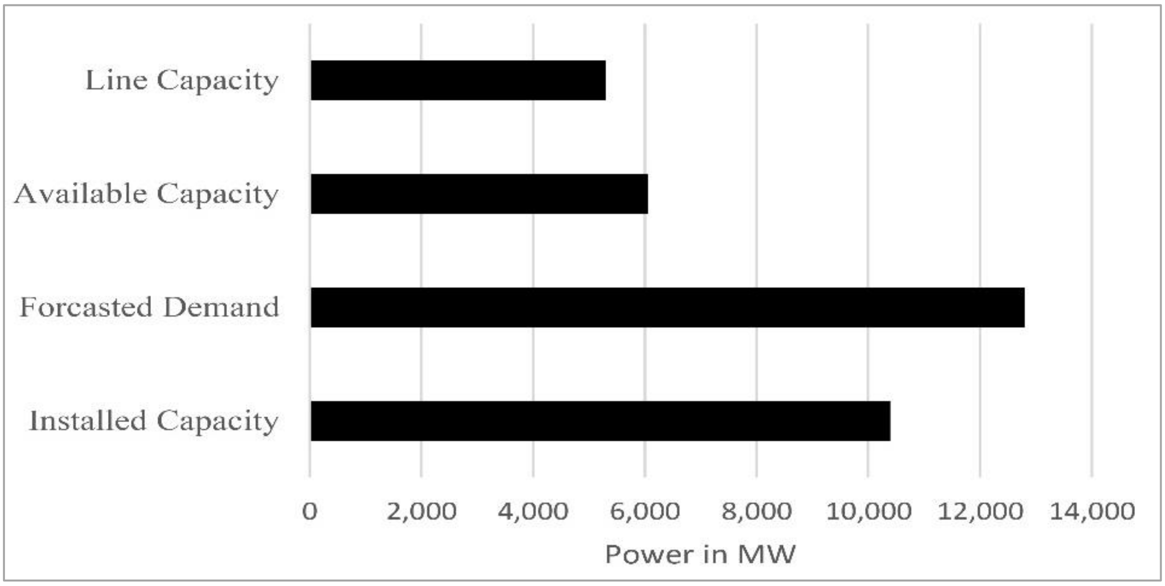

Figure 1. *The Nigerian Grid Status.*

3. Materials and Method

This section provides a concise summary of the research design, methods, and theoretical underpinnings that informed the analysis, setting the stage for the ensuing discussion.

3.1. DFIG-Grid Integration

Figure 2 depicts a Doubly Fed Induction Generator-based wind turbine connected to the grid (DFIG-WTG). This configuration includes a stator directly linked to the grid and a rotor connected via a two-stage power electronic converter (PEC) and a DC link bus. The rotor side converter (RSC) manages rotor speed for optimizing power output, while the grid side converter (GSC) controls power factor and maintains DC link bus voltage. The DFIG-WTG connects to the grid through transformer Tx on either the PQ or PV bus.

To accurately calculate the electrical output of wind turbines, it is essential to consider the efficiency of individual components, such as the generator, inverter, and transformer. The process begins by determining the mechanical energy captured by the turbine blades, which is then converted into electrical energy by the generator. However, not all this energy is usable, as some are lost as heat or vibration. The generator efficiency, typically ranging from 90% to 95%, takes these losses into account. Next, the electrical energy is sent through an inverter, which converts the turbine's DC power to AC power and synchronizes it with the grid frequency. Inverter efficiency, usually around 95% to 98%, also impacts the overall output. Finally, the energy is transformed to match the grid voltage, with transformer efficiency typically around 98% to 99%, affecting the final output.

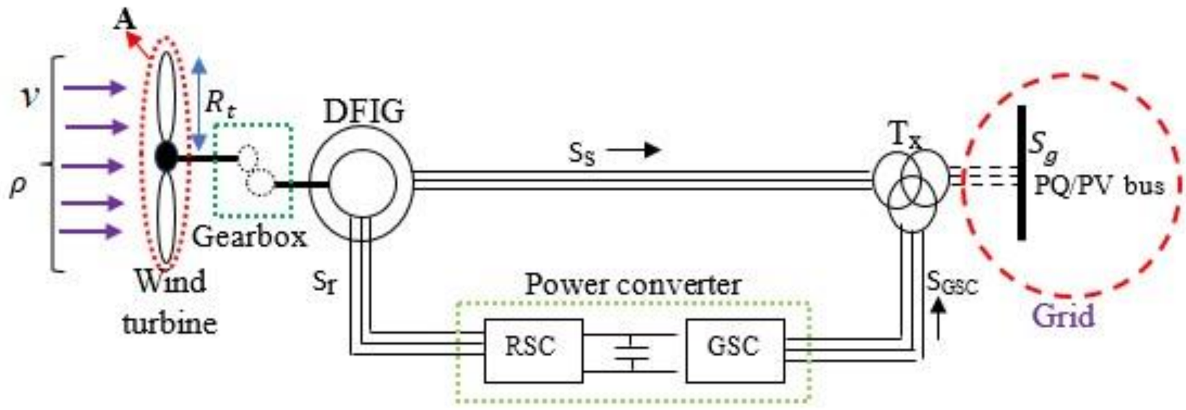

Figure 2. Schematic representation of a DFIG-based wind turbine connected to the grid.

The mechanical output power of a wind turbine is typically modeled as (1):

$$P_m = \frac{1}{2}\rho A C_p(\lambda, \alpha) v^3 \quad (1)$$

Here, (C_p) is the turbine performance coefficient, (λ) is the tip speed ratio, (α) is the blade pitch angle, (ρ) is the air density (kg/m^3), (A) is the turbine swept area (m^2) and (v) is the wind speed (m/s). (ω_m) represents the tip speed of the rotor (rad/s), and (A) is calculated as (πR_t^2), where (R_t), is the blade radius. The turbine performance coefficient, $C_p(\lambda, \alpha)$ measures a wind turbine's efficiency in converting wind energy into mechanical energy and typically ranges from 0.35 to 0.45 [26].

The mechanical power interacts with electrical torque as represented by (2):

$$\dot{\omega_m} = \frac{T_m - T_e}{2H_m} \quad (2)$$

Here, (T_e) denotes the electromagnetic torque, (H_m) is the inertial constant (KW s/kVA), and (T_m) represents the mechanical input torque of the DFIG. Equation (2) illustrates two dynamic aspects of wind energy integration: mechanical power dynamics influenced by wind speed variation (v), and electrical dynamics due to the DFIG's interaction with the grid. While wind speed (v), is stochastic, assumption is made that it remains relatively constant for the purpose of this paper, which focuses on exploring the capability of FACTS devices to enhance renewable energy penetration. A PQ-controlled model was adopted for the DFIG-WTG, maintaining a unity power factor, thereby integrating the DFIG-WTG into the network as a negative load.

3.2. Determining the Wind Farm Location

Previous studies highlight that the northern region of Nigeria boasts optimal conditions for onshore wind farms due to its high wind speeds [9, 27]. According to Okedu *et al.* [9], this area experiences average wind speeds ranging from 8.4 m/s to 14.7 m/s. While several northern states are suitable for wind farms, Ayodele *et. al*. [27] specifically identifies Plateau, Kano, Jigawa, Kastina, and Sokoto as particularly favorable locations.

For this study, the Jos bus (located in Plateau state) was selected as the connection point for the DFIG-WTG, based on our previous research indicating superior performance, especially in mitigating inter-area oscillations. A wind speed of 9 m/s was assumed, which is typical for the region, with a blade radius (Rt) of 75 m, a turbine performance coefficient (Cp) of 0.40, and an air density of 1.225 kg/m^3. These parameters result in an estimated average wind turbine output (Equation 1) of approximately 3 MW. A theoretical wind farm capacity was considered to be 900 MW, equivalent to a cluster of 300 MW wind turbines (3 × 300 MW).

3.3. Identifying Ideal Deployment Sites for STATCOM

Figure 3 shows a simplified representation of Nigeria's 50-bus power grid, comprising 14 generators (3 hydro and 11 gas-powered) and a total load demand of 4,300 MW.

The Egbin power station is designated as the slack bus generator, providing a reference point for power flow and voltage control in this study.

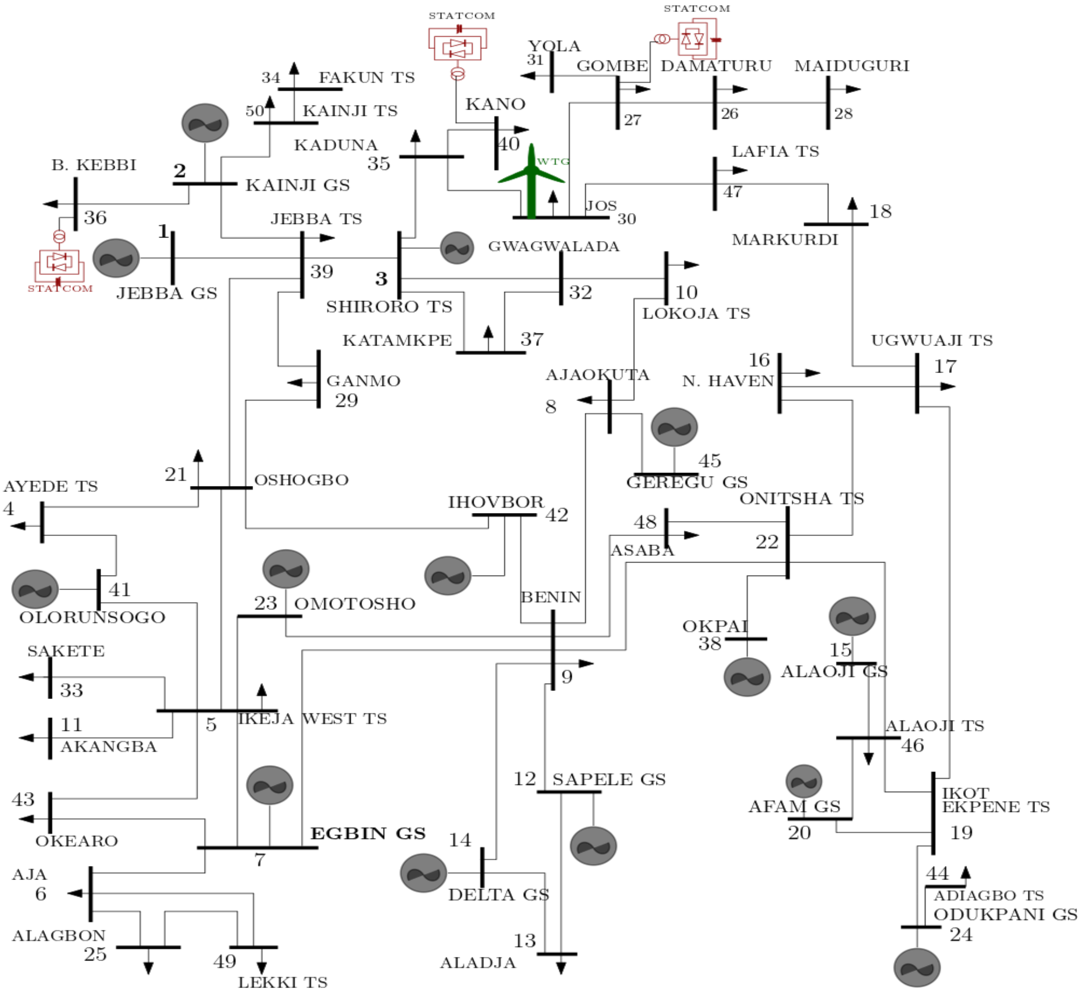

Figure 3. *Single-line diagram of the Nigerian 50-bus Power system.*

Parameters for modeling, obtained from the National Control Center in Osogbo, are available in Ugwuanyi *et. al.* [30]. Previous research on FACTS device placement has focused on minimizing power losses and ensuring voltage stability, overlooking rotor angle stability [28, 29]. However, this study employs the methodology outlined in Ugwuanyi *et. al.* [31] for optimal STATCOM placement, considering all three factors (losses, voltage, and angle stability). The method consists in determining the smallest eigenvalue of the power flow Jacobian, which serves as a metric for voltage collapse. Next, participation factor analysis is employed to identify all buses associated with the identified eigenvalue. These buses are the weakest points in the network. Finally, each of these buses is tested individually to evaluate the performance of STATCOM devices placed on them, in terms of power loss, voltage profile, and rotor angle stability. Using this approach, Gombe, Kano, and B/Kebbi were identified as the most suitable locations for STATCOM installation.

3.4. Defining the Level of Wind Energy Integration

In this study, DFIG-WTGs were utilized alongside gas-fired generators (GFGs), defining penetration as the ratio of DFIG-WTG generation to total active power generation. Specifically, the output of the three hydro generators—Kainji, Jebba, and Shiroro was unchanged, as they are renewable energy sources, while proportionally reducing the output of each GFG. Note that this does not imply that the output of hydro power plants remains constant despite changes in water levels due to seasonal variations. Rather, it means that hydro power output should not be intentionally curtailed, as the objective is to maximize renewable energy generation while reducing the output of gas-fired generators. It is assumed that the slack generator and primary power control will adapt accordingly to maintain power flow balance. Mathematically, the percentage penetration is expressed as:

$$\text{Penetration (\%)} = \frac{P_{DFIG}}{P_{DFIG}+P_{GFG}} \times 100 \qquad (3)$$

Here, P_{DFIG} represents the active power generation of the DFIG-WTG, and P_{GFG} denotes the total active power generation of all gas-fired generators in the system. The penetration limit, determined based on active power loss, indicates the threshold beyond which active power loss begins to increase.

It is important to note that achieving minimal active power loss through penetration adjustment might concurrently introduce angle instability in the system, necessitating further refinement of this limit if angle stability becomes a concern.

All methodologies and simulations described in this section are implemented using the Power System Analysis Toolbox (PSAT) within the MATLAB environment. Subsequently, results across three distinct cases are presented and analyzed:

Case 1: Base case analysis, representing the power system without DFIG-WTG or FACTS devices.

Case 2: Power system with DFIG-WTG included, but without FACTS devices.

Case 3: Power system integrating both DFIG-WTG and FACTS devices.

These cases allow us to assess the impacts of DFIG-WTG integration and FACTS device deployment on system performance and stability, providing insights crucial for optimizing renewable energy integration in practical power systems.

4. Results and Discussions

The power flow simulation was conducted on the base case to determine the total active power loss and voltage profile. The results revealed that seven buses, namely B/Kebbi, Damaturu, Gombe, Maiduguri, Jos, Yola, and Kano, had voltage values below the 5% tolerance, ranging from 0.66 p.u. to 0.92 p.u. The observed voltage violations align with the trends reported by NERC in their quarterly report for 2023-2024, demonstrating a strong correlation between the simulated and real-world systems. To address this, a DFIG-WTG was installed on the Jos bus, as detailed in Section 3.2. In Case 3, three STATCOMs were strategically placed on buses Kano, Gombe, and B/Kebbi using the methodology explained in Section 3.3. Then the wind energy penetration was gradually increased from 0% to 30% according to (3). Figure 4 illustrates the active power loss for different wind energy penetrations, comparing all cases.

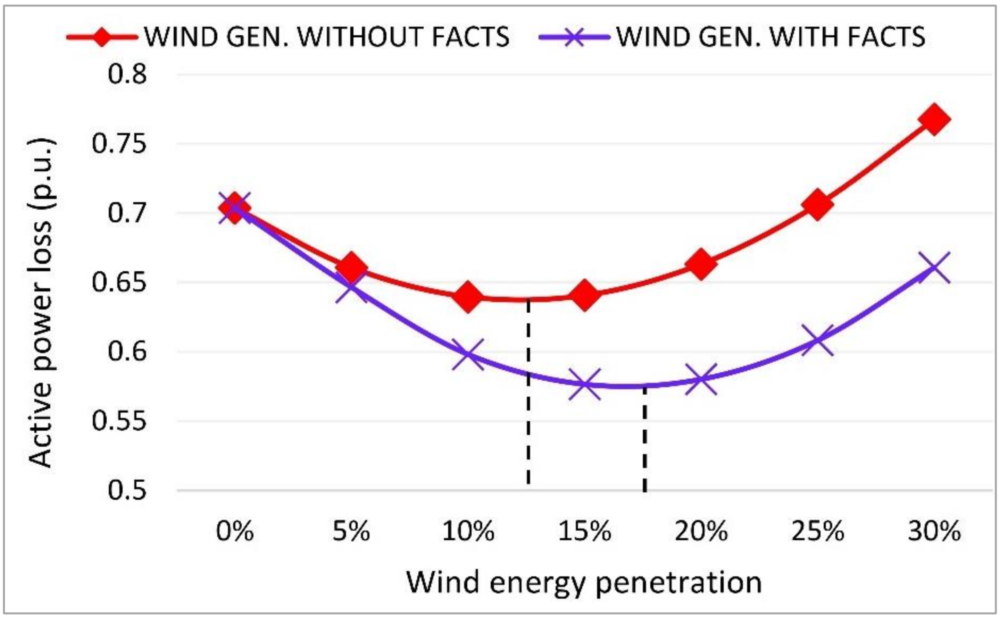

Figure 4. *Active power loss versus penetration limit for all cases.*

The results show that the penetration limit for Case 2 is approximately 12.5% (380 MW), beyond which losses begin to increase. In contrast, Case 3 with STATCOMs extends the penetration limit to about 17.5% (532 MW), representing a significant 40% expansion. This means that without STATCOMs, the system would reject 152 MW of wind energy due to its weak condition, but with STATCOMs, the active power loss decreases by 27%. To put into context, Ozioko *et al.* [11] conducted a comparable analysis on the Nigerian power system without FACTS devices and attained a mere 10% penetration limit. Notably, the resulting voltage profile closely mirrored the base case scenario. This stark contrast highlights the profound impact of incorporating FACTS devices, which can significantly enhance the system's performance and push the penetration limit beyond the 10% threshold.

For a thorough assessment, the voltage profile and angle stability of all three cases were analyzed, using the limits established by Case 2 as a benchmark. Figure 5 displays the voltage profiles of the three cases, revealing that Cases 1 and 2 share similar characteristics and exhibit a weaker voltage profile.

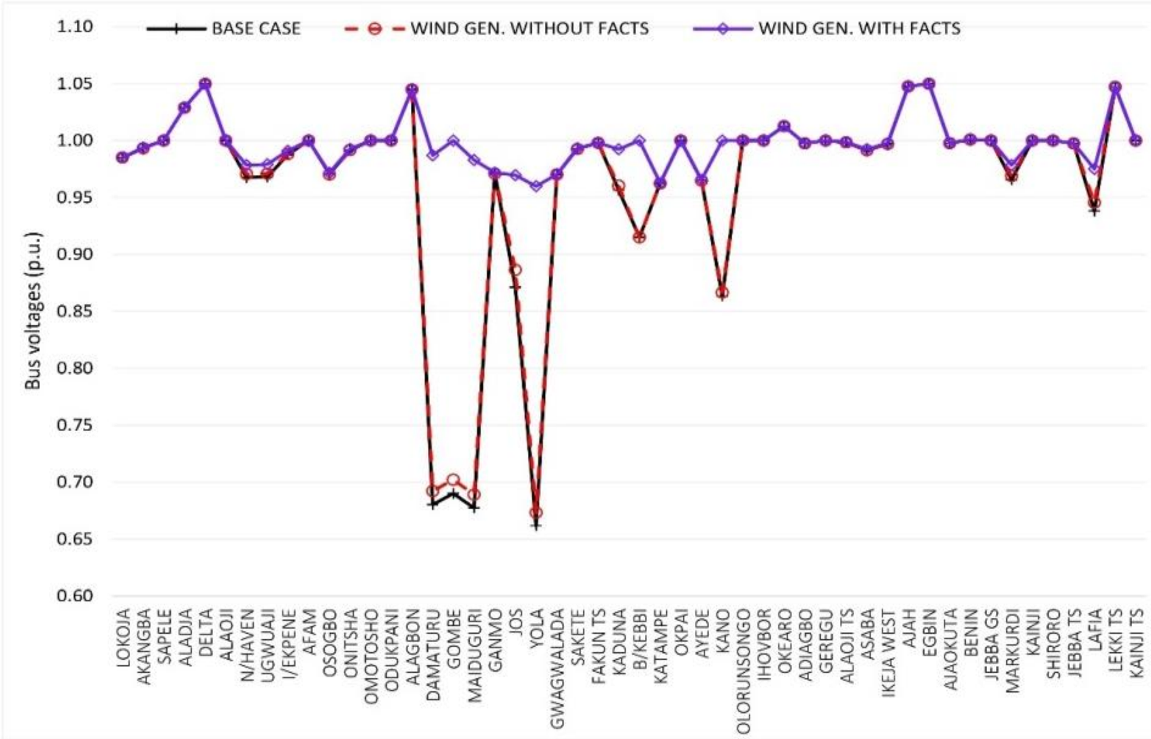

Figure 5. *Voltage profile of all cases.*

In contrast, Case 3 demonstrates a significantly improved voltage profile, attributed to the strategic placement of STATCOMs. The suboptimal voltage profile in Cases 1 and 2 is expected due to the use of PQ-controlled DFIG. However, it is important to note that when PV-controlled DFIG is combined with STATCOM, the system exhibits angle instability regardless of the penetration level, consistent with the findings of [4] that weak grids may pose limitations on integrating new energy sources.

When analyzing angle stability, the focus was on inter-area oscillations, which are typically the most severe oscillations in a power system, involving multiple generators. The power system studied has a slowest inter-area oscillation frequency of 0.66 Hz [32], mainly involving the Ihovbor and Sapele generators. To ensure consistency, a three-phase fault was introduced at Ihovbor and a 10% penetration was tested for Cases 2 and 3. The fault was cleared at the critical clearing time (CCT) of 0.55 seconds, determined for the base case. Figure 6 shows the rotor oscillation of the Ihovbor generator after fault clearance for all three cases. The results indicate that in Case 2, instability occurs at the base case's CCT, while the base case remains stable.

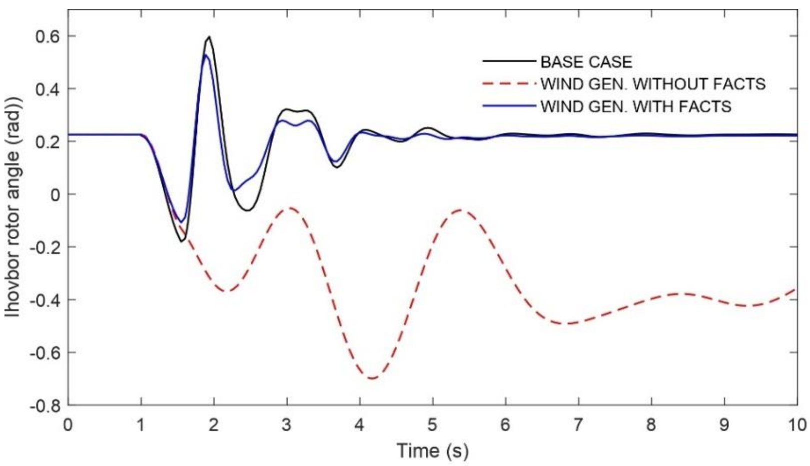

Figure 6. *Rotor angle of Ihovbor generator for all cases.*

This suggests that integrating wind energy has decreased the power system's stability due to its inherent weakness. In contrast, Case 3 exhibits more damped oscillations than the base case, indicating improved stability with the inclusion of DFIG-WTG. These findings imply that FACTS devices can increase the renewable energy penetration limit, enabling developing countries with weak grids to integrate more wind energy without significant modifications to their power system architecture. The results highlight the need for a robust control strategy to facilitate large-scale renewable energy integration into developing grids.

5. Conclusions

This study tackles the critical challenge of integrating renewable energy (RE) sources into the Nigerian power grid, which is constrained by its fragile infrastructure. By strategically deploying Flexible Alternating Current Transmission System (FACTS) devices, particularly Static Synchronous Compensators (STATCOMs), the study demonstrated a substantial extension of the renewable energy penetration limit. The incorporation of FACTS devices reduced the active power loss by 27% and boosted the penetration capacity by 40%, enabling the addition of 152 MW of wind energy without jeopardizing system stability. This enhancement highlights the crucial role of FACTS devices in supporting RE integration into weak grids, thus decreasing dependence on fossil fuels and promoting sustainable energy transitions. The results underscore the need for robust control strategies to facilitate the seamless integration of RE into developing grids, contributing to global efforts to combat climate change and enhance RE adoption.

It is important to note that the investigation has primarily focused on shunt FACTS devices, specifically STATCOMs, in conjunction with wind energy. Future research should explore other types of FACTS devices to determine which offers the most effective support for RE integration. Although the proposed scheme demonstrates promising results, robustness under adverse conditions warrants further investigation. Future studies should consider scenarios such as loss of a critical transmission line, over-generation from wind resources, reduced hydro power output due to unfavorable seasonal conditions, and other potential stressors. Examining performance under these challenging conditions better ensures reliability and effectiveness in real-world applications. Additionally, incorporating other RE sources, such as solar energy, into the analyses is essential, although plans are underway to address these aspects in future studies.

Abbreviations

RE	Renewable Energy
FACTS	Flexible Alternating Current Transmission System
STATCOM	Static Synchronous Compensator
DFIG	Doubly-Fed Induction Generator
GENCOS	Generation Companies
DISCOS	Distribution Companies
TCN	Transmission Company of Nigeria
NCC	National Control Center
SCADA	Supervisory Control and Data Acquisition
NERC	Nigerian Electricity Regulatory Commission
PEC	Power Electronic Converter
RSC	Rotor Side Converter
GSC	Grid Side Converter
WTG	Wind Turbine Generator
GFG	Gas-Fired Generator
CCT	Critical Clearing Time

Author Contributions

Nnaemeka Sunday Ugwuanyi: Conceptualization, Formal Analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing

Innocent Onyebuchi Ozioko: Data curation, Resources, Writing – review & editing

Uma Uzubi Uma: Validation, Writing – review & editing

Ogechi Akudo Nwogu: Validation, Writing – review & editing

Nestor Chima Ugwuoke: Data curation, Writing – review & editing

Arthur Obiora Ekwue: Supervision, Validation

Nathan Nwokocha: Resources, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] X. Dou, Y. Wang, P. Ciais, F. Chevallier, S. J. Davis, M. Crippa, G. Janssens-Maenhout, D. Guizzardi, E. Solazzo, F. Yan, D. Huo, B. Zheng, B. Zhu, D. Cui, P. Ke, T. Sun, H. Wang, Q. Zhang, P. Gentine, Z. Deng, and Z. Liu, "Near-real-time global gridded daily co2 emissions," The Innovation, Tech. Rep. 1, 2022, (Accesed 23 Mar 2024). [Online]. Available: https://doi.org/10.1016/j.xinn.2021.100182

[2] C. D. Iweh, S. Gyamfi, E. Tanyi, and E. Effah-Donyina, "Distributed generation and renewable energy integration into the grid: Prerequisites, push factors, practical options, issues and merits," *Energies*, vol. 14, no. 17, 2021. [Online]. Available: https://www.mdpi.com/1996-1073/14/17/5375

[3] N. Mararakanye and B. Bekker, "Renewable energy integration impacts within the context of generator type, penetration level and grid characteristics," *Renewable and Sustainable Energy Reviews*, vol. 108, pp. 441–451, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032119301856

[4] M. I. Saleem, S. Saha, L. Ang, U. Izhar, and T. K. Roy, "Factors affecting voltage stability while integrating inverter-based renewable energy sources into weak power grids," *IET Generation, Transmission & Distribution*, vol. 17, no. 6, pp. 1216–1231, 2023. [Online]. Available: https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/gtd2.12728

[5] N. S. Ugwuanyi, U. U. Uma, and A. O. Ekwue, "Fundamental study of oscillations in the nigerian power system," *Nigerian Journal of Technology*, vol. 40, no. 5, pp. 913–926, 2021. [Online]. Available: http://dx.doi.org/10.4314/njt.v40i5.17

[6] H. Abdulkarim, C. Sansom, K. Patchigolla, and P. King, "Statistical and economic analysis of solar radiation and climatic data for the development of solar pv system in nigeria," *Energy Reports*, vol. 6, pp. 309–316, 2020, the 6th International Conference on Energy and Environment Research - Energy and environment: challenges towards circular economy. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352484719306675

[7] O. A. Somoye, "Energy crisis and renewable energy potentials in nigeria: A review," *Renewable and Sustainable Energy Reviews*, vol. 188, p. 113794, 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032123006512

[8] D. O. Obada, M. Muhammad, S. B. Tajiri, M. O. Kekung, S. A. Abolade, S. B. Akinpelu, and A. Akande, "A review of renewable energy resources in nigeria for climate change mitigation," *Case Studies in Chemical and Environmental Engineering*, vol. 9, p. 100669, 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S266601642400063X

[9] K. E. Okedu, B. Oyinna, I. Colak, and A. Kalam, "Geographical information system based assessment of various renewable energy potentials in nigeria," *Energy Reports*, vol. 11, pp. 1147–1160, 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352484723016608

[10] C. Li, D. Chen, X. Liu, M. Shahidehpour, H. Yang, H. Liu, W. Huang, J. Wang, X. Deng, and Q. Zhang, "Fault mitigation mechanism to pave the way to accommodate over 90% renewable energy in electric power systems," *Applied Energy*, vol. 359, p. 122623, 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261924000060

[11] I. O. Ozioko, N. S. Ugwuanyi, A. O. Ekwue, and C. I. Odeh, "Wind energy penetration impact on active power flow in developing grids," *Scientific African*, vol. 18, p. e01422, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2468227622003283

[12] B. B. Adetokun and C. M. Muriithi, "Application and control of flexible alternating current transmission system devices for voltage stability enhancement of renewable-integrated power grid: A comprehensive review," *Heliyon*, vol. 7, no. 3, p. e06461, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2405844021005661

[13] I. Nkan, P. Obi, H. Natala, and O. Okoro, "Investigation of the transfer capability of the nigerian 330 kv, 58-bus power system network using facts devices," *ELEKTRIKA- Journal of Electrical Engineering*, vol. 22, no. 1, p. 53–62, Apr. 2023. [Online]. Available: https://elektrika.utm.my/index.php/ELEKTRIKA*Journal/article/view/*422

[14] N. S. Offiong, C. Kalu, and O. Nseobong, "Comparative evaluation of sssc and statcom facts devices power transfer capability enhancement on the nigerian 330kv power network," *International Multilingual Journal of Science and Technology (IMJST)*, vol. 7, no. 8, 2022. [Online]. Available: https://www.imjst.org/wp-content/uploads/2023/05/IMJSTP29120853.pdf

[15] O. Ogunbiyi, F. Adesina, L. M. and Ugwute, and C. Thomas, "Enhancement of the nigerian national grid performance with a fact compensator," *Nigerian Research Journal of Engineering and Environmental Sciences*, vol. 7, no. 2, pp. 506–518, 2022. [Online]. Available: http://doi.org/10.5281/zenodo.7496649

[16] G. A. Adepoju, M. A. Sanusi, and M. A. Tijani, "Application of sssc to the 330kv nigerian transmission network for voltage control," *Nigerian Journal of Technology*, vol. 36, no. 4, p. 1258–1264, 2017. [Online]. Available: http://dx.doi.org/10.4314/njt.v36i4.36

[17] I. B. Anichebe and A. O. Ekwue, "Improvement of bus voltage profiles of nigerian power network in the presence of static synchronous compensator (statcom) and doubly fed induction generator (dfig)," *Nigerian Journal of Technology*, vol. 39, no. 1, pp. 2467–8821, 2020. [Online]. Available: http://dx.doi.org/10.4314/njt.v39i1.26

[18] E. J. Okampo, N. Nwulu, and P. N. Bokoro, "Optimization of voltage security with placement of facts device using modified newton-raphson approach: A case study of nigerian transmission network," *Energies*, vol. 15, no. 12, 2022. [Online]. Available: https://www.mdpi.com/1996-1073/15/12/4211

[19] I. O. Ozioko, C. C. Okoli, N. G. Ajah, and N. S. Ugwuanyi, "Enhancement of power system transmission using static synchronous compensator (statcom)," in *2019 IEEE PES/IAS PowerAfrica*, 2019, pp. 482–486. [Online]. Available: http://dx.doi.org/10.1109/PowerAfrica.2019.8928629

[20] C. Chiatula, D. I. Chinda, R. Onoshakpor, and S. Abba-Aliyu, "Utilisation of facts devices in the nigerian transmission grid," in *2020 IEEE PES/IAS PowerAfrica*, 2020, pp. 1–5. [Online]. Available: http://dx.doi.org/10.1109/PowerAfrica49420.2020.9219961

[21] I. E. Nkan and A. B. Okpo, Ekom E. and Inyang, "Enhancement of power systems transient stability with tcsc: A case study of the nigerian 330 kv, 48-bus network," *INTERNATIONAL JOURNAL OF MULTIDISCIPLINARY RESEARCH AND ANALYSIS*, vol. 6, no. 10, pp. 4828–4841, 2023. [Online]. Available: http://dx.doi.org/10.47191/ijmra/v6-i10-37

[22] P. J. Fortune, E. N. Imo, and E. O. Ekom, "Improvement of power transfer capability of nigeria national grid with tcsc facts controller," *American Journal of Engineering Research (AJER)*, vol. 13, no. 1, pp. 37–43, 2024. [Online]. Available: https://www.ajer.org/papers/Vol-13-issue-1/13013743.pdf

[23] M. G. Hemeida, H. Rezk, and M. M. Hamada, "A comprehensive comparison of statcom versus svc-based fuzzy controller for stability improvement of wind farm connected to multi-machine power system," pp. 935 –951, 2018. [Online]. Available: https://doi.org/10.1007/s00202-017-0559-6

[24] O. Bamisile, Q. Huang, X. Xu, W. Hu, W. Liu, Z. Liu, and Z. Chen, "An approach for sustainable energy planning towards 100 % electrification of nigeria by 2030," *Energy*, vol. 197, p. 117172, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360544220302796

[25] B. Olubayo, B. Elutunji, T. Oluwatobi, A. Clement, D. Innocent, and E. I. Desmond, "Electricity sector assessment in nigeria: the post-liberation era," *Cogent Engineering*, vol. 10, no. 1, p. 2157536, 2023. [Online]. Available: https://doi.org/10.1080/23311916.2022.2157536

[26] M. Mahmoud, T. Salameh, A. A. Makky, M. A. Abdelkareem, and A. G. Olabi, "Chapter 3.5 - case studies and analysis of wind energy systems," in *Renewable Energy - Volume 1: Solar, Wind, and Hydropower*, A. G. Olabi, Ed. Academic Press, 2023, pp. 363–387. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780323995689000194

[27] T. Ayodele, A. Ogunjuyigbe, O. Odigie, and A. Jimoh, "On the most suitable sites for wind farm development in nigeria," *Data in Brief*, vol. 19, pp. 29–41, 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352340918304979

[28] R. Gandotra and K. Pal, "Optimal location of dg and facts devices under maximum loading capacity," in *2023 International Conference on Recent Advances in Electrical, Electronics & Digital Healthcare Technologies (REEDCON)*, 2023, pp. 554–558. [Online]. Available: http://dx.doi.org/10.1109/REEDCON57544.2023.10151114

[29] M. Zadehbagheri, R. Ildarabadi, and A. M. Javadian, "Optimal power flow in the presence of hvdc lines along with optimal placement of facts in order to power system stability improvement in different conditions: Technical and economic approach," *IEEE Access*, vol. 11, pp. 57 745–57 771, 2023. [Online]. Available: http://dx.doi.org/10.1109/ACCESS.2023.3283573

[30] N. S. Ugwuanyi, I. O. Oziokoand N. C. Ugwoke, "Dataset for the Nigerian 50-Bus 330 kV Power Grid". Zenodo, Jun. 18, 2024. [Online]. Available: https://dx.doi.org/10.5281/zenodo.12091189

[31] N. S. Ugwuanyi, O. A. Nwogu, I. O. Ozioko, and A. O. Ekwue, "An easy method for simultaneously enhancing power system voltage and angle stability using STATCOM," Scientific African, vol 25, e02248, 2024 [Online]. Available: https://dx.doi.org/10.2139/ssrn.4758631

[32] N. S. Ugwuanyi, U. U. Uma, and A. O. Ekwue, "Characterization of oscillations in developing power systems: The nigerian case study," in *2021 IEEE PES/IAS PowerAfrica*, 2021, pp. 1–5. [Online]. Available: http://dx.doi.org/10.1109/PowerAfrica52236.2021.9543195