Grid Stability Assessment of Emerging Power Systems with DFIG Wind Integration

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***Abstract* — Most electricity-generating plants today rely on fossil fuels that emit greenhouse gases and are a major contributor to global warming. Renewable energy sources such as wind power offer a sustainable alternative but can impact power system stability—particularly in developing grids. This study relies on a detailed case study model to investigate the impact of Doubly-Fed Induction Generator (DFIG)-based wind turbine generators (WTGs) on the transient stability of the Nigerian power system. Two scenarios were evaluated: (1) supplementing existing conventional generators with WTGs, and (2) replacing gas-fired generators (GFGs) entirely with WTGs. The most suitable connection points for each scenario were identified. Case study results indicate a 9% improvement in transient stability when WTGs supplement conventional generators, while replacing GFGs with WTGs led to a 9% reduction in stability. These findings underscore the need for appropriate inertial support or alternative stabilization measures during the transition to a high penetration of renewable energy in the Nigerian grid.**

***Index Terms* — Renewable energy, greenhouse gas emission, wind energy penetration, transient stability, power system.**

I. INTRODUCTION

Fossil fuel combustion contributes 83% of global energy consumption, causing climate change [1]. Renewable energy sources, like hydro, wind, and solar, account for 12.6% [2]. Rapid development and population growth increase fossil fuel consumption, necessitating an eightfold increase in renewable energy generation for 100% CO_2 reduction [2]. Recent technological advancements in renewable energy have made it possible to integrate it into the existing grid.

Currently, several power systems rely on generators that produce high CO_2 emissions [3]. Consequently, the integration of carbon-free renewable energy is necessary, but it poses challenges to the existing grid [4, 5]. Research efforts are underway to identify these challenges and improve the performance of the grid-connected renewable energy (RE).

Renewable energy (RE), despite its numerous positive contributions, raises a number of economic, environmental, and engineering issues that have been a major subject of research in recent years [4, 6]. Environmental impacts and the unpredictable nature of RE are the focus of the authors in [7]. Erdiwansyah et al. [8] highlight the voltage stability as one of the critical issues associated with integrating various types of RE into an electrical grid. They propose a voltage management scheme to address this issue. Impram et al.'s [9] survey on the impact of RE sources on voltage, frequency, and small-signal stability reveals that the effect depends on the level of penetration, which is consistent with the findings in [10]. They recommend implementing demand and supply management techniques to ensure adequate stability control. Studies [11] and [12] report an improved voltage of a power system with wind energy integration. Kuri and Brackenhammer [13] discuss harmonics, forecasting, and

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time scheduling as challenges of integrating RE into a power system. The authors in [13] design a Power Plant Controller for energy forecasting and time scheduling, while intelligent techniques are reported in [6] and [14] for accurate control of the grid with RE.

Furthermore, numerous studies highlight power quality as one of the most challenging aspects of grid-connected RE and suggest certain solutions that could remedy such conditions. Study [15] proposes an Adaptive Neuro-fuzzy Inference System (ANFIS) controller and a conventional controller to improve power quality. Ozioko et al. [16] analyze the impact of wind energy on the real power flow and conclude that optimal integration can reduce power losses, while high penetration increases active power losses. Similarly, Mastoi et al. [17] utilize a DFIG-WTG to reduce power losses in a power system. Other studies focus on improving the loadability of the grid-connected wind turbines using FACTS devices [18]. However, some researchers [19, 20] argue that integrating both FACTS devices and RE sources into an existing grid to enhance system performance may increase energy generation costs and reliability concerns.

The impact of RE penetration on the small-signal stability (SSS) of a grid has been studied by different researchers. Study [21] indicates that wind-solar energy integration favors the SSS of a power system compared to the performance of the grid with power electronics-based converter control. Moreover, He et al. [22] show that the participation of wind-solar energy systems in frequency regulation can improve the SSS of a grid. Modal analysis, Newton-Raphson power flow, and time-domain simulations are applied in [23] to assess SPV integration effects on voltage profiles, active power loss, and system stability in IEEE 4-machine and Nigerian 50-bus power systems. The findings point to varied impacts, stressing the need for a comprehensive approach considering voltage stability, power losses, and stability constraints. The effects of replacing conventional synchronous generators with inverter-based renewable (IBR) energy sources on the electromechanical oscillation are examined by Chen et al. [24] and Agrawal et al. [25]. According to [24], the SSS improves when the replaced states have higher participation factors in the electromechanical modes. Conversely, the replacement may worsen the SSS if participation factors are low. The authors of [25] note that a single trend could not be identified to correlate the impact of increased RES penetration levels with system's damping ratios.

The reviewed works primarily focus on integrating wind, solar, or both energy sources into the electrical grid and their impact on voltage, harmonics, and frequency. Some studies also explore grid small-signal stability when RE generators supplement conventional ones. However, more analysis is needed, especially regarding transient stability when replacing gas-fired generators (GFGs) and supplementing the GFGs with wind energy to cut down CO_2 emissions. Moreover, given the context-dependent nature of RE-research, it is necessary to explore the implication of replacing or supplementing conventional generators with DFIG-based wind turbines, especially in a developing grid, which is inherently weak. Our study fills these gaps, analyzing how DFIG-WTG impacts system stability, focusing on Nigeria's power system. This paper's primary contribution is that it examines how DFIG-WTG affects power system transient stability, viewing DFIG-WTG as both a supplement and a substitute for conventional synchronous generators within the same system. This holistic approach provides comprehensive insights into DFIG-WTG's impact on power system stability.

The remainder of the paper is organized as follows. Section 2 discusses the methodology, outlining the challenges faced by power supply, assessing the potential of renewable energy in Nigeria and identifying the CO_2 emission-affected area, with a focus on wind energy integration. Section 3 presents and discusses the findings obtained under different scenarios. Finally, section 4 concludes the study by stating limitations and recommendations.

II. METHODOLOGY

This section details the challenges faced by Nigeria's power system and the methodology we applied in this study.

A. The Power Supply Problem of the Nigeria Electricity Grid

Nigeria, Africa's most populous nation and largest economy in sub-Saharan Africa, faces severe power sector limitations that impede its economic growth [26]. Despite 26 operational grid-connected plants with 12 199 MW installed capacity, only about 4 000 MW is dispatched daily [27], which is insufficient. Even after government restructuring of the power sector into generation, transmission, and distribution companies for improved operation [26], electricity supply significantly lags behind demand, making Nigeria one of the world's most underpowered countries [27].

Nigeria's power system relies on 330 KV and 132 KV high-voltage transmission lines, alongside 33 KV, 11 KV, and 415 V sub-distribution lines, covering over 20 000 km high-voltage transmission lines [27]. However, the network faces constant technical challenges such as high losses, voltage degradation, and frequent collapses, preventing the utilization of at least 7 500 MW of its capacity [27]. Furthermore, most generators are GFGs suffering from inadequate gas supply that reduces generation. Even when gas supply is sufficient, these GFGs, however, contribute to high CO_2 emissions. On the other hand, Nigeria is endowed with abundant renewable energy resources, like wind and solar, with a wind farm under construction in Katsina State and several operational solar plants [28], though none are yet grid-connected.

B. *Wind Energy-Grid Integration*

This subsection represents the theoretical background of wind energy-grid integration.

1) Power Flow with WTGs

Wind energy conversion systems (WECS) can be integrated into the grid either at the load or generator buses. In either case, the power flow model will depend on whether the WTG is PV-controlled or PQ-controlled. The PQ-controlled model is usually adopted when the WTG is used to supplement the GFGs. In this case, the integration is done at a specified power factor, often unity, and the WTG power is modelled as a negative load [29, 30]. When the WTG is used to replace existing GFGs, it is common to model it as a PV-generator, much like the GFGs being replaced, while respecting the reactive power limits.

In a conventional load flow, real and reactive power on bus *i* can be expressed as

$$P_i = P_{gi} - P_{di}\,, \tag{1}$$

and

$$Q_i = Q_{gi} - Q_{di}\,, \tag{2}$$

where P_{gi}, P_{di}, Q_{gi}, and Q_{di} are the real power supply, real power demand, reactive power supply, and reactive power demand, respectively, on bus i.

For an n-bus system, total losses can be calculated by adding up the individual losses on the lines as

$$P_{realpowerloss} = \sum_{i=1}^{n} \left(\frac{P_i + Q_i}{V_i} \right)^2 R_i\,, \tag{3}$$

where R_i and V_i are resistance and voltage drop, respectively, on the i-th line.

For PQ-controlled WTG, equations (1) and (2) become

$$P_i = -P_{gi} + P_{di}\,, \tag{4}$$

and

$$Q_i = -Q_{gi} + Q_{di}\,. \tag{5}$$

Adopting the unity power factor for the PQ-controlled model leads to rewriting equation (3) as

$$P_{realpowerloss} = \sum_{i=1}^{n} \left(\frac{P_i}{V_i} \right)^2 R_i\,. \tag{6}$$

The power flow between the wind generator and the grid is driven by the mechanical power, P_m, expressed as

$$P_m = \frac{1}{2} C_p(\lambda, \alpha) \rho A V_{ws}^3\,, \tag{7}$$

where C_p is the turbine performance coefficient, λ is the tip speed ratio, α is the pitch angle of the blade, ρ is the density of the air (kg·m^{-3}), A is the swept area of the turbine (m^2), V_{ws} is the wind speed (m·s^{-1}). Equation (7) indicates how the wind energy is converted to mechanical power. This mechanical power is later converted to electrical power through DFIG electrical dynamics. The conversion system is summarized in Figure 1.

When WTGs replace conventional generators, the power flow remains unchanged. However, due to different dynamic characteristics, stability will not be the same. For instance, synchronous generators contribute more to inertia

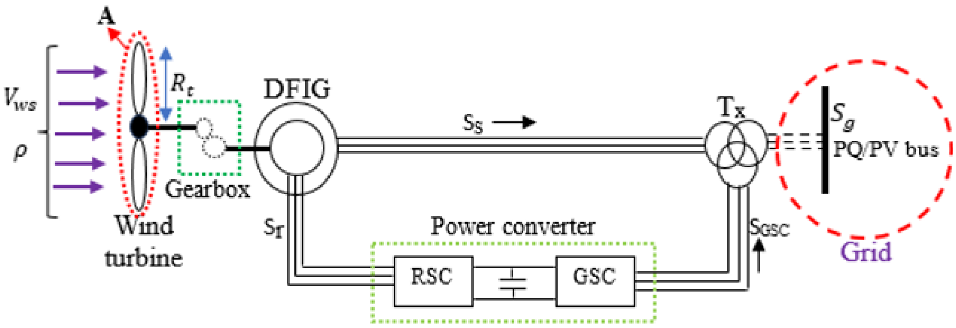


Fig. 1. DFIG-Based wind energy conversion system.

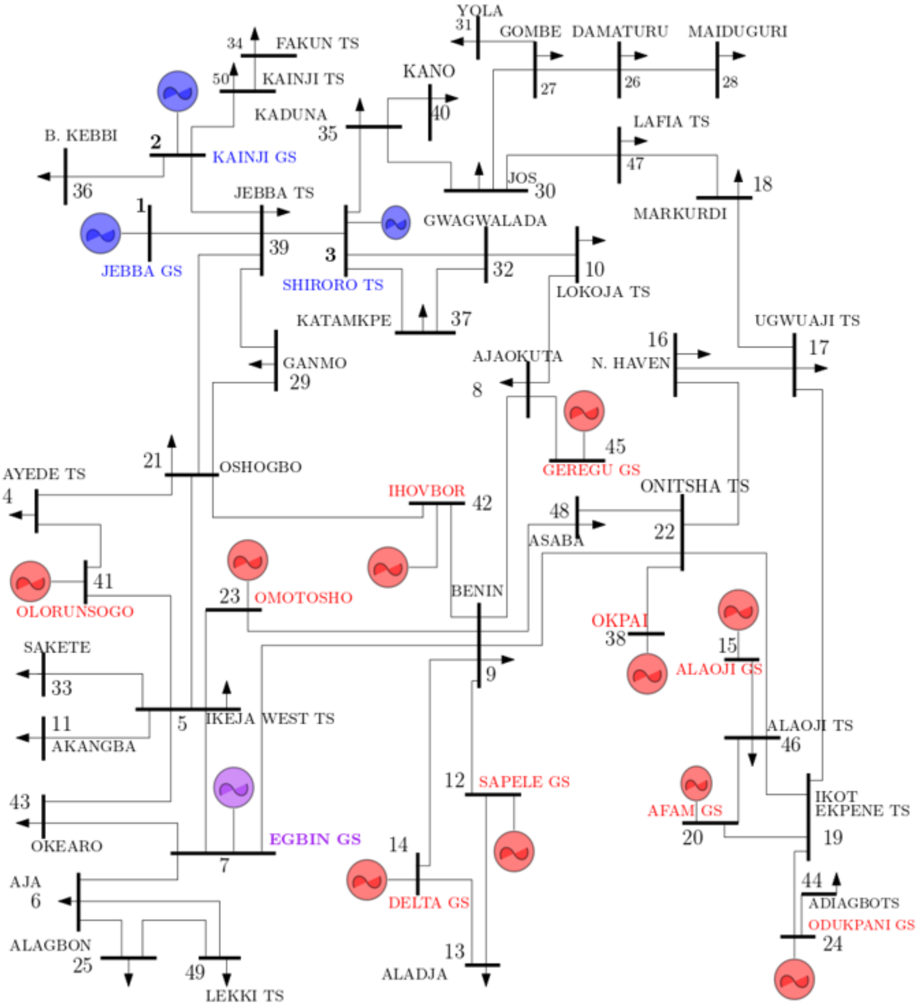


Fig. 2. The Nigerian 330 kV, 50-bus system [33].

than WTGs. In the stability analysis of DFIG wind turbines, the drive-train model is crucial. It is assumed that converter control can handle the shaft dynamics. Therefore, both mechanical dynamics resulting from wind speed variability and electrical dynamics resulting from wind turbine interactions with the grid are given by equation

$$\dot{\omega}_m = \frac{(T_m - T_e)}{2H_m}, \qquad (8)$$

where ω_m is the tip speed of the rotor (rad/s), T_e is the electromagnetic torque expressed as $T_e = X_m i_{qr} i_{ds} - X_m i_{dr} i_{qs}$, H_m is the inertial constant (kW s/kVA), and T_m is the mechanical power input. In the expression for the electromagnetic torque, X_m is the magnetization reactance (Ohm), i_{qr} and i_{dr} are q- and d-axis rotor current, respectively, i_{ds} and i_{qs} are d- and q-axis stator current, respectively. The comprehensive DFIG-based WECS model parameters used in this analysis are as shown in Table 1. Equation (8) indicates that the wind turbine will introduce oscillation to the power system due to the imbalance between the mechanical and electrical torques. An ideal case is when these two torques are equal, which is the objective of the WTG control strategies.

2) Calculation of WTGs Penetration

In this study, we define wind energy penetration as the ratio of the wind energy injected to the total generation in the system. The percentage penetration is expressed formally as shown in equation

$$P_{\%windpenetration} = \left[\frac{P_{wind}}{\sum \left(P_{gen.(i)} + P_{wind} \right)} \right] \times 100, \qquad (9)$$

where $P_{\%windpenetration}$ is the percentage of wind power

TABLE 1. The DFIG-Based WECS Model Parameters

Parameter	Value	Parameter	Value
Number of blades	3.0	ρ (kg/m^3)	1.225
The length of blade (m)	75.0	Gear box ratio	1/89
Frequency (Hz)	50.0	Number of poles, P	4.0
Power rating (MW)	2.0	Inertia constants, H_m (KWs/KVA)	3.0
Number of turbines in the farm	900	Magnetization reactance, X_m (p.u)	3.0
Wind speed (m/s)	7.7	Rotor reactance (p.u)	0.08
Voltage rating (kV)	330	Rotor resistance (p.u)	0.01
Coefficient of Power (Cp)	0.40	Stator reactance (p.u)	0.10
Capacity factor	40%	Stator resistance (p.u)	0.01
Pitch control gain (p.u)	10.0	Time constants (s)	3.0
Voltage control gain, Kv (p.u)	10.0	Power control time constants, T_e (s)	0.01

penetration in the system; P_{wind} is the wind energy generator capacity in the system, p.u.; $P_{gen.(i)}$ is the *i*-th conventional generator’s capacity, p.u. For every additional wind power generator in the grid, the contribution of each of the other existing generators is adjusted proportionately. However, the power of the already existing RE generators remains unchanged.

3) Selection of the Wind Farm Connection Bus

Figure 2 shows a schematic of the Nigerian power system, operating at 330 kV. The network consists of two primary types of generators: hydro plants and gas-fired generators, located in the northern and southern regions of the country, respectively. Notably, almost all GFGs are concentrated in the southern part of the country, resulting in substantial gas emissions in the region. However, this area also has significant wind energy potential, as identified in [31]. Replacing GFGs with WTGs could significantly enhance Nigeria's electricity supply and mitigate its current shortage, as reported by the International Renewable Energy Agency (IRENA) in 2023 [32].

To integrate WTGs and reduce the share of GFGs, we identified suitable connection points in the southern region following a two-stage process. First, we screened for strong buses, defined as those that maintain a voltage profile within the ±5% grid code tolerance under normal operation. Second, from this pool of strong buses, we identified the optimal candidates by simulating incremental wind energy injection to find the buses that yielded the minimal active power loss, adopting a loss minimization approach. This ensures that the chosen connection points are both robust and efficient.

When replacing GFGs with WTGs, we conduct a sequential replacement process, allowing for priority-based replacement order to prevent any deterioration of system stability. This approach enables the identification of the most suitable replacement strategy, ensuring the efficient integration of WTGs and minimizing potential disruptions to the power system.

4) Considered Cases

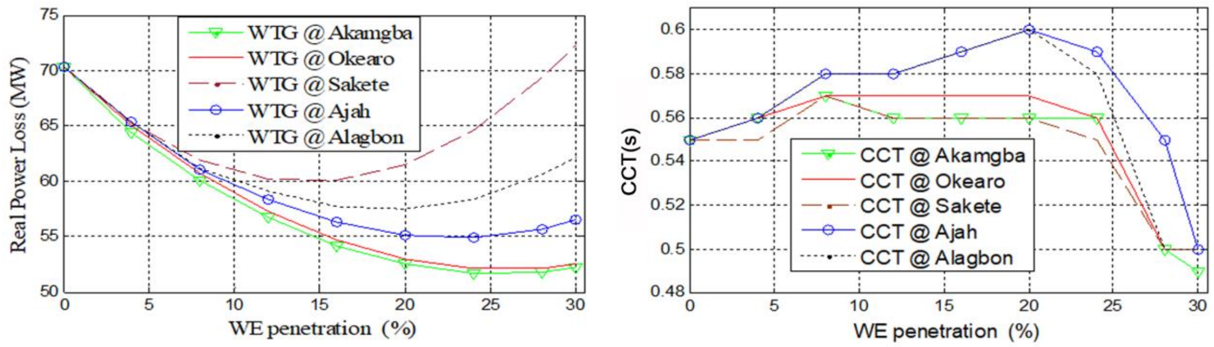
The study examines the impact of DFIG-based wind turbine generators (WTG) on Nigeria's grid stability. We consider three cases. **Case 1**: the base case that assumes no use of wind energy. **Case 2**: WTGs supplement the GFG output. **Case 3**: the power system has gas-fired generators replaced by the equivalent capacity of wind turbines. The presentation and discussion of results relies onPSAT®, a MATLAB® toolbox for electric power system analysis and simulation.

III. RESULTS AND DISCUSSION

This section presents and discusses the findings of our analysis as detailed in the following subsections.

A. Analysis of Cases 1 and 2

The base case power flow analysis revealed a real power loss of 70 MW. Additionally, five key buses in southern Nigeria, namely Akamgba, Okearo, Sakete, Ajah, and Alagbon, were identified as strong buses. The best WTG connection point was deemed the bus that exhibited the lowest real power loss as wind energy penetration levels increased on the strong buses. Figure 3a shows the real power loss evolution on selected buses with increased wind energy penetration (base case: 0%). Akamgba, Okearo, and Ajah had minimum losses (51.70, 52.10, and 55 MW,



(a) (b)

Fig. 3. (a) Evolution of real power loss against the penetration on the selected load buses, (b) Critical clearing time (CCT) against the penetration on the selected load buses

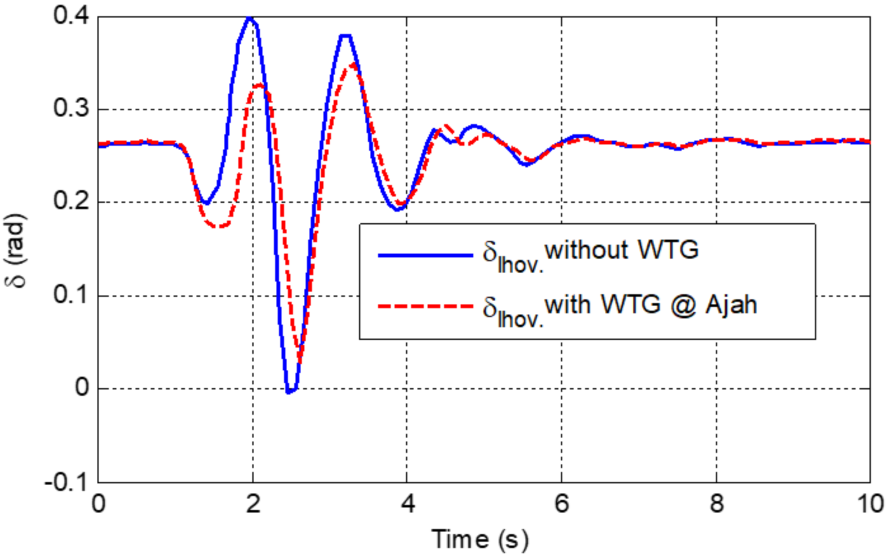


Fig. 4. Oscillation of the base case versus WEI at Ajah.

respectively) at 24% penetration. Sakete and Alagbon had minimum losses (60.10 and 58 MW) at 16% and 20% penetration, respectively. This shows that buses handle renewable energy differently. Akamgba is the preferred candidate for Wind Energy Integration (WEI) due to its lowest minimum real power loss compared to the base case, with Okearo and Ajah considered as viable alternatives. While Akamgba excels in loss minimization, this does not guarantee stability, so each bus will undergo further stability testing.

Focusing on the severe inter-area oscillation, a three-phase fault was simulated at the Ihovbor generator bus, which is known for the system's slowest oscillation (0.67 Hz) [34, 35]. We then determined the critical clearing time (CCT); a higher CCT indicates improved transient stability and greater wind energy integration. CCT with increasing wind penetration is shown in Figure 3b. In the base case (0% penetration), the system records a CCT of 0.55 s. At low penetration levels, wind integration enhances transient stability across all candidate buses. However, stability declines beyond certain levels — after 7.5% for Sakete and Akamgba (both with CCT = 0.57 s), and after 20% for Okearo (CCT = 0.57 s), Alagbon (CCT = 0.60 s), and Ajah (CCT = 0.60 s). In contrast, the loss-based analysis (Fig. 3a) indicates that Sakete can accommodate up to 12.5% wind penetration and Akamgba up to 24%, underscoring the trade-off between minimizing real power losses and maintaining transient stability. Ajah and Alagbon exhibit the best stability performance, each achieving a maximum CCT of 0.60 s at 20% penetration (a 9% improvement over the base case). When both stability and loss reduction are considered, Ajah emerges as the most favorable site, having the lower real power loss (55 MW) compared to Alagbon (58 MW).

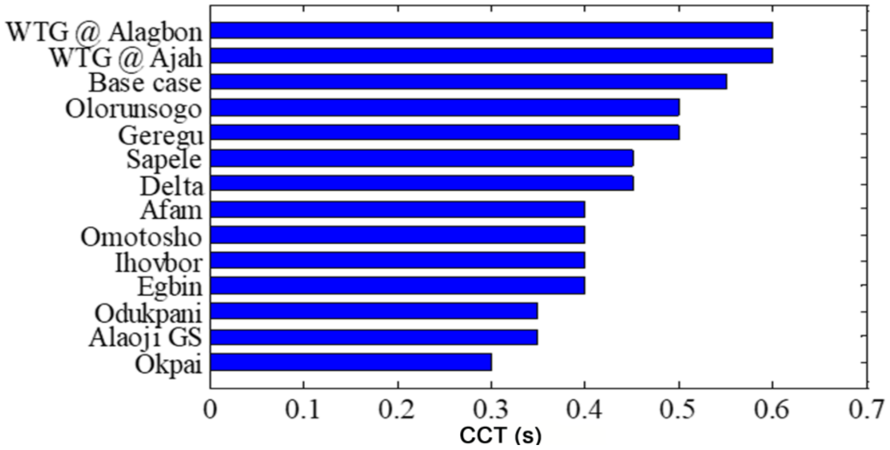


Fig. 5. CCT of GFGs replacement compared to the base case and best load buses.

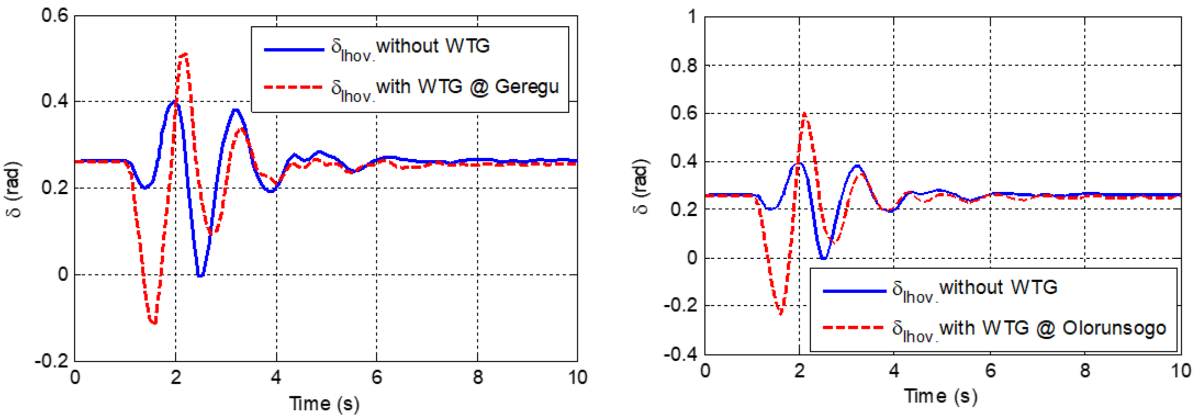
Figure 4 displays the rotor oscillation of the WTG at Ajah at 20% penetration. The reduced amplitude in Case 2 compared to Case 1 confirms enhanced stability when Wind Turbine Generators (WTG) supplement Gas Fired Generators (GFGs). This demonstrates grid stability at 20% penetration (626 MW), as the system with WEI exhibits faster oscillation damping than in the base case.

B. Analysis of Case 3

In this case, we analyzed the impact of replacing GFGs with WTGs of equivalent capacity. The methodology involved a sequential, one-by-one replacement of each GFG in the southern part of the grid. For each replacement, a transient stability analysis was performed to calculate the CCT, with the fault located, similarly to Cases 1 and 2, at the Ihovbor bus. This systematic process allowed us to identify which GFG replacements were the least detrimental to system stability. The CCT results for each replacement scenario are presented in Figure 5.

For comparison, the Figure also includes cases where WTGs are connected at the Alagbon and Ajah load buses, allowing assessment of stability improvements from supplementing generation at load buses versus replacing GFGs. The results indicate that replacing GFGs with DFIG-WTGs reduces transient stability due to the associated loss of rotational inertia, underscoring the need for alternative mechanisms to compensate for this unbalance. Among the replacement cases, substituting Olurunsogo and Geregu generators provided the best outcome, though the CCT still declined from 0.55 to 0.50 s — a 9% reduction in stability. Overall, Figure 5 demonstrates that WTGs enhance system stability more effectively when supplementing existing generation at load buses than when replacing conventional GFGs.

Figure 6 displays the Ihovbor generator's rotor angle



(a) (b)

Fig. 6. (a) Comparing rotor angle oscillation in the base case against the WTG at Geregu, (b) Comparing rotor angle oscillation in the base case against the WTG at Olorunsogo.

with sequential replacements at Olorunsogo and Geregu, confirming reduced stability due to higher oscillation amplitudes. It is noteworthy that the Ihovbor generator has a high participation factor in the dominant 0.67 Hz electromechanical oscillation, yet stability decreases. This observation does not agree with [24] which found that replacing the state significantly contributing to the electromechanical oscillation with a virtual synchronous generator improves stability. In fact, in our case, the stability deteriorates irrespective of generator replacement, thus emphasizing the context-dependent nature of RE studies.

C. Discussion and Contextual Comparison

The above study of the Nigerian grid demonstrates that DFIG-based wind integration can enhance transient stability at low penetration levels, but margins deteriorate once penetration exceeds relatively modest thresholds (≈7.5–20%, depending on the connection point). While integration at load buses shows these limits, replacing existing synchronous generators further exacerbates stability deterioration. This pattern arises from two coupled effects: (i) the limited reactive-power capability of DFIGs during faults, which aggravates voltage dips and short-term instability; and (ii) the displacement of synchronous generators, which reduces system inertia and weakens frequency and transient response. These outcomes are consistent with international experience, although the thresholds at which issues emerge vary with the system’s strength and topology.

Akhmatov’s Danish case study [36] highlighted similar short-term voltage stability challenges in a system with high wind and CHP contributions. Induction-machine turbines were shown to absorb significant reactive power during faults, deepening voltage sags and, in some cases, triggering cascaded disconnections. The study further distinguished between large offshore wind farms — required to ride through disturbances — and local units that often trip under undervoltage, and proposed mitigation measures such as dynamic reactive compensation and wind-turbine ramp-rate controls. These findings reinforce the conclusion that adequate reactive support and effective fault-ride-through capability are critical for secure DFIG integration.

In the UK context, Xia et al. [37] emphasized frequency-domain risks in a stronger, meshed grid. Their results show that higher DFIG shares increase ROCOF and reduce critical fault-clearance times (CFCT), with penetrations above 40–50% yielding CFCT values below Grid Code requirements. Stability could be preserved only through additional measures such as SVCs, HVDC reinforcements, enhanced primary reserves, or synthetic inertia. The UK network study illustrated that robust grids can tolerate higher non-synchronous penetration before instability arises, but only with extensive ancillary-service deployment.

The Algerian case [38] provided a distribution-level perspective in weak, radial systems. Simulations showed that DFIG farms are highly vulnerable to poor fault-ride-through and voltage collapse unless supported by D-FACTS devices. Both D-SVC and D-STATCOM improved stability, though with cost–performance trade-offs: D-STATCOM delivered stronger and faster support at higher costs, whereas D-SVC provided more economical but slower compensation. These findings highlighted the need to tailor remedies to the level of grid connection and economic feasibility.

More recently, Shabani et al. [10], instead of analyzing a national grid, employed a benchmark Single Machine Infinite Bus (SMIB) model to examine how equipment-level factors influence transient stability. Their results showed that the CCT improves with increasing wind penetration up to about 0.7 p.u. but declines thereafter, which is consistent with our findings. They also demonstrated that reactive power support from DFIGs enhances stability but increases converter current stress, pointing to the need for external devices such as STATCOMs.

Taken together, the Nigerian, Danish, UK, and Algerian case studies reveal a consistent picture: the mechanisms driving stability degradation — loss of inertia, limited MVAr support, and altered power flows — are universal, but the penetration thresholds and mitigation strategies are system-dependent. Stronger grids such as in the UK can accommodate 40–60% penetration before serious risks emerge [37], while weaker or less meshed systems such as in Nigeria (as demonstrated in this study), Denmark [36], and Algeria [38] experience critical issues at much lower levels.

IV. CONCLUSION, RECOMMENDATIONS, AND LIMITATIONS

This paper studied wind energy integration's impact on the Nigerian grid's stability, focusing on WTGs supplementing or replacing GFGs. We have identified optimal connection points and quantified the stability impacts for each scenario. The key conclusions are as follows:

i) Optimal placement of supplementary WTGs, specifically at a strong load bus like Ajah, can improve system transient stability. A 20% wind energy penetration (626 MW) at this location extended the CCT by 9%, from 0.55 to 0.60 s.
ii) A trade-off exists between power loss minimization and stability enhancement. The optimal penetration level for stability (20%) was found to be lower than the level for maximum loss reduction (24%), indicating that stability is the more constraining factor.
iii) Replacing GFGs with equivalent WTG capacity universally reduces system stability due to the loss of synchronous inertia. The least disruptive replacements (Geregu and Olorunsongo) still resulted in a 9% stability decrease, underscoring the need for compensatory measures.

A. Practical Recommendations for System Operators

The findings and the contextual comparison point to the following priorities:

i) Enforce enhanced grid-support functions in WTGs, including synthetic inertia, fast frequency response, and reactive capability;
ii) Deploy targeted compensation (SVC/STATCOM or D-FACTS) at weak nodes; and
iii) Site large wind plants at strong connection points or reinforce weak networks. These combined measures — also advocated in the Danish [36], UK [37], and Algerian [38] case studies as well as in study [10] — are essential to balancing efficiency with stability as wind penetration grows.

B. Limitations and Future Work

This study assumed a constant wind speed, which simplifies analysis but may overestimate stability margins since real wind turbulence and wake effects introduce power fluctuations that reduce the critical clearing time (CCT). In addition, the standard DFIG model used did not include advanced features such as Low Voltage Ride Through (LVRT), which affect fault dynamics.

Future studies should therefore consider variable wind speed profiles, conduct sensitivity analyses of system parameters, and evaluate advanced inverter controls (e.g., grid-forming technologies) to better capture the impact of large-scale wind integration on Nigerian grid stability.

REFERENCES

[1] C. Liu, “Empirical analysis of the relationship between renewable energy consumption and economic growth based on the Grey Markov model,” *Journal of Mathematics*, vol. 2022, Art. no. 5679696, 2022.

[2] J. L. Holechek, H. M. E. Geli, M. N. Sawalhah, R. Valdez, “A global assessment: can renewable energy replace fossil fuels by 2050?,” *Sustainability*, vol. 14, no. 8, Art. no. 4792, 2022.

[3] D. O. Obada, M. Muhammad, S. B. Tajiri, M. O. Kekung, S. A. Abolade, S. B. Akinpelu, A. Akande, “A review of renewable energy resources in Nigeria for climate change mitigation,” *Case Studies in Chemical and Environmental Engineering*, vol. 9, Art. no. 100669, 2024.

[4] A. Q. Al-Shetwi, “Sustainable development of renewable energy integrated power sector: Trends, environmental impacts, and recent challenges,” *Science of The Total Environment*, vol. 822, Art. no. 153645, 2022.

[5] M. M. Islam, T. Yu, G. Giannoccaro, Y. Mi, M. L. Scala, M. R. Nasab, J. Wang, “Improving reliability and stability of the power systems: A comprehensive review on the role of energy storage systems to enhance flexibility,” *IEEE Access*, vol. 12, pp. 152738–152765, 2024. DOI: 10.1109/ACCESS.2024.3476959.

[6] M. Khalid, “Smart grids and renewable energy systems: Perspectives and grid integration challenges,” *Energy Strategy Reviews*, vol. 51, Art. no. 101299, 2024. DOI: 10.1016/j.esr.2024.101299.

[7] J. Wang, X. Chen, M. Zhuang, Y. Li, Z. Ruan, Y. Wang, N. Zhang, J. Song, K. He, X. Lu, “Accelerating exploitation and integration of global renewable energy,” *The Innovation*, vol. 6, Art. no. 100873, 2025. DOI: 10.1016/j.xinn.2025.100873.

[8] Erdiwansyah, Mahidin, H. Husin, Nasaruddin, M. Zaki, Muhibbuddin, “A critical review of the integration of renewable energy sources with various technologies,” *Protection and Control of Modern Power Systems*, vol. 6, no. 3, pp. 1–18, 2021. DOI: 10.1186/s41601-021-00181-3.

[9] S. Impram, S. V. Nese, B. Oral, “Challenges of renewable energy penetration on power system flexibility: A survey," *Energy Strategy Reviews*, vol. 31, Art. no. 100539, 2020.

[10] H. R. Shabani, A. Hajizadeh, M. Kalantar, M. Lashgari, M. Nozarian, “Transient stability analysis of DFIG-based wind farm-integrated power,” *Electrical Engineering*, vol. 105, no. 6, p. 3719–3735, 2023.

[11] B. B. Adetokun, C. M. Muriithi, “Impact of integrating large-scale DFIG-based wind energy conversion system on the voltage stability of weak national grids: A case study of the Nigerian power grid,” *Energy Reports*, vol. 7, no. 2021, pp. 654–666, 2021.

[12] O. Olanite, M. N. Nwohu, B. A. Adegboye, O. J. Tola, “Large scale penetration impact of PMS-WTGs on Voltage and power loss for 52-bus, 330kV system of the Nigerian grid,” *Nigerian Journal of Technology*, vol. 43, no. 1, pp. 115–122, 2024.

[13] A. Kuri, E. Brackenhammer, “Challenges for integration of renewable energy in public grid,” in *21st Wind and Solar Integration Workshop (WIW 2022)*, Hybrid Conference, Netherlands, 2022.

[14] S. Islam, N. K. Roy, “Renewables integration into power systems through intelligent techniques: Implementation procedures, key features, and performance evaluation,” *Energy Reports*, vol. 9, pp. 6063–6087, 2023. DOI: 10.1016/j.egyr.2023.05.063.

[15] P. Cholamuthu, B. Irusappan, S. K. Paramasivam, S. K. Ramu, S. Muthusamy, H. Panchal, R. S. S. Nuvvula, P. P. Kumar, B. Khan, “A grid-connected solar PV/wind turbine based hybrid energy system using ANFIS controller for hybrid series active power filter to improve the power quality,” *International Transactions on Electrical Energy Systems*, pp. 1–14, 2022.

[16] I. O. Ozioko, N. S.Ugwuanyi, A. O. Ekwue, C. I. Odeh, “Wind energy penetration impact on active power flow in developing grids,” *Scientific African*, vol. 18, Art. no. e01422, 2022.

[17] M. S. Mastoi, M. J. Tahir, M. Usman, D. Wang, S. Zhuang, M. Hassan, “*Research* on power system transient stability with wind generation integration under fault condition to achieve economic benefits,” *IET Power Electronics*, vol. 15, no. 3, pp. 263–274, 2022.

[18] N. S. *Ugwuanyi*, I. O. Ozioko, U.M. Uma, O. A. Nwogu, N. C. Ugwuoke, N. Nwokocha, “Enhancing renewable energy-grid integration by optimally placed FACTS devices: The Nigeria case study,” *Science Journal of Energy Engineering*, vol. 12, no. 2, pp. 16–25, 2024.

[19] J. Shair, H. Li, J. Hu, X. Xie, “Power system stability issues, classifications *and* research prospects in the context of high-penetration of renewables and power electronics,” *Renewable and Sustainable Energy Reviews*, vol. 145, Art. no. 111111, 2021.

[20] B. Shakerighadi, N. Johansson, R. Eriksson P. Mitra, A. Bolzoni, “An overview of stability challenges for power-electronic-*dominated* power systems: The grid-forming approach,” *IET Generation, Transmission, & Distribution*, vol. 17, no. 2, pp. 284–306, 2023.

[21] A. Pepiciello, J. L. Dominguez-Garcia, A. Vaccaro, “The impact of *frequency* support by wind turbines on the small-signal stability of power systems,” *Energies*, vol. 15, Art. no. 8470, 2022.,” *Energies*, vol. 15, no. 22, Art. no. 8470, 2022.

[22] T. He, S. Li, S. Wu, K. Li, “Small-signal stability analysis for power system *frequency* regulation with renewable energy participation,” *Mathematical Problems in Engineering*, vol. 2021, no. 1, Art. no. 5556062, 2021.

[23] N. S. Ugwuanyi, N. C. Ugwuoke, P. I. Obi, “Impact of grid-scale solar photovoltaic integration on power system performance,” *Vokasi Unesa Bull. Eng. Technol. and Appl. Sc.*, vol. 2, no. 2, pp. 189–198, 2025. https://doi.org/10.26740/vubeta.v2i2.35474, 2025.

[24] M. Chen, D. Zhou, F. Blaabjerg, “High penetration of inverter-based power sources with VSG control impact on electromechanical oscillation of power system,” *International Journal of Electrical Power and Energy Systems*, vol. 142, part B, Art. no. 108370, 2022.

[25] U. Agrawal, R. Huang, Z. Huang, “Analysis of the impact of the increasing inverter-based resources on inter-area modes of the U.S.,” *TechRxiv*, vol. 1, 2022.

[26] O. Bamisile, Q. Huang, X. Xu, W. Hu, W. Liu, Z. Liu, Z. Chen, “An approach for sustainable energy planning towards 100% electrification of Nigeria in 2030,” *Energy*, vol. 197, Art. no. 117172, 2020.

[27] A. U. Adoghe, T. M. Adeyemi-Kayode, V. Oguntosin, I. I. Amahia, “Performance evaluation of the prospects and challenges of effective power generation and distribution in Nigeria,” *Heliyon*, vol. 9, Art. no. e14416, 2023.

[28] O. A. Somoye, “Energy crises and renewable energy potentials in Nigeria: A review,” *Renewable and Sustainable Energy Reviews*, vol. 188, Art. no. 113794, 2023.

[29] M. H. Haque, “incorporation of fixed speed wind farms in power flow analysis,” in *2nd IET Renewable Power Generation Conference (RPG 2013)*, Beijing, 2013.

[30] A. E. Feijoo, J. Cidras, “Modeling of wind farms in the load flow analysis,” *IEEE Transactions on Power Systems*, vol. 15, no. 1, pp. 110–115, 2000.

[31] U. C. Ben, A. E. Akpan, C. C. Mbonu, C. H. Ufuofuonye, “integrated technical analysis of wind speed data for wind energy potential assessment in parts of southern and central Nigeria,” *Cleaner Engineering and Technology*, vol. 2, Art. no. 100049, 2021. DOI: 10.1016/j.clet.2021.100049.

[32] “Renewable energy roadmap: Nigeria,” International Renewable Energy Agency (IRENA), Abu Dhabi, 2023, 126 p.

[33] N. S. Ugwuanyi, I. O. Ozioko, N. C. Ugwuoke, “Dataset for the Nigerian 50-bus 330 kV power grid,” *Zenodo*, pp. 1–7, 2024. DOI: 10.5281/zenodo.12091189.

[34] N. S. Ugwuanyi, U. U. Uma, A. O. Ekwue, “Characterization of oscillation in developing power systems: The Nigeria case study,” in *2021 IEEE/IAS Power Africa*, Kenya, 2021.

[35] N. S. Ugwuanyi, U. U. Uma, A. O. Ekwue, “Fundamental study of oscillations in the Nigerian power systems,” *Nigeria Journal of Technology*, vol. 40, no. 5, pp. 913–926, 2021.

[36] V. Akhmatov, “System stability of large wind power networks: A Danish study case,” *International Journal of Electrical Power and Energy Systems*, vol. 28, no. 1, pp. 48–57, 2006.

[37] J. Xia, A. Dysko, J. O'Reilly, “Future stability challenges for the UK network with high wind penetration levels,” *IET Generation, Transmission and Distribution*, vol. 9, no. 11, pp. 1160–1167, 2015.

[38] L. Wang, K. D. E. Kerrouche, A. Mezouar, A. V. D. Bossche, A. Draou, L. Boumeddiene, “Feasibility study of wind farm grid-connected project in Algeria under grid fault conditions using D-FACTS devices,” *Applied Science*, vol. 8, no. 11, Art. no. 2250, 2018.

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