
SMALL-SIGNAL STABILITY ASSESSMENT OF DFIG-BASED WIND ENERGY INTEGRATION IN STATCOM-COMPENSATED NIGERIAN TRANSMISSION NETWORK: A MODAL ANALYSIS APPROACH

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ABSTRACT

The increasing integration of wind energy into transmission networks introduces interactions that can affect power system stability, particularly in weak and highly interconnected networks. This study assesses the small-signal stability implications of DFIG-based wind energy integration in the Nigerian 330-kV transmission network using eigenvalue-based modal analysis. A 50-bus representation of the Nigerian transmission network is investigated under six operating scenarios comprising the base network, STATCOM-Compensated operation, and DFIG wind-penetration levels of 5% 10%, 15%, and 20%. Power flow analysis is first performed to establish the steady-state operating conditions and evaluate network transmission losses. The resulting operating points are then subjected to linearized state-space analysis to determine critical eigenvalues, oscillation frequencies, and damping ratios. The results show that active losses decrease to 0.58 p at 15% DFIG penetration, while reactive power losses increase substantially at higher penetration. The critical-mode damping ratio improves from 16.092% in the base case to 17.81% at 15% penetration. However, at 20% penetration, the critical eigenvalue shifts to $+0.0210 \pm j0.5781$, producing a negative damping ration of -3.637% and indicating small-signal instability. The finding demonstrates that moderate DFIG penetration can be accommodated under the investigated conditions, while higher penetration requires additional stability-enhancement measure.

Keywords: DFIG; wind energy integration; small-signal stability; modal analysis; STATCOM; Nigerian transmission network

1. INTRODUCTION

The increasing integration of renewable energy sources (RESs) into modern power systems is driven by the need to improve energy security, reduce dependence on conventional fossil-fuel generation, and support sustainable electricity development (Saleh *et al.*, 2025). Wind energy is particularly attractive because of its scalability and relatively low environmental impact. However, large-scale integration of wind generation introduces additional dynamic interactions into power networks and can influence voltage regulation, power flow patterns, and electromechanical oscillations (Ali *et al.*, 2021). These issues are particularly important in developing power systems where transmission networks may be characterized by long transmission corridors, weak voltage profiles, and limited reactive power support.

In Nigeria, the increasing demand for reliable electricity and need to diversify the generation mix have created growing interest in renewable energy integration. The Nigerian transmission network presents particular challenges for large-scale renewable integration because of its geographical extent, transmission constraints, and susceptibility to voltage and stability problems (Adetokun & Muriithi, 2021). Consequently, the integration of wind energy must be assessed not only from the perspective of additional generation capacity but also in terms of its influence on the dynamic behaviour of the interconnected power system.

Doubly Fed Induction Generator (DFIG) is widely used in variable speed wind energy conversion systems (WECSs) because its partial-scale converter allows a variable speed operation while requiring a lower converter rating (30%) than a fully rated converter configuration that utilized

permanent magnet synchronous generator technology (Musbahu *et al.*, 2021). Nevertheless, the converter-based characteristics of DFIG system introduce dynamic interactions that differ from those of conventional synchronous generators. As wind penetration increases, these interactions can modify the damping characteristics of existing electromechanical modes and potentially introduce poorly damped oscillatory modes (Kishor *et al.*, 2026). Therefore, small-signal stability assessment is essential when determining the acceptable level of DFIG penetration in an interconnected transmission network.

Flexible AC Transmission System (FACTS) devices provide an additional means of improving transmission system performance. In particular, a Static Synchronous Compensator (STATCOM) can provide dynamic reactive power compensation and voltage support, making it suitable for improving the operating condition of transmission networks with renewable generation (Ugwuanyi *et al.*, 2024a). However, the presence of adequate voltage support does not necessarily guarantee satisfactory small-signal stability under all renewable penetration levels. It is therefore necessary to evaluate the combined influence of STATCOM compensation and increasing DFIG penetration on the modal characteristics of the network.

Small-signal stability analysis provides a systematic means of determining how system oscillations respond to small disturbances. Eigenvalue analysis can identify the location of critical modes in complex plane, while the associated damping ratio and oscillation frequency provide quantitative measures of the quality of the system damping. A negative real part of an eigenvalue indicates a stable oscillatory mode, whereas an eigenvalue with positive real part indicates small-signal instability (Aliyu *et al.*, 2024; Kouider *et al.*, 2023).

While previous studies have independently explored wind-energy integration, FACTS-based voltage support, and stability assessment (Adetokun & Muriithi, 2021; Ahiakwo *et al.*, 2022; Anyanor *et al.*, 2020; Olabisi & Ayeni, 2023; Ugwuanyi *et al.*, 2024b), there is a pressing need to examine their combined effects within the Nigerian transmission network. Specifically, understanding how critical eigenvalues and damping characteristics change with increasing DFIG penetration can inform strategies for enhancing the integration of renewable energy resources.

This study evaluates the small-signal stability of Nigeria's 330 kV transmission network as DFIG penetration rises, utilizing STATCOM compensation. It examines six scenarios, including the base network, STATCOM conditions, and DFIG levels of 5%, 10%, 15%, and 20%. Initially, power flow analysis assesses steady-state conditions and transmission losses, followed by eigenvalue-based modal analysis to determine critical oscillatory modes, their frequencies, and damping ratios. The focus is on identifying the penetration level at which dominant modes become insufficiently damped or unstable. The findings offer a quantitative assessment of moderate DFIG penetration and the need for enhanced damping measures at higher levels.

2. LITERATURE REVIEW

2.1 DFIG-Based Wind Integration and Grid Stability

The increasing penetration of wind energy has introduced new technical challenges for power-system operation and stability (Nkosi *et al.*, 2023). Unlike conventional synchronous generators, wind turbine generators (WTGs) based on power electronic converters exhibit different dynamic characteristics and therefore interact with transmission network in different ways. These interactions can influence voltage regulation, power flow distribution, and the damping of electromechanical oscillations, particularly as the proportion of converter-based generation increases (Ayodele *et al.*, 2020).

The Doubly Fed Induction Generator is widely employed in variable-speed wind energy conversion systems because it permits variable-speed operation while requiring a partially rated converter (Abad *et al.*, 2011). The converter controls the rotor-side electrical quantities and enables independent control of active and reactive power systems. Consequently, changes in wind energy penetration modify the location and damping of critical eigenvalues and may result in poorly damped or unstable oscillatory modes (Adetokun *et al.*, 2020). For weak highly stressed transmission network, these effects can become more significant. The Nigerian transmission network is particularly relevant because of its long transmission corridors and varying voltage-strength conditions particularly in northern region (Adetokun & Muriithi, 2021).

2.2 STATCOM and Small-Signal Stability

FACTS (Flexible AC Transmission Systems) devices have been extensively studied to enhance the performance of transmission networks by providing controllable reactive power compensation and voltage support. Among these devices, Static Synchronous Compensation (STATCOM) is particularly well-suited for systems with renewable energy generation because it can quickly regulate reactive power and support bus voltage under varying operational conditions (Mbuli, 2026).

In wind-integrated transmission systems, STATCOM compensation can improve voltage conditions and influence the operating point from which the dynamic stability of the system is assessed (Ugwuanyi *et al.*, 2024a). However, improved steady-state voltage performance does not necessarily indicate enhanced small-signal stability. Therefore, the interactions between the STATCOM, Doubly Fed Induction Generator (DFIG) controllers, and conventional synchronous generators must be considered when evaluating the overall system response.

Small-signal stability analysis is typically conducted by linearizing the differential-algebraic representation of the power system around an operating point and analysing the eigenvalues of the resulting state matrix. This analysis is crucial for assessing the impact of increased wind penetration and determining the need for additional damping control measures at higher penetration levels.

For an eigenvalue represented by (Abdulrahman & Energy, 2019);

$$\lambda_i = \sigma_i + j\omega_i \quad (1)$$

Where, σ_i , determine whether the corresponding mode is stable, while the imaginary part ω_i determine its oscillatory characteristics.

3. METHODOLOGY

3.1 Study System Overview

The Nigerian 330 kV transmission network considered in this study is represented by a 50-bus system comprising 14 synchronous generators (i.e. of which 11 are gas-fired and 3 hydro-based at Shiroro, Kainji, and Jebba), transmission lines, and aggregated loads. The network is used to investigate the effect of increasing DFIG-based generation on the steady-state and small-signal stability. The study follows a sequential approach in which the network operating point is first established using power-flow analysis. The approach allows the influence of increasing DFIG penetration to be assessed under comparable operating conditions.

A STATCOM is incorporated into the network to provide dynamic reactive power compensation and voltage support. The STATCOM-compensated network serves as the reference configuration for evaluating the subsequent DFIG penetration scenarios.

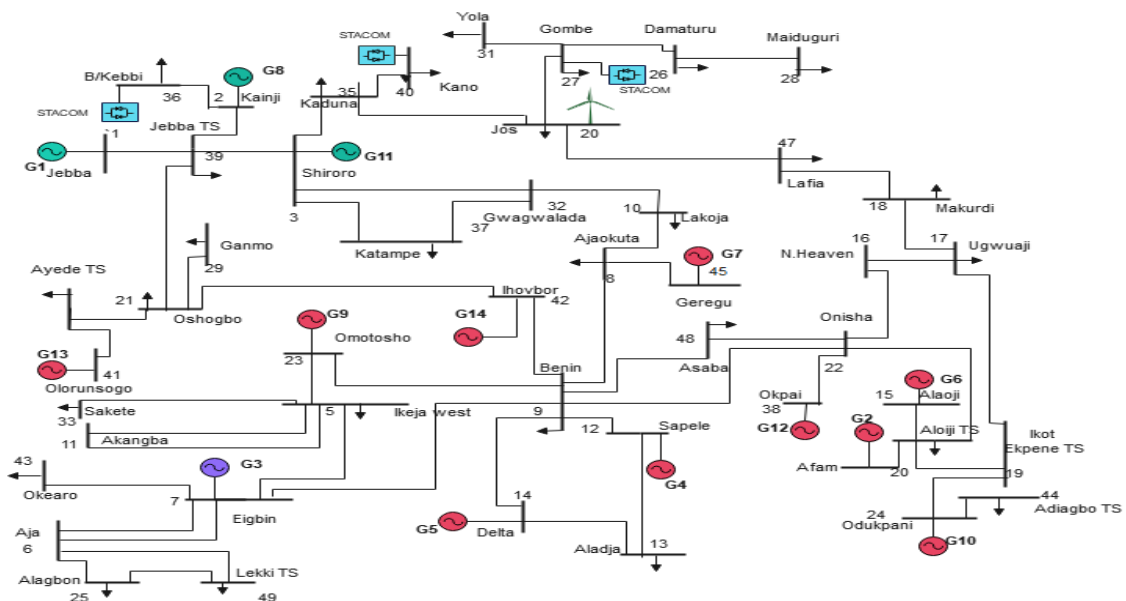


Figure 1: STATCOM-compensated Nigerian Transmission Network with DFIG-Integration

The single line diagram of the studied system was presented in Figure 1, its parameters collected from the national control centre located at Oshogbo Osun state as reported by Ugwuanyi N.S *et al.* (2024) and implemented in Power System Analysis Toolbox (PSAT) software platform.

3. 2 DFIG and STATCOM Integration Scenarios

The DFIG-based WECS is represented using a dynamic model incorporating principal electrical and electromechanical states required for small-signal stability analysis. The DFIG is connected at bus 19 (**Jos**) and its power contribution is progressively increased to represent different wind penetration levels. The wind turbine has a radius of 0.75 m, performance coefficient (C_p) of 0.4 and air density of 1.225 kg/m^3 and a wind speed of 9 m/s. A wind turbine with an average output of 3 MW and a total capacity of 900 MW wind farm was considered, making an equivalent cluster of (3 x 300 MW) wind turbines. The STATCOM is modelled as a controllable reactive-power compensation device connected to the transmission network rated 100 MVA and current control gain of 50 and 0.1 s time constant. Its inclusion provides voltage support capability and establishes the compensated operating condition against which the effect of DFIG integration can be evaluated. The DFIG penetration is defined the ratio of DFIG-active power to the total power generation, mathematically expressed as;

$$DFIG_{Penetration}(\%) = \frac{P_{DFIG}}{P_{GFG} + P_{DFIG}} \times 100 \quad (2)$$

Where, P_{GFG} is active power generation from the 11 gas-fired generator as the 3 hydros geniting station outputs were maintained as they are also renewable resources.

Six operating scenarios are investigated to provide progressive assessment of the effect of wind penetration as detailed in Table 1.

Table 1: Study Scenarios

Scenario	STATCOM	DFIG Penetration	Operating Condition
Case 1	No	0%	Base Network
Case 2	Yes	0%	STATCOM-Compensated network
Case 3	Yes	5%	Low DFIG penetration
Case 4	Yes	10%	Moderate DFIG penetration
Case 5	Yes	15%	High DFG penetration
Case 6	Yes	20%	Very high DFIG penetration

3. 2 Power Flow Analysis

Power flow is initially performed for each operating scenario to establish the stead-state operating point. The analysis determines bus voltages, phase angles, active and reactive power generation, load demand, and transmission losses. The active and reactive powers balances is expressed as (Kouider *et al.*, 2023);

$$\begin{cases} P_{Gen} = P_{Load} + P_{Loss} \\ Q_{Gen} = Q_{Load} + Q_{Loss} \end{cases} \quad (3)$$

The resulting power flow are used to evaluate the effect of DFIG penetration on network operating conditions and losses before proceeding to the dynamic stability assessment.

3.3 Small-Signal Stability and Modal Analysis

Following the computation of power flow, the dynamic model is linearized around the corresponding steady-state operating point. The linearized system can be represented in state space forms as (Aliyu *et al.*, 2024);

$$\dot{x} = Ax \quad (4)$$

$$\det(\lambda I - A) = 0 \quad (5)$$

Where x represents the vector of dynamic state variables and A is the system state matrix. The eigenvalues of state matrix are obtained from; The oscillation frequency (f) and damping ratios (ζ) are computed by;

$$\begin{cases} f = \frac{\omega}{2\pi} \\ \zeta = -\frac{\sigma}{\sqrt{\sigma^2 + \omega^2}} \end{cases} \quad (6)$$

The critical mode is identified as the oscillatory mode with the least favourable damping characteristics among the modes considered. The eigenvalues, oscillation frequencies, and damping ratios are compared across the six scenarios to determine how increasing DFIG penetration affect system stability.

4. RESULTS AND DISCUSSION

The simulations conducted using PSAT software on a 100 MVA, 50 Hz base, under a load demand of 4,300 MW, with Egbin generator serving as the slack or reference generator. The Nigerian power system was modified by integrating a DFIG wind farm at the Jos bus.

According to Ugwuanyi *et al.* (2024b) and other researchers, Jos has been identified as the optimal location for the DFIG wind farm due to its superior performance.

4.1 Power-Flow Performance

The power flow results for the six operating scenarios are presented in Table 2. The results illustrate how the integration of STATCOM compensation and the increasing penetration of DFIG (Doubly Fed Induction Generator) impacts the generation balance and transmission losses in the Nigerian 330 kV transmission network. In Case 1, the base network experiences an active power loss of 0.704 p.u. Introducing a STATCOM in Case 2 increases this loss slightly to 0.720 p.u. However, integrating DFIG leads to a significant reduction in active power losses, achieving a low of 0.580 p.u in Case 5 (a 19.4% reduction from Case 2) at 15% penetration. This shows that local wind power can decrease active power transfer through the transmission network. At 20% penetration, losses rise slightly to 0.600 p.u, although they remain lower than in Case 2, indicating that reductions in losses have limits with increased wind penetration.

Table 2: Power Flow Performance

Scenario	P_{Gen} (p.u)	Q_{Gen} (p.u)	P_{Load} (p.u)	Q_{Load} (p.u)	P_{Loss} (p.u)	Q_{Loss} (p.u)
Case 1	43.18	30.78	42.49	25.04	0.704	5.74
Case 2	45.61	32.24	44.88	26.30	0.72	5.94
Case 3	45.52	31.85	44.88	26.30	0.64	5.55
Case 4	45.48	32.22	44.88	26.30	0.60	5.92
Case 5	45.46	33.41	44.88	26.30	0.58	7.11
Case 6	45.47	35.81	44.87	26.29	0.60	9.52

Conversely, reactive power losses behave differently. Case 3 shows the lowest reactive loss at 5.55 p.u, which climbs to 9.52 p.u by Case 6. The rise at 20% penetration highlights the growing reactive power needs with higher wind integration. Overall, while moderate DFIG penetration enhances active power efficiency, the increasing reactive losses underscore that assessing the feasibility of higher wind penetration requires a broader evaluation of network dynamics.

4.2 Small-Signal Stability and Modal Evolution

The critical eigenvalues modal characteristics obtained from the eigenvalue analysis are presented in Table 3. The results demonstrate a clear change in the dominant oscillatory behaviour as DFIG penetration increases.

The variation in the dominant mode with increasing DFIG penetration indicates that the small-signal stability response is non-monotonic and is governed by modal interaction rather than by a uniform deterioration of all electromechanical modes. At 5% penetration, the critical mode is associated with ω_{13} and δ_{13} of generator 13 with an equivalent damping ratio of 17.004%. At 10% DFIG penetration, the a low-frequency mode associated with ω_{12} and δ_{12} of generator 12 becomes critical, reducing the damping ratio to 10.389% while at 15% penetration the critical mode returns to the $\omega_{13} - \delta_{13}$ pair, with damping ratio increasing to 17.807%.

Table 3: Critical Eigenvalues Modal Characteristics

Scenario	DFIG Penetration	Dominant State	Critical Eigenvalue	Frequency (Hz)	Damping Ratio (%)	Stability
Case 1	0%	$\omega_{13}\delta_{13}$	$-0.6772 \pm j4.1532$	0.670	16.092	Stable
Case 2	0% +STATCOM	$\omega_{13}\delta_{13}$	$-0.7125 \pm j4.1779$	0.675	16.812	Stable
Case 3	5%	$\omega_{13}\delta_{13}$	$-0.7221 \pm j4.1848$	0.675	17.004	Stable
Case 4	10%	$\omega_{12}\delta_{12}$	$-0.0595 \pm j0.5695$	0.091	10.389	Stable
Case 5	15%	$\omega_{13}\delta_{13}$	$-0.7555 \pm j4.1917$	0.678	17.807	Stable
Case 6	20%	$\omega_{12}\delta_{12}$	$0.0210 \pm j0.5781$	0.092	-3.637	Unstable

This behaviour is physically attributable to changes in network power-flow distribution, synchronizing torque, and the dynamic interaction among synchronous generators, DFIG converter controls and STATCOM voltage regulation as the operating point changes. Mathematically, the state matrix $\mathbf{A}$, is a function of the operating points and wind penetration, its eigenvalues do not necessarily vary monotonically with penetration, in which different oscillatory modes become the least-damped mode at different penetration. However, at 20% penetration, the critical eigenvalue moves into the right half of the complex plane, rendering the system unstable with a damping ratio of -3.637%.

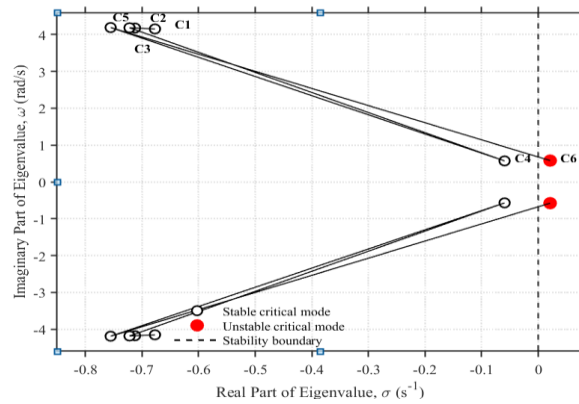


Figure 2: Critical Eigenvalue Migration

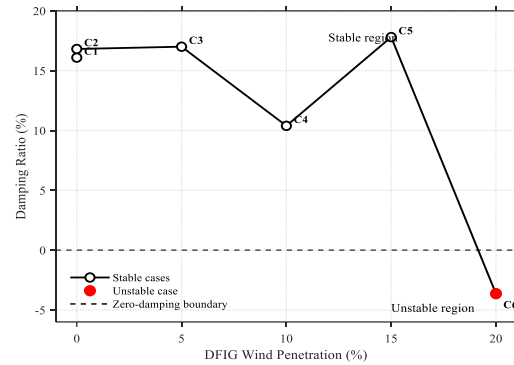


Figure 3: Damping Ratio with increasing DFIG Penetration

Figures 2 and 3 illustrate eigenvalue migration and critical damping variations with DFIG penetration, respectively. Overall, the network maintains small-signal stability up to 15% penetration, while the 20% scenario is unstable, highlighting the stability boundary for the investigated network configuration and operating conditions rather than a universal wind penetration limit for the Nigerian transmission network.

4. CONCLUSION

This study evaluates the small-signal stability of integrating DFIG-based wind generation into Nigeria's 330 kV transmission network through eigenvalue-based modal analysis using the Power System Analysis Toolbox (PSAT) in MATLAB. Six scenarios were assessed including; uncompensated network, STATCOM compensation, and DFIG penetration levels of 5%, 10%, 15%, and 20%.

Initial power flow analysis showed that moderate DFIG penetration enhances active power transmission and reduces losses but increases reactive power losses, particularly at higher penetration levels. Modal analysis revealed that DFIG integration affects system stability in a nonlinear manner, altering oscillatory behaviour with increasing DFIG penetration.

Results indicate that a STATCOM-supported network can maintain small-signal stability with DFIG penetration up to 15%, while suggesting that additional stability measures are needed for 20% penetration. Future research should focus on coordinated damping control strategies, including supplementary DFIG and wide-area damping controllers, to improve stability margins and facilitate higher wind energy integration in Nigeria's transmission network.

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