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Sensitivity-Based Critical Bus Ranking for Available Transfer Capability Assessment of the Nigeria 330 kV Transmission Network under N–1 Contingencies

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ABSTRACT

Background: Increasing loadings and recurring contingency of the 330 kV transmission system in Nigeria have led to concerns about voltage stability and available transfer capability (ATC). The determination of these critical buses, which have a great influence on the network performance, is an important issue for planning, operation, and focused reinforcement.
Aims and Methods: In this study, a sensitivity oriented approach is developed to rank critical bus and ATC assessment for 330 kV Nigerian grid under N−1 contingency conditions. The framework combines voltage deviation evaluation, ATC calculation, sensitivity ranking, cumulative sensitivity contribution analysis, voltage-ATC coupling evaluation, and post-contingency recovery analysis with a first order exponential model.
Result: The findings indicate that system vulnerability is highly location dependent and varies significantly over the network. Bus 22 (Alagbon TS) was identified as the most critical bus with the highest normalised sensitivity index of 1.000 and the most reduction in ATC of 1.65 MW. The cumulative sensitivity analysis showed that the top 15 buses contributed approximately 42% of the total network sensitivity, confirming that vulnerability is concentrated within a relatively small number of locations. The voltage–ATC coupling analysis indicated a strong relationship between the voltage degradation and the transfer capability reduction while the post-contingency recovery assessment proved recovery stability with a recovery time constant of 2.5 s.
Conclusion: The proposed sensitivity based approach is used to identify critical buses and to make targeted reinforcement decisions to enhance the reliability and operational security of the Nigeria 330 kV transmission system.

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1. Introduction

The operation of modern power systems is becoming more difficult to be guaranteed due to ever increasing electricity demand, aging system infrastructure and increasing integration of renewable and distributed energy resources which impact available transfer capability and security margin (Meng *et al.*, 2024; Chauhan, 2023; Huangpu, 2024). While these challenges are global in nature, they are particularly pronounced in the Nigeria 330 kV grid due to recurring operational disturbances and operation close to stability limits (Onyegbadue *et al*., 2024; Fasina *et al*., 2024; Obi *et al*., 2026). Under these conditions, it is also important to keep voltage stability and available transfer capability (ATC) at high levels in order to achieve secure and reliable power delivery (Ezeonye *et al*., 2024a). The 330 kV transmission system of Nigeria is the backbone of the national grid, linking the large power plants to main load centres across the country. Kainji, Jebba, Shiroro, Egbin, Afam, and Alaoji, are some of the major generating stations exporting power through well-developed transmission lines, while substations like Benin, Osogbo, Ikeja West, Akangba, and Alagbon serve as nodes of regional power supply (Ezeonye *et al*., 2024b). Yet the system is often under strain from the demands of long distance transmission, disproportionate loading, weak reactive power support and old equipment. These lead to a higher probability for voltage instability and noticeable reductions in ATC during contingency conditions (Ezeruigboa *et al*., 2021; Olabisi, and Ayeni, 2023; Werkie *et al*., 2025).

The ATC is an important operation index, which is defined as the largest additional power that can be transferred in a network without violating any thermal, voltage, or stability limits. In accordance with the established reliability criteria, ATC represents the remaining transfer capability after accounting for existing commitments and reliability margins (NERC, 2019). During contingency events such as line trips and generator trips, the impact of these factors on ATC is not insignificant and ATC may decrease rapidly due to voltage collapses, changing power flow patterns, and reduced reactive power margins. Therefore, it is necessary to analyse the influence of voltage magnitude on transfer capability for the safe operation and planning of a system (Zhang *et al*., 2023; Wei *et al*., 2024).

There are many methods for calculating ATC, including continuation power flow, probabilistic analysis and optimisation based methods. Continuation power flow methods are still widely used for determining voltage stability margins and evaluating system loadability (Meng *et al*., 2024). However, these methods tend to be computationally difficult in the application to large networks, limiting their application in real-time situation. As a result, sensitivity-based solutions have recently received considerable attention due to their low computational complexity and the capacity to determine critical components in the power systems (Mokred & Wang, 2024). Sensitivity analysis quantifies the effect of small disturbances in system variables, like voltage magnitude, on performance indices including the transfer capability. This is particularly important in contingency screening and ranking, where rapid identification of vulnerable locations is required. Previous studies have shown that sensitivity based indices are successful for voltage stability evaluation and contingency ranking especially under N−1 conditions (Al-Anbarri, 2020; Baleboina and Mageshvaran, 2023; Weigert-Dalagnol *et al*., 2023). These approaches enable system operators to focus on the most critical buses and lines rather than applying uniform reinforcement methods across the network. A number of studies have been conducted on voltage stability and system performance during stressed operating condition in the Nigerian power system. Studies also demonstrate that voltage stability is a recurrent problem in the 330 kV grid, often caused by inadequate reactive power support and long transmission distances (Esobinenwu, 2025). Although these works offer important information regarding the system behaviour, many of them are mainly focused on the improvement of the voltage profiles or the employment of device-based compensation techniques, having no direct connection of the voltage deviations with the reduction of the available transfer capability considering contingency conditions. such a gap would prevent a planner from prioritising interventions according to their effective impact on system transfer performance.

Although there has been a lot of work on ATC improvements, voltage stability assessment, contingency analysis, and candidate bus identification (Zhou *et al*., 2025), few studies have examined critical bus ranking in terms of their impact on transfer capability degradation under contingency conditions. Most of the existing work deals with the compensation method, the improvement of the voltage profile or the reinforcement strategy considering optimisation, and there is not much work on dealing with the quantification of the individual bus contribution in the overall network vulnerability.

Accordingly, a sensitivity based critical bus ranking for the Nigeria 330 kV transmission system is presented under N−1 contingency scenario in this paper. The approach considers voltage deviation, available transfer capability, sensitivity ranking, cumulative sensitivity contribution, voltage-ATC coupling, and post-contingency recovery analysis in an integrated manner. Instead of using conventional methods of determining weak buses from voltage magnitude or loading levels, this paper introduces a sensitivity index that combines voltage deviation and ATC reduction to quantify the contribution of each bus to transfer capability degradation and overall system vulnerability. The study contributes to the literature by providing a systematic critical bus ranking procedure, developing a voltage–ATC coupling framework to evaluate the interaction between voltage disturbances and transfer capability reduction, and incorporating post contingency recovery assessment to provide additional insight into network resilience. The findings provide a practical basis for prioritising reinforcement measures, improving operational reliability, and supporting transmission planning decisions.

2. Methods

2.1 Overview of the Analytical Framework

This study employs a sensitivity-based analytical approach to find critical buses and to analyse the ATC of Nigeria 330 kV transmission system under contingency conditions. This procedure combines steady-state power flow analysis with voltage deviation assessment, sensitivity and dynamic recovery models to outline vulnerabilities in the network and to quantify their operational implications. All simulations and computations were performed in MATLAB environment along with power system analytical tool (PSAT). This allows for reproducible calculations, scalability to large systems, and efficient processing of system data, making it suitable for both academic and practical planning purposes.

The complete analytical procedure involves modelling the Nigerian 48-bus transmission network, running contingency-based power flow simulations, monitoring voltage and ATC deviations, and calculating sensitivity indices based on which critical buses are ranked. The procedure is intended to be computationally efficiency, physically interpretable, and meaningful for operational planning.

2.1.1 Simulation Environment and Modelling Assumptions

All the simulations were done in MATLAB R2024a with the Power System Analysis Toolbox (PSAT) version 2.1.11. The 330 kV transmission system of Nigeria was studied based on a 100 MVA system base. Newton–Raphson power flow method was used because of its well-known robustness and fast convergence for large-scale transmission systems. During the entire process, the bus voltage magnitudes were limited to the permissive operating range of 0.95 pu and 1.05 pu. For ensuring numerical accuracy and solution stability, the convergence tolerance for all the power flow computations was 1×10^{-6} pu. Available transfer capability calculations and contingency assessments were performed under N−1 transmission line outage conditions using identical network operating assumptions for all simulation scenarios.

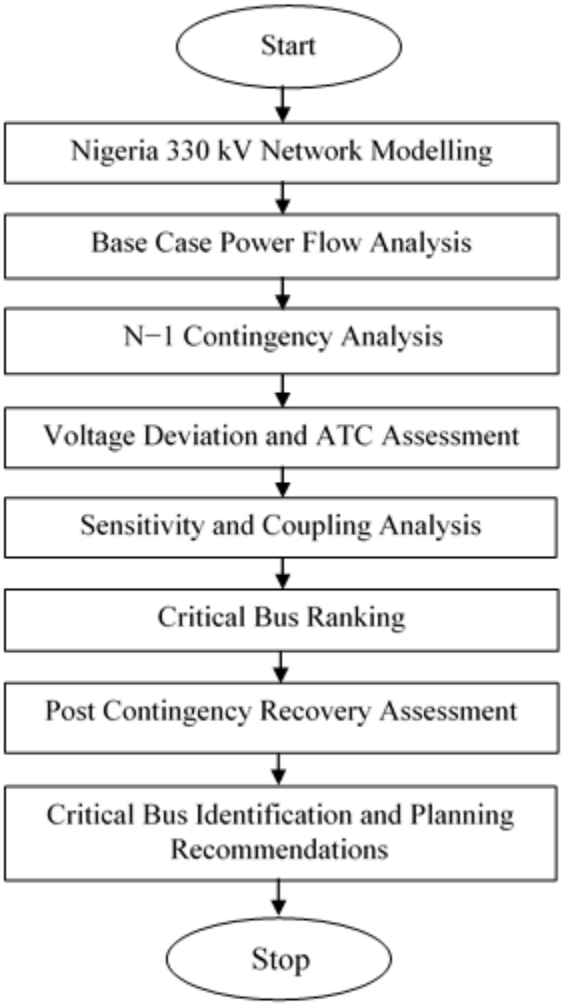

Figure 1. Methodological Flowchart.

The overall analytical procedure adopted in this study is illustrated in Figure 1. The workflow comprises network modelling, contingency analysis, available transfer capability evaluation, sensitivity assessment, critical bus ranking, and post contingency recovery analysis.

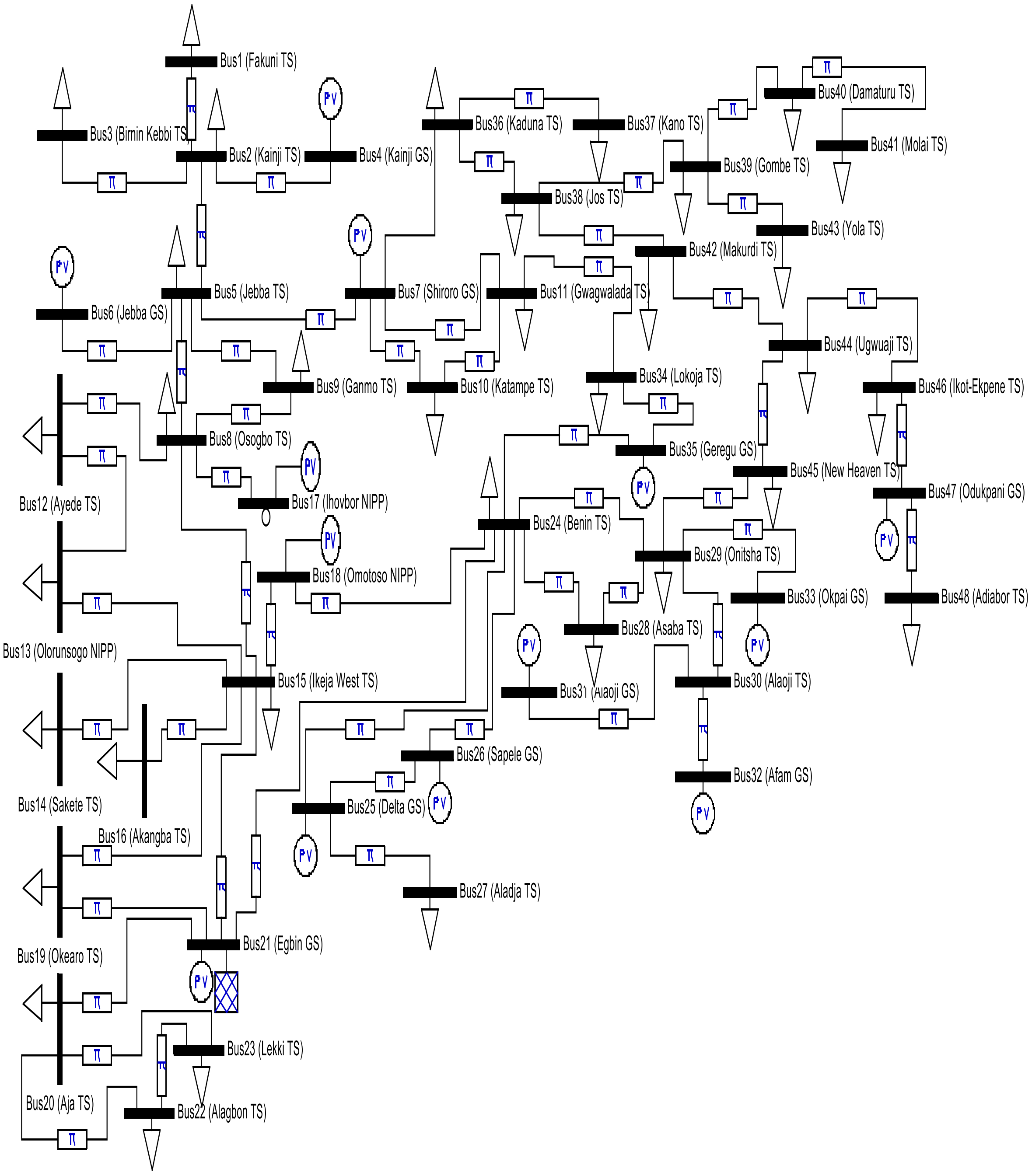

Figure 2. Single-line representation of the Nigeria 330 kV 48-bus transmission network.

The single-line diagram of Nigeria's 330 kV transmission network utilised in this work, depicting the connection of the generating stations, transmission lines and major load centres are shown in Figure 2.

2.2 Network Modelling and System Description

The entire 330 kV Nigerian transmission network incorporated in this study is made up of 48 number of buses which are major generation station, transmission substation and interconnection points within the country. Generation nodes include Kainji, Jebba, Shiroro, Egbin, Afam, Olorunsogo, Omotoso and

Alaoji, whilst significant load centers are Ikeja West, Akangba, Alagbon, Benin, Onitsha and Aba. The network topology is a realistic representation of the actual Nigerian transmission grid operating structure, gives a good approximation of the geographical area and the inter-area power transfers. Newton–Raphson (NR) power flow was used to carry out the load flow study. The NR method is the most utilised load flow method due to its numerical stability and quick convergence in large power systems (Ezeonye *et al*., 2025a). The base case was set at an operating point under normal conditions for all bus voltages, line flows, and generator outputs within allowable ranges. The network model was developed using transmission line and generation data obtained from the National Control Centre (NCC), Osogbo, Nigeria. The dataset includes generating station characteristics, transmission line lengths, sequence impedance parameters, and network connectivity information. Detailed transmission line parameters are presented in Table 1, while additional information on bus classifications, generator characteristics, and representative transmission line data is provided in Appendix A.

Table 1. Parameters of 330 kV Transmission Lines

S/N	Line Name	Length (km)	R_1 (pu)	X_1 (pu)	R_0 (pu)	X_0 (pu)
1	Aja – Egbin	14	0.1711	1.2057	0.0022	0.0155
2	Egbin – Ikeja West	62	0.0386	0.2723	0.0022	0.0155
3	Akangba – Ikeja West	18	0.1331	0.9378	0.0022	0.0155
4	Ikeja West – Papalanto	30	0.0390	0.2760	–	–
5	Ayede – Ikeja West	137	0.0389	0.2711	0.0049	0.0341
6	Ayede – Osogbo	115	0.0388	0.2756	0.0041	0.0291
7	Ikeja West – Osogbo	252	0.0212	0.1474	0.0049	0.0341
8	Ikeja West – Benin	218	0.0390	0.2760	–	–
9	Benin – Osogbo	251	0.0386	0.2759	0.0089	0.0636
10	Afam – Alaoji	25	0.3920	0.2614	0.0090	0.0060
11	Alaoji – Onitsha	138	0.3867	0.2762	0.0490	0.0350
12	New Haven – Onitsha	96	0.0386	0.2723	0.0030	0.0240
13	Onitsha – Benin	137	0.0389	0.2758	0.0049	0.0347
14	Aladja – Delta	32	0.0783	0.5445	0.0023	0.0160
15	Aladja – Sapele	63	0.0398	0.2766	0.0023	0.0160
16	Benin – Delta	107	0.0234	0.1628	0.0023	0.0160
17	Benin – Sapele	50	0.0392	0.2744	0.0018	0.0126
18	Benin – Ajaokuta	195	0.0391	0.2736	0.0070	0.0490
19	Jebba – Osogbo	157	0.0388	0.2761	0.0056	0.0398
20	Jebba – Shiroro	244	0.0299	0.2767	0.0067	0.0620
21	Kaduna – Shiroro	96	0.0386	0.2779	0.0034	0.0245
22	Jebba – Kainji	81	0.0390	0.2756	0.0029	0.0205
23	Jebba GS – Jebba TS	8	0.0408	0.2723	0.0003	0.0020
24	Shiroro – Abuja	144	0.0394	0.2740	–	–
25	Birnin Kebbi – Kainji	310	0.0390	0.2761	0.0111	0.0786
26	Kaduna – Kano	230	0.0388	0.2746	0.0082	0.0580
27	Kaduna – Jos	197	0.0387	0.2709	0.0070	0.0490
28	Jos – Gombe	265	0.0390	0.2753	0.0095	0.0670
29	Jos – Makurdi	230	0.0394	0.2740	–	–
30	Makurdi – Alaoji	435	0.0394	0.2740	–	–
31	Kashimbila – Makurdi	170	0.0394	0.2740	–	–

Note: R_1 and X_1 represent positive sequence resistance and reactance, respectively, while R_0 and X_0 represent zero sequence resistance and reactance. All impedance values are expressed in per unit on a 100 MVA base. The data correspond to the base operating conditions of the Nigeria 330 kV transmission network and were obtained from the National Control Centre (NCC), Osogbo, Nigeria.

2.3 Contingency Analysis Framework

Contingency analysis was performed at credible N−1 transmission lines outages to assess the system performance during stressed operating conditions. In each contingency a single transmission line is removed, and the system operating conditions are recomputed under the new topology using power flow. This practice follows by a re-evaluation of system operating conditions through power flow analysis. The method reflects standard reliability assessment practices recommended by system operators and reliability organisations (NERC, 2019). Voltage magnitudes and power flow patterns for each contingency were investigated for detecting any difference from base case. Voltage deviation was calculated as the absolute difference between pre-contingency and post-contingency voltage amplitudes at each bus. These are a direct indication of how severe voltage instability is as a result of network disturbances.

Table 2. N−1 Contingency Scenarios Considered in the Study

Scenario	Outaged Transmission Line	Associated Bus
C1	Birnin Kebbi–Kainji	Birnin Kebbi TS
C2	Akangba–Ikeja West	Akangba TS
C3	Lekki–Alagbon	Lekki TS
C4	Aladja–Delta	Aladja TS
C5	Alaoji–Onitsha	Alaoji TS

The contingency analysis focused on selected N−1 transmission line outage scenarios, in relation to critical nodes in the Nigeria 330 kV transmission system as shown in Table 2. Each outage was simulated separately with the rest of the network elements kept in service. The contingencies considered here were selected to determine the effect of transmission line outages on voltage stability and available transfer capability at weak points in the network.

2.4 Available Transfer Capability Assessment

The thermal, voltage, and system stability limits were studied to determine the ATC, which quantifies the amount of transfer power that can be increased without violating any of these constraints. The ATCs for base-case and contingency-case are calculated to consider the effects of disturbances on transfer capability. The employed ATC calculation method is the standard ATC definition based on the methodology of the North American Electric Reliability Corporation (NERC), where ATC is expressed as the remaining transfer capability after accounting for existing transmission commitments and reliability margins (Ezeonye *et al*., 2025b). Under contingency conditions, the ATC decrease was the result of interaction of voltage reduction, power redistribution and reactive power limitations. In this study, ATC was calculate based on a continuation power flow technique, which represents the maximum additional power transfer that can be accommodated in the system without violating any thermal, voltage, or stability constraints. The evaluation was conducted on a bus basis in order to evaluate the effect of single bus outages on network transfer capability in the event of contingencies. Instead of a particular market transaction or established transfer corridor, the ATC was computed for the investigated buses under both base case and contingency operating conditions. This approach enables direct comparison of bus vulnerability and supports the sensitivity based ranking methodology developed in this work.

To apply continuation method to power flow problem, a loading parameter must be inserted into the power flow equations to parameterise the load-flow equation. A uniform power factor model is expressed as follows:

$$\mathrm{P_{Gi} - P_{Di} - Q_{Di} = 0} \tag{1}$$

Subject to:

$$\mathrm{P_{Gi} - P_{Di} - \sum_{j=1}^{n} |U_i||U_j|\left(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}\right) = 0} \tag{2}$$

$$\mathrm{Q_{Gi} - Q_{Di} - \sum_{j=1}^{n} |U_i||U_j|\left(G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}\right) = 0} \tag{3}$$

$$\mathrm{|U_i|_{min} \leq |U_i| \leq |U_i|_{max}} \tag{4}$$

$$\mathrm{\left|S_{ij}\right| \leq \left|S_{ij}\right|_{max}} \tag{5}$$

$$\mathrm{|\delta_{Gi}(t) - \delta_{Gi}(t)| \leq \delta_{Gmax}} \tag{6}$$

Where $\mathrm{P_D}$: the total real power load on all load buses, $\mathrm{P_{tie-lines}}$: the summation of real power flow on tie lines, $\mathrm{P_{Gi}}$, $\mathrm{Q_{Gi}}$: the active and reactive power generation at bus i, $\mathrm{P_{Di}}$, $\mathrm{Q_{Di}}$: the active and reactive power at bus i, n: number of system buses, $\mathrm{|U_i|}$: Voltage magnitude at bus i, $\mathrm{G_{ij}}$, $\mathrm{B_{ij}}$: real and imaginary part of the ij$^{\mathrm{th}}$ component of bus admittance matrix, δ_{ij}: voltage angle difference between bus i and bus j, $\mathrm{S_{ij}}$: apparent power flow in line ij, $\mathrm{|U_i|_{min}}$: lower limit of voltage magnitude at bus i, $\mathrm{|U_i|_{max}}$: upper limit of voltage magnitude at bus i,$\mathrm{\left|S_{ij}\right|_{max}}$: thermal limit of line ij, $\mathrm{\delta_{Gi}(t)}$: rotor angle of generator i, $\mathrm{\delta_{Gmax}}$: maximum secure relative swing angle.

In the process of calculation, $\mathrm{P_{Gi}}$, $\mathrm{P_{Di}}$ and $\mathrm{Q_{Di}}$ are changed in following ways

$$\mathrm{P_{Gi} = P_{Gi}^{0}(1 + \lambda K_{Gi})} \tag{7}$$

$$\mathrm{P_{Di} = P_{Di}^{0}(1 + \lambda K_{Di})} \tag{8}$$

$$\mathrm{Q_{Di} = Q_{Di}^{0}(1 + \lambda K_{Di})} \tag{9}$$

Where $\mathrm{P_{Gi}}$: base case power transfer at bus i, $\mathrm{P_{Di}^{0}}$, $\mathrm{Q_{Di}^{0}}$: base case real and reactive load at bus i, λ: increment factor in bus load and generation, $\mathrm{K_{Gi}}$, $\mathrm{K_{Di}}$: constants specifying the rate of change in generation and load.

At the maximum loading parameter (λ_{max}), the ATC is calculated using:

$$\mathrm{ATC} = \sum_{\mathrm{i \in sink}} \mathrm{P_L^i}\,(\lambda_{\mathrm{max}}) - \sum_{\mathrm{i \in sink}} \mathrm{P_L^{i0}} \tag{10}$$

Equation (10) defines the ATC as the maximum additional transferable load that can be accommodated at the sink buses when the loading parameter gets to its limiting value, λ_{max}. The difference between the maximum transferable loading condition and the corresponding base case loading shows the ATC margin of the network. For each investigated bus, the ATC was evaluated under both base case and contingency conditions and subsequently used to determine the transfer capability reduction resulting from network disturbances.

The reduction in available transfer capability was calculated as:

$$\Delta\mathrm{ATC}_{i} = \mathrm{ATC}_{Base,i} - \mathrm{ATC}_{Cont,i} \tag{11}$$

Where $\mathrm{ATC}_{\mathrm{Base},i}$ and $\mathrm{ATC}_{\mathrm{Cont},i}$ represent the available transfer capability of bus iii under base case and contingency conditions, respectively.

2.5 Sensitivity Index Formulation

To identify critical buses, a sensitivity index (SI) was defined to quantify the relationship between voltage deviation and ATC variation. The sensitivity index for each bus is expressed as:

$$SI_i = \frac{\Delta ATC_i}{\Delta V_i} \tag{12}$$

Where ΔATC_i represents the change in available transfer capability at bus i, and ΔV_i represents the corresponding voltage deviation bus i. The sensitivity index has units of MW/kV and quantifies the reduction in available transfer capability associated with a unit voltage deviation. Larger values indicate buses whose voltage disturbances produce greater transfer capability degradation.

To enable comparison across the network, a normalized sensitivity index (NSI) was computed as:

$$NSI_i = \frac{SI_i}{\max{(SI)}} \tag{13}$$

Where max (SI) is the maximum sensitivity value across all buses.

Higher values of NSI indicate buses whose voltage disturbances have a stronger influence on system transfer capability, thereby identifying critical locations within the network. The normalised sensitivity index was obtained by dividing each sensitivity index by the maximum sensitivity index observed in the study, resulting in values between 0 and 1. Since all investigated contingencies produced measurable voltage deviations, no near zero denominator was encountered during the calculations.

2.6 Cumulative Sensitivity and Coupling Analysis

To estimate the combined effect of critical buses on the system vulnerability, a cumulative sensitivity contribution was determined by arranging the sensitivity index in descending order, and computing their cumulative sum to the total sensitivity. This makes it clear that overall system vulnerability is dominated by a small number of buses. Furthermore, a voltage-ATC coupling index, which depicts the relationship between voltage deviation and ATC decrease, is proposed. This measure enables one to understand the extent to which voltage instability impacts power transfer capability, and identifies buses, where voltage support would have the largest operational benefit.

To quantify the overall contribution of individual buses to system vulnerability, the cumulative sensitivity contribution is defined as:

$$CSC_K = \frac{\sum_{i=1}^{K} NSI_i}{\sum_{i=1}^{N} NSI_i} \tag{14}$$

Where N is the total number of buses in the system. In order to estimate the concentration of network vulnerability, the cumulative sensitivity contribution of the highest ranked buses was examined. The percentage share of the first 5, 10 and 15 buses in the total system sensitivity was computed and used to identify the degree of network vulnerability domination by a small number of critical buses.

To evaluate the degree of interaction between voltage deviation and ATC degradation, a coupling index is defined as:

$$CI_i = \left(\frac{\Delta V_i}{\max{(\Delta V)}}\right) \times \left(\frac{\Delta ATC_i}{\max{(\Delta ATC)}}\right) \tag{15}$$

In addition to the coupling index evaluation, the relationship between voltage deviation and available transfer capability reduction was examined to determine the degree to which voltage disturbances contribute to transfer capability degradation across the network.

2.7 Dynamic Recovery Analysis

In order provide an approximate of post contingency recovery response, a simplified first order exponential recovery model was used. The model is not a dynamic simulation of the generator, excitation system, or governor dynamics. It is, rather, a computationally convenient way to model the slow returning of voltage and transfer capacity after a disturbance. A recovery time constant of 2.5 s was selected to model the typical response of a transmission system and applied for all studied cases.
The recovery model is expressed as:

$$X(t) = X_{cont} + (X_{base} - X_{cont})(1 - e^{-\frac{t}{\tau}}) \tag{16}$$

Where X(t) represents either voltage or ATC at time t, X_{cont} is the post-contingency value, X_{base} is the steady-state value, and τ is the recovery time constant. The selected time constant of 2.5 s was chosen to provide a representative approximation of short term post contingency recovery behaviour and to enable comparative assessment of recovery characteristics among critical buses.

3. Results and Discussion

This section describes the results of the sensitivity-based evaluation of the Nigeria 330 kV transmission network under the contingency situations. The study examine the behaviour of voltage deviation, available transfer capability (ATC) variation, sensitivity ranking of buses, and the dynamic recovery of critical buses after the disturbances. The results yield quantitative measures for the vulnerability of particular network locations, and highlight their impact on transmission system planning and operational reliability.

3.1 Voltage Deviation under Contingency Conditions

Voltage deviation profile of the 48-bus Nigeria 330 kV transmission network under contingency situations is shown in Figure 3. The results presents non-uniform voltage drops across the network, indicating that certain buses experience significantly higher voltage stress during contingency events. This non-uniformity confirms that system disturbances do not propagate evenly across the grid but instead concentrate around electrically weak or heavily loaded buses.

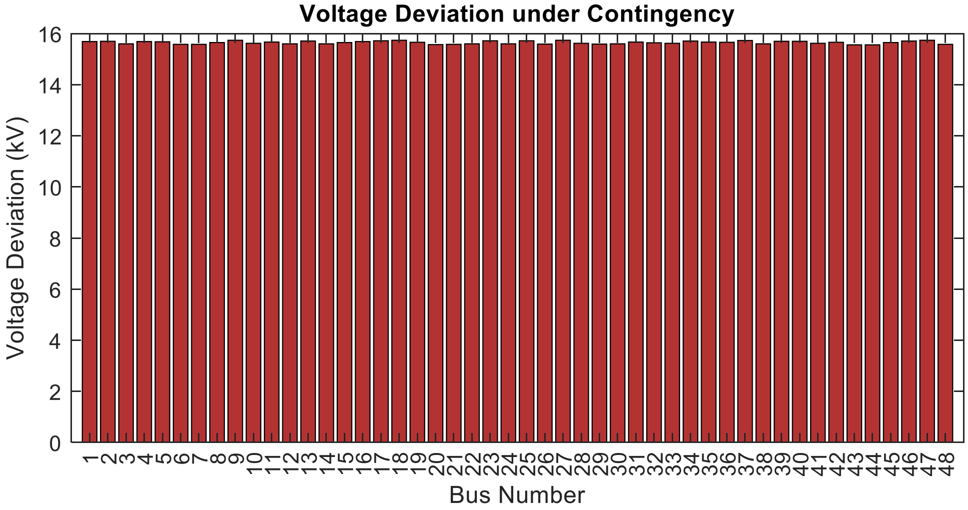

Figure 3. Voltage deviation of the Nigeria 330 kV network under contingency conditions.

Several buses have significantly higher voltage deviations, which illustrates their sensitivity to power flow interruptions. Such buses are typically located close to heavily loaded lines or electrically remote areas of the network. The voltage deviations that have been observed illustrate the inherent vulnerability of these locations and validate the need for specific location reinforcement strategies as opposed to uniform network upgrades. The results also indicate that voltage stability is still one of the most critical factors limiting sustainable power transfer over the Nigerian 330 kV grid, particularly during stressed system conditions. The maximum voltage deviation observed during the contingency analysis was 15.74 kV (0.0477 pu). The buses exhibiting the largest voltage deviations under contingency conditions are further identified and ranked in Table 3 presented in Section 3.3.

3.2 Available Transfer Capability under Contingency

Figure 4 shows the distribution of base-case ATC and contingency ATC over the whole network. Generally, there is a systematic decrease in the transfer capability throughout most buses, which corroborates the negative impact of contingency events on the operation margin of the system.

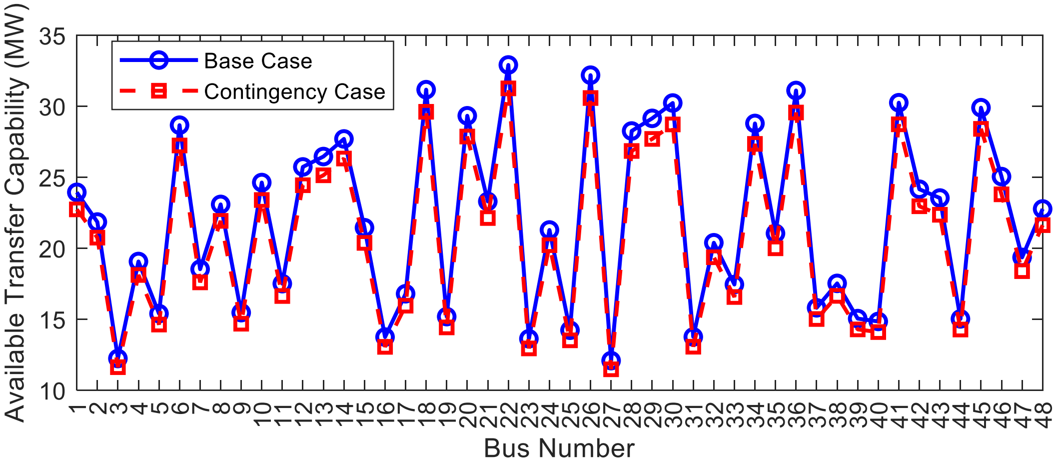

Figure 4. Comparison of available transfer capability under base-case and contingency conditions

In some locations, the decrease in ATC is large and the system is nearly constrained for more power transfers under disturbances. That decrement is critical especially for buses which are acting as a major transmission corridor or a major interconnector between generation and load centers. The largest ATC reduction was recorded at Alagbon TS, where the transfer capability decreased by 1.65 MW from a base case value of 32.92 MW, representing approximately 5.01%. Similar reductions were observed at Sapele GS (1.61 MW, 5.00%), Omotoso NIPP (1.56 MW, 5.00%), Makurdi TS (1.55 MW, 4.98%), and Molai TS (1.52 MW, 5.02%). These locations therefore represent the buses most affected by contingency induced transfer capability degradation. These findings validate that network flexibility is heavily influenced under contingency conditions and that stability-oriented planning measures should play an important role in network expansion and reinforcement procedures.

3.3 Sensitivity-Based Ranking of Critical Buses

Figure 5 shows the sensitivity index for all the 48 buses. It measures the strength of impact that changes in voltage has on ATC for each bus. Larger values represent buses where small voltage deviations cause much larger reductions in ATC.

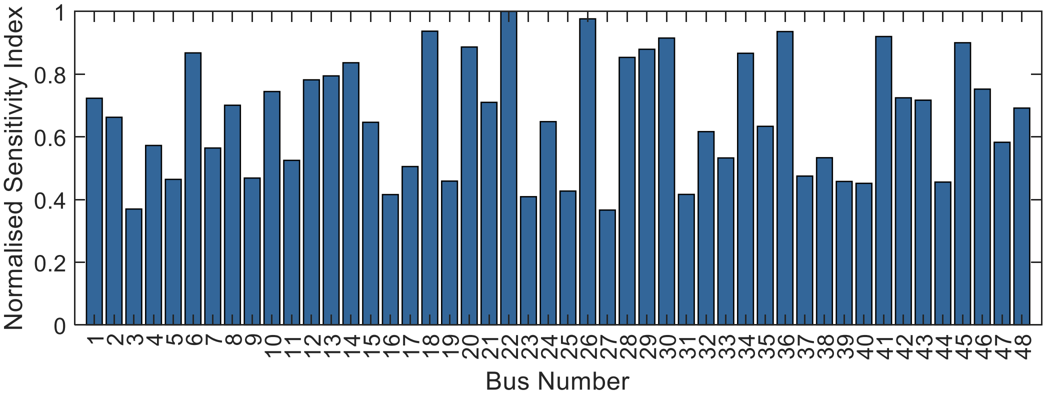

Figure 5. Sensitivity-based ranking of critical buses in the Nigeria 330 kV transmission network

It is found that only a portion of the buses is highly sensitive and the rest contribute very little to the system vulnerability. This finding is significant because system strengthening can be targeted and need not be spread evenly throughout the network. Sensitivity indices of the most sensitive buses are critical nodes whose strengthening would lead to the largest increase in system robustness and hence its operational security. These results give a useful guide on how to focus on investments in voltage support devices, network reinforcement, or advanced control techniques. Table 3 summarises the voltage deviation, available transfer capability reduction, and normalised sensitivity index obtained for the most critical buses under the investigated N−1 contingency conditions.

Table 3. Critical Bus Ranking and Contingency Response Characteristics

Rank	Bus No.	Bus Name	ΔV (kV)	ΔV (pu)	ΔATC (MW)	SI (MW/kV)	NSI
1	22	Alagbon TS	15.60	0.0473	1.65	0.1058	1.000
2	26	Sapele GS	15.59	0.0472	1.61	0.1033	0.976
3	18	Omotoso NIPP	15.74	0.0477	1.56	0.0991	0.937
4	42	Makurdi TS	15.66	0.0475	1.55	0.0990	0.936
5	41	Molai TS	15.62	0.0473	1.52	0.0973	0.920
6	30	Alaoji TS	15.60	0.0473	1.51	0.0968	0.915
7	20	Aja TS	15.57	0.0472	1.46	0.0938	0.886
8	46	Ikot-Ekpene TS	15.65	0.0474	1.49	0.0952	0.901
9	29	Onitsha TS	15.59	0.0472	1.45	0.0930	0.879
10	13	Olorunsogo GS	15.71	0.0476	1.32	0.0840	0.795

Table 3 shows that Alagbon TS exhibited the highest normalised sensitivity index of 1.000 and the largest available transfer capability reduction of 1.65 MW, indicating the strongest influence on system vulnerability under contingency conditions. Sapele GS, Omotoso NIPP, Makurdi TS, and Molai TS also recorded high sensitivity values and significant transfer capability reductions. Most of the highly ranked buses are located along major transmission corridors or near important generation and load centres, highlighting their strong influence on power transfer capability and voltage stability.

3.4 Cumulative Sensitivity Contribution

Figure 6 demonstrates the individual buses to the overall system sensitivity. This indicates that a small number of buses contribute largely to the total sensitivity. This behaviour confirms that there exist dominant vulnerability points in the network.

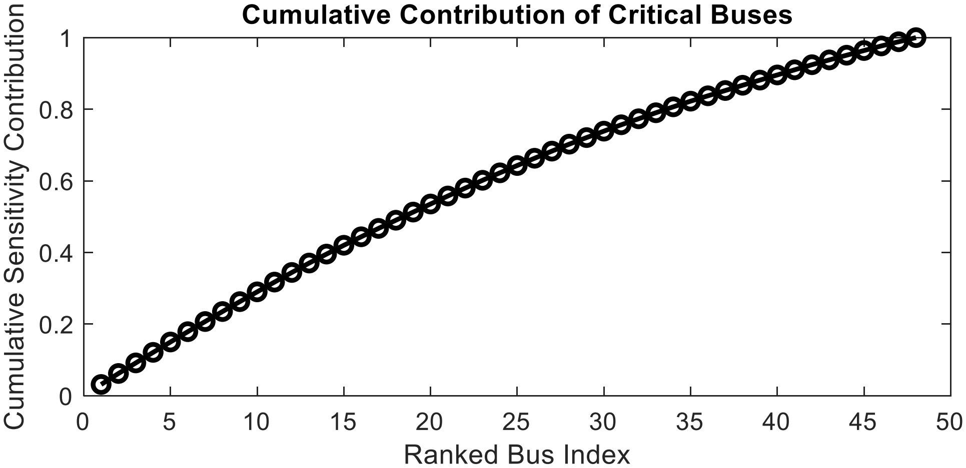

Figure 6. Cumulative sensitivity contribution of critical buses.

The cumulative sensitivity analysis results can guide system planners in focusing on the minimum number of buses, for which the strengthening result in most improvement in the performance of the whole Power system. It is evident from the results that the top 5, top 10, and top 15 buses cover about 15.0%, 29.0%, and 42.0% of the cumulative network sensitivity, respectively. This shows that the system vulnerability is concentrated at a relatively small number of locations rather than being uniformly distributed across the network. Thus, the reinforcement of these critical buses will be more beneficial than the evenly distributed reinforcement of the entire network.

3.5 Voltage–ATC Coupling Behaviour

Figure 7 shows the voltage–ATC coupling index, which represents a combined effect of voltage deviation and ATC reduction. High coupling indices among those buses at which voltage instability leads directly into power transfer capability reduction are those with high coupling indices.

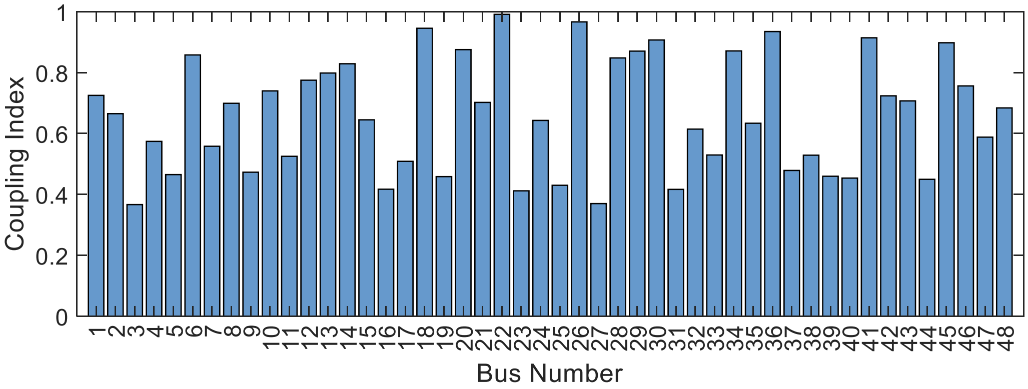

Figure 7. Voltage–ATC coupling index of the Nigeria 330 kV transmission network

This result provides a deeper understanding of the relationship between voltage stability and transmission capacity. It is shown that voltage support at some specially chosen buses can greatly improve the performance of the whole system. Thus, the coupling index is a useful indicator to determine the priority locations to install voltage control devices, such as flexible alternating current transmission system (FACTS) devices. The voltage–ATC coupling results indicate a strong positive relationship between voltage deviation and transfer capability reduction across the investigated buses.

3.6 Dynamic Recovery Characteristics of Critical Buses

Figures 8 and 9 show the voltage and ATC recovery patterns for the most critical bus after a disturbance. The recovery profiles reveal a gradual approach to steady state, with an exponential response typical of power system recovery dynamics. Bus 22 (Alagbon TS) was selected for recovery analysis because it exhibited the highest normalised sensitivity index and the largest available transfer capability reduction among all investigated buses under contingency conditions.

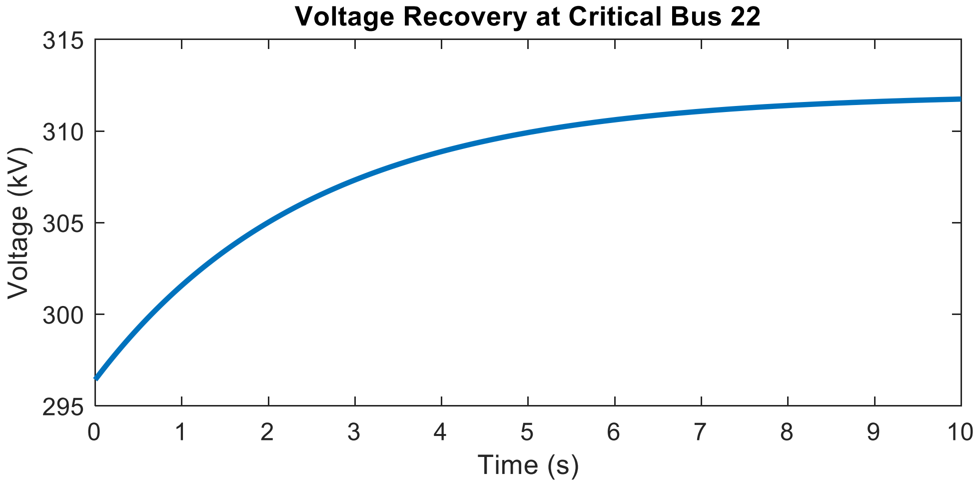

Figure 8. Voltage recovery profile of the most critical bus following a contingency event

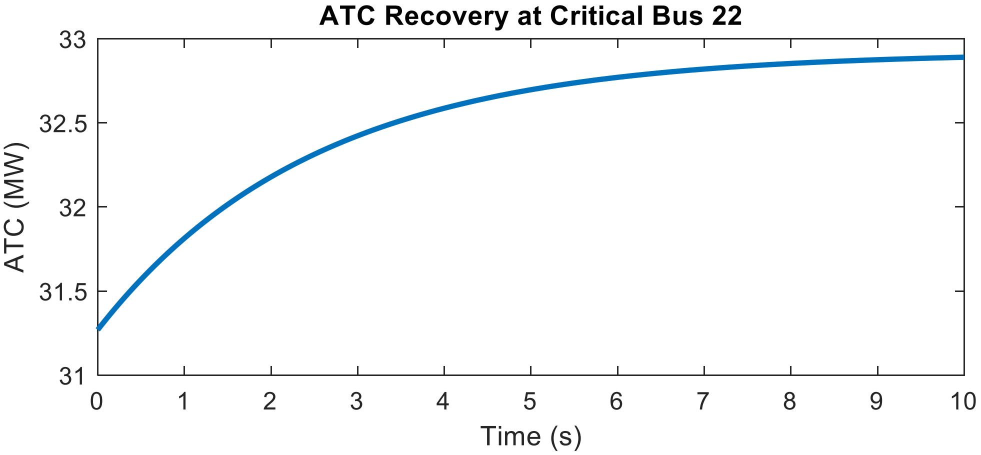

Figure 9. ATC recovery profile of the most critical bus following a contingency event

The recovery of the voltages profile from the disturbance shows that, although the system voltage is recoverable, the rate of recovery is a function of the severity disturbance and the network strength at the bus. Similarly, the ATC recovery profile illustrates that transfer capability restoration lags behind voltage recovery, highlighting the post-contingency operational vulnerability. These results emphasise the importance of enhancing dynamic support mechanisms to improve system resilience and reduce recovery time following disturbances.

The overall results show that the vulnerability of subsets of the system within the Nigeria 330 kV transmission network is clearly location-dependent. Instead of applying the same reinforcement solution to the whole network, the results indicate that reinforcing a small number of identified critical buses is a more efficient and cost-effective way of improving system performance and reliability.

4. Conclusion

This study proposed a sensitivity analysis-based critical bus evaluation for enhancing ATC in Nigeria 330 kV transmission system. By combining voltage deviation analysis, ATC calculation, sensitivity ranking, and dynamic recovery evaluation, the study also offered an organised structure for analysing system vulnerability under contingency situations. These results suggest that system vulnerability is highly dependent on location and that only a few buses have an outsized effect on the overall network. Among all buses investigated, Bus 22 (Alagbon TS) was identified as the most critical location, exhibiting the highest normalised sensitivity index of 1.000 and the largest available transfer capability reduction of 1.65 MW under contingency conditions. The maximum voltage deviation observed during the contingency analysis was 15.74 kV (0.0477 pu). Furthermore, the cumulative sensitivity analysis showed that the top 5, top 10, and top 15 buses contributed approximately 15.0%, 29.0%, and 42.0% of the total network sensitivity, respectively. These critical buses also have large reductions in their transfer capability during moderate voltage disturbances, which further confirms their importance as a system reliability determinant. Results show that selective strengthening of such areas is more effective and economically feasible than overall, homogeneous strengthening of the system. The combined sensitivity and voltage-ATC coupling information also implied that focusing on a small number of critical buses can substantially enhance network robustness. Further, the dynamic recovery analysis demonstrated that although the system is capable of restoring stability following disturbances, recovery performance strongly depends on the electrical strength of affected buses. From these results, it is advised that prospective network reinforcement approaches should focus on the critical buses by utilising voltage support and control devices such as static compensators (STATCOMs) and static var compensators (SVCs). The application of sensitivity-based evaluation in periodic planning and operational analysis is anticipated to enable better system decisions, increased system reliability, and more operational flexibility. This study considered steady state contingency analysis and a basic first order recovery model. In future studies, detailed dynamic simulations and evaluation of other types of reinforcement, such as the use of FACTS devices, inclusion of renewable energy and expansion of the transmission network, may be taken into account. In general, the developed methodology provides an effective and scalable method to improve the resilience and performance of the Nigeria 330 kV transmission grid, and can be extended to large-scale power systems with similar operational challenges.

5. Authors Note

The authors declare that there is no conflict of interest regarding the publication of this article and confirm that the paper was free of plagiarism.

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Appendix

Appendix A: Summary of Network Data Used in the Simulation Model

Table A1. Bus Classification and Nominal Voltage Levels

Bus Name	Bus Type	Nominal Voltage (kV)	Description
Egbin	PV	330	Generator bus
Kainji	PV	330	Generator bus
Shiroro	PV	330	Generator bus
Jebba	PV	330	Generator bus
Afam	PV	330	Generator bus
Papalanto	PV	330	Generator bus
Osogbo	PQ	330	Load bus
Benin	PQ	330	Load bus
Ikeja West	PQ	330	Load bus
Akangba	PQ	330	Load bus
Remaining buses	PQ	330	Transmission and load buses within the Nigeria 330 kV network

Note: Bus classifications correspond to the modelling assumptions adopted in the PSAT simulation environment.

Table A2. Summary of Generator Parameters Used in the Simulation Model

Station	Units	Type	Rated Power (MVA)	Terminal Voltage (kV)	Power Factor
Egbin	ST1–ST6	Steam	245.8	16	0.90
Delta IV	GT15–GT20	Gas	133.75	11.5	0.85
Sapele	ST1–ST6	Steam	133.97	15.75	0.90
Jebba	2G1–2G6	Hydro	119	16	0.85
Kainji	1G5–1G12	Hydro	85–126	16	0.95
Shiroro	Unit 1–4	Hydro	176.5	15.65	0.85
Afam V	GT15–GT20	Gas	110–162.69	11.5–15.75	0.80–0.85

Source: National Control Centre (NCC), Osogbo, Nigeria.

Table A3. Representative Transmission Line Parameters of the Nigeria 330 kV Network

From Bus	To Bus	Length (km)	R (pu)	X (pu)	B (pu)	Line Type
Aja	Egbin	14	0.1711	1.2057	0.0172	DC
Egbin	Ikeja West	62	0.0386	0.2723	0.0172	DC
Akangba	Ikeja West	18	0.1331	0.9378	0.0172	SC
Ikeja West	Papalanto	30	0.0390	0.2760	0.0190	SC
Benin	Osogbo	251	0.0386	0.2759	0.0763	SC
Jebba	Shiroro	244	0.0299	0.2767	0.0702	SC

Note: R, X, and B denote the series resistance, series reactance, and shunt susceptance, respectively. All parameters are expressed in per unit on a 100 MVA base. SC and DC represent single circuit and double circuit transmission lines, respectively. Complete transmission line data are available from the corresponding author upon reasonable request.