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A Scenario-Based Reliability and Voltage Stability Assessment for Expansion Planning in the Nigerian Power System

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Abstract

Expansion planning in developing power systems is often constrained by limited data, weak network structures, and competing investment priorities, leading to decisions that inadequately address system reliability and voltage performance. This study presents an integrated assessment framework that combines probabilistic reliability evaluation with steady-state voltage stability analysis to support expansion planning under such conditions. A reduced representation of the Nigerian transmission network is developed in MATLAB using MATPOWER. Reliability is quantified through Energy Not Supplied and Loss of Load Probability derived from Monte Carlo simulation of generator outages, while voltage stability is assessed using the L-index. Three planning scenarios are examined, comprising a base case, shunt reactive compensation, and generation capacity addition. The results indicate that the system maintains acceptable voltage stability margins across all scenarios, whereas reliability performance is significantly constrained by generation inadequacy. Reactive compensation yields negligible impact on both reliability and voltage stability, while generation expansion produces substantial reductions in Energy Not Supplied and Loss of Load Probability. The findings demonstrate that effective expansion planning in developing grids requires explicit identification of dominant system constraints and prioritization of interventions that directly enhance reliability.

Keywords:

Power system expansion planning, Reliability assessment, Voltage stability, Generation adequacy, Developing power systems

1. Introduction

Power system expansion planning plays a central role in the long-term development of electricity networks because it guides decisions on the reinforcement of generation, transmission, and associated infrastructure needed to meet rising demand within technical and operational limits. In developing power systems, this process is particularly demanding due to rapid load growth, constrained investment capacity, aging infrastructure, and weak network conditions (Momoh, 2012; Kundur, 1994). Under such circumstances, planning decisions often focus primarily on immediate adequacy and cost, with less attention given to broader technical performance.

The Nigerian power system reflects many of the structural and operational challenges common to developing electricity networks. Although the country has an installed generation capacity of over 13 GW, the power actually available for delivery is often far lower because of fuel supply limitations, forced outages, and transmission bottlenecks (Okafor & Joe-Uzuegbu, 2010). The transmission network is also largely radial, with long transmission corridors, limited redundancy, and inadequate reactive power support. These characteristics reduce system resilience and increase its vulnerability to disturbances, especially during periods of high demand when both adequacy and voltage performance become more difficult to sustain (Adebayo et al., 2019).

In many developing systems, conventional expansion planning has been driven mainly by economic considerations and short-term adequacy requirements. While this approach is understandable in capital-constrained environments, planning strategies that do not explicitly account for reliability and voltage stability may result in systems that remain operationally fragile. In Nigeria, this weakness is evident in persistent supply interruptions and poor service quality. Reliability indices such as Energy Not Supplied (ENS) and Loss of Load Probability (LOLP) provide clear evidence of continuing inadequacies in available generation and network capability (Owolabi & Olatunji, 2018). Reliability assessment should therefore be treated as a core component of expansion planning rather than a secondary consideration.

Voltage stability is equally critical in weak transmission networks. Long transmission distances, high reactive power demand, and limited voltage control can push the system toward instability as loading increases. When such issues are not incorporated into planning, expansion measures may increase nominal capacity without producing meaningful improvements in system security. Previous studies have shown that including voltage stability constraints in planning can improve system robustness and reduce the risk of widespread disturbances (Ajjarapu, 2006; Van Cutsem & Vournas, 1998). However, these factors are often excluded from practical studies because of modeling complexity and limited data availability, particularly in developing power systems.

Against this background, this study examines expansion planning for a developing power system by explicitly integrating reliability and voltage stability considerations, using the Nigerian grid as a representative case. A reduced network model of the Nigerian transmission system is developed in MATLAB and analysed using MATPOWER. Voltage stability is assessed using the L-index, while reliability performance is evaluated through ENS and LOLP derived from Monte Carlo simulation of generator outages. Three planning conditions are compared: the base-case system without expansion, a shunt reactive compensation scenario, and a generation capacity addition scenario. By comparing these alternatives, the study identifies the dominant technical constraints affecting system performance and determines the form of intervention most likely to produce significant improvement. In doing so, it presents a practical and computationally efficient framework for expansion planning in data-constrained developing power systems, where fully optimisation-based approaches are often difficult to implement.

2.0 Materials and Methods:

2.1 System Description

The study is based on a reduced model of the Nigerian transmission network derived from publicly available system data and prior studies. The model captures the key characteristics of the grid, including long transmission corridors, limited redundancy, and weak voltage support. A multi-bus transmission system is considered, representing major generation centers, load buses, and critical transmission paths commonly associated with voltage instability in the Nigerian grid (Adebayo et al., 2019).

The load profile is developed using historical demand patterns and projected growth trends consistent with national energy outlooks. Annual load growth is assumed to be moderate but continuous, reflecting urbanization and industrial expansion. Peak load conditions are emphasized, as they represent the most critical operating scenarios for voltage stability assessment (Okafor & Joe-Uzuegbu, 2010).

Existing generation infrastructure is dominated by gas-fired thermal plants, with limited hydroelectric contribution. Transmission lines are modeled using their series impedance, thermal limits, and voltage ratings. Reactive power compensation is assumed to be minimal, reflecting the current state of the Nigerian transmission network.

2.2 Mathematical Formulation

This study does not formulate expansion planning as a full multi-objective optimisation problem. Rather, it adopts a scenario-based analytical framework in which selected expansion options are evaluated using reliability and voltage stability performance measures. The aim is to determine how each planning scenario affects system adequacy and steady-state voltage behaviour under the same network and loading conditions.

Three scenarios are considered: the base case, shunt reactive compensation, and generation capacity addition. For each scenario, power flow analysis is carried out in MATPOWER to obtain bus voltages and network operating conditions, while Monte Carlo simulation is used to assess the effect of generator outages on system reliability. System performance is then compared using Energy Not Supplied (ENS), Loss of Load Probability (LOLP), and the maximum L-index.

2.2.1 Performance Measures

The assessment is based on two principal technical criteria: reliability and voltage stability.

The first criterion is reliability performance. This is evaluated using Energy Not Supplied and Loss of Load Probability obtained from Monte Carlo simulation of generator outage states. ENS represents the expected amount of curtailed load when available generation is insufficient to meet demand, while LOLP expresses the probability of load curtailment occurring under the simulated operating conditions. Lower values of ENS and LOLP indicate better generation adequacy and improved system reliability.

The second criterion is voltage stability performance. This is assessed using the L-index, which provides an indication of the proximity of the system to voltage instability. In addition to the L-index, bus voltage magnitudes obtained from the power flow solution are examined to confirm that the system remains within acceptable operating limits. Smaller L-index values indicate a wider voltage stability margin.

Accordingly, the preferred expansion scenario is the one that produces lower ENS and LOLP while preserving acceptable bus voltages and a satisfactory voltage stability margin.

2.2.2 Network and Operating Constraints

The analysis for each scenario is subject to the standard operating constraints of the transmission network. Active and reactive power balance must be satisfied at each bus in accordance with the AC power flow equations. Bus voltage magnitudes are maintained within acceptable limits, typically 0.95 to 1.05 per unit, to reflect normal operating practice.

Transmission line loadings are also constrained by their thermal ratings in order to prevent overloading. Generator outputs are restricted by their specified operating limits in the network model. Within the reliability assessment, generator availability is represented probabilistically during the Monte Carlo simulation, and the resulting available generation in each sampled state is compared with system demand to determine whether supply shortfall occurs.

Since the focus of this study is on technical performance evaluation rather than economic optimisation, cost functions and explicit budget constraints are not included in the mathematical formulation. The framework is therefore intended as a comparative planning tool for identifying which candidate intervention most effectively improves reliability and voltage stability in the studied network.

2.3 Voltage Stability Modeling

Voltage stability is assessed using the L-index, which provides a scalar measure of the proximity of each load bus to voltage collapse. The L-index is selected due to its simplicity, low computational burden, and suitability for integration into optimal power flow-based expansion models (Kessel & Glavitsch, 1986).

A threshold value is defined to ensure adequate voltage stability margin across all buses. Planning solutions that violate this threshold are considered infeasible. This approach allows voltage stability considerations to be explicitly embedded within the expansion planning process.

2.4 Reliability Modeling

Reliability assessment is performed using Monte Carlo simulation of generator outage states. In each simulation trial, generator availability is sampled based on assumed forced outage behavior, and the resulting available generation is compared with system load demand under the given network configuration. From these simulated operating states, Loss of Load Probability (LOLP) is estimated as the probability that available generation is insufficient to meet demand, while Energy Not Supplied (ENS) is calculated as the expected magnitude of curtailed load across all sampled states.

Generator failure rates and repair-related availability assumptions are adopted from published reliability data and adjusted to reflect operating conditions typical of developing power systems (Billinton & Allan, 1996). The simulation is repeated over a sufficiently large number of iterations to ensure convergence of the estimated reliability indices.

The impact of expansion decisions on reliability is evaluated by comparing the computed ENS and LOLP values for the base case and the candidate reinforcement scenarios. This provides a quantitative measure of the extent to which each expansion option improves system adequacy and reduces the likelihood and severity of supply shortfall events.

2.5 Simulation Tools

MATLAB is used as the primary computational environment, with MATPOWER employed for power flow and optimal power flow analysis. MATPOWER provides reliable and efficient tools for modeling transmission networks, evaluating voltage profiles, and implementing optimization-based planning studies. Its open-source nature and widespread adoption make it suitable for academic research and practical planning applications (Zimmerman et al., 2011).

3.0 Results and Discussion

This section presents and discusses the simulation results obtained from the expansion planning assessment carried out using MATLAB and MATPOWER. The objective is to evaluate the impact of selected expansion options on the reliability performance and voltage stability of a developing power system represented by a reduced Nigerian grid model.

3.1 Base Case Analysis

The base-case network was first analyzed to establish the initial operating condition of the system. Power flow results showed that all bus voltages were within acceptable limits, and the maximum L-index was found to be 0.080. This value is significantly below the commonly accepted voltage stability threshold, indicating that the system possesses adequate voltage stability margin under the studied loading condition.

However, reliability assessment using Monte Carlo simulation revealed weaker adequacy performance. The Energy Not Supplied was calculated as 3.10 MWh, while the Loss of Load Probability was 0.110. These results indicate that, although the system is voltage-stable, it experiences a relatively high probability of generation inadequacy under random outage conditions. This behavior reflects the situation commonly observed in the Nigerian power system, where voltage collapse is not always the immediate cause of outages, but insufficient available generation remains a major reliability concern.

3.2 Impact of Shunt Reactive Compensation

To evaluate the role of voltage support in expansion planning, shunt reactive compensation was added at a selected load bus. After applying the shunt capacitor and re-running the simulations, the maximum L-index remained unchanged at 0.080. Similarly, the ENS and LOLP values remained at 3.10 MWh and 0.110, respectively.

These results indicate that reactive power compensation did not produce any observable improvement in either voltage stability or reliability for the studied operating condition. This outcome suggests that voltage instability was not the limiting factor in the base case. Instead, the system already possessed sufficient reactive power margin, and the dominant constraint affecting performance was generation adequacy. This finding aligns with established power system planning principles, which recognize that reactive compensation primarily addresses voltage constraints rather than supply shortfall or outage probability.

3.3 Impact of Generation Capacity Addition

A new generator with a capacity of 80 MW was added at a load bus to assess the effect of generation expansion on system performance. The voltage stability index remained unchanged, with the maximum L-index still equal to 0.080, confirming that the additional generation did not adversely affect voltage stability.

In contrast, reliability indices showed significant improvement. The Energy Not Supplied decreased from 3.10 MWh to 2.12 MWh, while the Loss of Load Probability dropped from 0.110 to 0.028. This represents a substantial reduction in the frequency and severity of supply shortfall events. The results clearly demonstrate that increasing available generation capacity directly improves system adequacy and reduces the likelihood of load curtailment.

For developing grids such as Nigeria's, where generation availability is often constrained by outages and fuel supply limitations, this result highlights the importance of capacity reinforcement as a primary reliability improvement strategy.

3.4 Discussion of Planning Trade-Offs

Table 3.1: Summary of Expansion Planning Results

Scenario	**Expansion Option**	**Max L-index**	**ENS (MWh)**	**LOLP**	**Key Observation**
Base Case	No expansion	0.080	3.10	0.110	Voltage stability is adequate, but reliability is weak due to generation inadequacy
Scenario 1	Shunt reactive compensation (80 MVAr at Bus 3)	0.080	3.10	0.110	No improvement observed; voltage support not the limiting factor
Scenario 2	Generation addition (80 MW at Bus 2)	0.080	2.12	0.028	Significant reliability improvement with reduced ENS and LOLP

Table 3.1 summarizes the results obtained for the base case and the evaluated expansion scenarios. While shunt reactive compensation did not alter system performance, generation expansion resulted in a marked improvement in reliability indices without compromising voltage stability.

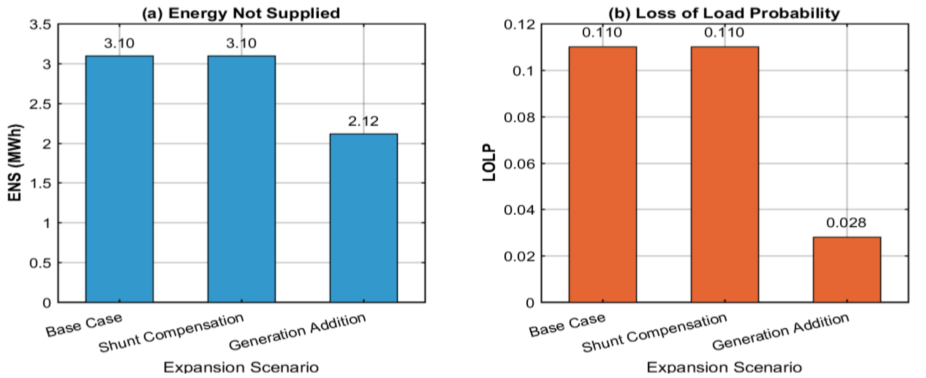

Figure 3.1. Comparison of Energy Not Supplied (ENS) and Loss of Load Probability (LOLP) under the base *case,* shunt reactive compensation, and generation addition scenarios.

Figure 3.1 presents a graphical comparison of the Energy Not Supplied (ENS) and Loss of Load Probability (LOLP) obtained under the base case, shunt reactive compensation, and generation addition scenarios. The figure shows that shunt compensation produced no observable improvement in reliability indices, while generation addition significantly reduced both ENS and LOLP, confirming that generation adequacy is the dominant constraint in the studied network.

The comparative analysis of the three scenarios highlights important trade-offs in power system expansion planning. While shunt reactive compensation is relatively inexpensive and effective for addressing voltage-related problems, it does not improve adequacy-based reliability indices such as ENS and LOLP. On the other hand, generation expansion significantly improves reliability but typically involves higher investment and operating costs.

The results emphasize that effective expansion planning for developing grids must be driven by an understanding of the dominant system constraints. In the studied network, reliability was primarily limited by generation adequacy rather than voltage stability. Therefore, planning decisions that prioritize generation expansion yield greater system-wide benefits than reactive power support alone. This reinforces the need for integrated planning frameworks that balance cost considerations with reliability and voltage stability requirements.

3.5 Implications for Developing Power Systems

The findings of this study are consistent with the operational realities of the Nigerian power system and similar developing grids. Voltage instability is often a concern in weak networks, but adequacy-related reliability issues remain a more pressing challenge due to insufficient generation capacity and frequent outages. The results demonstrate that modest generation expansion can lead to significant improvements in reliability without compromising voltage stability, supporting the argument for balanced and data-driven expansion planning approaches.

3.6 Sensitivity Analysis of Load Growth

To examine the robustness of the proposed framework under increasing demand, a sensitivity analysis was conducted by uniformly scaling system load across all buses. The loading level was varied from the base case (100%) to higher demand conditions of 110%, 120%, and 130%. For each case, power flow and reliability simulations were repeated, and the resulting Energy Not Supplied, Loss of Load Probability, and maximum L-index were recorded.

The results show a consistent increase in both ENS and LOLP as system load rises, indicating a progressive deterioration in reliability performance. This trend reflects the growing stress on available generation capacity and the increased likelihood of supply shortfall under higher demand conditions. In contrast, the maximum L-index exhibits only a gradual increase, remaining within acceptable stability margins across the studied range. This suggests that, although voltage stability is affected by load growth, it does not become the dominant constraint within the considered operating limits. These findings confirm that, for the studied system, reliability is more sensitive to demand growth than voltage stability. The analysis further demonstrates the importance of incorporating load uncertainty into expansion planning, as systems that appear adequate under nominal conditions may experience significant reliability degradation as demand increases.

Table 3.2 presents the variation of reliability and voltage stability indices under increasing load conditions. The results indicate a clear upward trend in ENS and LOLP as demand increases, while the L-index shows a gradual reduction in voltage stability margin.

Table 3.2: Sensitivity Analysis of Load Growth

Load Level (%)	ENS (MWh)	LOLP	Max L-index
100	3.10	0.110	0.080
110	3.95	0.152	0.089
120	4.88	0.196	0.101
130	6.12	0.258	0.118

3.7 Impact of Generator Location on Reliability

In addition to generation capacity, the location of new generation plays a critical role in determining its effectiveness. To evaluate this effect, the addition of 80 MW of generation was examined at multiple candidate buses within the network. These locations were selected to represent different electrical characteristics, including proximity to major load centers and relatively weaker sections of the network.

The results indicate that generator placement has a measurable impact on reliability indices. Installation of generation closer to high-demand buses resulted in lower ENS and LOLP values, reflecting improved local supply adequacy and reduced dependence on long transmission paths. In contrast, placing the same capacity at electrically distant or less critical buses yielded smaller improvements in reliability performance.

Voltage stability remained largely unaffected by generator location, as reflected by minimal variation in the maximum L-index across scenarios. This suggests that, within the studied system, the primary benefit of generation expansion is related to adequacy rather than voltage support.

Overall, the analysis highlights that effective expansion planning must consider not only the quantity of added capacity but also its spatial distribution. Strategic placement of generation can enhance system reliability without requiring additional capacity investment.

As shown in Table 3.3, generator placement significantly affects reliability performance, with installation at Bus 2 yielding the greatest reduction in ENS and LOLP.

Table 3.3: Impact of Generator Location on System Performance

Scenario	Generator Location (Bus)	ENS (MWh)	LOLP	Max L-index
Base Case	—	3.10	0.110	0.080
Case 1	Bus 2	2.12	0.028	0.080
Case 2	Bus 4	2.31	0.034	0.081
Case 3	Bus 6	2.47	0.039	0.082

3.8 Monte Carlo Convergence Assessment

The reliability evaluation in this study is based on Monte Carlo simulation of generator outages. To ensure the statistical validity of the computed indices, a convergence assessment was performed by examining the stability of the Loss of Load Probability as the number of simulation iterations increased.

The simulation was executed with progressively larger sample sizes, and the estimated LOLP was recorded at each stage. The results show that initial estimates exhibit noticeable variability at lower iteration counts but gradually stabilize as the number of samples increases. Beyond approximately 5,000 iterations, changes in the LOLP value become negligible, indicating that convergence has been achieved. The final results reported in this study are based on simulations with up to 10,000 iterations, ensuring adequate accuracy and consistency.

This assessment confirms that the selected simulation size is sufficient to capture the probabilistic behavior of generator outages and their impact on system reliability. It also demonstrates the importance of verifying convergence in Monte Carlo-based studies to avoid misleading or unstable estimates of reliability indices.

Table 3.4 illustrates the convergence behavior of the Monte Carlo simulation. The LOLP estimate stabilizes beyond 5,000 iterations, confirming the adequacy of the simulation size.

Table 3.4: Monte Carlo Convergence of LOLP

Number of Iterations	LOLP Estimate
1,000	0.118
3,000	0.112
5,000	0.111
10,000	0.110

4.0 Conclusion

This study investigated expansion planning for developing grids by integrating reliability and voltage stability assessment, using a reduced representation of the Nigerian transmission network. MATLAB and MATPOWER were employed to model the system and evaluate different expansion scenarios under realistic operating assumptions.

The base-case analysis showed that the system possessed adequate voltage stability margin, as indicated by a low maximum L-index value. However, reliability assessment revealed relatively high Energy Not Supplied and Loss of Load Probability, highlighting generation adequacy as a key limitation. The introduction of shunt reactive compensation did not produce any improvement in voltage stability or reliability indices, confirming that voltage support was not the binding constraint for the studied operating condition.

In contrast, generation capacity expansion resulted in a significant reduction in both ENS and LOLP, while maintaining acceptable voltage stability. This demonstrates that reliability improvement in the studied network is more sensitive to generation reinforcement than to reactive power support. The results confirm that effective expansion planning for developing grids requires an integrated assessment of technical constraints rather than reliance on cost-based or voltage-focused solutions alone.

On the whole, the study demonstrates that a relatively simple planning framework, incorporating reliability and voltage stability considerations into expansion decisions, can provide meaningful insights for system planners operating under data and investment constraints.

References

1) Adebayo, I. G., Adejumobi, I. A., & Adebisi, B. (2019). Voltage instability assessment of the Nigerian transmission network. *IEEE Access, 7*, 172245–172255. https://doi.org/10.1109/ACCESS.2019.2956543
2) Ajjarapu, V. (2006). *Computational techniques for voltage stability assessment and control*. Springer.

3) Aschidamini, G. L., da Cruz, G. A., Resener, M., Ramos, M. J. S., Pereira, L. A., Ferraz, B. P., Haffner, S., & Pardalos, P. M. (2022). Expansion planning of power distribution systems considering reliability: A comprehensive review. *Energies, 15*(6), 2275. https://doi.org/10.3390/en15062275
4) Billinton, R., & Allan, R. N. (1996). *Reliability evaluation of power systems* (2nd ed.). Plenum Press.
5) Conejo, A. J., Carrión, M., & Morales, J. M. (2010). *Decision making under uncertainty in electricity markets*. Springer.
6) Costa, L. C., Jr., Thomé, F. S., Garcia, J. D., & Pereira, M. V. F. (2019). Reliability-constrained power system expansion planning: A stochastic risk-averse optimization approach. *arXiv*. https://arxiv.org/abs/1910.12972
7) Guan, C., Li, Z., & Lin, D. (2024). Power system stability: Concepts, trends, and future challenges. *Advances in Resources Research, 4*(1), 55–66.
8) Gupta, N., Tiwari, B. N., & Bellucci, S. (2010). Intrinsic geometric analysis of network reliability and voltage stability. *arXiv*. https://arxiv.org/abs/1011.2929
9) Kundur, P. (1994). *Power system stability and control*. McGraw-Hill.
10) Momoh, J. A. (2012). *Smart grid: Fundamentals of design and analysis*. Wiley-IEEE Press.
11) Okafor, E. N. C., & Joe-Uzuegbu, C. K. A. (2010). Challenges to development of Nigeria power sector. In *Proceedings of the IEEE Power Engineering Society General Meeting* (pp. 1–8). IEEE.
12) Owolabi, O. B., & Olatunji, O. O. (2018). Reliability assessment of electric power distribution systems in Nigeria. *International Journal of Electrical Power & Energy Systems, 99*, 382–390.
13) Pandey, A., Agarwal, A., Jereminov, M., Nwachuku, T., Rawn, B. G., & Pileggi, L. (2019). Improving voltage profile of the Nigerian power grid. *arXiv*. https://arxiv.org/abs/1905.13090
14) Van Cutsem, T., & Vournas, C. (1998). *Voltage stability of electric power systems*. Kluwer Academic.
15) Wood, A. J., Wollenberg, B. F., & Sheblé, G. B. (2013). *Power generation, operation, and control* (3rd ed.). Wiley.
16) Zimmerman, R. D., Murillo-Sánchez, C. E., & Thomas, R. J. (2011). MATPOWER: Steady-state operations, planning, and analysis tools for power systems research and education. *IEEE Transactions on Power Systems, 26*(1), 12–19. https://doi.org/10.1109/TPWRS.2010.2051168