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Improving Voltage Stability using Static Synchronous Compensator: A Contingency Assessment of Nigeria Transmission Network

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Abstract: Analyzing power systems for network planning and operation requires a thorough understanding of network parameters to evaluate system performance. Effective monitoring and management depend on power flow analysis and contingency assessment. This paper examines an electric power system with a focus on these critical aspects to enhance planning and operational efficiency. A regional transmission network is used as a case study, with simulations conducted using Power System Simulation (PSS) software. The network's performance under various N-1 contingency cases was evaluated, emphasizing voltage stability and line loading violations. Vulnerable buses were identified through separate voltage and line loading violation analyses. This study also examines the interaction between STATCOM and the network during N-1 contingencies, demonstrating its effectiveness in improving voltage stability and reducing overloads. To assess voltage collapse proximity and outage effects on reactive power margin, QV curves were plotted for the most affected buses. STATCOM was placed at each affected bus to determine optimal performance, mitigating N-1 contingency effects. By effectively compensating for reactive power, the network's power handling capacity was enhanced. Consequently, applying STATCOM significantly improved voltage profiles and increased the power handling capacity of affected buses before and after contingency scenarios, ensuring a more stable and resilient transmission network.

Keywords: Contingency analysis, Network Planning, Power system operation, Power system simulation (PSS), Voltage collapse.

1 Introduction

THE increasing demand for reliable and stable electricity supply has underscored the critical need for effective voltage stability solutions in power systems, particularly in developing regions like Nigeria. Voltage instability has emerged as a significant challenge, often leading to frequent blackouts and an unreliable power supply. The Nigerian transmission network, characterized by its extensive 330 kV grid, faces unique challenges due to a combination of high reactive power demands and inadequate infrastructure. This situation necessitates innovative solutions to enhance voltage stability and overall system reliability. Among the various technologies available, the Static Synchronous Compensator (STATCOM) has gained prominence due to its ability to supply flexible reactive power support and enhance voltage profiles across transmission networks [1], [2].

Static Synchronous Compensators (STATCOMs) represent a promising technology for improving voltage stability in transmission networks. These devices can supply flexible reactive power support, which is essential for maintaining voltage levels during

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contingencies. The application of STATCOMs in Nigeria's transmission network could mitigate the adverse effects of voltage fluctuations and enhance the overall reliability of the power system [3]. Earlier research has shown that Flexible AC Transmission Systems (FACTS) based devices, such as the Thyristor Controlled Series Compensators (TCSC), play a major role in enhancing transient stability and damping oscillations within the Nigerian power grid [4], [5], [6]. Such advancements are crucial for addressing the voltage instability issues that have historically plagued the region.

Despite the recognized benefits of STATCOMs, there remains a notable research gap regarding their optimal deployment within the Nigerian transmission network. Previous studies have primarily focused on the transient stability improvements offered by FACTS devices, including STATCOMs, but have often overlooked a comprehensive contingency assessment that considers the unique operational challenges faced by the Nigerian grid [7]. For instance, while [8] explored the impact of static VAR compensators on voltage profiles in a specific transmission line; their findings do not extend to a broader analysis of the entire Nigerian transmission network under various contingency scenarios. This limitation highlights the need for further research that integrates contingency assessments with the deployment of STATCOMs to enhance voltage stability across the entire grid.

However, existing literature has predominantly concentrated on the theoretical aspects of voltage stability enhancement through FACTS devices, often neglecting practical implementation challenges and real-world operational conditions. For example, while [9] and [10] Provided a systemic method for the optimal placement of FACTS devices, their study did not specifically address the complexities associated with the Nigerian transmission network, such as geographical constraints and varying load demands. This gap indicates a pressing need for empirical research that not only evaluates the effectiveness of STATCOMs in improving voltage stability but also considers the specific operational context of the Nigerian power system.

Moreover, incorporating renewable energy sources into the Nigerian grid introduces further challenges to voltage stability. As noted by [11], [12], integrating renewable sources such as wind and solar affects the grid's dynamic performance and stability due to their intermittent nature. While FACTS devices, including STATCOMs, have been proposed as solutions to mitigate these issues, there is insufficient research that systematically evaluates their performance in conjunction with renewable energy integration under various contingency conditions. This oversight necessitates a focused investigation into how STATCOMs can be effectively utilized to enhance voltage stability in a grid increasingly influenced by renewable energy sources.

The need for empirical studies that assess the performance of STATCOMs in real-world conditions cannot be overstated. Research by [13] further highlights the challenges associated with incorporating renewable energy sources into the power grid in operation. The dynamic behavior of these renewable sources necessitates robust voltage stability solutions, and STATCOMs could play an important role in this regard. However, the effectiveness of STATCOMs in mitigating voltage instability in the presence of renewable energy sources remains an area requiring further investigation.

In addition to the theoretical frameworks, practical implementations of STATCOMs have shown promising results in various contexts. For instance, the work of [14] Illustrates the operational principles and field performance of current source converter-based STATCOMs, which provide continuous control of reactive power output independent of AC system voltage. This capability is particularly beneficial in regions like Nigeria, where voltage fluctuations are prevalent due to varying load conditions and infrastructural inadequacies. The adaptability of STATCOMs to different operational scenarios makes them a viable option for enhancing voltage stability in the Nigerian grid.

The integration of advanced control strategies, such as those proposed by [15], [16], can further enhance the effectiveness of STATCOMs in voltage regulation. Their research emphasizes the importance of internal nonlinear control mechanisms within STATCOMs, which can significantly improve voltage regulation capabilities in dynamic conditions. This is particularly relevant for the Nigerian context, where the power system is often subjected to sudden load changes and disturbances.

Comparative studies have shown that FACTS devices such as the Static Var Compensator (SVC) and the Thyristor Controlled Series Capacitor (TCSC) have been used to enhance voltage stability and power transfer in transmission systems, including weak and stressed networks. For example, [17] carried out a comparative analysis of static VAR systems and demonstrated that SVCs are effective for steady-state voltage regulation, but their reactive support diminishes under deep voltage sags because their capacity is proportional to the square of the bus voltage. On the other hand, TCSC is often applied to control line reactance and increase transfer capability, thereby alleviating congestion, but it does not inject reactive power directly into weak buses and thus offers limited direct support for voltage collapse prevention in remote parts of the network [18]. In contrast, STATCOM, being a voltage source converter (VSC) based, can supply nearly full reactive current even when the system voltage is low, enabling it to maintain voltage support during contingencies. In the present study, STATCOM placement under N-1 contingencies not only eliminated all voltage violations in the examined scenarios, but also shifted Q–V curves outward, increasing reactive margins, an outcome not generally achieved in the SVC/TCSC works. Thus, relative to prior SVC and TCSC results, our STATCOM-based contingency and Q–V analysis demonstrates superior effectiveness for voltage stability enhancement in the Nigerian network.

The potential of STATCOMs to improve voltage stability in the transmission network is acknowledged, while the research gaps remain. These gaps include the need for comprehensive contingency assessments, practical implementation strategies, and evaluations of the interaction between STATCOMs and the network. Addressing these gaps is crucial for developing effective voltage stability solutions that can support the growing demand for reliable electricity in Nigeria. This study aims to fill these gaps by conducting a thorough contingency assessment of the Nigerian transmission network, focusing on the role of STATCOMs in enhancing voltage stability under various operational scenarios.

The key contributions of this paper can be outlined as follows:

- The concept of the QV curve has been explored to highlight the proximity of buses to voltage collapse during N-1 contingency, enabling early detection and proactive interventions to prevent cascading failures.
- Proposes a technique for STATCOM placement and operation to ensure voltage stability under different contingency cases
- Provides insights into the interaction between STATCOM and the regional power network during N-1 contingency scenarios, demonstrating its effectiveness in enhancing voltage stability and mitigating bus voltage violations.
- Identifies vulnerable buses in the network through separate analyses of voltage violations and line loading violations, offering a targeted approach to improving network reliability.
- Demonstrates the capability of STATCOM to mitigate voltage violations in the network, addressing critical challenges in modern power systems, and ensuring robust operation under contingency conditions.

2 Materials and Method

Contingency analysis in power systems involves analyzing the effects of various potential failures or disruptions in the system on the overall power flow and stability of the grid. This is typically done using mathematical models and algorithms that simulate the behavior of the system under different contingencies.

One commonly used methodology for contingency analysis is the N-1 criterion, which involves simulating the effects of a single-element failure on the system and ensuring that the system remains stable and able to supply sufficient power to meet demand. In this study, a deterministic criterion is employed, which comprises the outage of one of the system elements and studying the voltage and load flow before and after the contingency.

The basic procedure involves:

- Disconnecting a system element
- Performing the power flow analysis of the system.
- Studying the system conditions

2.1 Load Flow Formulation

A steady-state network uses power flow solutions in solving N-1 security analysis. Iterative methods are needed to solve for the unknown parameters in nonlinear algebraic equations that typically represent the true and reactive power at a bus.[19].

The non-linear power flow equation is described below:

$$P_i = \sum_{k=1}^{N} |Y_{ik} V_i V_k| \cos(\emptyset_{ik} + \delta_k - \delta_i)) \qquad (1)$$

$$Q_i = \sum_{k=1}^{N} |Y_{ik} V_i V_k| sin(\emptyset_{ik} + \delta_k - \delta_i) \qquad (2)$$

where;

P_i = Real power at ith bus

Q_i = Reactive power at ith bus

V_i = Voltage magnitude at ith bus

δ_i = Voltage angle at the ith bus

δ_k = Voltage angle at the kth bus

V_k = Voltage magnitudes at the kth node

θ_{ik} = Angle subtended from i and k buses in the admittance matrix

N = Number of nodes in the network.

2.2 Performance Index

The line performance index is used to identify and mitigate potential risks while enhancing the stability and reliability of the power system by prioritizing critical components and determining the most likely points of failure.

$$F = \min(SI) \tag{3}$$

$$\min(SI) = \alpha . f_1 + \beta . f_2 \tag{4}$$

$$f_1 = \sum_{i=1}^{Nb} \frac{W_{vi}}{2n} \left[\frac{|V_i| - |V_i^{sp}|}{\Delta V_i^{lim}} \right]^{2n} + \sum_{i=1}^{N_g} \frac{W_{Qi}}{2n} \left[\frac{Q_i}{Q_i^{max}} \right]^{2n} \tag{5}$$

$$f_2 = \sum_{2n}^{N_l} \frac{W_{li}}{2n} \left[\frac{S_i^{post}}{S_i^{max}} \right]^{2n} \tag{6}$$

$$\alpha + \beta = 1 \quad for\ 0 < \mu \ \leq 1 \tag{7}$$

where;

F: Objective function

f_1: Voltage reactive performance index

f_2: *Line MVA performance index*

μ: Weighting operator

SI: Line overload severity index

W: Active non-negative weighting factor

n: Exponent order

V_i^{sp}: Specified voltage magnitude at node I

V_i: Voltage magnitude at node I

ΔV_i^{lim}: Voltage limit deviation at node I

Q_i^{max}: Maximum reactive power at node I

S_i^{max}: Maximum apparent power (VA) at node I

S_i^{post}: Post-iteration apparent power (VA) at node I

α *and* β: Objective function weighting coefficients

2.3 Line current following a single-line outage

$$I'_{ij} = I_{ij} - \frac{z_X}{z_{ij}} \left[\frac{(Z_{im} - Z_{in}) - (Z_{jm} - Z_{jn})}{(Z_{mm} - Z_{nn} - 2Z_{mn}) - z_X} \right] I_X^0 \tag{8}$$

where;

I_{ij}: Line current before contingency between buses i and j

z_{ij}: Series impedance of the line connecting buses i and j

z_x: Series impedance of the removed line between buses m and n (denoted as z_{mn})

I_x^0: Pre contingency line current flowing through z_x (i.e.,through z_{mn})

$Z_{im}, Z_{in}, Z_{jm}, Z_{jn}, Z_{mm}, Z_{nn}, Z_{mn}$: Pre contingency elements of the Z_Bus matrix

I_{ij}': Line current after N-1 contingency in line i-j,

where

$i = 1, 2, 3, \ldots, N;\ j = 1, 2, 3, \ldots, N;\ i \neq j;\ i \neq m;\ j \neq n$

(m and n represent the buses where the line was removed)

2.4 Power Flow Model of STATCOM

A synchronous compensator is analogous to STATCOM. It was an improvement over the Static Var Compensator and is a shunt-connected compensator. It is a voltage source converter, and the following model can be used to represent its power flow solution:

Let:

$V_j \angle \delta_j$ = bus voltage at bus j.

$V_{sc} \angle \delta_{sc}$ = inverted voltage at the STATCOM output

X_{sc} = STATCOM reactance.

Q_{sc} = reactive power exchange for the STATCOM with the bus.

Therefore, the above variables define the equation (9).

$$Q_{sc} = \frac{|V_j|^2}{X_{sc}} - \frac{|V_j||V_{sc}|}{X_{sc}} \cos(\delta_j - \delta_{sc}) \tag{9}$$

$Q_{sc} = \frac{|V_j|^2}{X_{sc}} - \frac{|V_j||V_{sc}|}{X_{sc}}, \quad if\ \delta_j = \delta_{sc}$ (for a lossless STATCOM)

If $|V_j| < |V_{sc}|$, the reactive power Q_{sc} becomes negative, causing the STATCOM to generate reactive power. Conversely, if $|V_j| > |V_{sc}|$, Q_{sc} becomes positive, and the STATCOM absorbs reactive power.

$$V_{sc} = |V_{sc}|(\cos \delta_{sc} + j\ sin\delta_{sc}) \tag{10}$$

The upper and lower limits of $|V_{sc}|$ are determined by the STATCOM capacitor rating. The phase angle, δ_{sc} can range from 0° to 180°, but it is typically maintained close to a specific value for optimal operation.

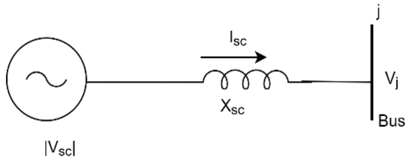

Fig 1. Shunt Operated STATCOM equivalent circuit.

$$I_{sc} = Y_{sc}(V_{sc} - V_j) \tag{11}$$

$$Y_{sc} = \frac{1}{Z_{sc}} = G_{sc} + jB_{sc} \tag{12}$$

$$S_{sc}(complex\ power\ flow) = V_{sc} I_{sc}^*$$

$$= V_{sc} Y_{sc}^* (V_{sc}^* - V_j^*) \tag{13}$$

However,

$$V_{sc} = |V_{sc}|(\cos \delta_{sc} + j\ sin\delta_{sc}) \tag{14}$$

Substituting V_{sc} in the equation (3.18), S_{sc} gives:

$$P_{sc} = |V_{sc}|^2 G_{sc} - |V_{sc}||V_j|[G_{sc}\cos(\delta_{sc} - \delta_j) + \\ + B_{sc}\sin(\delta_{sc} - \delta_j) \quad (15)$$

$$Q_{sc} = -|V_{sc}|^2 G_{sc} - |V_{sc}||V_j|[G_{sc}\sin(\delta_{sc} - \delta_j) + \\ + B_{sc}\cos(\delta_{sc} - \delta_j) \quad (16)$$

We can assume a lossless STATCOM to simplify the equation, i.e., $G_{sc} = 0$ and that the STATCOM cannot transfer active power, (thus $P_{sc} = 0$). Also $\delta_{sc} \cong \delta_j$.

$$Q_{sc} = -|V_{sc}|^2 B_{sc} - |V_{sc}||V_j|B_{sc} \quad (17)$$

The equation for power mismatch can be expressed as:

$$\begin{bmatrix} \Delta P_j \\ \Delta Q_{sc} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_j}{\partial \delta_j} & \frac{\partial P_j}{\partial |V_{sc}|} \\ \frac{\partial Q_{sc}}{\partial \delta_j} & \frac{\partial Q_{sc}}{\partial |V_{sc}|} \end{bmatrix} \begin{bmatrix} \Delta \delta_j \\ \Delta |V_{sc}| \end{bmatrix} \quad (18)$$

After iteration k, the voltage variable $|V_{sc}|$ can be adjusted as:

$$|V_{sc}|^{(p+1)} = |V_{sc}|^{(p)} + \Delta |V_{sc}|^{(p)} \quad (19)$$

2.5 Methodology

Figure 2 illustrates the step-by-step approach adopted in this study. The process begins with load flow analysis to assess bus parameters after modeling the network using PSSE software. Following that, is an N-1 security assessment with contingency analysis to identify vulnerable buses that are prone to network violations. Further identification of vulnerable buses was conducted using the QV curve. To achieve optimal performance, the STATCOM device was strategically placed near the identified weak buses to determine the most effective location.

2.6 Data Collation

The data used for modeling and simulation are presented in Tables 1, 2, and 3. This provides a comprehensive overview of the active and reactive power parameters across the buses, as well as the line and transformer characteristics.

The collected data consists of:

i. **Bus Characteristics** – This encompasses the classification of buses, including generator buses, slack buses, and non-generator buses. Additionally, it involves the specified voltage magnitude, phase angle, active power generation or consumption, and reactive power levels associated with each bus.

ii. **Transmission Line Attributes** – These consist of key electrical properties such as the length of the transmission line, its electrical resistance and reactance measured in ohms per kilometer (Ω/km), and the charging capacitance expressed in microfarads per kilometer (μF/km). To facilitate standardized analysis, all these parameters were normalized to per-unit values based on a system base of 100 MVA.

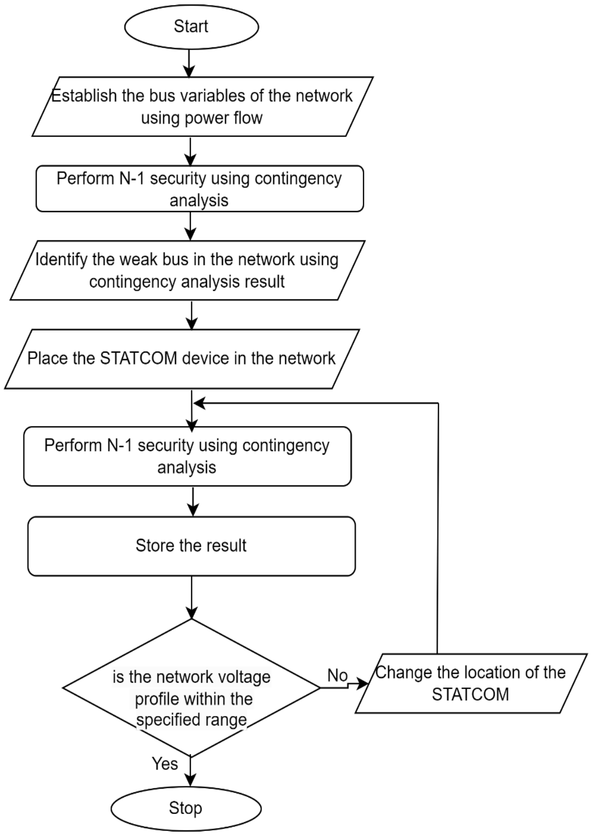

Fig 2. Flow Chart for Evaluation of Voltage Stability.

iii. **Load Data** – The selected load is based on transformer loading at the respective buses. The dataset provides active and apparent load values, while the reactive load (MVA) was derived from the given data

$$pf = \frac{real\ power(MW)}{apparent\ power(MVA)} \quad . (20)$$

2.7 N-1 Contingency Analysis Algorithm

The N-1 contingency analysis algorithm is an essential technique for evaluating the reliability of a power system, designed to assess the impact of the failure of a single component on the overall system performance [20]. This analysis is essential for ensuring operational security and preventing cascading failures. The following steps outline the methodology for implementing the N-1 contingency analysis algorithm: 1.

1. Develop a detailed representation of the power system, including all components and their operational states.
2. Identify potential single-component failures that could impact system security.
3. Prioritize the most critical contingencies based on their potential impact.

4. For each selected contingency, perform a load flow analysis to determine how the system operates under the new conditions. The goal is to calculate the new voltage levels, power flows, and overall system stability after the contingency occurs
5. Assess the power flow analysis results for any operational limit violations, indicating system vulnerabilities.
6. Create a report detailing the contingencies analyzed, results, and recommendations for improving system security.

Table 1. Network Bus Parameters.

ID	Bus Number	Bus Name	Voltage (kV)	P_{load} (MW)	Q_{load} (Mvar)	Pgen (MW)	V (p.u)	Angle	Code
1	173	GANMO TR II	132.0	46.0	12.00	-	-	-	1
2	180	ILORIN I	132.0	43.0	10.00	-	-	-	1
3	185	OMUARAN	132.0	19.3	4.83	-	-	-	1
4	183	OFFA I	132.0	9.8	2.50	-	-	-	1
5	177	IFE I	132.0	24.5	6.13	-	-	-	1
6	179	ILESHA I	132.0	19.5	4.88	-	-	-	1
7	178	IWO I	132.0	10.8	2.52	-	-	-	1
8	181	ISEYIN	132.0	22.6	5.65	-	-	-	1
9	182	JERICHO I	132.0	32.2	8.05	-	-	-	1
10	176	IBADAN NORTH	132.0	54.3	13.58	-	-	-	1
11	170	AYEDE I	132.0	73.5	18.38	-	-	-	1
12	192	SHAGAMU	132.0	23.8	5.95	-	-	-	1
13	193	IJEBU ODE	132.0	18.6	4.63	-	-	-	1
14	171	OSOGBO IV T1	132.0	74.0	20.00	-	-	-	1
15	197	AYEDE	330.0	0.0	0.00	-	-	-	1
16	198	OSOGBO III	330.0	0.0	0.00	-	-	-	1
17	155	OLORUNSOGO G1	10.5	-	-	60	1	-	2
18	355	JEBBA II G3	16.0	-	-	160	1	-	2
19	356	JEBBA GS	16.0	-	-	-	1	0	3

Table 2. Network line parameters.

ID	From Bus Number	From Bus Name	Voltage (kV)	To Bus Number	To Bus Name	Voltage (kV)	Line R (pu)	Line X (pu)	Charging (pu)	Length (km)
1	38	OLORUNSOGO	330	197	AYEDE	330.00	0.002	0.018	0.228	60.00
2	170	AYEDE I	132	176	IBADAN NORTH	132.00	0.004	0.014	0.019	12.00
3	170	AYEDE I	132	182	JERICHO I	132.00	0.001	0.005	0.006	2.00
4	170	AYEDE I	132	192	SHAGAMU	132.00	0.065	0.207	0.029	92.00
5	171	OSOGBO IV T1	132	178	IWO I	132.00	0.104	0.333	0.471	148.00
6	171	OSOGBO IV T1	132	183	OFFA I	132.00	0.037	0.118	0.167	43.50
7	171	OSOGBO IV T1	132	194	ILESHA TEE I	132.00	0.010	0.033	0.046	14.70
8	173	GANMO TR2	132	180	ILORIN I	132.00	0.004	0.011	0.016	5.00
9	176	IBADAN NORTH	132	178	IWO I	132.00	0.013	0.040	0.057	18.00
10	177	IFE I	132	194	ILESHA TEE I	132.00	0.014	0.044	0.062	19.50
11	178	IWO I	132	181	ISEYIN	132.00	0.050	0.160	0.226	71.00
12	179	ILESHA I	132	194	ILESHA TEE I	132.00	0.014	0.045	0.064	20.30
13	180	ILORIN I	132	183	OFFA I	132.00	0.034	0.107	0.151	47.53
14	183	OFFA I	132	185	OMUARAN	132.00	0.034	0.107	0.151	47.53
15	192	SHAGAMU	132	193	IJEBU ODE	132.00	0.029	0.092	0.130	41.00
16	197	AYEDE	330	198	OSOGBO III	330.00	0.004	0.035	0.437	115.00
17	198	OSOGBO III	330	200	GANMO III	330.00	0.002	0.014	0.179	47.00
18	198	OSOGBO III	330	289	JEBBA TS	330.00	0.006	0.048	0.596	157.00
19	200	GANMO III	330	289	JEBBA TS	330.00	0.004	0.013	0.418	110.00

Table 3. Winding Transformer parameters.

ID	From Bus Number	From Bus Name (kV)	To Bus Number	To Bus Name (kV)	Specified R (pu or watts)	Specified X (pu)	RATE1 (MVA)	RATE2 (MVA)	Winding MVA Base
T1	38	OLORUNSOGO (330)	155	OLORUNSOGO G (10.5)	0	0.14	105	115	105
T2	38	OLORUNSOGO (330)	156	O1ORUNSOGO G (10.5)	0	0.14	105	115	105
T3	170	AYEDE I (132)	197	AYEDE (330)	0	0.1	90	90	90
T4	170	AYEDE I (132)	197	AYEDE (330)	0	0.1	90	90	90
T5	171	OSOGBO IV T1 (132)	198	OSOGBO III (330)	0	0.1	150	150	150
T7	171	OSOGBO IV T1 (132)	198	OSOGBO III (330)	0	0.1	150	150	150
T6	173	GANMO TR2 (132)	200	GANMO III (330)	0	0.1	150	150	150
T8	173	GANMO TR2 (132)	200	GANMO III (330)	0	0.1	150	150	150
J1	289	JEBBA TS (330)	355	JEBBA II G3 (16)	0.0035	0.1062	119	130.9	119
J2	289	JEBBA TS (330)	355	JEBBA II G3 (16)	0.0035	0.1062	119	130.9	119

2.8 Voltage Stability Analysis Algorithm

This evaluation closely resembles transfer limit analysis but emphasizes situations in which voltage regulation influences the network's power transmission capacity. Voltage stability pertains to the risk of system voltage collapse, which may occur as a result of rising load demand or increased power transfer across the network. Two commonly used techniques for assessing a system's susceptibility to voltage collapse are:

- **Power-voltage (PV) curves**, which monitor voltage levels as power transfer varies.
- **Reactive power-voltage (QV) curves**, which evaluate reactive power margins concerning voltage fluctuations [21].

The QV curve method is employed to assess the network's operating point and detect possible stability concerns. This approach involves graphically representing the relationship between reactive power and voltage at a specific bus. The following steps detail the process of constructing a QV curve:

1. **Identify the Target Bus** – Select the network node where the QV curve analysis will be conducted.
2. **Collect Data** – Obtain voltage and reactive power measurements for the chosen bus under different operating conditions, either through real-time system monitoring or simulations.
3. **Construct the QV Curve** – Plot reactive power demand against voltage magnitude to visualize their interaction.
4. **Evaluate the QV Curve** – Assess the curve's shape to identify potential voltage instability or reactive power regulation issues, comparing it with standard QV models.
5. **Implement corrective actions** – If necessary, apply control measures such as adjusting transformer tap settings or deploying automatic voltage control systems.
6. **Continuous monitoring** – Continuously update and analyze the QV curve to maintain voltage

stability and enhance overall power system reliability.

2.9 Q-V Curve Analysis: Requirement and Motivation

The Q-V curve analysis is essential for evaluating voltage stability in power systems, particularly under conditions of varying reactive power demand. This method provides insights into the reactive power margin and identifies the critical voltage at which instability occurs. The motivation to carry out Q-V curve analysis lies in its ability to assess the system's capability to withstand voltage collapse, reactive power margin, and ensure reliable operation amidst growing renewable energy integration and dynamic load variations. The requirement for the QV curve includes the reactive power demand to the bus voltage at a particular instance.

2.10 PSSE Simulation for QV Curve

Power System Simulation for Engineers (PSSE) is a widely used software tool for power system analysis, particularly in voltage stability assessment and reactive power management. One of its key functionalities is generating Voltage-Reactance (QV) curves, which offer critical insights into the relationship between voltage and reactive power at different buses within a power network. This analysis is essential for evaluating how reactive power compensation devices, such as STATCOMs, improve voltage stability under both normal and contingency conditions.

The QV curve, derived from load flow studies in PSSE, represents voltage variations at a given bus as a function of injected or absorbed reactive power. Due to the complex interplay of reactive power and voltage, the curve typically exhibits nonlinear characteristics. PSSE enables engineers to simulate multiple scenarios, analyzing how changes in reactive power influence voltage stability under different loading conditions and network configurations.

The QV curve is instrumental in determining the system's voltage stability limits by identifying the minimum and maximum levels of reactive power that could be supplied without triggering voltage collapse. Integrating STATCOM into the network significantly modifies the QV characteristics, as illustrated in Figures 11 and 12. By dynamically providing reactive power support, STATCOM shifts the QV curve, thereby enhancing the system's voltage stability margin.

Additionally, PSSE supports contingency analysis, allowing engineers to simulate outage scenarios and assess the system's response to stress conditions such as line failures or sudden load changes. These simulations help develop effective operational strategies and optimize reactive power compensation schemes, ensuring stable and reliable power system performance.

3 Results and Discussion

3.1 Description of the Case Study

The electrical network described consists of a structured arrangement of buses, generators, and transformers that facilitate the transmission of electrical power from generation points to load centers. This network includes 24 buses, among which three are designated as generator buses, and one serves as the slack bus. The generator buses, specifically Jebba GS and Olorunsogo GS, operate at distinct voltage levels of 16 kV and 10.5 kV, respectively. The slack bus maintains a specified voltage magnitude and phase, which is pivotal for the operation and stability of the entire system.

The transformation of voltage levels is a critical process in this network. The output from the generator buses and the slack bus stepped up through transformers to reach the 330 kV level. This high-voltage transmission is necessary to minimize losses over long distances and to ensure efficient power delivery. The 330 kV buses are interconnected with other buses, including Ganmo, Osogbo, and Ayede TS, forming a robust transmission network. The subsequent step-down to 132 kV through power transformers is equally significant, as it prepares electricity for distribution to non-generator buses where loads are connected.

The representation of loads at the 132 kV level is indicative of the network's design to accommodate various consumer demands. The loads connected to the non-generator buses are critical for analyzing the performance and reliability of the power system.

3.2 N-1 Security Analysis Results

The findings from the case study network are summarized in Table 4. Under normal operating conditions, when all network components are functioning without any equipment failures, the system is in its base case or “no contingency” state. In this condition, a network violation was observed in the form of transformer overloading, with the affected transformer operating at 119% of its rated capacity.

Several contingency scenarios were simulated, and their impacts are visually represented in Figure 4, which details the number of voltage violations, overload violations, the most severe overload conditions, and the most critical under-voltage issues encountered in each scenario.

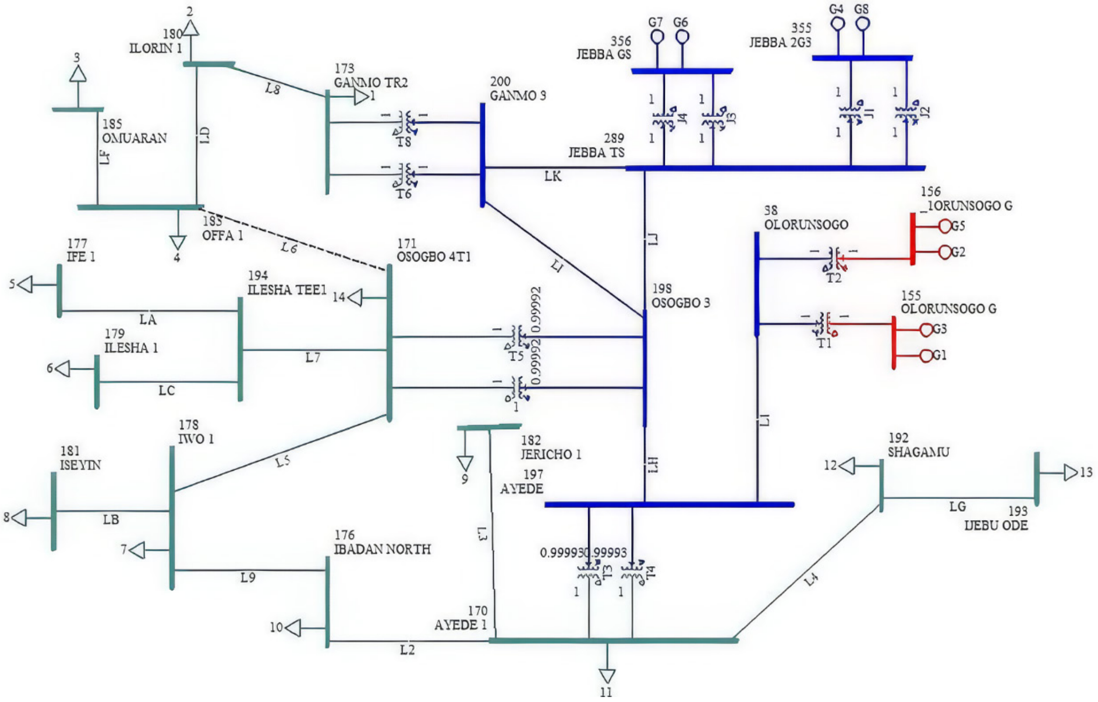

Fig 3. Description of Osogbo regional transmission network.

Table 4. N-1 Contingency outline of the network.

Primary Contingency (ID)	Overload Violations	Voltage Violations	Worst Overload Violation (%)	Worst Under-voltage Violation (p.u)
BASE CASE	2	1	119.1	0
197.0 - 198.0 (LH)	1	8	105.1	0.8466
200.0 - 289.0 (LK)	2	1	119.6	0
170.0 - 176.0 (L2)	0	2	0	0.8827
289.0 - 356.0 (J3)	3	1	179.3	0
170.0 - 197.0 (T3)	1	0	221.8	0.9499

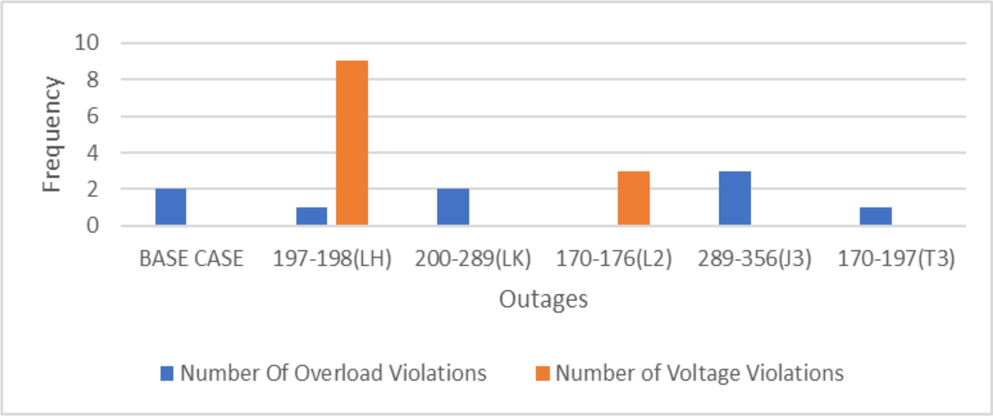

Fig 4. Performance Summary of the Contingency Cases.

The analysis revealed that network instability primarily occurred at the 132 kV voltage level, given the existing generation and load demand patterns. The study identified the 330 kV transmission link between Osogbo and Ayede substations as the most critical line, as it serves as the only direct connection between these two major substations. Transformer overloading was also observed when one of the parallel transformers in a branch was taken out of service, causing the remaining units to bear excessive load.

To improve system security, reducing generation levels at the connected bus was found to be an effective mitigation strategy. However, detailed insights into voltage violations and line loading violations for the various contingencies are provided in Tables 5 and 6, respectively.

Figure 4 indicates that the branch linking bus 197-198, identified as LH, experienced the highest number of violations in the network, with a total of nine (9) voltage violations and one overload violation. Additionally, other critical network components include line L2, which connects bus 170-176, and transformer J3, linking bus 289-356. These elements recorded three (3) voltage violations and three (3) overload violations, respectively, as shown in Figure 4.

Table 5. Voltage Violations.

Bus ID	Bus Name	Voltage Level (kV)	Initial Voltage (p.u)	Contingency Voltage (p.u) LH	Contingency Voltage (p.u) L2
38	OLORUNSOGO	330.0	1.0185	**0.9495**	1.0063
155	OLORUNSOGO G I	10.5	1	1	1
156	OLORUNSOGO G I	10.5	1	1	1
170	AYEDE I	132.0	1.0146	**0.8927**	0.9885
171	OSOGBO IV TI	132.0	1.0330	0.9776	0.9988
173	GANMO TR2	132.0	1.0235	0.9947	1.0078
176	IBADAN NORTH	132.0	1.0155	**0.8884**	**0.8827**
177	IFE I	132.0	1.0254	0.9687	0.9906
178	IWO I	132.0	1.0283	**0.8893**	**0.8962**
179	ILESHA I	132.0	1.0265	0.9702	0.9918
180	ILORIN I	132.0	1.0224	0.9934	1.0068
181	ISEYIN	132.0	1.0263	**0.8810**	**0.8883**
182	JERICHO I	132.0	1.0140	**0.8918**	0.9876
183	OFFA I	132.0	1.0292	0.9988	1.0129
185	OMUARAN	132.0	1.0259	0.9949	1.0093
192	SHAGAMU	132.0	0.9897	**0.8530**	0.9605
193	IJEBU ODE	132.0	0.9857	**0.8466**	0.9558
194	ILESHA TEE I	132.0	1.0299	0.9739	0.9954
197	AYEDE	330.0	1.0198	0.9327	1.0044
198	OSOGBO III	330.0	1.0273	0.9934	1.0088
200	GANMO III	330.0	1.0240	0.9964	1.0092
289	JEBBA TS	330.0	1.0258	1.0052	1.0147
355	JEBBA II G3	16.0	1	1	1
356	JEBBA GS	16.0	1	1	1

Table 6. Line Loading Violationsh.

Primary Contingency	**Monitored Element (Overloaded branches)**		**Base Case Rating**		**Contingency**	
Outages		**Voltage (kV)**	(MVA)	(MVA)	(MVA)	(%)
BASE CASE	170 AYEDE I || 132-197 AYEDE T3	330.00	90	107.18	N/A	N/A
BASE CASE	170 AYEDE I || 132-197 AYEDE T4	330.00	90	107.18	N/A	N/A
197.0 - 198.0 (LH)	171 OSOGBO IV T1 || 132-178 IWO L5	132.00	125.7	39.39	142.11	105.07
200.0 - 289.0 (LK)	170 AYEDE I || 132-197 AYEDE T3	330.00	90	107.18	107.6	119.56
200.0 - 289.0 (LK)	170 AYEDE I || 132.00 197 AYEDE T4	330.00	90	107.18	107.6	119.56
289.0 - 356.0 (J3)	170 AYEDE I || 132-197 AYEDE T3	330.00	90	107.18	107.12	119.03
289.0 - 356.0 (J3)	170 AYEDE I || 132-197 AYEDE T4	330.00	90	107.18	107.12	119.03
289.0 - 356.0 (J3)	289 JEBBA TS || 330-356 JEBBA GS J4	16.00	105	104.46	206.22	179.33
170.0 - 197.0 (T3)	170 AYEDE I || 132-197 AYEDE T4	330.00	90	107.18	199.66	221.84

The Voltage Violations During Contingencies

Table 5 highlights the two contingency scenarios that resulted in voltage violations. The removal of line LH from the network led to the highest number of voltage violations, with the most severe cases occurring at bus 176, 178, and 181, corresponding to Ibadan North 132kV, Iwo 132kV, and Iseyin 132kV, respectively. Notably, these three buses also experienced voltage violations during contingency L2, indicating their vulnerability and instability within the network. This emphasizes the need for a thorough voltage stability assessment for these weak buses.

Line Loading Violations Under Contingencies

Table 6 provides a comprehensive summary of transmission line loading violations detected under various contingency scenarios. The analysis includes the base case condition, primary contingencies, and the specific transmission branches experiencing overload. In the base case configuration, transmission lines T3 and T4, linking Ayede 330kV to Ayede 132kV, were already operating beyond their rated capacity. These branches remained overloaded across multiple contingency scenarios, as detailed in Table 6. Other critical network elements, such as branches L5 and J4, were also monitored, with their respective loading conditions in both the base case and contingency scenarios outlined.

3.3 Voltage Stability Margin

This section examines the stability of the identified weak buses using QV curve analysis. The QV curve is derived by gradually increasing both active and reactive load at a specific bus while conducting successive power flow simulations to observe voltage fluctuations. This graphical representation, which plots either active power demand against voltage or reactive power injection against voltage, is essential for evaluating a bus's stability margin.

To analyze voltage stability, QV curves were generated for the three buses that exhibited voltage violations under the two contingency scenarios detailed in Table 5. The findings offer valuable insights into the reactive power margins of these buses and their vulnerability to voltage instability.

The QV curves of the three buses that were most impacted in the base-case and various contingency scenarios are displayed in Figures 5, 6, and 7. In each instance, the bus's reactive power limit is indicated. The allowed voltage range (0.95-1.05pu) is the reactive limit for contingency cases 1 (line LH) and 3 (line L2) [22]. Within the designated voltage range, the QV curve for various contingency scenarios during regular operation without correction takes distinct trajectories. This demonstrates how the network behaves in a contingency. It is important to remember that not every contingency scenario has an impact on the network buses' voltage. As a result, attention was paid to the impacted buses.

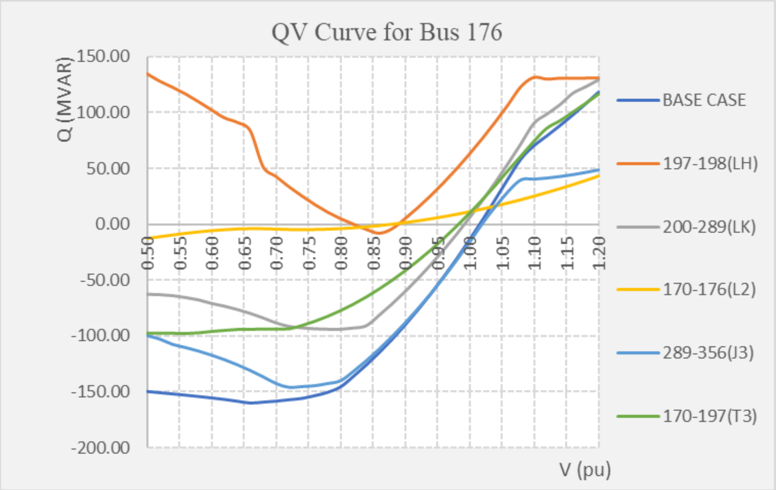

Fig 5. QV Curves of Ibadan North Contingencies cases.

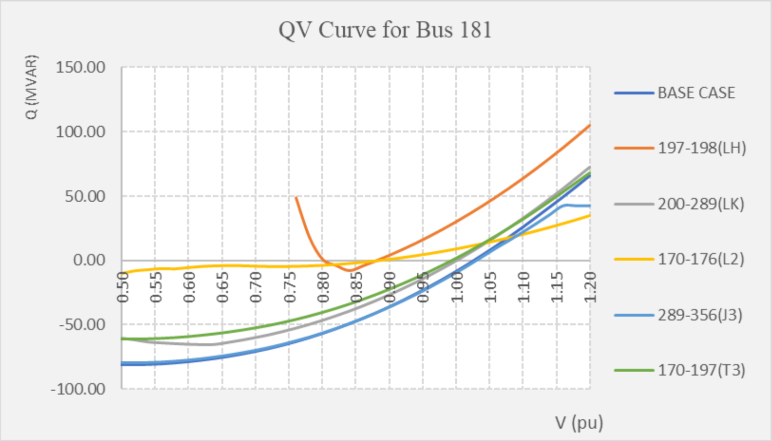

Fig 6. QV Curves of Iseyin Contingencies cases.

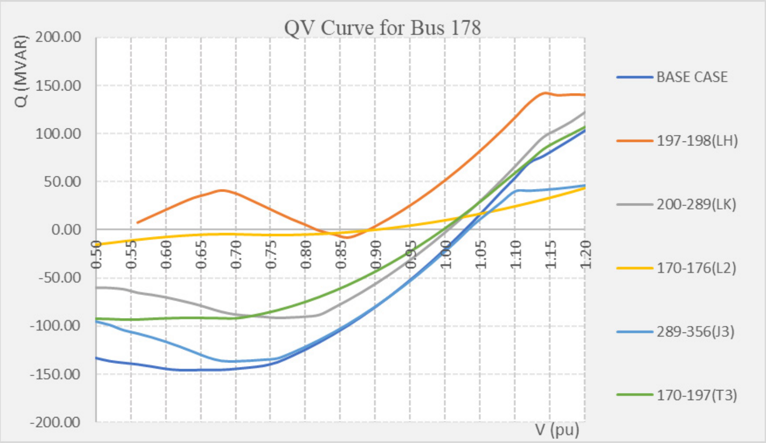

Fig 7. QV Curves of Iwo Contingencies cases.

3.4 Using the Facts Device to Improve the Voltage Profile (STATCOM)

In terms of voltage profile and line loading, FACTS devices are able to adjust for network profiles. Depending on the kind, size, and location within the network, it can have a particular impact on its properties.

The influence of a STATCOM on the network to enhance the voltage profile and power transfer capability in both the base case and the contingency is the main emphasis of this work. After being added to the network, the impact of the STATCOM was examined and reported.

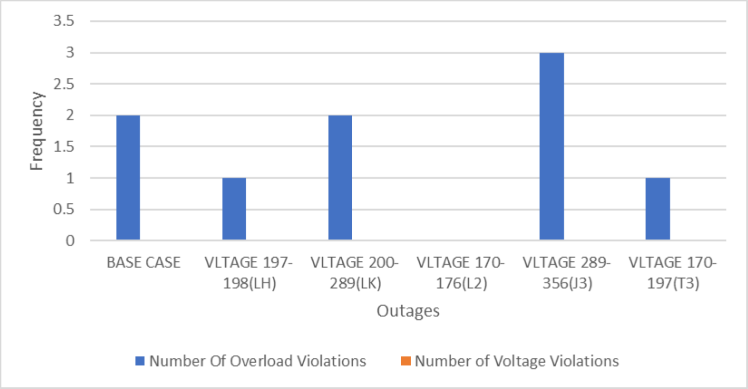

Fig 8. Case study contingency performance summary using STATCOM on bus 176.

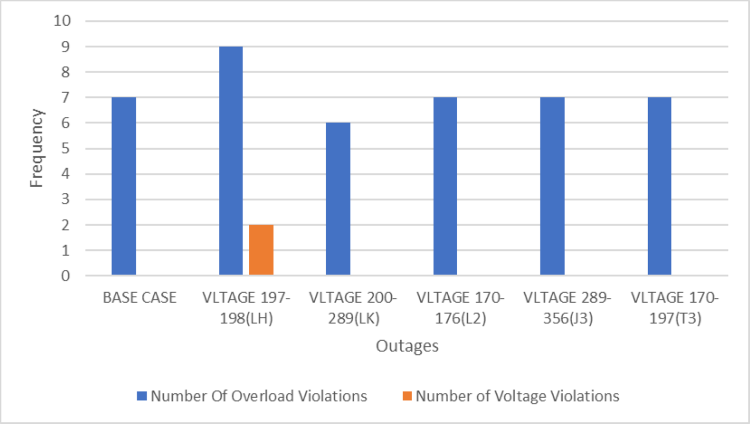

Fig 9. Case Study Contingency Performance Summary with STATCOM on Bus 178.

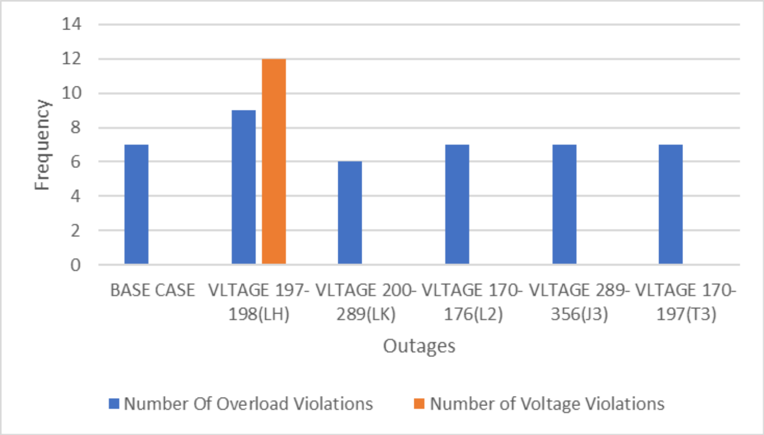

Fig 10. Case Study Contingency with STATCOM Performance Summary on Bus 181.

As described by [23], the FACTS device is located at or near the impacted buses. Figures 8, 9, and 10 above depicted the case study's performance summary during the base case and contingency scenario when the device was positioned at various locations of the most afflicted buses. In certain instances, the number of overload violations increases while the voltage violation decreases. For the compensating device to be placed optimally and to be planned and operated effectively, it must be carefully placed. As seen in Figure 8, bus 176 (Ibadan North) had the network's best performance. recording a voltage violation of zero while keeping the overload violations unaddressed.

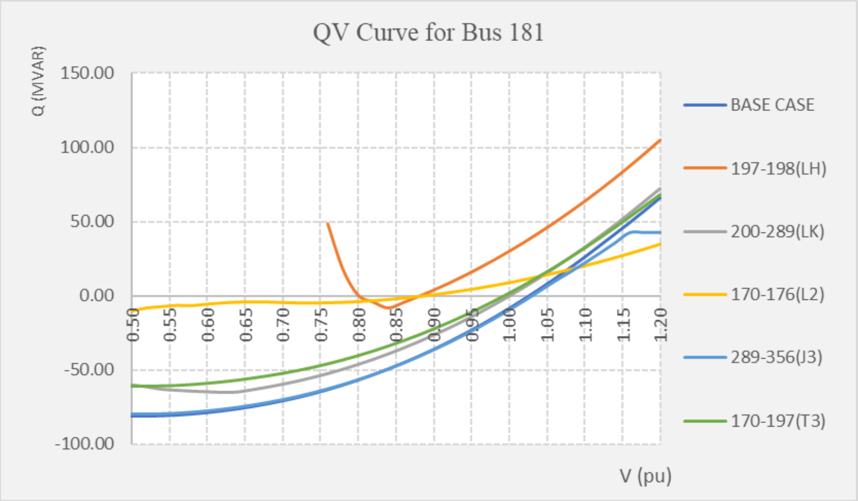

Fig 11. QV curve of bus 181 Iseyin without STATCOM.

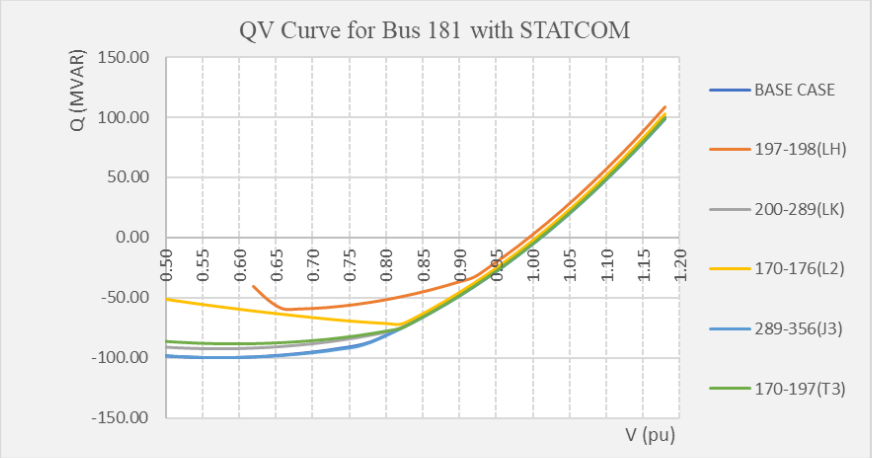

Fig 12. Bus 176 Ibadan North's QV curve using STATCOM for bus 181 Iseyin.

The QV curves of buses 178 and 181 (Iwo and Iseyin buses) are shown in Figures 11 and 12 following the installation of STATCOM at bus 176 (Ibadan North). After examining the impact on other impacted regions, the FACTS device's site was chosen. The place with the best performance was selected and examined.

As seen in figures 11 and 12, the addition of STATCOM to the network enhances the buses' reactive power capability and voltage profile, boosting the network's capacity for power transfer. Within the designated voltage range, the curve's trajectory exhibits negligible variations between the base and contingency instances.

4 Conclusion

Power flow and contingency analysis are essential for the effective management and strategic planning of power system networks. By employing mathematical modeling and simulation methods, these analyses allow operators to assess how the network performs under normal conditions and during faults. This facilitates prompt corrective measures to maintain the reliability and security of the system.

This research centers on creating a model and simulating the single-line phases of the Osogbo regional transmission network. Using PSS software, power flow analysis was conducted to evaluate the effects of line outages on the network, specifically focusing on how these outages affect the reactive power margins of the involved buses while keeping voltage levels within acceptable ranges. The findings underscore the importance of incorporating a STATCOM device into the Osogbo regional transmission network to improve voltage stability and enhance overall system resilience. The findings demonstrate that the inclusion of the STATCOM effectively mitigates the voltage violations, reducing the number of voltage violation cases from twelve to zero. Additionally, the device enhances the network's reactive power handling capacity, ensuring improved voltage stability and reliability under both normal and contingency conditions. By addressing critical issues such as voltage collapse and reactive power deficiencies, the STATCOM integration significantly enhances the performance and security of the power system network. It is worth noting, however, that this study relies exclusively on simulation results; validation against field data remains a future research direction, to be pursued through collaboration with the Transmission Company of Nigeria (TCN) to obtain operational measurements for further verification of the results.

Conflict of Interest

The authors declare no conflict of interest.

Competing Interest

The authors hereby declare of no competing interests.

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References

[1] I. B. Anichebe and A. O. Ekwue, "Improvement of bus voltage profiles of Nigerian power network in the presence of Static Synchronous Compensator (STATCOM) and Doubly Fed Induction Generator (DFIG)," *Nigerian Journal of Technology*, vol. 39, no. 1, pp. 228–237, Apr. 2020, doi: 10.4314/njt.v39i1.26.

[2] M. S. Alatshan, I. Alhamrouni, T. Sutikno, and A. Jusoh, "Improvement of the performance of statcom in terms of voltage profile using ann controller," *International Journal of Power Electronics and Drive Systems*, vol. 11, no. 4, pp. 1966–1978, Dec. 2020, doi: 10.11591/ijpeds.v11.i4.pp1966-1978.

[3] I. K. Okakwu, P. E. Orukpe, and E. A. Ogujor, "Application of Superconducting Fault Current Limiter (SFCL) in Power Systems: A Review," *European Journal of Engineering Research and Science*, vol. 3, no. 7, p. 28, Jul. 2018, doi: 10.24018/ejers.2018.3.7.799.

[4] U. N. Asibeluo and T. C. Madueme, "Risk-based security assessment of power system voltage drop: a case study of Nigerian 330KV 41-bus transmission grid," *Nigerian Journal of Technology*, vol. 37, no. 3, p. 735, Jul. 2018, doi: 10.4314/njt.v37i3.24.

[5] I. Jude, B. Baams, J. Usman, S. Samuel, and I. I. Jude, "EFFECTIVINESS OF FACTS DEVICES FOR THE CONTROL OF POWER SYSTEM TRANSIENT STABILITY USING DIFFERENT INTELLINGENT TECHNIQUES," 2018. [Online]. Available: www.globalscientificjournal.comwww.globalscientificjournal.com

[6] I. E. Nkan, E. E. Okpo, and A. B. Inyang, "Enhancement of Power Systems Transient Stability with TCSC: A Case study of The Nigerian 330 kV, 48-Bus Network," *INTERNATIONAL JOURNAL OF MULTIDISCIPLINARY RESEARCH AND ANALYSIS*, vol. 06, no. 10, Oct. 2023, doi: 10.47191/ijmra/v6-i10-37.

[7] * Ogunbiyi, O. Adesina, L. M. Ugwute, and Thomas, "Enhancement of the Nigerian National Grid Performance with a FACT Compensator ARTICLE INFORMATION ABSTRACT," *506 Nigerian Research Journal of Engineering and Environmental Sciences*, vol. 7, no. 2, p. p, 2022, doi: 10.5281/zenodo.7496649.

[8] J. F. Udo and M. A. Aminu, "Transient Stability Improvement on Jos – Gombe 330kV Line Using Static Var Compensator," *J Sci Res Rep*, pp. 1–7, Sep. 2019, doi: 10.9734/jsrr/2019/v24i530166.

[9] M. Mohammadalizadeh-Shabestary, H. Hashemi-Dezaki, S. Mortazavian, H. Askarian-Abyaneh, and G. Gharehpetian, "A general approach for optimal allocation of FACTS devices using equivalent impedance models of VSCs," *International Transactions on Electrical Energy Systems*, vol. 25, no. 7, pp. 1187–1203, Jul. 2015, doi: 10.1002/etep.1896.

[10] A. Korashy, S. Kamel, F. Jurado, and A. R. Youssef, "Hybrid Whale Optimization Algorithm and Grey Wolf Optimizer Algorithm for Optimal Coordination of Direction Overcurrent Relays," *Electric Power Components and Systems*, vol. 47,

no. 6–7, pp. 644–658, Apr. 2019, doi: 10.1080/15325008.2019.1602687.

[11] N. Ugwuanyi *et al.*, "Enhancing Renewable Energy-Grid Integration by Optimally Placed FACTS Devices: The Nigeria Case Study," *Science Journal of Energy Engineering*, vol. 12, no. 2, pp. 16–25, Aug. 2024, doi: 10.11648/j.sjee.20241202.11.

[12] B. B. Adetokun and C. M. Muriithi, "Application and control of flexible alternating current transmission system devices for voltage stability enhancement of renewable-integrated power grid: A comprehensive review," Mar. 01, 2021, *Elsevier Ltd*. doi: 10.1016/j.heliyon.2021.e06461.

[13] R. Sadiq, Z. Wang, C. Y. Chung, C. Zhou, and C. Wang, "A review of STATCOM control for stability enhancement of power systems with wind/PV penetration: Existing research and future scope," Nov. 01, 2021, *John Wiley and Sons Ltd*. doi: 10.1002/2050-7038.13079.

[14] H. F. Bilgin and M. Ermis, "Current source converter based STATCOM: Operating principles, design and field performance," *Electric Power Systems Research*, vol. 81, no. 2, pp. 478–487, Feb. 2011, doi: 10.1016/j.epsr.2010.10.003.

[15] M. Darabian, A. Jalilvand, A. Ashouri, and A. Bagheri, "Stability improvement of large-scale power systems in the presence of wind farms by employing HVDC and STATCOM based on a non-linear controller," *International Journal of Electrical Power and Energy Systems*, vol. 120, Sep. 2020, doi: 10.1016/j.ijepes.2020.106021.

[16] D. Soto and R. Pena, "Nonlinear control strategies for cascaded multilevel STATCOMs," *IEEE Transactions on Power Delivery*, vol. 19, no. 4, pp. 1919–1927, Oct. 2004, doi: 10.1109/TPWRD.2004.835394.

[17] J. L. Olabarrieta Rubio, P. Eguia Lopez, E. Torres Iglesias, and A. Etxegarai Madina, "A Comparative Study of Static VAR Systems for ImprovingVoltage Stability in Expansion of Mining Projects with Gearless Motor Drives," *International Transactions on Electrical Energy Systems*, vol. 2023, pp. 1–16, Jul. 2023, doi: 10.1155/2023/2218048.

[18] J. L. Olabarrieta Rubio, P. Eguia Lopez, E. Torres Iglesias, and A. Etxegarai Madina, "Use of FACTS for Improving Voltage Stability in Mining Applications," *RE&PQJ*, vol. 17, no. 3, Jan. 2024, doi: 10.24084/repqj17.326.

[19] E. Naderi, H. Narimani, M. Pourakbari-Kasmaei, F. V. Cerna, M. Marzband, and M. Lehtonen, "State-of-the-art of optimal active and reactive power flow: A comprehensive review from various standpoints," Aug. 01, 2021, *MDPI AG*. doi: 10.3390/pr9081319.

[20] L. Nan, Y. Liu, L. Wu, T. Liu, and C. He, "Graph Theory Based N1 Transmission Contingency Selection and Its Application in Security-constrained Unit Commitment," *Journal of Modern Power Systems and Clean Energy*, vol. 9, no. 6, pp. 1458–1467, Nov. 2021, doi: 10.35833/MPCE.2019.000602.

[21] D. Stanelytė and V. Radziukynas, "Analysis of Voltage and Reactive Power Algorithms in Low Voltage Networks," Mar. 01, 2022, *MDPI*. doi: 10.3390/en15051843.

[22] L. M. Adesina, "Contingency Assessment of Medium Voltage Distribution System ARTICLE INFORMATION ABSTRACT," *Nigerian Research Journal of Engineering and Environmental Sciences*, vol. 7, no. 1, p. p, 2022, doi: 10.5281/zenodo.6722319.

[23] M. Nadeem *et al.*, "Optimal placement, sizing and coordination of FACTS devices in transmission network using whale optimization algorithm," *Energies (Basel)*, vol. 13, no. 3, 2020, doi: 10.3390/en13030753.

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