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Towards Improved Power Supply: Investigating the Trans-Amadi 33kV Distribution Network Using Continuation Power Flow Algorithm

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ABSTRACT

There is a need to improve conditions of poor loading margin from electric utilities to avoid unallowable bus loading limits. In this study, the Trans-Amadi 33kV Distribution Network in Port Harcourt, Niger Delta, Nigeria was investigated using the continuation power flow algorithm. Load parameters were considered as declared variables with loading trends at an incremental step of 2%:2:10% at a constant loading factor (λ) of 1. For the studied load buses (1 to 10), their capacities were 182, 15.5, 174, 274, 375.08, 312, 80, 74, 51, and 56kW, respectively at corresponding perturb incremental parameters of 185.64, 15.8, 177.48, 279.48, 382.58, 318, 81,6, 75.08, 52.02, and 57.12kW. Results showed that a 2-% load bus indicates a voltage stability margin with no violations. A 4-% load bus showed violation of buses 4 to 6, 6% load buses showed violations of buses 3 to 6 that were later compensated using reactive power controller, while the remaining buses were unviolated. An 8% incremental step showed violation of buses 4 to 7, leaving the remaining buses unviolated. This predictive and corrective optimal control mechanism puts the system's behaviour on continuous check and control to avoid early system instability, which may eventually lead to network collapse. Additionally, a 10% incremental loading step showed violations at buses 3 to 8 while others were classified unviolated. These results provided the incremental loading trend for studied load buses for the detection of minimum and maximum loadability limits to avoid early system collapse due to poor loading margin that can result in network instability (blackout).

1. Introduction

Blackouts and steadily declining voltages are symptoms of voltage collapse, which occur in overloaded electric power networks. Preventing voltage collapse is essential for the safe functioning of any power system. An undesired phenomenon in the power supply, voltage collapse, happens when the system is overwhelmed. A complete or partial blackout of the electricity grid may result from this collapse. When the electrical grid cannot provide the necessary reactive power, an overload occurs. The role of a flexible alternating current transmission system (FACTS) is necessary at this point. Voltage instability may be resolved by injecting or absorbing reactive power required by the load with the insertion of FACTS controllers at the proper position. The ability of the transmission lines to convey data is significantly affected by FACTS controllers. According to Shakil et al. (2014), they are also used in power distribution networks to provide stable voltages and better power quality.

Transmission lines with a high voltage are the most efficient means of transferring electricity from power plants to consumers and other parts of the power grid. Towers, foundations, insulators, and line conductors make up transmission lines. Transmission cables that run above dangle from insulators that are held aloft by poles or towers. The permissible sag in the line determines the span between two towers. The typical span for steel towers carrying very high voltage lines is between 370 to 460m (Idoniboyeobu, 2018). However there have been major issues with the network's voltage and power flow across the transmission lines (Onojo et al., 2013).

The four distributed characteristics that define the transmission line are the series inductance, shunt conductance, series resistance, and shunt capacitance. The effects of electric and magnetic fields around the conductors are represented by the shunt capacitance and series inductance. Shunt capacitors account for current leakage along the insulator strings and ionized air pathways. This leakage is often disregarded since its effect is little. For studies of power systems in general, the following factors are necessary to build a practical transmission model (Idoniboyeobu, 2018).

According to Idoniboyeobu (2018), a typical power system consists of a generation section, transmission section, and distribution and load section. The generation section consists of generators, protection devices, generation transformers, Bus bars, and station Auxiliaries. A typical generation voltage in Nigeria is 11kV. The transmission section consists of transmission lines, towers, protection, and signaling devices as well as transformers. Typical transmission voltages in Nigeria are 132 and 330kV. The distribution and load section consists of distribution lines, transformers, protection devices, bus bars, and loads. Typical distribution voltages in Nigeria are 11 and 33kV (Idoniboyeobu, 2018).

The FACTS system has improved the utility of transmission lines and introduced a new method for managing power flows. To transmit alternating current (AC), a conventional FACTS device uses static equipment. Its purpose is to enhance the power system's capacity for transferring electricity. The concept of FACTS was defined by Amaize et al. (2017). Power semiconductor applications often include manipulating electrical variables and parameters like voltages, impedance, phase angle, current, and active and reactive powers. Considering the massive obstacles already present in the system as well as the development opportunities, FACTS devices are very pertinent to Nigeria's electricity network to boost the network's efficiency and ongoing deregulation/unbundling in the electricity market (Amaize et al. 2017; Ebune et al., 2018; Ya-Chin, 2012).

According to Ebune et al. (2018), the power transmission infrastructure in Nigeria must be upgraded and expanded regularly to keep up with the country's constantly increasing power consumption. Generation companies in Nigeria reduced their energy loading consumption by 3,014.8 MW on 19 August 2019, from an average of 3,578MW in the previous month, while keeping their available generation capacity at 4,000MW, according to the most recent data from the National Control Centre (NCC), Osogbo (Energy Mix Report, 2019). To prevent a potential voltage collapse due to the analysis of the network flow, which has a poor loading margin, a load of around 75.37%, or 3,014.8MW, has been maintained throughout time (Energy Mix Report, 2019). The focus here is on how changes to system characteristics or controls may significantly improve the loading margin of Nigeria's 330kV transmission network.

When considering system limitations and nonlinearities, power system architecture provides an appropriate evaluation measure of the closeness to voltage collapse. According to Greene et al. (2014) and Joel (2016), the power system's loading margin varies as system parameters charge. To meet the demand for greater electricity, modern power systems are often complicated (Akter et al., 2012). According to Sode-Yome et al. (2013), this kind of issue is more likely to occur in current power systems due to the underinvestment in new generation and transmission infrastructure as well as the overutilization of current facilities driven by rising load demand. According to Sode-Yome et al. (2013), voltage instability may be caused by changes in the design of the power system, patterns of generation, and loads. Thorough stability analyses of the power system are essential for system security.

Upgrading utilization while preserving stability and security is of utmost importance in today's very complex linked power networks. Despite some transmission lines being fully charged, others can be overloaded, which might affect voltage levels and compromise system security. To satisfy the demands for power transfer, it is crucial to regulate the flow of electricity over transmission lines. Flexible alternating current transmission system (FACTS) was a concept developed by the Electric Power Research Institute (EPRI) in the late 1980s as a solution to the issue of power system design and operation (Komoni et al., 2012). Improving power system security and stability, as well as facilitating power flow and control, are the primary goals of FACTS (Komoni et al., 2012). With the advent of FACTS technology, new possibilities for managing power flow and increasing the useful capacity of existing and future lines have opened. One complicated piece of electrical equipment that may optimize power flows in a power transmission system and manage a local bus voltage at the same time is the Unified Power Flow Controller (UPFC) (Adebisi et al., 2018). The goals of FACTS are to manage the flow of electricity across specific transmission lines and to enhance the capacity of transmission (Joshi & Sahay, 2017).

When it comes to improving the network's power quality, FACTS devices employ power electronic technology to effectively control electrical quantities like active and reactive power, phase angles and bus voltages, line impedances and terminal voltages.

According to Eseosa & Roland (2013), these devices guarantee power system stability even when the network is exposed to excessive active and reactive loadings, and they also enable the power system network at generating, transmission, and distribution stations to be used effectively.

Due to its significance and the tremendous amount of effort invested in it because of the previous blackouts linked to it, voltage stability plays a key role in maintaining the system's operational status. The primary goal of voltage stability is to keep the voltage profile within a certain acceptable range regardless of the operating circumstances (Raouf et al., 2014). The magnitudes and phase angles of the load bus voltages, the reactive powers and voltage phase angles at the generator bus, the real and reactive power flow on the transmission lines, and the power at the reference bus are the main pieces of information that are retrieved from the load flow analysis (Efe, 2016). Shunt capacitors or flexible alternating current transmission system (FACTS) controllers placed at the power system's weakest bus may alleviate voltage instability (Sode-Yome et al., 2013). System operators have much more control over the generation pattern than the load pattern. In this pattern, all participating generators increase their production at the same pace, according to a preset rate, or their spinning reserves (Sode-Yome et al., 2013). To boost a transmission line's power transmission capacity while still meeting the essential transmission requirements; namely, a flat voltage profile and stability, compensation is defined by Kumar & Agnihotri (2014) as modifying the line's electrical properties. Some main categories under which the gearbox system's compensation falls. Include compensation via sectioning, line length compensation, and surge independence compensation (Kumar & Agnihotri, 2014).

The Nigerian power systems are already over-stressed following the trajectory of power flow demand, and convergence characteristics of the existing system under investigation. The continuation power flow (CPF) technique is a tool that can determine the points of system overload, critical overload, or otherwise. Having noted the Nigeria network being confronted with overload, weak network, and obsolete facility, the power system has become vulnerable to voltage instability that may result in system collapse. This means that constant, increasing electricity demand will make the system experience the utility of the network parameters, therefore it is very necessary to determine the exact load margin, of the network in the view to enhance reliable power supply, using the continuation power flow algorithms.

In a study conducted by Norziana et al. (2010), the authors compared the MLPs produced by the CPF and Hybrid Particle Swarm optimization methods. They found that their levels of accuracy are similar (Norziana et al. 2010). By solving the power flow issue using the continuing power flow approach, we may improve the simulation performance (Vasquez & Sousa, 2017). According to Vasquez & Sousa (2017), the method is a mathematical path methodology used to solve systems of nonlinear equations by adopting a locally parameterized continuation method as shown in Figure 1.

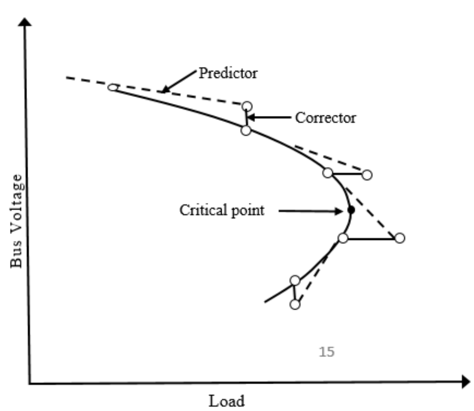

Figure 1: Predictor-Corrector used in the Continuation Power Flow Analysis

This study focused on the CPF for the investigation of the Trans-Amadi 33kV distribution network for improved power quality. Specifically, the study involved the application of the CPF technique in the analysis and calculation of: (1.) the steady-state operation of power supply under various operating (preloading, loading/overloading conditions), which previous researchers failed to consider and (2.) the 33kV distribution network loading margin, which is in line with the statutorily declared nominal operating conditions. This is because there is a need to determine the loading margin to allow for system upgrade and expansion using the CPF technique as a compensator in the Electrical Transient Application Programme (ETAP) environment for improved power quality. To ensure the success of this study, the following objectives were addressed.

i. Collate the network data for the study case particularly TCN Trans-Amadi 33/0.415 kV.
ii. Conduct a load flow of the base case in the study area in an ETAP environment.
iii. Perform Continuation Power Flow on the network severally to bifurcation after identifying weak buses using ETAP.
iv. Introduce numerical load margins to measure the system violations of the affected buses and compensate the vulnerable buses by the injection of reactive power particularly the penetration of the capacitor bank.
v. Perform load flow for the improved network case to determine the system power losses and compare the results of the study case and improved case for validity.

2. Materials and Methods

2.1 Materials

The materials used for this study are as follows:

i. ETAP version 19.0.1.
ii. Bus data
iii. Computer system
iv. Microsoft Excel

2.2 Methods

The continuation Power Flow method was used to model and effectively carry out the load demand analysis of the Nigerian 33kV distribution network. Equal increment loading was conducted to ascertain the load demand of the network.

2.2.1 Algorithm in Implementing Continuation Power Flow Technique

i. Start with the base power flow solution: In ETAP, data is entered, and the system is simulated begin by performing a power flow analysis to determine the initial operating conditions of the system. This involves solving the power flow equations to calculate the bus voltages line flows, and generator outputs.
ii. Identify the parameter changes or contingencies: Determine the changes or contingencies that need to be considered in the CPF analysis. These include changes in load demand, variations in generation output, and switching operations or lines.
iii. Modify the system parameters: Apply the identical parameter changes to the base case power flow, the solution, for example, adjust the load demand values, modify generator outputs, or represent the effects of line outages by changing line parameters or disconnecting lines.
iv. Update the power flow equations: Modify the power flow equations to reflect the changes in the system parameters. This may involve adjusting the load flow equations, updating the admittance matrix to account for changed line parameters or topology, and incorporating any additional constraints or equations required by the specific network configuration.
v. Solve the updated power flow equations: Using an iterative method, solve the modified power flow equations to obtain the new bus voltage, line flows, and generator outputs. The solution may be covered after a few iterations, or it may require further iterations depending on the complexity of the system and the magnitude of the parameter changes.
vi. Check Convergences and where repeat necessary: After obtaining a solution, check for convergences that the solution is within the acceptable and tolerable limits, however, if the solution does not converge or the convergences criteria are not met this means that the process iterates by returning to step 3 and repeating the process until convergence is achieved.
vii. Perform sensitivity analysis: Once the CPF analysis has converged, perform sensitivity analysis to evaluate the impact of the parameter changes on various system variables. This can help identify potential bottlenecks, voltage violations, or overloads that may occur under different operating conditions.

2.2.2 Load Analysis for the Study Case, Using Continuation Power Flow Technique

Considering the CPF expression in equation 1.

$$P_d = P_{dio} + \lambda(L_F \times P_{di}) \quad (1)$$

Were, λ = Load parameter, L_F = Loading factor, P_{di} = Power demand, P_{dio} = Power demand original capacity. Equation 1 is derived from the power flow equation shown in equation 2.

$$P_d = P_{dio} + (1-\lambda)P_{di} \quad (2)$$

Equation 2 is the more generic power flow equation, but with some improvements as shown in equation 3.

$$P_d = P_{dio} + (1-\lambda)(P_{di} - P_{do}) \quad (3)$$

Where P_{di} = Increase in power due to load, P_{do} = Power consumed by the load at no load condition. Equation 3 is related to the Newton-Raphson approach to studying load flows, specifically the power mismatch equation, which is shown in equation 4.

$$\Delta P = P_d - P_e \quad (4)$$

Where, ΔP = Power mismatch, P_d = Delivered power, P_e = Scheduled power. Equation 4 is then expanded and linearized using Taylor series expansion, resulting in equation 5.

$$\Delta P = -\lambda\,(P_{di} - P_{do}) \quad (5)$$

Rearranging equation 5 to solve for P, we have equation 6 as in equation 2, which is then simplified to equation 7.

$$P_d = P_{dio} + (1 - \lambda)(P_{di} - P_{do}) \quad (6)$$

$$P_d = P_{dio} + \lambda(l_F \times P_{di}) \quad (7)$$

Equation 7 is then used to determine numerically the power demand (P_d) in each bus at different loading conditions (L_F) where the power demand original capacity (P_{dio}) is known and λ = 1. The tolerable loading margin is 5% of the known power demand original capacity (P_{dio}).

3. Results and Discussion

3.1 System Assessment Using Mathematical Model

Building on the work of Vasquez et al. (2017) on the analysis of voltage stability using the CPF method, this study investigated voltage stability in a 33kV distribution network. This study applied similar concepts to a real-world distribution network, demonstrating the practical application of voltage stability analysis.

The findings on the effectiveness of capacitor bank penetration in improving voltage stability aligned with Vasquez et al. (2017)'s results, which showed that adding shunt capacitors enhances voltage stability. The introduction of numerical loading margins and simulation of bus violations using ETAP software extended Vasquez et al. (2017)'s work, providing a more comprehensive analysis of voltage stability.

Both studies highlight the importance of reactive power compensation in maintaining voltage stability. However, this research provided additional insights into the impact of loading margins and bus violations on voltage stability, demonstrating the value of the approach in identifying potential vulnerabilities in the distribution network.

While Vasquez et al. (2017)'s work focused on a sample test system, this study's application to a real-world distribution network enhanced the relevance and applicability of the findings. The use of ETAP software for simulation also provided a more accurate representation of real-world scenarios, further justifying the contributions to the field of voltage stability analysis.

3.1.1 System Variable Assessments for 2% Loading Margin

Table 1 shows the predictive pattern for reliable and continuation power flow after being subjected to loading conditions. The violation was within the declared acceptable limit for system operating conditions. The mismatch was adequate for the network operating performance. The perturb load buses were immediately restored to follow the CPF of the existing network.

Table 1: The Load Parameters (P) and Incremental Load Parameters for System Components.

System component	Load parameter, P_{dio} (kW)	Load parameter increase, P_d (kW)
bus-1	182	185.64
bus-2	15.5	15.8
bus-3	174	177.48
bus-4	274	279.48
bus-5	375.08	382.58
bus-6	312	318
bus-7	80	81.6
bus-8	74	75.08
bus-9	51	52.02
bus-10	56	57.12

3.1.2 System Variable Assessments for 4% Loading Margin

Table 2 shows the system variability of a 4% loadability margin. The incremental loading condition was to assess the performance of the load buses for prediction and correction to evaluate voltage instability and sensitivity. The tendency to increase the existing capacity of the network, particularly active power, was to determine how the system can be restored after sudden increments. Increasing the 4% loadability condition on the network introduced mismatches between existing and loaded states, essentially buses 4, 5, and 6, respectively. However, the introduction of the capacitor bank (1×0.2kVAr, 1×0.4MVAr, and 1×0.6MVAr) enhanced network performances.

Table 2: The Load Parameters(P), Incremental Load Parameters for System Components.

System component	Load parameter, P_{dio} (kW)	Load parameter Increase, P_d (kW)
bus-1	182	189.28
bus-2	15.5	16.12
bus-3	174	180.96
bus-4	274	284.96
bus-5	375.08	390.08
bus-6	312	324.48
bus-7	80	83.2
bus-8	74	76.96
bus-9	51	53.04
bus-10	56	58.24

3.1.3 System Variable Assessments for 6% Loading Margin

This study also considered a 6% incremental loading condition to evaluate the continuation power flow analysis to determine minimum and maximum loadability limits with a view to causing system perturbation for estimating minimum and maximum capacity of the buses to eliminate large iteration count process.

Table 3 shows the distribution of 6% incremental loading condition for monitoring system behaviour of existing load and incremental load capacity with the view to evaluating the prediction of system mismatches and corrections. The violations were observed at buses 4, 5, and 6 while system normal operating CPF occurred at buses 1, 2, 3, 7, 8, 9, and 10. The simulation of the existing network was modelled in an ETAP version 19.0.1 to observe violated buses that need to be compensated using a capacitor bank as reactive power penetration.

Table 3: The Load Parameters (P), Incremental Load Parameters for System Components.

System component	Load parameter, P_{dio} (kW)	Load parameters increase, P_d (kW)
bus-1	182	192.92
bus-2	15.5	16.443
bus-3	174	184.44
bus-4	274	290.44
bus-5	375.08	397.85
bus-6	312	330.72
bus-7	80	84.80
bus-8	74	78.44
bus-9	51	53.04
bus-10	56	59.36

3.1.4 System Variable Assessments for 8% Loading Margin

Table 4 shows the numerical presentation of the study case under investigation at 8% load increase, which was now modelled and simulated in an ETAP environment, to examine system violations. The system was incrementally loaded up to 8% of the existing bus load capacity. The observed violations of the simulated network were buses 3, 4, 5, 6, and 7, while the unviolated buses that were restored after incremental loading were buses 1, 2, 8, 9, and 10). That is increasing the active power load affects the continuation of power flow from one bus to another. The mismatch buses that were affected are compensated using a capacitor bank.

Table 4: The Load Parameters (P), Incremental Load Parameters for System Components.

System component	Load parameter P_{dio} (kW)	Load parameters increase P_d (kW)
bus-1	182	196.56
bus-2	15.5	16.74
bus-3	174	187.92
bus-4	274	295.92
bus-5	375.08	405.09
bus-6	312	336.96
bus-7	80	86.4
bus-8	74	79.92
bus-9	51	55.08
bus-10	56	60.48

3.1.5 System Variable Assessments for 10% Loading Margin

Power system analysis is very crucial to the assessment of load-bus capacity performance in terms of robustness concerning incremental loading conditions. Table 5 shows the representation of the study case at 10% load increase, which was modelled in the ETAP for the simulation of the loaded buses to observe network behavior discrepancy.

The system was subjected to a 10% incremental loading condition to observe system discrepancy using the prediction and correction CPF technique, the system active power load increment includes violation of buses 2, 3, 4, 5, 6, and 7 while unviolated buses are 1, 2, 3, 8, 9, and 10. The system mismatches are within the accepted IEEE regulatory standard for minimum permitted change in load flow analysis. The pre-position of a power electronic controller (reactive power capacitor bank) was introduced to improve reliable power supply, particularly to the overload buses, to enhance performance.

Table 5: The Load Parameters (P), Incremental Load Parameters for System Components.

System component	Load parameter, P_{dio} (kW)	Load parameters increase, P_d (kW)
bus-1	182	200.2
bus-2	15.5	17.05
bus-3	174	191.4
bus-4	274	301.4
bus-5	375.08	412.59
bus-6	312	343.2
bus-7	80	88
bus-8	74	81.4
bus-9	51	56.1
bus-10	56	61.6

3.2 Simulation using Electrical Transient Analyzer Programme (ETAP)

This simulation was carried out with a view to analyzing and investigating the voltage and power profile of the study area under investigation. Figure 2 shows the existing study case modelled in the ETAP — simulated and violated buses are compensated using the reactive power controller (capacitor) for improved reliable power supply.

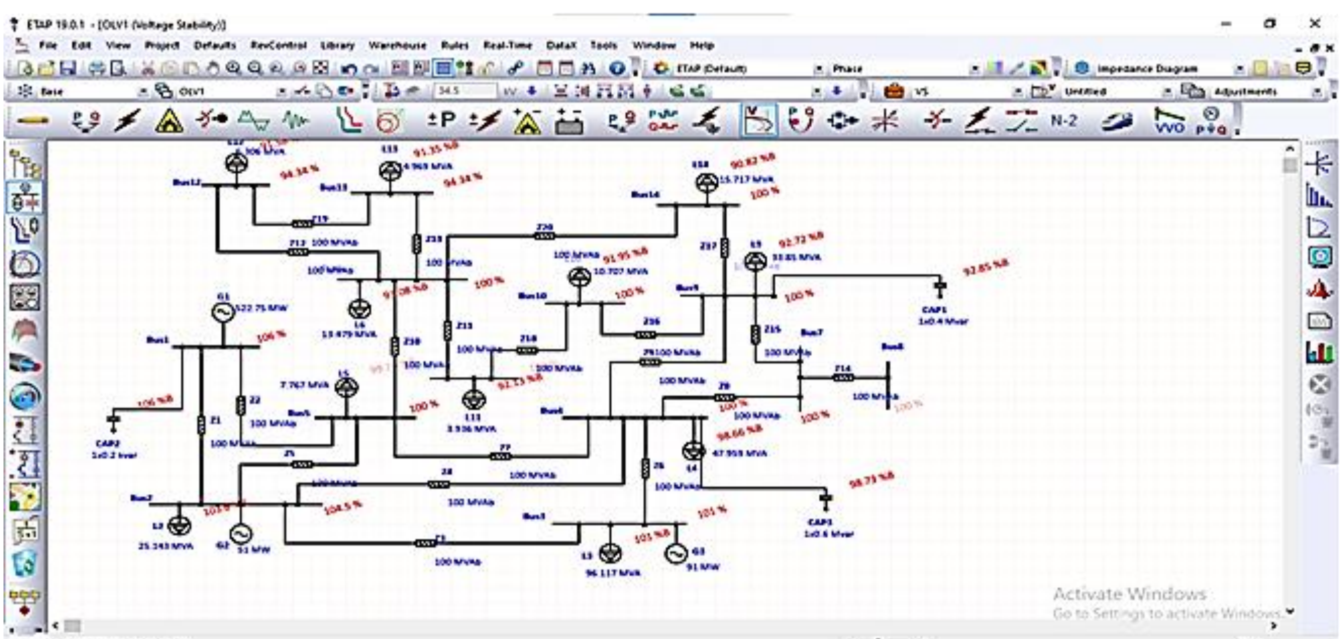

Figure 2: The Existing Study Case under Investigation, Modelled, Simulated, and Compensated with Capacitor Bank.

4.0 Conclusions

The following conclusions are drawn from the findings of this study.

i. Voltage stability has a significant focus on the power system dynamics. This provides the calculation for load margins to voltage collapse, particularly in static load flow equations. However, numbers of predictive indices can also be used to indicate the proximity of voltage collapse or instability.

ii. The introduction of numerical loading margins in the order of 2, 4, 6, 8, and 10% was considered to measure the violation of system vulnerability of the following buses: bus 1, 2, 6, 7, 8, 9, and 10. After penetration of capacitor bank, the system improved for reliable power supply.

iii. The simulation of the network bus violations of the system was determined using the penetration of the reactive power controller with capacitor sizes of 1×2KVAr, 1×0.4MVAr, and 1×0.5MVAr for system performance violation.

iv. Essentially, the violations of the system were modelled and simulated with a view to examining system overload, making the network experience power outages. This scenario prompted the penetration of FACTS device to enhance system performance and better power quality.

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