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Improved Voltage Stability in Nigerian Eastern Zone 132kV Transmission Network Using Continuation Power Flow and Static Var Compensator

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Abstract

The Eastern zone of Nigeria transmission network experiences frequent voltage instabilities issues due to a combination of high load demands, inadequate infrastructure, and network configuration complexities. These issues can lead to power outages and reduce the reliability of the electrical supply, affecting economic and social activities in the zone. To improve electricity access, the challenges need to be properly identified. This study aimed to stabilize the Nigerian eastern zone 132kV transmission network. The study explores the application of Continuation Power Flow (CPF) method to assess and improve the voltage stability margins of the zone electrical grid. The process involves modelling the 132kV transmission network and load profiles of the Eastern Zone. The network modelling and simulations was done using Electrical Transient Analyzer Program, ETAP20.0 software. The Q-V sensitivity analysis performed indicates that five critical buses were identified (Owerri: 1%Mvar, Umuahia: 0.816%Mvar, Abakaliki: 0.8%Mvar, Nsukka: 0.634%Mvar and Oji River: 0.620%Mvar) whose sensitivity shows proximity to voltage collapse as reactive power is adjusted in the system. The Q-V sensitivity analysis results obtained from the five critical buses; Owerri: 73.55%, Umuahia: 74.89%, Abakaliki: 77.25%, Nsukka 82.86% and Oji River: 84.63% whose operating voltage violates the statutory requirements limit of 85-105% for bus voltage of 132kV transmission network, according to Transmission Company of Nigeria, TCN grid code. Results from the CPF analysis indicate significant improvements in voltage stability margins when reactive power support was strategically deployed by addressing identified weaknesses and implementing recommended measures. However, when Static Var Compensators, SVC of 30 Mvar was deployed in the 132kV transmission network of the Nigerian eastern zone, the voltage profiles of the identified weakest buses were improved; Owerri: 92.9%, Umuahia: 92.6%, Abakaliki: 91.8 %, Nsukka 91.9% and Oji River: 87.8% to meet the operational regulatory requirements for bus voltage and to ensure reliable, resilience and efficient power grid. The total megawatts obtained with CPF was 1304.45MW before bifurcation point at 1229.66 MW. After inclusion of SVC, the total magawatts rose to 1405.42 MW before bifurcation point was experienced at 1295.19 MW. This study provides a foundation for future studies and practical interventions aimed at ensuring stable and reliable electricity for the Eastern zone growing population and industrial base, which can be replicated in other zones facing similar challenges.

Keywords: ***Continuation Power Flow (CPF), Static Var compensator (SVC), Electrical Transient Analyzer Program (ETAP)***.

INTRODUCTION

The Nigerian national electricity grid is a network of generation, distribution, and Transmission. In Nigeria, private companies are allowed to generate and distribute electricity. These companies are saddled with the responsibility of carrying out the functions relating to the generation, transmission, trading, distribution, and bulk supply as well as resale of electricity in the country (Oseni, 2011). Electricity has been in existence in Nigeria for more than two decades with various reforms of the electricity sector but its development and availability to Nigerians have been a challenge.

Voltage stability is a critical aspect of power system operation, ensuring that the network can maintain acceptable voltages at all buses even under varying load conditions and disturbances. The nation's electricity utility grid comprises of three (four after 2012) hydro power plants and six thermal generating stations with total installed capacity of 10,942 MW but the production has never exceeded 3000 MW. To improve electricity access, the challenges need to be properly identified. Nigeria's electricity access has been low for a very long time with no improvement in sight. Energy availability is crucial for a sustainable development in an economy while its non-availability may present some adverse effect which are detrimental to the society at large. Energy cannot be substituted in key areas of the economy such as industries, agriculture, transportation, and service sector. With the increase in the world population, standard of living and rapid industrialization, the future energy is expected to grow (Oyedepo, 2012).

The Nigerian Eastern zone 132kV transmission network is characterized by impoverished generation, poor infrastructure, aged equipment, inadequate transmission capacity and poor maintenance culture. The above inadequacies together with other usual power system contingencies (change in loads, switching actions, loss of generation faults etc) have continued to impact negatively on the stability and reliability of the power networks in the Eastern zone of Nigeria. Africa is indeed endowed with the widest possible range of energy resources for electricity generation such as coal, natural gas, petroleum, solar, hydro, geothermal, nuclear, etc. but the continent's power sector remains severely underdeveloped and the energy consumptions are relatively low (Economic Commission for Africa (2004) in Mayo, 2012).

The implications of sustained poor system security and instabilities on the power network is that the power network becomes prone to frequent and long outages, loss of loads, cascaded outages, and eventual voltage collapse. Long and frequent outages, or worse still blackouts, have adverse effects on both system equipment and users. Inadequate power supply impacts negatively on socio-economic development of the end users. On the other hands, frequent power interruptions can lead to failure of some system equipment, thereby increasing cost of operation of the system; (Aneke & *et al.;* 2021, Aneke & Ngang 2021; Ezekiel & Engla 2019).

Objectives

The study specific objectives are to:

i. Study and model the existing 132kV grid network of the Eastern Zone.
ii. Formulate governing equations and simulate existing study case.
iii. Determine critical lines and buses in the existing 132kV grid network that may result to voltage collapse or instability using CPF.
iv. Determine voltage instability of the existing 132kV grid network using Q-V sensitivity analysis.
v. Determine real and reactive power loadability limits and its impacts to the point of voltage collapse in the existing 132kV grid network using Q-V sensitivity analysis.
vi. Evaluate the existing 132kV network for improvement using Continuation Power flow with penetration of Static Var compensator.

II. LITERATURE REVIEW

The transmission system is distinctly different, in both its operation and characteristics, from the distribution system. Whereas the latter draws power from a single source and transmits it to individual loads, the transmission system not only handles the largest blocks of power but also the system. The main difference between the transmission system and the distribution system shows up in the network structure. The former tends to be a loop structure and the latter generally, a radial structure.

The modern power distribution network is constantly being faced with an ever-growing load demand. Distribution networks experience distinct change from a low to high load level everyday. In certain industrial areas, it has been observed that under certain critical loading conditions, the distribution system experience voltage collapse. Kundur *et al.* (2014) have reported the actual recordings of this phenomenon in which system voltage collapses periodically and urgent reactive compensation needs to be supplied to avoid repeated voltage collapse.

Voltage collapse has become one of the important issues in today's highly developed power systems as several major blackouts in recent years could be traced to voltage collapse. Past incidents of voltage collapse have caused millions of dollars of equipment damage and have produced service interruptions to thousands of customers at a time. One method to prevent voltage collapse from occurring requires online voltage monitoring tools to predict the point of collapse and make corrective actions before the system enters critical condition. However, accurate estimation of the voltage collapse point proves to be a challenge.

Literature survey shows that a lot of work has been done on the voltage stability analysis of transmission systems, but hardly any work has been done on the voltage stability analysis of radial distribution networks. Okoro (2017) studied the voltage stability analysis of radial networks. They have represented the whole network by a single line equivalent. The single line equivalent derived by these authors is valid only at the operating point at which it is derived. It can be used for small load changes around this point. However, since the power equations are highly nonlinear, even in a simple radial system, the equivalent would be inadequate for assessing the voltage stability limit. Also, their techniques do not allow for the changing of the loading pattern of the various nodes which would greatly affect the collapse point.

III. Materials and Method

Materials

Materials used for the study include:

i. Single line diagram of the existing132kV transmission network of the Nigerian eastern zone showing the installed capacity of transmission substations, rating of the power transformers connected to the stations and load capacity.

ii. Bus and Line data of the existing 132kV transmission network of the Nigerian eastern zone under study.

iii. Static Var compensator for improving the loading margin of the buses closer to the point of voltage collapse.

iv. Electrical Transient Analyzer Program, ETAP version 20.0 software for modeling and simulations of the 132kV transmission network of the Nigerian Eastern Zone.

Method

The method used in this study is the Continuation Power Flow, CPF. Continuation power flow is an advanced power flow analysis technique that extends the traditional power flow methods. It tracks how system solutions changes as the system load or generation is increased.

Description of Existing Network

The existing Nigerian eastern zone network under study consist of four (4) 132kV substations of capacities 2X150MVA, (1x120MVA & 1x90MVA), 2X150MVA and 1X150MVA duly linked to 330kV transmission line at Aloaji, Onitsha, Enugu and Ugwaji respectively. The network is managed and controlled by TCN which is responsible for monitoring the grid operations in all the 330kV and 132kV transmission networks of Nigeria. The data used for this work were obtained from the logbooks and up to date records from the substations under study. Verbal interaction and oral consultation were also carried out with the most senior and principal Engineers of both the staff of Aloaji, Onitsha, Enugu, and Ugwaji respectively. The interview gave an in-depth knowledge on the current state of the network under study. The tool used for designs and simulations is Electrical Transient Analyzer Program, ETAP20.0 software. Figure 1 below shows the single line diagram of the Eastern zone network of Nigeria.

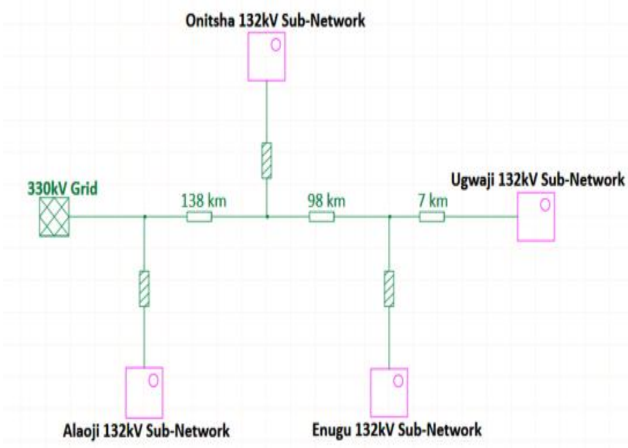

Figure1: Single Line Diagram of the Eastern Zone of Nigerian 330/132kV Grid Network

Applications of Continuation Power Flow with Parameter, λ and Loading Factor

Continuation Power Flow method was deployed to model and obtain the loading margin of the Eastern Zone 132kV transmission network. In the analysis, Static Var Compensator was embraced after bifurcation point for the improvement of voltage stability in the Eastern zone network.

1st Load Increase with load parameter λ = 1.2 and loading factor of 0.02p.u

From equation (3.22), $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$:

Aba: P_{Di} = 89.566 + 1.2 (0.02 x 89.566) = 91.72 MW

Abakaliki: P_{Di} = 77.646 + 1.2 (0.02 x 77.646) = 79.51 MW

Agu Awka: P_{Di} = 42.768 + 1.2 (0.02 x 42.768) = 43.79 MW

Alaoji: P_{Di} = 119.953 + 1.2 (0.02 x 119.953) = 122.83 MW

GCM: P_{Di} = 44.228 + 1.2 (0.02 x 44.228) = 45.89 MW

New Heaven: P_{Di} = 80.654 + 1.2 (0.02 x 80.654) = 82.59 MW

Nibo Awka: P_{Di} = 70.145 + 1.2 (0.02 x 70.145) = 71.83 MW

Nkalagu: P_{Di}= 57.512 + 1.2 (0.02 x 57.512) = 58.89 MW

Nsuka: P_{Di} = 66.385 + 1.2 (0.02 x 66.385) = 67.97 MW
NEW: P_{Di} = 54.988 + 1.2 (0.02 x 54.988) = 56.31 MW
Oji River: P_{Di} = 69.244 + 1.2 (0.02 x 69.244) = 70.91 MW
Onitsha: P_{Di} = 44.280 + 1.2 (0.02 x 44.280) = 44.34 MW
Owerri: P_{Di} = 82.418 + 1.2 (0.02 x 82.418) = 84.40 MW
Ugwaji: P_{Di} = 51.005 + 1.2 (0.02 x 51.005) = 52.23 MW
Umuahia: P_{Di} = 101.169 + 1.2 (0.02 x 101.169) = 103.60 MW
Total 1076.77 MW

The 2nd -9th Load Increase with load parameter λ = 1.2 and loading factor of 0.04p.u - 0.18 p.u respectively were all calculated and inculcated in accordance.

10th Load Increase with load parameter λ = 1.2 and loading factor of 0.20p.u

From equation (3.22), $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$:
Aba: P_{Di} = 89.566 + 1.2 (0.20 x 89.566) = 111.06 MW
Abakaliki: P_{Di} = 77.646 + 1.2 (0.20 x 77.646) = 96.28 MW
Agu Awka: P_{Di} = 42.768 + 1.2 (0.20 x 42.768) = 53.03 MW
Alaoji: P_{Di} = 119.953 + 1.2 (0.20 x 119.953) = 148.74 MW
GCM: P_{Di} = 44.228 + 1.2 (0.20 x 44.228) = 54.85 MW
New Heaven: P_{Di} = 80.654 + 1.2 (0.20 x 80.654) = 100.01 MW
Nibo Awka: P_{Di} = 70.145 + 1.2 (0.20 x 70.145) = 86.98 MW
Nkalagu: P_{Di} = 57.512 + 1.2 (0.20 x 57.512) = 71.32 MW
Nsuka: P_{Di} = 66.385 + 1.2 (0.20 x 66.385) = 82.32 MW
NEW: P_{Di} = 54.988 + 1.2 (0.20 x 54.988) = 68.19 MW
Oji River: P_{Di} = 69.244 + 1.2 (0.20 x 69.244) = 85.86 MW
Onitsha: P_{Di} = 44.280 + 1.2 (0.20 x 44.280) = 54.91 MW
Owerri: P_{Di} = 82.418 + 1.2 (0.20 x 82.418) = 102.20 MW
Ugwaji: P_{Di} = 51.005 + 1.2 (0.20 x 51.005) = 63.25 MW
Umuahia: P_{Di} = 101.169 + 1.2 (0.20 x 101.169) = 125.45 MW
Total 1304.45 MW

11th Load Increase with load parameter λ = 1.2 and loading factor of 0.22p.u

From equation (3.22), $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$:
Aba: P_{Di} = 89.566 + 1.2 (0.22 x 89.566) = 113.21 MW
Abakaliki: P_{Di} = 77.646 + 1.2 (0.22 x 77.646) = 98.14 MW
Agu Awka: P_{Di} = 42.768 + 1.2 (0.22 x 42.768) = 54.06 MW
Alaoji: P_{Di} = 119.953 + 1.2 (0.22 x 119.953) = 151.62 MW
GCM: P_{Di} = 44.228 + 1.2 (0.22 x 44.228) = 55.90 MW
New Heaven: P_{Di} = 80.654 + 1.2 (0.22 x 80.654) = 101.94 MW
Nibo Awka: P_{Di} = 70.145 + 1.2 (0.22 x 70.145) = 88.66 MW
Nkalagu: P_{Di} = 57.512 + 1.2 (0.22 x 57.512) = 72.70 MW
Nsuka: P_{Di} = 66.385 + 1.2 (0.22 x 66.385) = 83.91 MW
NEW: P_{Di} = 54.988 + 1.2 (0.22 x 54.988) = 69.50 MW
Oji River: P_{Di} = 69.244 + 1.2 (0.22 x 69.244) = 87.52 MW
Onitsha: P_{Di} = 44.280 + 1.2 (0.22 x 44.280) = 55.97 MW
Owerri: P_{Di} = 82.418 + 1.2 (0.24 x 82.418) = 104.18 MW
Ugwaji: P_{Di} = 51.005 + 1.2 (0.22 x 51.005) = 64.47 MW
Umuahia: P_{Di} = 101.169 + 1.2 (0.22 x 101.169) = 127.88 MW
Total 1229.66 MW

Here bifurcation point was experienced at **1229.66 MW** without SVC.

IV. Results and Discussion

Results of Voltage Stability Sensitivity

The CPF method was applied to assess the voltage stability of the Nigerian Eastern Zone 132kV transmission network. The analysis helped determine the maximum loading point where the system is about to experience voltage collapse.

Table 1: Q-V Sensitivity Analysis

Bus ID	Bus Name	Nominal (kV)	Q-V Sensitivity	Rank
1	Aba	132	0.259	12
2	Abakaliki	132	0.806	3
3	Agu Awka	132	0.558	6
4	Alaoji	132	0.221	14
5	GCM	132	0.304	9
6	Enugu	132	0.210	15
7	Nibo Awka	132	0.513	7
8	Nkalagu	132	0.353	8
9	Nsukka	132	0.639	4
10	NEW	132	0.297	10
11	Oji River	132	0.619	5
12	Onitsha	132	0.287	11
13	Owerri	132	1.000	1
14	Ugwaji	132	0.247	13
15	Umuahia	132	0.828	2

Table 1 shows the result of voltage stability sensitivity due to parameter changes in the existing eastern zone 132kV grid network**.** By computing Q-V sensitivities on every bus in the system, the system voltage stability can be ascertained and buses near voltage collapse can be identified. If the system is voltage stable, the value of the Q-V sensitivity will be positive for all buses. However, if the system is voltage unstable, the value of the Q-V sensitivity will be negative for at least one bus. Table 1 shows the existing eastern zone 132kV grid network is voltage stable as all values of Q-V sensitivity are positive which is an indication that voltage at any bus in the existing eastern zone 132kV grid network will increase if reactive power is injected into the same bus. Figure 2 shows the plot of bus sensitivity to parameter change in the existing eastern zone 132kV grid network. The ranking is provided in an ascending order to let the user know the sensitivity of the bus voltage as reactive power is adjusted in the system. A quick look at the plot shows five (5) critical buses highlighted in red whose sensitivity need to monitor are Owerri: 1.000%Mvar, Umuahia: 0.816%Mvar, Abakaliki: 0.800%Mvar, Nsukka: 0.634%Mvar, Oji River: 0.620%Mvar.

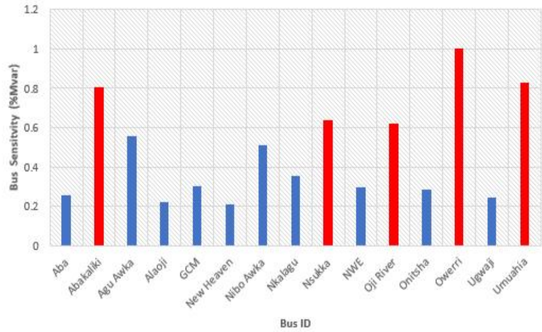

Figure 2: Voltage Stability Sensitivity vs Bus ID of the Eastern zones 132kV Grid Network

Table 2: Bus Voltage Profile

Bus ID	Bus Name	Nominal (kV)	Operating (kV)	Operating (%)
1	Aba	132	126.57	95.89
2	Abakaliki	132	101.97	77.25
3	Agu Awka	132	123.79	93.78
4	Alaoji	132	128.11	97.05
5	GCM	132	119.46	90.50
6	Enugu	132	130.85	99.13
7	Nibo Awka	132	121.73	92.22
8	Nkalagu	132	126.43	95.78
9	Nsukka	132	109.38	82.86
10	NEW	132	126.64	95.94
11	Oji River	132	111.71	84.63
12	Onitsha	132	119.87	90.81
13	Owerri	132	97.09	73.55
14	Ugwaji	132	128.26	97.17
15	Umuahia	132	98.85	74.89

A quick look at Table 2 shows that all buses in the existing Eastern zone 132kV grid network are within the voltage statutory limit except for Owerri: 73.55%, Umuahia: 74.89%, Abakaliki: 77.25%, Nsukka 82.86% and Oji River: 84.63% whose operating voltage violated the voltage statutory limit of 85-105% for 132kV network according to TCN grid code for bus constraints.
Figure 3 shows the plot of voltage profile in the existing eastern zone 132kV grid network with five (5) critical buses where voltage collapse or instability may occur are highlighted in pink.

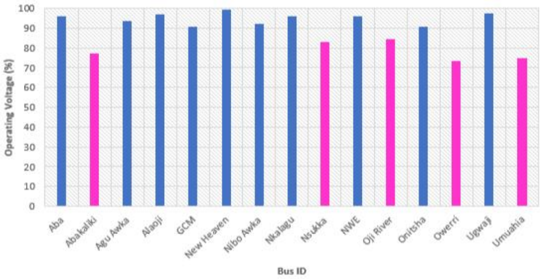

Figure 3: Operating (%) Voltage Profile Vs Bus ID of the Eastern zone 132kV Grid Network

Figure 4, 5 and 6 shows the reactive power-voltage curve of Bus 13, Bus 15, and Bus 2 respectively. The graphs show the improvement achieved after optimal placement of static var compensator on the vulnerable buses and showcases the maximum voltage loadability of the buses.

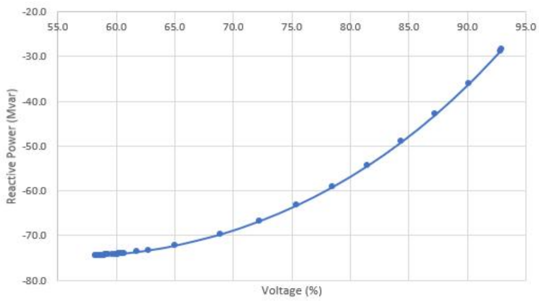

Figure 4: Reactive Power Vs Voltage Curve for Bus13 (Owerri Improved System)

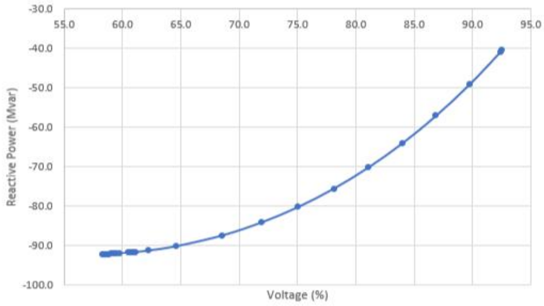

Figure 5: Reactive Power Vs Voltage Curve for Bus15 (Umuahia Improved System)

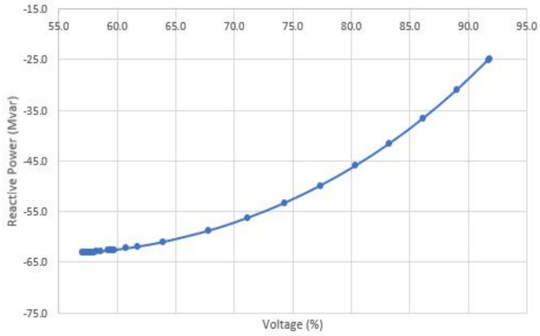

Figure 6: Reactive Power Vs Voltage Curve for Bus2 (Abakaliki Improved System)

V. Conclusions

The study examined improved voltage stability analysis in the Nigerian Eastern Zone 132kV transmission network using continuation power flow (CPF).
Following the completion of the research, the study successfully addressed the objectives set out from the beginning of the research. CPF helps identify voltage stability limits by continuously tracking the power flow solution as load or generation varies, providing insights into system stability margins and potential voltage collapse points. The network modelling and simulations carried out was successful through Electrical Transient Analyzer Program (ETAP 20.0).

The Q-V sensitivity analysis carried out identified five critical buses whose sensitivity shows proximity to voltage collapse as reactive power is adjusted in the system, which is an indication that the voltage will increase if reactive power is injected into the same buses. The five critical buses were the Owerri: 1%Mvar, Umuahia: 0.816%Mvar, Abakaliki: 0.8%Mvar, Nsukka: 0.634%Mvar and Oji River: 0.620%Mvar. The sensitivity analysis show that Owerri: 73.55%, Umuahia: 74.89%, Abakaliki: 77.25%, Nsukka 82.86% and Oji River: 84.63% which violates the Transmission Company of Nigeria (TCN) grid code regulatory requirements limit of 85-105% for bus voltage of 132kV transmission network. when static var compensator of 30 Mvar was deployed in the existing network, the voltage profile of the identified weakest buses were all improved; Owerri: 92.9%, Umuahia: 92.6%, Abakaliki: 91.8 %, Nsukka 91.9% and Oji River: 87.8% to meet the operational regulatory requirements by TCN for 132kV bus voltage.

The analysis shows that inculcating Continuation Power Flow for voltage stability assessment and the penetration of Static Var Com;pensators in the Nigerian Eastern Zone 132kV transmission network significantly increases voltage stability to handle higher loads, and improves system performance.

Finally, the assessment of the existing 132kV network were improved from 1304.45 MW without SVC to 1405.42 MW after the inclusion of the reactive power capacity (measure in VAR) to meet up the operational regulatory requirements for bus voltage of 132kV and to ensure reliable and efficient power grid of the Nigeria Eastern Zone.

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RECOMMENDATIONS

From the results obtained in this study, the application of the following recommendations will improve loadability by optimizing voltage level, provide reactive power support, and enhancing the overall stability and efficiency of the existing 132kV transmission network of the Nigerian eastern zones.

1. Incorporating the achieved models involving Q-V sensitivity analysis, continuation power flow and Static Var Compensators into the existing 132kV transmission network of the Nigerian eastern zone will improve voltage stability and reliability analysis.
2. Enhancing the Voltage Stability Margin (VSM) with Static Var Compensators at the identified weak buses for better reactive power injection in the existing network of the Eastern zone will improve voltage stability.
3. Participation of other power system components such as generators and transmissions line to voltage stability should be investigated and their sensitivities determined.
4. on-load tap changers (OLTCs) should be installed inside the transformer main tank for adequate voltage output.

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