Voltage Stability Evaluation in the Nigeria 44 Bus Grid Network using Modal Analysis

E. N. Aneke[1*], B. E. Ibekwe[1], J. C. Iyidobi[1] and E. N. C. Okafor[2]

[1]*Electrical and Electronics Engineering Department, Enugu State University of Science and Technology, Agbani, Enugu PMB 01660, Nigeria.*
[2]*Electrical and Electronics Engineering Department, Federal University of Technology, Owerri, Imo State PMB 1526 Nigeria.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

This paper focused on the application of modal analysis method to determine the voltage stability of the Nigeria 44 bus 330kV transmission grid network and to determine the network's weakest buses. Modal method calculates the smallest eigenvalue and all the associated eigenvectors of the reduced Jacobian matrix, J_R using steady state mode. The network model was developed in PSAT-MATLAB and load flow was performed on the network. Results and analysis showed that the Nigeria 44 Bus grid network was found to be unstable as the modal analysis revealed the presence of eigenvalue with a negative real part. Gombe, Damaturu and Yola buses were also discovered to be the vulnerable buses since their voltage profile fell below the IEEE standard voltage level of (0.95-1.05) pu. Yola bus was spotted as the weakest bus based on the analysis of the participating factors.

1. INTRODUCTION

The increase in population and industrial activities of several countries in the world has resulted in the increase in energy consumption and utilization in various nations of the world. This has resulted to difficulty in meeting reactive power requirement especially under planned or

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*Corresponding author: Email: ENG.Ezekiel.Aneke@ieee.org;

sudden changes in voltages, and hence maintaining the bus voltage within acceptable limits has been a major hurdle in the power system [1]. The need for steady and adequate supply of electrical power in Nigeria has risen tremendously due to increase in population, industrial activities and increases in the use of electrically powered gadgets. In order to meet these challenges, power system networks have been developed and are being modified on continuous basis.

The grid system is usually the platform that provides interconnection of network of transmission lines to load centres throughout the country. Due to proximity of fuel and other requirements for generation, generating stations are usually situated thousands of kilometres from one another and from load centres. The power obtained from generating stations uses the grid system to transmit energy to load centres so that electrical energy can be accessible to customers.

There are challenges in the area of planning, construction, operation and control of a complex interconnection of electric power system networks. Adequate knowledge, experience and engineering skills are required to properly handle these challenges adequately.

The Nigeria 330kV transmission network is characterized by poor generation, poor infrastructure, aged equipment, inadequate transmission capacity and poor maintenance culture. The above inadequacies together with other usual power system contingencies (such as change in loads, switching actions, loss of generation faults etc) have continued to impact negatively on the stability and security of the power networks. 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 users. On the other hand, frequent power interruptions can lead to failure of some system equipment, thereby increasing cost of operation of the system.

Considering the above undesirable impacts of voltage instability and blackouts on the socio-economic development of any society; it is important that the voltage stability of any grid network is constantly evaluated and monitored to ensure that the system's voltage profiles at all buses never operate outside the IEEE acceptable range of 0.95pu to 1.05pu. Usually, power system operators have had to deal more with low voltage profiles than over voltages. It is therefore common to see one form of reactive power compensation or the other being implemented in power grid networks. Previous studies in power systems have revealed that network compensation is more effective when implemented at the weakest bus(s) in the network. Determination of the weakest bus(s) in a network has therefore become one of the key steps needed to achieve an effective reactive power compensation and voltage stability improvement in a grid network [2].

Fortunately, dynamic voltage stability is evaluated by observing the eigen-value of the linearized system as the power system is increasingly loaded. Instability occurs when a pair of complex eigen-value crosses to the right half plane. This system represents the dynamic voltage instability [3]. Modal analysis technique has therefore proven to be a reliable tool for computing and evaluating voltage stability with high level of accuracy and precision. One unique advantage of this technique is that with its capacity to give accurate insight on the participating factors; modal analysis is able to reveal the most vulnerable buses in the network. This is key information needed for a successful implementation of network compensation that restores system stability after a disturbance.

This research work is therefore targeted on voltage stability evaluation and determination of weakest buses in the Nigeria 44 bus 330kV transmission grid Network using modal analysis.

2. THEORY/REVIEW OF RELATED LITERATURE

The power system is generally made up of synchronous machines operating in synchronism. For the power systems to run continuously, it is expected that they retain their synchronism under steady-state conditions. When the system experiences disturbance, it creates a restoring force at which it becomes stable or normal. In other words, the capacity of the power system to maintain its stability to its normal state after being disturbed is known as stability.

However, it is observed that systems continuously experience a small magnitude of power/voltage fluctuations. In other words, in order to assess the stability of a system subjected to a specified disturbance, there is a need to assume that the system is initially in an exact steady-state operating condition. This condition gives provision for Modal analysis used for this research.

Power system stability is classified into three basic types. They are rotor angle stability, frequency stability, and voltage stability.

Rotor angle stability is the ability of interconnected synchronous machines of the power system network to maintain its synchronism, i.e., to be in unison with the phase of alternating current producing them, after being subjected to a disturbance.

Frequency stability is the ability of a power system to retain its steady frequency after a severe system upset that result in an imbalance between generated power and load.

Voltage stability is the ability of a power system to maintain steady voltages at all buses in the system after being affected by the disturbance resulting from a given prior operating condition [4,5,6] proposed an evaluation method for carrying out static and transient voltage stability analysis in electric power systems. In their analysis, they integrated ten voltage stability indices to form a multi-index system to overcome the limitations associated with single-index in the evaluation of voltage stability. Using the wind farms of an actual power grid in Hami City, China they obtained a result and analysis that show that the proposed study is an efficient and innovative means for identifying the weakest bus in power systems.

[7] proposed the analysis and the use of modal based method of estimating voltage stability of a bulk power systems. In their work, they used the Jacobian matrix to determine the eigenvalues needed for the evaluation of the voltage stability of the power system network. The method was implemented on IEEE 14 bus system and the various eigenvalues were calculated and one with the lowest magnitude value used to determine the participating factors that indicated buses that will contribute highest total voltage instability of the system.

[8] proposed a Continuation Power Flow (CPF) method used to estimate the voltage stability of the Khouzestan power system in Iran. The method assessed both the normal and for contingency operations of the power system. Also, they used Modal analysis to complete the voltage stability evaluation of the system at a peak load condition. The calculation results determined the weakest bus where corrective action may be required for voltage support.

[9] presented a voltage stability estimation method for power systems with load uncertainty. In their work, boundary fixing method is used to repair damaged load elements and determine the load distribution. Low limit of load interval is assigned to be the current operation point while the available load relic is shared between individual bus using the lower boundary of total load gotten from its top boundary. This method estimates the riskiest routes when there is continuous flow of power at the current operating point. The efficiency and simplicity of this method are observed on IEE14-bus and 57-bus system.

[10] used Monte Carlo simulation (MCS) to determine voltage stability indices in power systems. They simulated the increase in load of all load buses with the required random numbers and their probability which helps to calculate the indices with repeated trials. Line stability index (L_{mn}), line stability factor (LQP), Fast voltage stability index (FVSI) are the indicators used in determining the capability of reactive power loading at the given bus position. A 5-bus system was used to demonstrate the stability of the system, and the results obtained shows that the weakest bus of the system can be identified.

3. VOLTAGE STABILITY DETECTION METHODS AND EVALUATION TECHNIQUES

An indicator is needed to interpret the definitions in a measure that can be evaluated, in order to know if the voltage of a system is stable or not. There are various tools that can be used to evaluate or indicate if the voltage of a system is stable or not and how near the system is to instability. Some of the methods in power system engineering literature are discussed below.

3.1 Impedance-based Methods

The most popular impedance-method depends on the point of maximum power transfer [11], it states that:

$$|Z_{load}| = |Z_{line}| \qquad (1)$$

Where,

Z_{load} = the equivalent complex impedance of the load.
Z_{line} = the equivalent complex impedance of the line.

In the two impedances, their ratio provides a means to determine the distance to the point of maximum power transfer. The major differences between the two are the determination of their equivalent impedances.

3.2 Continuation Power Flow (CPF) based Methods

Continuation load flow analysis is a static voltage stability assessment method that suitably modifies conventional load flow equations to become stable in the singular point of the P-V curve and therefore capable to calculate both upper and lower part of the P-V curve. A continuation parameter is defined (often the load demand) and the power flow equations are solved for increasing values of this parameter. This method gives voltage stability in terms of the parameter called loading margin. Loading margin is the allowable load increase from the base load condition before the system enters voltage collapse. The procedure involves first, a prediction of the solution for the next value of the continuation parameters is made; secondly, the prediction is corrected based on the actual load flow solution. The requirement of the corrector step is to correct the linear prediction of non-linear equations. For the correction step, a parameter called the continuation parameter is fixed. This step is crucial as it forces the system to come back to the solution [12].

4. MODAL/EIGENVALUE ANALYSIS

A system's voltage was assumed to be stable if the eigenvalues of J_R were all positive. However, in the analysis of dynamic systems the eigenvalues with negative real parts were stable. The interaction between system voltage stability and eigenvalues of the J_R matrix is best understood by relating the eigenvalues with the V-Q sensitivities of each bus (which must be positive for stability). J_R can be taken as a symmetric matrix and therefore the eigenvalues of J_R were close to being purely real. If all the eigenvalues were positive, J_R was positive definite and the V-Q sensitivities were also positive, indicating that the system was voltage stable. The system was considered voltage

unstable if one or more of the eigenvalues was found to be negative. A zero eigenvalue of J_R means that the system was on the point of voltage instability. In essence, small eigenvalue of J_R determines the proximity of the system to being voltage unstable [13]. There was no need to evaluate all the eigenvalues of J_R of a large power system because it was known that once the minimum eigenvalues became zeros the system Jacobian matrix became singular and voltage instability occurred. Therefore, the eigenvalues that were vital were the critical eigenvalues of the reduced Jacobian matrix J_R. This implied that the smallest eigenvalues of J_R were taken to be the least stable nodes of the system. The rest of the eigenvalues were not considered because these nodes were considered to be vital in the determination of stability of the system.

The modal analysis concept is fundamentally a static method, and is a special tool for executing voltage stability analysis. The modal analysis method is employed to identify the weakest bus by evaluation of the participation factor and sensitivity factor. According to [3], the power flow Jacobian matrix is given as stated below:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ |\Delta V| \end{bmatrix} \qquad (2)$$

Where

ΔP = incremental change in bus real power
ΔQ = incremental change in bus reactive power
$\Delta\theta$ = incremental change in bus voltage angle
ΔV = incremental change in bus voltage magnitude

Power system voltage stability is largely affected by the reactive power.

Keeping real power as constant at each operating point, the Q-V analysis can be carried out.

Assuming that $\Delta P = 0$ (For calculating V-Q sensitivities, it follows from equation 2, the reduced Jacobian matrix as obtained is expressed as:

$$\Delta J_R = \left[J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{PV} \right] \qquad (3)$$

$$\Delta Q = J_R \Delta V \qquad (4)$$

$$\Delta V = J_R^{-1} \Delta Q \qquad (5)$$

Hence,

$$\Delta V = J_R^{-1}.\Delta Q \qquad (6)$$

The matrix J_R represents the linearized relationship between the incremental changes in bus voltage (ΔV) and bus reactive power injection (ΔQ). It's well known that, the system voltage is affected by both real and reactive power variations. The eigenvalues and eigenvectors of the reduced order Jacobian matrix J_R are used for the voltage stability characteristics analysis

Now Putting in 6.

$$J_R = \xi \Lambda \eta \qquad (7)$$

Where

ξ = right eigenvector matrix
η = left eigenvector matrix
Λ = diagonal eigenvalue matrix
Then, inverting equation 7 produces

$$J_R^{-1} = \xi \Lambda^{-1} \eta \qquad (8)$$

And substituting equation 8 in equation 6 gives

$$\Delta V = \xi \Lambda^{-1} \eta \Delta Q \qquad (9)$$

$$\Delta V = \sum_i \frac{\xi_i \eta_i}{\delta_i} \Delta Q \qquad (10)$$

Where η_i is the ith row of the left eigenvector of J_R, and ξ_i is the ith column of the right eigenvector. The ith mode of the Q-V response is defined by the ith eigenvalue δ_i, and the corresponding right and left eigenvectors ξ_i and η_i. Equation (9) can be presented as

$$\eta \Delta V = \Lambda^{-1} \eta \Delta Q \qquad (11)$$

By defining $v=\Lambda^{-q}$ as the vector of modal voltage changes and as the vector of modal reactive power changes, the first-order equations can be broken down as

$$v = \Lambda^{-1} q \qquad (12)$$

Therefore, for the ith mode, we have

$$v_i = \frac{1}{\delta_i} q_i \qquad (13)$$

At the instant where $\delta_i > 0$, the ith modal voltage and the ith modal reactive power changes align in the same direction, indicating voltage stability of the system; whereas $\delta_i < 0$ denotes the instability of the system. The magnitude of δ_i signifies an average level of instability of the ith modal voltage. The smaller the magnitude of a positive δ_i, the nearer the ith modal voltage to experience instability.

4.1 Network Characterization

In order to characterize the network, a Load flow study was performed on the network with the data of the NNG 330KV 44 bus transmission network already obtained. Load flow computes the base values of the network's variables including: bus voltage magnitude and angles, real and reactive power losses, real and reactive power flows in the lines. Also, Load flow must be carried out before any modal analysis technique can be applied.

The load-flow problem is non-linear; hence the solution obtained using Power System Analysis Tool (PSAT) applies iterative numerical method of Newton-Raphson, its flow chat is as shown in appendix2. One advantage of the Newton-Raphson method (NR) is the speed of convergence especially in very large power system networks. The problem of power flow envisages what the electrical state of the network will be when the system is placed on a specified loading situation. The outcome of the power flow is the voltage magnitude and the angle of each of the system nodes. These bus voltage magnitudes and angles form the system state variables [3].

The need for developing this model cannot be over stressed. One, it is used in the running of load flow on the network. Also, the eigenvalue analysis will be carried out using the network model. The Simulink model was developed and configured to reflect the values specified in bus Data and Line data. A Simulink model of the test network in PSAT-Matlab is shown in Fig. 1.

System eigenvalues are determined by running modal analysis in PSAT. This can be done by loading the Simulink model of the system into the PSAT environment and then performing load flow after a successful extraction of the bus and line data from the model by PSAT. Modal analysis is then implemented by pressing the relevant button in the PSAT environment. The eigenvalues and its plot for the network at normal working condition are presented in result and analysis section.
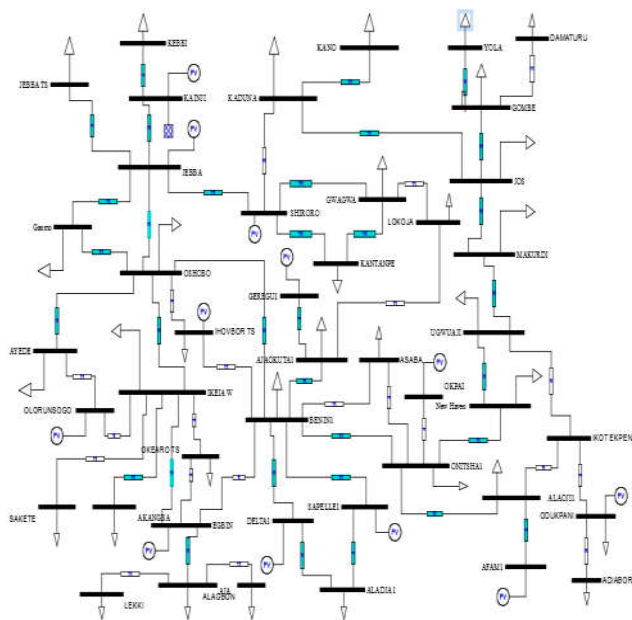
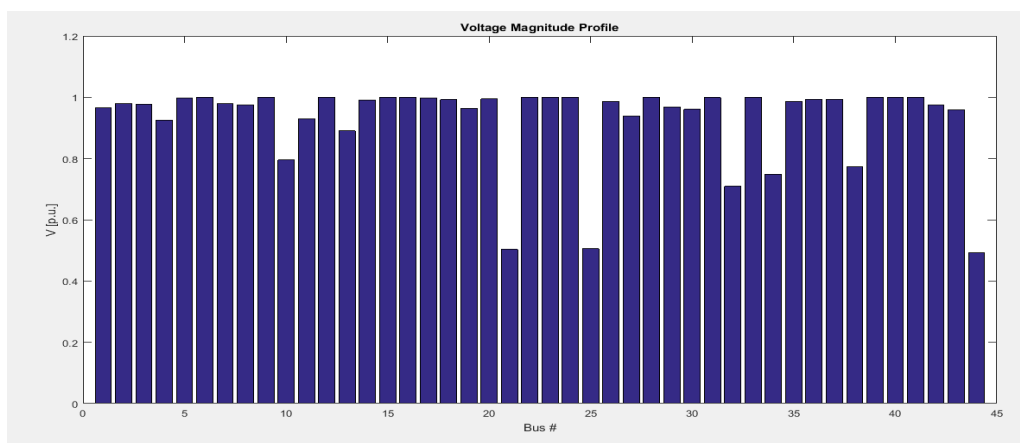**Fig. 1. Psat Simulink Model of the Nigeria 44bus Grid Network**

Fig. 2. Plot of Voltage profile against bus number after load flow on the test network

Table 1. Eigenvalue of Base case

Eigenvalue No	Real part	Imaginary Part
1	4865.577	0
2	4537.908	0
3	4373.63	0
4	3493.507	0
5	2198.755	0
6	2119.248	0
7	1706.192	0
8	1622.686	0
9	1444.039	0
10	1244.96	0
11	1269.521	0

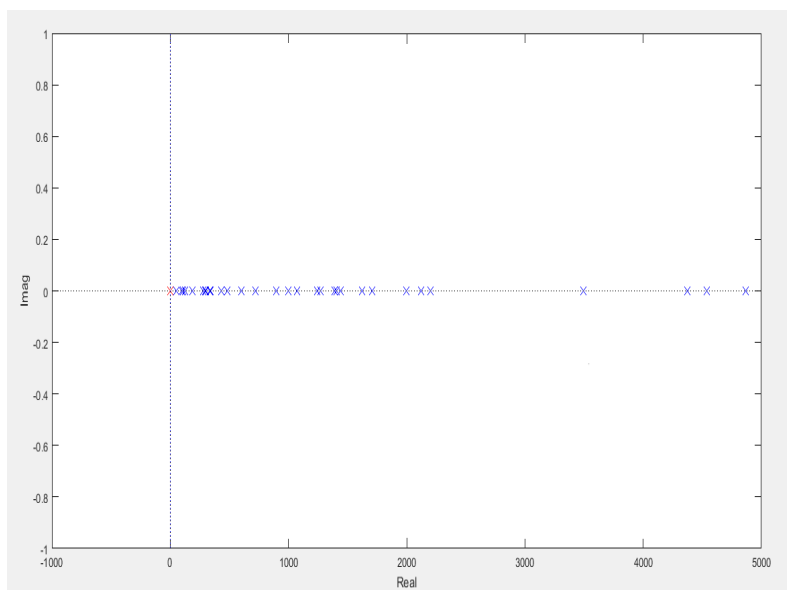| Eigenvalue No	Real part	Imaginary Part
12	1392.258	0
13	1407.318	0
14	1073.094	0
15	897.0822	0
16	723.1333	0
17	601.1593	0
18	484.8858	0
19	480.4669	0
20	431.121	0
21	-0.83142	0
22	52.63287	0
23	186.2027	0
24	278.083	0
25	302.2202	0
26	296.84	0
27	98.94662	0
28	127.3142	0
29	107.0852	0
30	341.6976	0
31	123.9063	0
32	999	0
33	999	0
34	999	0
35	999	0
36	999	0
37	999	0
38	999	0
39	999	0
40	1998	0
41	338.0854	0
42	999	0
43	999	0
44	999	0

Fig. 3. Plot of real and imaginary part the system eigenvalue for normal working condition

Table 2. Participation Factor for the most critical mode under normal working condition

Critical Mode (Eigenvalue No 21)	Participation Factor	Corresponding Bus
-0.83142	9.04E-08	AKANGBA
	9.94E-15	ALAGBON
	1.12E-14	LEKKI
	1.23E-07	SAKETE
	7.47E-17	AJA
	0	JEBBA
	2.27E-08	OKEARO TS
	7.07E-05	ALAOJI
	0	SAPELLE1
	0.013425	KADUNA
	0.001163	New Haven
	0	SHIRORO
	0.003713	UGWUAJI
	4.78E-14	ADIABOR
	0	AFAM
	1.53E-06	AJAOKUTA
	9.54E-15	ALADJA
	3.33E-05	ASABA
	6.50E-07	AYEDE
	4.32E-06	BENIN
	0.294023	DAMATURU
	0	DELTA
	0	EGBIN
	0	GEREGU
	0.290749	GOMBE
	1.97E-07	GWAGWA
	3.21E-06	GANMO
	0	IHOVBOR TS
	8.86E-08	IKEJA W
	0.000339	IKOT EKPENE
	5.80E-22	JEBBA TS
	0.048184	JOS
	0	KAINJI
	0.01599	KANO
	5.20E-08	KANTANPE
	0	KEBBI
	8.21E-07	LOKOJA
	0.023162	MAKURDI
	0	ODUKPANI
	0	OKPAI
	0	OLORUNSOGO
	0.000125	ONITSHA
	1.35E-06	OSHOBO
	0.309011	YOLA

5. RESULTS AND ANALYSIS

The result of the load flow performed on the 44 bus Nigeria grid network is shown in Figure 2 and the appendix1. From the load flow results, it can be seen that some of the buses are already very close to the minimum acceptable voltage value (0.95pu). This suggests that the system is not strong and will most likely slip into instability with any little contingency. To determine however

the true state of the system's stability as it concerns voltage; modal analysis was then carried out after the load flow.

The modal analysis result shown in Table 1 and Figure 3 shows that bus eigenvalue corresponding to bus 21 recorded a negative real part of value (-0.83142). From the theory of modal analysis presented earlier; this shows that the 44 bus grid network is not stable with respect to network voltage. To determine the weakest bus of the network, the participating factors were also computed. The result of the participating factors presented in Table 2. Yola Bus was found to be the weakest bus since it contains the most positive real value of the eigenvalue results.

6. SUMMARY AND CONCLUSION

The weakest bus(es) in the modelled Nigeria 44 bus grid network was identified after the evaluation exercise. This was achieved by performing load flow study on the network as this was a basic requirement for implementing modal analysis using PSAT software. Modal analysis was then run to determine whether the network was stable or not. Results and analysis showed that the Nigeria 44 Bus grid network was found to be unstable as the modal analysis revealed the presence of eigenvalue with a negative real part. Gombe, Damaturu and Yola buses were also discovered to be the vulnerable buses since their voltage profile fell below the acceptable level of 0.95pu. Yola bus was identified as the weakest bus based on the result analysis of the participating factors.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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