Application of Newton Raphson Method to Voltage Stability Analysis of the Nigeria 330kV Transmission Grid

Peter .O. Ohiero
Department of Electrical and Electronic Engineering,
Cross River University of Technology,
Calabar, Nigeria

***Abstract*— This paper presents the voltage stability analysis of the Nigeria 330kV transmission network using Newton Raphson load flow method. A model of the existing 56-bus transmission network was developed and simulations have been carried out using Electrical Transient and Analyzer Program (ETAP) software. The simulation results show that the voltage magnitudes of buses; Aliade (0.9469pu<-26.18^{0}), Damaturu (0.8961pu<-39.39^{0}), Gombe (0.9000pu<-37.04^{0}), Jalingo (0.8721pu<-25.51^{0}), Jos (0.9112pu<-32.95^{0}), Kaduna (0.8833pu<-34.56^{0}), Kano (0.7805pu<-44.59^{0}), Makurdi (0.9432pu<-27.66^{0}), Maiduguri (0.8961pu<-39.38^{0}), Yola (0.8920pu<-23.39^{0}) fall below the acceptable voltage limit of 0.95pu. These buses are the weak buses in the existing Nigeria 330kV transmission network that contribute more to system collapse and blackouts. This work also demonstrates the effectiveness of voltage stability analysis in proper identification of weak buses and proper location of reactive power compensation devices. Hence, in order to improve on the stability of the power system network, there is need for reactive power compensation devices to be located on these buses.**

Keywords*— *Voltage Stability, Voltage Instability, Voltage Collapse, Newton Raphson load flow method, Nigeria 330kV Transmission Grid.

I. INTRODUCTION

Voltage and frequency are important parameters used to determine the stability, security, quality and performance of a power system network. Power system network and it components are designed to operate at a constant and specified value of voltage and frequency. This is achieved when there is a balance between the power generation and power demand. In other words, the power generation must be equal to power demand and losses.

In Nigeria, electricity is transmitted through transmission lines at a high voltage of 330kV. This voltage is to be maintained at the acceptable operational value of 330kV±5% that is, between 315.5kV and 346.5kV or 0.95pu to 1.05pu stability limit. However, numerous challenges facing the Nigeria power system have been forcing the transmission network to operate out of the stability limit. Some of these challenges are inability to maintain a balance between power generation and power demand; the power generation is less than power demand due to increasing population and industrialization, sudden increase in load, increasing reactive power demand without adequate reactive power support, slow pace of rehabilitation and expansion, erratic power supply, long radial, fragile transmission lines with limited transmission wheeling capacity without redundancies, aged power system equipment, high losses [1].

At present, there are twenty three (23) power generating plants with a total installed capacity 10,396MW connected to the Nigeria national grid but with only available capacity of 6,056MW [2]. Even if all the existing generating plants are operational, there is a great limitation to dispatch the generated power by the transmission and distribution infrastructures. The transmission network has a theoretical wheeling capacity of 7,500MW and a current transmission wheeling capacity of 5,300MW which is overstressed and overloaded. When the generated reactive power is greater than or less than the demanded reactive power, the voltage level goes up and down and results to voltage instability. Voltage instability is direct opposite of voltage stability. Voltage instability occurs when a power system is unable to maintain its bus voltages within the acceptable operational limit under normal condition and after being subjected to disturbance. Voltage instability causes overheating, excessive voltage drop and power losses, and force the components of the power system to operate above their thermal limits and consequently reduces power quality, efficiency, reliability and performance and leads to a wide scale supply disruptions, resulting to grid collapse and blackout. In a power system, some components and buses are more prone to voltage variation than the other because of their location with regards to the sources of electricity and load demand. A power bus which voltage fall outside of the acceptable voltage range of ±5% of nominal value is a weak bus. Weak buses poses great challenge in the operation, reliability and security of power system. A weak bus cannot support additional loads and have negative effect on generation, transmission and distribution of electricity to industrial and residential customers. Several studies and methods have been used to know the operational voltage and identify weak buses in power system network [3][4][5][6].

Voltage stability can be analyzed using power flow analysis, continuation power flow, bifurcation diagram, V-P curves, P-Q sensitivity analysis, Q-V modal analysis, Q-V curves, and minimum singular value methods, modal/eigen value, Fast Voltage Stability Indices (FVSI). Voltage Stability Analysis of Nigerian 330kV Power Grid using Static P-V Plots was investigated in [7]. In their approach, the real power P of electric load, at a particular area or bus is varied in steps at a fixed power factor while the value of the voltage V is recorded. The plot of the PV curve is used to determine the voltage stability of the system. Two solutions were arrived at for the voltage, one for the high voltage but within the voltage stability limit which is the stable solution and the other one is the low voltage but outside the minimum voltage stability limit which the unstable solution. Their results showed the maximum power point, at which the two solution for voltage is equal beyond which increase in real power P and reactive power Q will make the voltage unstable. In another work, the fast voltage stability indices (FVSI) was analysed and presented [8]. They used the fast voltage stability indices (FVSI) to identify the critical lines and buses to install the FACTS controllers. The line stability indices were evaluated for each loading condition and line outage. The line that gives FVSI value close to one were taken to be the most critical line corresponding to the bus causing the power system to tend towards instability. The simulation results by using PSAT software for the IEEE-14 bus system shows the proper location of UPFC as identified by the FVSI in a particular line connected to the most critical bus to maintain the stability of the system. When a power system network is subjected to voltage instability, there is need for reactive power compensation, expansion and upgrade. The problem of voltage instability can be solved with reactive power compensating devices such as shunt capacitors, UPFC, SVC, FACTS and under load tap changing (ULTC) transformer [9][10]. The location of reactive power compensating devices must be accurately known and located to improve the stability of the power system network. The challenge most power system operators and engineers faced is the proper and optimal location of the point where voltage instability originates from and the correct placement of reactive power compensator [11]. Reference [12] studied the compensation effect on the interconnected Nigerian Electric Power grid and concluded that concentrating the compensation on the problem buses gives best results. Hence, there is need to investigate the voltage stability of the entire power system network to know in advance the parts or buses likely to contribute more to voltage instability and system collapse or blackouts in order to correctly locate voltage compensation devices. In this paper, the load flow method approach is used to analyse voltage stability. It involves carrying out a load flow analysis to know the voltage magnitude and angle at each bus, the real and reactive power of the generator and loads and the power flow and losses along the transmission lines. Once, the bus voltage magnitude and angle is known, it becomes easier to know the buses whose voltage limit is violated.

II. FORMULATION OF NEWTON RAPHSON LOAD FLOW METHOD

Load flow analysis can be carried out using any of the following; Newton Raphson, Gauss Seidel and Fast Decoupled methods. Among these, Newton Raphson is widely used because it has better accuracy, less iterative time and very fast convergence speed.

Newton Raphson method is an iterative method in which a set of linear simultaneous equations is obtained from a set of nonlinear simultaneous equations by successive approximation using Taylor's series expansion [13]. It is widely applied to solving load flow problems and only first approximation is taken. It begins with an initial estimate or a guess at the solution and at the end of an iteration, the solution is checked of its closeness to the actual solution, the solution is updated until the solution converges and a final solution is obtained.

Considering an i_{th} bus as shown in a single line diagram in Fig. 1 below, the current injection into the i_{th} bus I_i is a function of the voltage at i_{th} bus V_i and the impedance of the line Z_{ij} between the i_{th} bus and another bus say j_{th} bus given as;

$$I_i = \frac{V_i}{Z_{ij}} \tag{1}$$

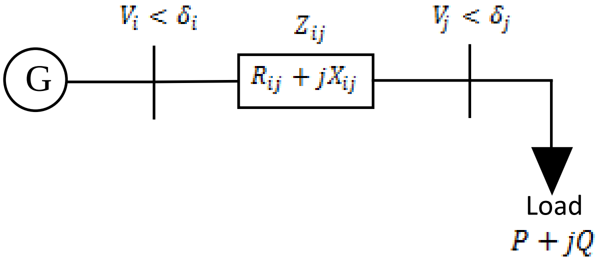

Fig. 1. Single line diagram of a two bus system.

In order to eliminate the burden of calculation in (1), the relationship between impedance and admittance can be used and (1) becomes;

$$I_i = V_i y_{ij} \tag{2}$$

Where, y_{ij} is the admittance of the line between bus *i* and *j*.

In an n-bus power system, the current injection into i_{th} bus is calculated based on Kirchhoff Current Law (KCL) as;

$$I_i = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} V_j y_{ij} \quad j \neq i \tag{3}$$

Equation (3) can be written in terms of the bus admittance matrix Y_{ij} as;

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \text{, for } i = 1, 2, 3, \ldots n \tag{4}$$

Where V_i and V_j are given as,

$$V_i = |V_i| \angle \delta_i = |V_i| (\cos \delta_i + j \sin \delta_i) \qquad (5)$$

$$V_j = |V_j| \angle \delta_j = |V_j| (\cos \delta_j + j \sin \delta_j) \qquad (6)$$

And

$$Y_{ij} = |Y_{ij}| \angle \theta_{ij} = |Y_{ij}| (\cos \theta_{ij} + j \sin \theta_{ij}) \qquad (7)$$

Substituting equations (6) and (7) into equation (4), the current injected into the i_{th} bus can be expressed in polar form as

$$I_i = \sum_{j=1}^{n} |Y_{ij}| |V_j| \angle \theta_{ij} + \delta_j \qquad (8)$$

The complex power at i_{th} bus is given by,

$$P_i - jQ_i = V_i^* I_i = V_i^* \sum_{j=1}^{n} Y_{ij} V_j \qquad (9)$$

$$P_i - jQ_i = V_i^* I_i = |V_i| \angle -\delta_i \sum_{j=1}^{n} |Y_{ij}| |V_j| \angle \theta_{ij} + \delta_j \qquad (10)$$

Where, P_i is the real power in bus-*i* and Q_i is the reactive power in bus-*i* and V_i^* is the conjugate of the voltage at bus-*i* Substituting equations(5), (6) and (7) into (10) and simplify, the real and reactive power at i_{th} bus are given by;

$$P_i = \sum_{j=1}^{n} |Y_{ij}| |V_j| |V_i| \cos(\theta_{ij} + \delta_j - \delta_i) \qquad (11)$$

$$Q_i = -\sum_{j=1}^{n} |Y_{ij}| |V_j| |V_i| \sin(\theta_{ij} + \delta_j - \delta_i) \qquad (12)$$

Equations (11) and (12) are nonlinear equations with voltage magnitude $|V|$ and voltage angle δ and are called power flow equations. These equations can be solved iteratively by Newton Raphson method starting with an initial estimate. Assuming that the slack bus is the first bus with a fixed voltage angle/magnitude, the voltage magnitude and angle at each bus or area of the power system is determined by the matrix form of Newton Raphson method as;

$$\begin{bmatrix} \Delta P_2 \\ . \\ . \\ . \\ \Delta P_n \\ \Delta Q_2 \\ . \\ . \\ . \\ \Delta Q_{1+n_0} \end{bmatrix} = J \begin{bmatrix} \Delta \delta_2 \\ . \\ . \\ . \\ \Delta \delta_n \\ \dfrac{\Delta |V_2|}{|V_2|} \\ . \\ . \\ . \\ \dfrac{\Delta |V_{1+n_0}|}{|V_{1+n_0}|} \end{bmatrix} \qquad (13)$$

Where, J is the Jacobian matrix which element is divided into sub-matrices; J_1, J_2, J_3, J_4 as shown in (14).

$$\begin{vmatrix} \Delta P_i \\ \Delta Q_i \end{vmatrix} \begin{vmatrix} J_1 & J_2 \\ J_3 & J_4 \end{vmatrix} \begin{vmatrix} \Delta \delta_i \\ \Delta |V_i| \end{vmatrix} \qquad (14)$$

Where, ΔP_i is the real power mismatch, ΔQ_i is the reactive power mismatch, $\Delta \delta_i$ is the changes in the bus voltage angle, ΔV_i is the changes in the bus voltage magnitude. At each iteration a jacobian matrix is formed and sub-matrices are computed with the partial derivatives of the real and reactive power (11) and (12) with respect to small changes in the bus voltage magnitude and angle given. The element of the sub-matrices $J_1, J_2, J_3\ and\ J_4$ can be expressed as;

The diagonal element of J_1 is

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{\substack{j=1 \\ j \neq i}}^{n} |Y_{ij}| |V_j| |V_i| \cos(\theta_{ij} + \delta_j - \delta_i) \qquad (15)$$

The off-diagonal element of J_1 is

$$\frac{\partial P_i}{\partial \delta_j} = -|Y_{ij}| |V_j| |V_i| \sin(\theta_{ij} + \delta_j - \delta_i) \qquad (16)$$

The diagonal element of J_2 is

$$\frac{\partial P_i}{\partial |V_i|} = 2|V_i| |Y_{ij}| \cos \theta_{ii} + \sum_{\substack{j=1 \\ j \neq i}}^{n} |Y_{ij}| |V_j| \cos(\theta_{ij} + \delta_j - \delta_i) \qquad (17)$$

The off-diagonal element of J_2 is

$$\frac{\partial P_i}{\partial |V_j|} = |V_i| |Y_{ij}| \cos(\theta_{ij} + \delta_j - \delta_i) \qquad (18)$$

The diagonal element of J_3 is

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{\substack{j=1 \\ j\neq i}}^{n} \left|Y_{ij}\right|\left|V_j\right|\left|V_i\right|\cos(\theta_{ij} + \delta_j - \delta_i) \qquad (19)$$

The off-diagonal element of J_3 is

$$\frac{\partial Q_i}{\partial \delta_j} = -\left|Y_{ij}\right|\left|V_j\right|\left|V_i\right|\cos(\theta_{ij} + \delta_j - \delta_i) \qquad (20)$$

The diagonal element of J_4 is

$$\frac{\partial Q_i}{\partial \left|V_i\right|} = 2\left|V_i\right|\left|Y_{ij}\right|\sin\theta_{ii} - \sum_{\substack{j=1 \\ j\neq i}}^{n} \left|Y_{ij}\right|\left|V_j\right|\sin(\theta_{ij} + \delta_j - \delta_i) \quad (21)$$

The off-diagonal element of J_4 is

$$\frac{\partial Q_i}{\partial \left|V_j\right|} = -\left|V_i\right|\left|Y_{ij}\right|\sin(\theta_{ij} + \delta_j - \delta_i)$$

(22)

The iteration continues until it converges thereby reaching a satisfactory solution. The changes in the bus real power, ΔP_i and reactive power, ΔQ_i are the mismatches which are the difference between the calculated and scheduled values of the real and reactive power given as;

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)} \qquad (23)$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)} \qquad (24)$$

Where, P_i^{sch} and Q_i^{sch} are the scheduled real ad reactive power while $P_i^{(k)}$ and $Q_i^{(k)}$ the calculated real and reactive power respectively. From (23) and (24), the new estimates for the voltage magnitude $\left|V^{(k+1)}\right|$ and angle $\delta^{(k+1)}$ are given by

$$\left|V^{(k+1)}\right| = \left|V_i^{(k}\right| + \Delta\left|V_i^{(k}\right| \qquad (25)$$

$$\delta^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \qquad (26)$$

III. MATERIALS AND METHOD

In order to carry out voltage stability analysis of the existing Nigeria transmission network, it is necessary to first perform load flow analysis. For this research, the load flow analysis is based on Newton Raphson method performed using Electrical Transient and Analyzer Program (ETAP) software. ETAP is a computer-aided software suitable for design, modelling, simulation and analyzing generation, transmission and distribution power system as well as renewable energy generation. The single line diagram of the existing 330kV Nigeria Transmission network used in this study was drawn as shown in Fig. 2. A model of the 56 bus system of the Nigeria 330kV transmission network was developed in ETAP software. The model requires input data, which are the real and reactive power of the generating plants, the voltages and power rating of the transformers, voltages, real and reactive power of the loads, the length of transmission lines, real and reactive power of generator buses. The input data of the generators and loads as obtained from the Transmission Company of Nigeria is shown in Table 1. The transmission line model in ETAP requires basic data such as the type of conductor, the length of lines, the voltage rating of the lines, the number of parallel lines, the type and configuration of circuits (e.g. single and double circuit), the number of conductor per phase, the height of towers, the spacing of conductors in the bundle and spacing between phases. The type of conductor used in the existing 330kV overhead transmission lines in the Nigeria power system network is 350mm^2 Aluminium Conductor Steel Reinforced (ACSR) twin conductor bundle “Bison” conductor with an average spacing of the conductor in the bundle as 400mm and the spacing between the phases as 10.5m [12]. The supporting structure are made of steel towers and spanned at an average distance of 500m apart, with a height of 75 metres for the double circuits and 54 metres for the single circuit [11]. These data were inputted into the transmission line model in ETAP and the transmission line parameters were obtained as shown in Table 2. All the components were adequately represented in the model of the transmission network as shown in Fig. 3 and Fig. 4. With Egbin power plant as the slack bus because of its location in the far western part of the country, these data were used for the simulation analysis. The bus voltages and angles, real and reactive power flow and losses under steady state were recorded.

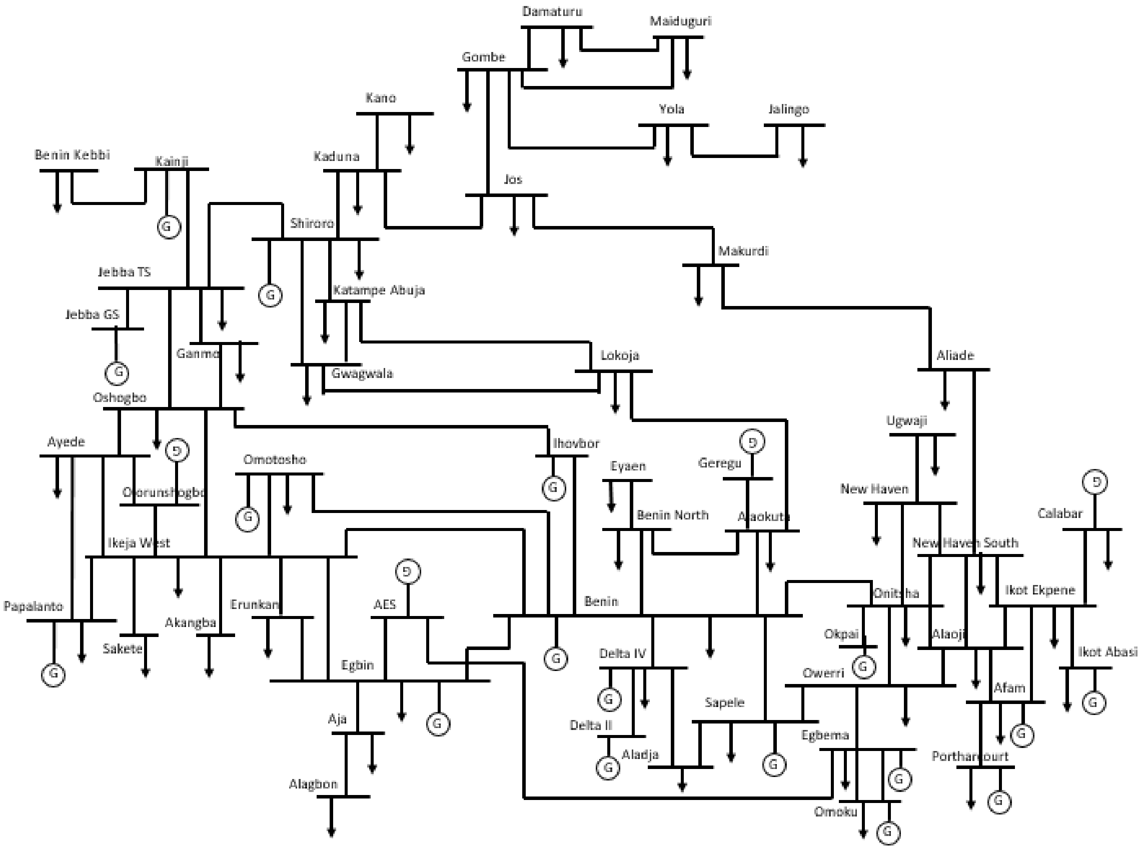

Fig. 2. Single line diagram of the 56-bus Nigerian 330kV Transmission Network.

Table 1. Generator and Load Bus Data for the existing Nigerian 330kV Transmission Grid

SN	Bus Name	Bus Nominal Voltage (V)	Generation		Load	
	From		Max. Active Power (MW)	Active Power Schedule (MW)	Active (MW)	Reactive (MVAr)
1	AES	330	270	200	-	-
2	Afam GS	330	776	500	-	-
3	Ayiede	330	-	-	270	166.10
4	Aja	330	-	-	220	103
5	Ajaokuta	330	-	-	96	45
6	Akamgba	330	-	-	471	156.071
7	Aladja	330	-	-	167	20
8	Alaoji	330	1079	450	266.18	155
9	Alaogbon	330	-	-	220	103
10	Aliade	330	-	-	136	84
11	B.Kebbi	330	-	-	112	60
12	Benin	330	-	-	298	131.2
13	Benin North	330	-	-	80	50
14	Calabar	330	561	240	110.75	60.37
15	Damaturu	330	-	-	75	259.18
16	Delta I -IV	330	960	620	-	-
17	Egbema	330	378	200	-	-
18	Egbin PS	330	1320	610	-	-
19	Egbin TS	330	-	-	-	-
20	Erunkan	330	-	-	14.5	8.93
21	Ganmo	330	-	-	270	223.35
22	Geregu	330	434	200	-	
23	Gombe	330	-	-	180	100
24	Gwagwalada	330	-	-	75	65
25	Ihovbor	330	451	182	-	-
26	Ikeja West	330	-	-	510	115

27	Ikot Abasi	330	195	0	-	-
28	Ikot Ekpene	330	-	-	45.8	20
29	Jalingo	330	-	-	75	50
30	Jebba GS	330	590	475	-	-
31	Jebba TS	330	-	-	360	180
32	Jos	330	-	-	141	155
33	Kainji	330	760	313	-	-
34	Kaduna	330	-	-	193	144
35	Kano	330	-	-	180	100
36	Katampe (Abuja)	330	-	-	290	60
37	Lokoja	330	-	-	75	65
38	Makurdi	330	-	-	75	37.7
39	Maiduguri	330	-	-	70	50
40	New Haven	330	-	-	140	10
41	New Haven South	330	-	-	40	27
42	Olorunshogo	330	335	195	-	-
43	Omotosho	330	335	220	-	-
44	Omoku	330	150	75	-	-
45	Oshogbo	330	-	-	201	150
46	Okpai	330	480	330	-	-
47	Onitsha	330	-	-	162	28
48	Owerri	330	-	-	100	60
49	Papalanto	330	1020	450	-	-
50	PortHarcourt	330	200	100	316	159
51	Sapele	330	1020	550	-	-
52	Sakete	330	-	-	145	70
53	Shiroro	330	600	450	-	-
54	Shiroro TS	330	-	-	97.5	22.75
55	Ugwuaji	330	-	-	75.7	46.8
56	Yola	330	-	-	112	65

Table 2. Transmission Line Data (of Bison, two conductors per phase & 2x350 mm^2 X-section Conductor) for the 330KV Lines obtained from ETAP.

SN	**Bus Name**		**Length (km)**	**Type of Circuit**	**R1 (Ω/km)**	**X1 (Ω/km)**	**Y1 (μS/km)**	**R0 (Ω/km)**	**X0 (Ω/km)**	**Y0 (μS/km)**
	From	**To**								
1	Afam GS	Alaoji	25	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
2	Afam GS	Ikot Ekpene	90	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
3	Afam GS	PortHarcourt	45	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
4	Ayiede	Oshogbo	115	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
5	Ayiede	Ikeja West	137	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
6	Ayiede	Papalanto	60	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
7	Aja	Egbin PS	14	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
8	Aja	Alagbon	26	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
9	Ajaokuta	Benin North	195	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
10	Ajaokuta	Geregu	5	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
11	Ajaokuta	Lokoja	38	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
12	Akamgba	Ikeja West	18	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
13	Aladja	Sapele	63	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
14	Aladja	Delta PS	32	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
15	Alaoji	Owerri	60	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
16	Alaoji	Onitsha	138	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
17	Alaoji	Ikot Ekpene	38	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
18	Aliade	New Haven South	150	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
19	Aliade	Makurdi	50	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
20	B.Kebbi	Kainji	310	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
21	Benin	Ikeja West	280	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
22	Benin	Sapele	50	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
23	Benin	Delta PS	41	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
24	Benin	Oshogbo	251	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
25	Benin	Onitsha	137	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
26	Benin	Benin North	20	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
27	Benin	Egbin PS	218	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
28	Benin	Omotosho	51	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
29	Benin North	Eyaen	5	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
30	Calabar	Ikot Ekpene	72	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
31	Damaturu	Gombe	135	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
32	Damaturu	Maiduguri	140	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
33	Egbema	Omoku	30	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438

34	Egbema	Owerri	30	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
35	Egbin PS	Ikeja West	62	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
36	Egbin PS	Erunkan	30	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
37	Erunkan	Ikeja West	32	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
38	Ganmo	Oshogbo	87	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
39	Ganmo	Jebba TS	80	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
40	Gombe	Jos	264	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
41	Gombe	Yola	240	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
42	Gwagwalada	Lokoja	140	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
43	Gwagwalada	Shiroro	114	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
44	Gwagwalada	Katampe	30	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
45	Ikeja West	Oshogbo	252	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
46	Ikeja West	Omotosho	200	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
47	Ikeja West	Papalanto	30	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
48	Ikeja West	Sakete	70	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
49	Ikot Abasi	Ikot Ekpene	75	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
50	Ikot Ekpene	New Haven South	143	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
51	Jalingo	Yola	132	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
52	Jebba TS	Oshogbo	157	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
53	Jebba TS	Jebba GS	8	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
54	Jebba	Kainji	81	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
55	Jebba	Shiroro	244	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
56	Jos	Kaduna	196	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
57	Jos	Makurdi	230	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
58	Kaduna	Kano	230	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
59	Kaduna	Shiroro TS	96	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
60	Abuja (Katampe)	Shiroro GS	144	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
61	New Haven	Onitsha	96	Single	0.03809	0.033368	3.42768	0.23426	1.09356	1.75899
62	New Haven	New Haven South	5	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
63	Okpai	Onitsha	60	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438
64	Onitsha	Owerri	137	Double	0.01879	0.14976	8.08147	0.17972	1.02342	1.93438

IV. RESULTS AND DISCUSSIONS

The developed model was simulated based on Newton Raphson load flow method using ETAP software as shown in Figs. 3 and 4 below. The simulation results of the bus voltage magnitudes and angles were recorded and presented as shown in Table 3. The voltage profile in Fig. 5 shows the buses which voltages violates the acceptable bus voltage limit of 0.95pu – 1.05pu. They are Aliade (0.9469pu<-26.8^0), Damaturu (0.8961pu<-39.39^0), Gombe (0.9000pu<-37.04^0), Jalingo (0.8721pu<-25.51^0), Jos (0.9112pu<-32.95^0), Kaduna (0.8833pu<-34.56^0), Kano (0.7805pu<-44.59^0), Makurdi (0.9432pu<-27.66^0), Maiduguri (0.8961pu<-39.38^0), Yola (0.8920pu<-23.39^0). These buses contribute more to the voltage instability been experienced in the Nigeria 330kV transmission network.

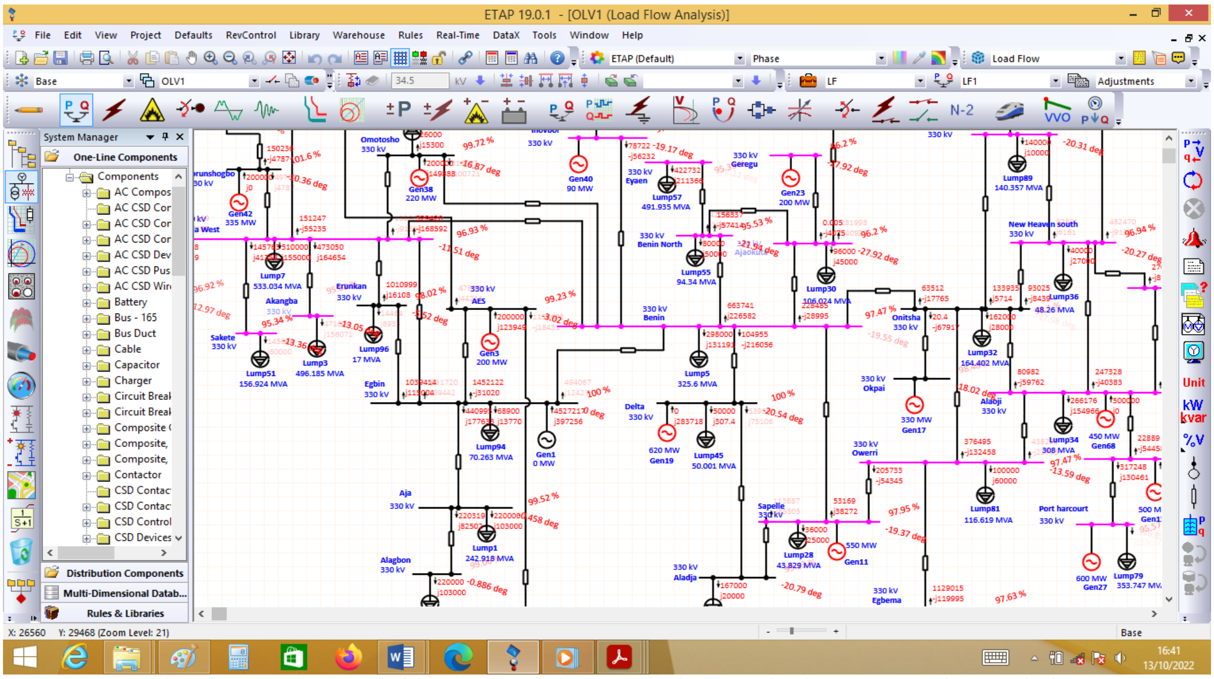

Fig. 3. A simulation model of the Nigeria’s 330kV Transmission network using Newton Raphson Method.

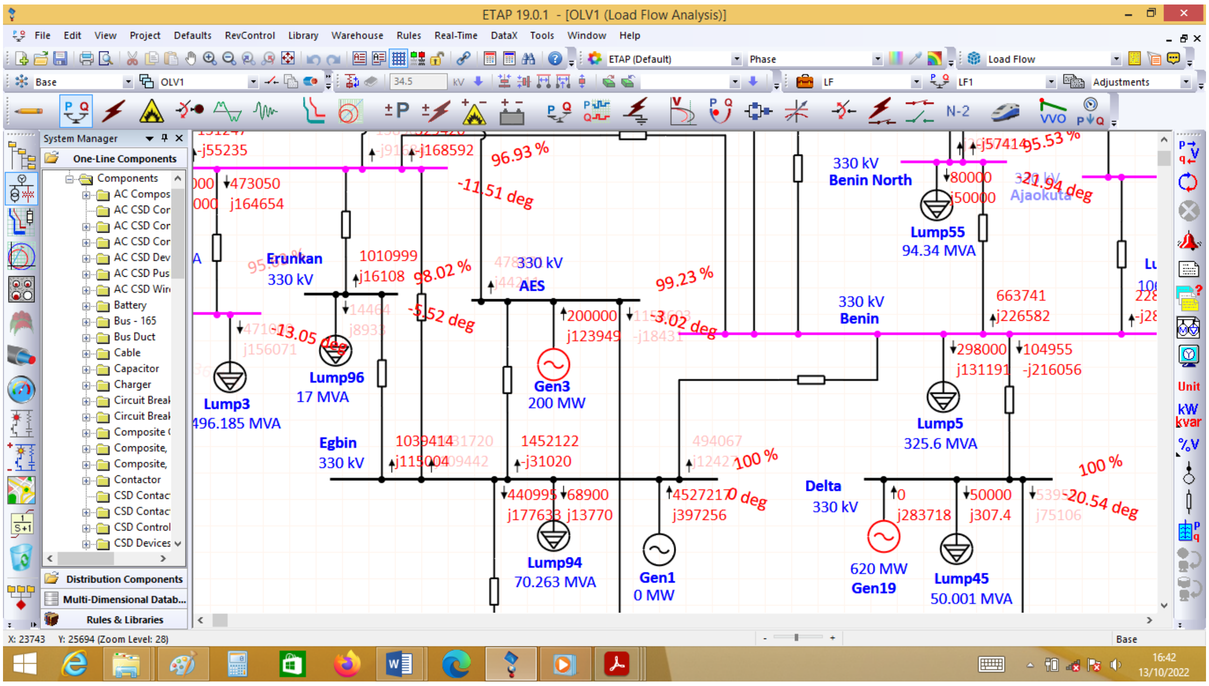

Fig. 4. A Zoomed section of the simulation model of the Nigeria’s 330kV Transmission network using Newton Raphson Method.

Table 3. Simulation Results of Bus Voltages

S/N	Bus Name	Bus Nominal Voltage (kV)	Operational Voltage (%)	Operational Voltage (kV)	V (pu)	Angle (^{0})
1	AES	330	99.24	327.492	0.9924	-2.99
2	Afam GS	330	96.93	319.869	0.9693	-15.57
3	Ayiede	330	96.90	319.77	0.9690	-14.93
4	Aja	330	99.52	328.416	0.9952	-0.458
5	Ajaokuta	330	96.10	317.13	0.9610	-27.48
6	**Akamgba**	**330**	**95.74**	**315.942**	**0.9574**	**-13.01**
7	Aladja	330	99.25	327.525	0.9925	-20.48
8	Alaoji	330	97.08	320.364	0.9708	-15.63
9	Alaogbon	330	99.06	326.898	0.9906	-0.886
10	**Aliade**	**330**	**94.69**	**312.477**	**0.9469**	**-26.18**
11	B.Kebbi	330	98.51	325.083	0.9851	-23.39
12	Benin	330	97.73	322.509	0.9773	-19.32
13	Benin North	330	95.76	316.008	0.9576	-21.68
14	Calabar	330	96.59	318.747	0.9659	-17.5
15	**Damaturu**	**330**	**89.61**	**295.713**	**0.8961**	**-39.39**
16	Delta	330	100.0	330.00	1.0000	-20.26
17	Egbema	330	97.68	322.344	0.9768	-10.64
18	Egbin PS	330	100.0	330.00	1.0000	0
19	Erunkan	330	98.08	323.664	0.9808	-5.51
20	**Ganmo**	**330**	**95.40**	**314.82**	**0.954**	**-20.75**
21	Geregu	330	96.01	316.833	0.9601	-27.5
22	**Gombe**	**330**	**90.00**	**297.00**	**0.9000**	**-37.04**
23	Gwagwalada	330	95.84	316.272	0.9584	-29.11
24	Ihovbor	330	96.61	318.813	0.9661	-19.14
25	Ikeja West	330	97.04	320.232	0.9704	-11.48
26	Ikot Abasi	330	96.55	318.615	0.9655	-17.39
27	Ikot Ekpene	330	96.64	318.912	0.9664	-17.38
28	**Jalingo**	**330**	**87.21**	**287.793**	**0.8721**	**25.51**
29	Jebba GS	330	100	330.00	1.0000	-18.5
30	Jebba TS	330	99.65	328.845	0.9965	-18.79
31	**Jos**	**330**	**91.12**	**300.696**	**0.9112**	**-32.95**
32	Kainji	330	100.9	332.97	1.0090	-17.25
33	**Kaduna**	**330**	**88.33**	**291.489**	**0.8833**	**-34.56**
34	**Kano**	**330**	**78.05**	**257.565**	**0.7805**	**-44.59**
35	Katampe (Abuja)	330	95.75	315.975	0.9575	-29.28
36	Lokoja	330	95.95	316.635	0.9595	-28.38
37	**Makurdi**	**330**	**94.32**	**311.256**	**0.9432**	**-27.66**
38	**Maiduguri**	**330**	**89.61**	**295.713**	**0.8961**	**-39.98**
39	New Haven	330	97.0	320.10	0.9700	-20.13
40	New Haven South	330	97.01	320.133	0.9701	-20.09
41	Olorunshogo	330	101.8	335.94	1.018	-10.37
42	Omotosho	330	100.0	330.00	1.0000	-16.50
43	Omoku	330	97.79	322.707	0.9779	-10.64
44	Oshogbo	330	97.41	321.453	0.9741	-18.92
45	Okpai	330	98.61	325.413	0.9861	-17.84
46	Onitsha	330	98.23	324.159	0.9823	-17.81
47	Owerri	330	97.6	322.08	0.976	-13.45
48	Papalanto	330	97.09	320.397	0.9709	-12.97
49	PortHarcourt	330	95.69	315.777	0.9569	-16.69
50	Sapele	330	98.31	324.423	0.9831	-19.04
51	Sakete	330	95.22	314.226	0.9522	-13.31
52	Shiroro	330	95.51	315.183	0.9551	-28.22
53	Ugwuaji	330	96.89	319.737	0.9689	-20.21
54	**Yola**	**330**	**89.20**	**294.36**	**0.892**	**-23.39**

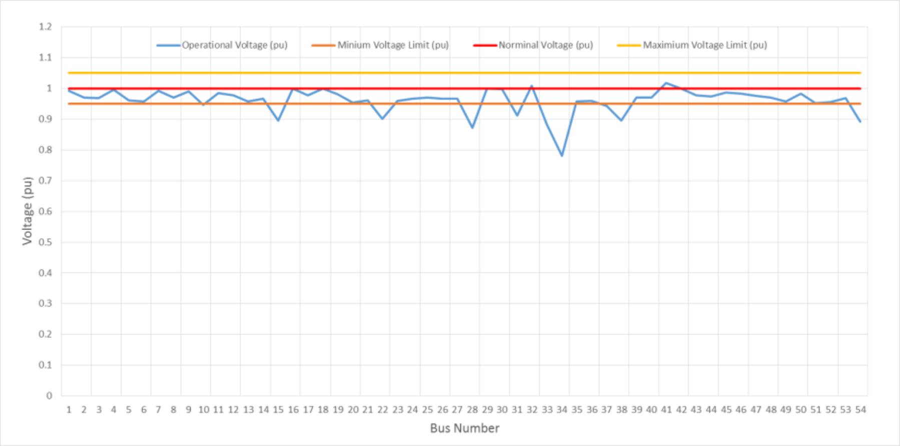

Fig. 5. Voltage profile of the existing Nigeria 330kV transmission network

V. CONCLUSION

The voltage stability of the Nigeria 330kV transmission network have been simulated and analysed. The results revealed the buses that operates at voltage outside the acceptable operational voltage limit of 330kV±5% which is between 313.5kV – 346.5kV. These buses constitute the weak buses that cause voltage instability and system collapse in the network and require serious attention. It is therefore necessary to put in place adequate reactive power compensation in these buses to reduce or avoid voltage stability problems and system collapse.

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