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Load Flow Assessment of the Nigeria 330-kV Power System

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Abstract The Nigerian 330kV grid network is characterized with major problems like voltage instability (voltage profile violation), long transmission lines, nature of transmission lines and high power losses which affect power generation and distribution systems. This paper considered the load-flow study of the Nigerian 330-kV consisting of 32 buses, 11 generating stations and 36 transmission lines. Newton-Raphson iteration technique was used to carry out the analysis because of its fast convergence nature as compared to other iterative techniques. The data used for the study is obtained from Power Holding Company of Nigeria (PHCN). MATLAB/SIMULINK software was used to carry out the simulations. The results obtained shows that some of the bus voltages lie outside the prescribed limit of 0.95-1.05 pu (313.5 – 346.5kV). These buses include buses 16 (Kano 0.8721pu), 17(Kaduna, 0.9046pu), 18(Jos, 0.8580pu), 19(Gombe 0.8735pu) and 21(Katampe, 0.9167pu). The total active power loss is 268.622MW and that of reactive power loss is 2247.42Mvar. It is therefore inferred from the results obtained that the existing Nigerian 330-kV grid network is fraught with high line losses that require compensation using reactive power supports such as Flexible Alternating Current Transmission Systems (FACTS) devices, for effective line utilization.

Keywords: *load flow, Newton Raphson, losses, voltage, transmission line*

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1. Introduction

Since Electrical Energy is the pivotal upon which a country’s development is anchored, hence, the ever-increasing demand of electric power. Power is usually generated at specific locations far from load centers before it is delivered to consumers through transmission and distribution systems. The Nigerian power system network, like any other networks elsewhere is made up of the large interconnected network that spans across the country nationwide. One of the main challenges combating this network is the fact that most Northern parts of the system usually experience poor voltage profile as a result of shortage of reactive power support. Other challenges include fragile transmission lines, inability of transmission lines to transport more than 400MW of power, radial network and high losses [1]. This study classifies buses whose voltages are extremely below statutory limit of ±5% (346.6kV [1.05pu] to 313.5kV [0.95pu] as a result of reactive power shortage as “weak buses”. This problem is more amplified in relatively weak networks having high resistance to reactance ratios [1,2].

In load flow study, the main objective is to determine the complex bus voltages, and real and reactive power injected into the transmission system as well as real and reactive power at the slack bus with other parameters being specified. Load flow analysis usually finds its application during power network design and planning. It is also useful for obtaining the system behavior during operation in order to predict the loading conditions of transmission lines and equipment’s within the system. The system is usually assumed to be operating under a balance condition such that the analysis can be carried out using a balanced single-phase representation [3].

2. Nigeria 330kV Transmission Network

The increasing demand for electricity in Nigeria like many other developing countries, is extremely greater than what is been generated, which results to the transmission network being heavily loaded and stressed beyond permissible limits. The Nigeria grid network consist of few generating stations like many other developing countries and his located mostly in remote areas near the raw materials required for generation. Power Holding Company of Nigeria (PHCN) has the statutory function of generation, transmission, distribution and marketing of electricity in Nigeria. The single line diagram (Figure 1) of the Nigeria 330kV network consist of eleven (11) generating stations comprising of three (3) hydro and eight (8) thermal, twenty one (21) load stations and thirty six (36) transmission lines with a total installed capacity of 6500MW. The thermal generating stations are mainly located in the Southern part of the country like Okpai, Afam, Sapele, Delta (Ughelli), Egbin, Olorunshogo and

Omotosho, while the hydro generating stations are located mainly in the Middle Belt/Northern part of the country like Kainji, Shiroro and Jebba [4].The Nigeria 330-kV grid network can be grouped into three (3) sections: North, South-east and South-west sections. The Northern and South-west are connected through one double circuit between Jebba TS and Oshogbo. The South-East is connected to the South-West through a single line from Osogbo to Benin and then one double circuit line from Ikeja West to Benin. The line diagram and data of the Nigerian 330kV grid network were sourced from the National Control Centre (NCC) of the PHCN, Oshogbo, Nigeria [5].

3. Data Collection

The data used for this study were obtained from Power Holding Company of Nigeria (PHCN) and are presented in Table 1 and Table 2. Computer software programmed using MATLAB/SIMULINK were used in conducting the simulation.

Table 1. Nigeria 330kV Transmission Line Parameters

S/N	Transmission line		Length	Impedance		Shunt Admittance
	From	**To**	**L(km)**	**Resistance (Rpu)**	**Inductance (Xpu)**	**1/2 Bpu (S)**
1	Egbin G.S	Ikeja West	62	0.001122	0.008625	0.064345
2	Egbin G.S	Aja	14	0.000253	0.001948	0.014529
3	Benin	Ikeja West	280	0.005065	0.038953	0.290589
4	Benin	Omotosho G.S	51	0.001826	0.015501	0.096916
5	Benin	Oshogbo	251	0.008989	0.076291	0.476977
6	Benin	Ajaokuta	195	0.003492	0.029635	0.18528
7	Benin	Onitsha	137	0.002453	0.02082	0.130171
8	Benin	Sapele G.S	50	0.000904	0.006956	0.051891
9	Benin	Delta G.S	41	0.001468	0.012462	0.077913
10	Ikeja West	Akangba	17	0.000304	0.002584	0.016`53
11	Ikeja West	Sakete	70	0.002507	0.021276	0.133021
12	Ikeja West	Olorunshogo G.S	30	0.001074	0.009118	0.057009
13	Ikeja West	Omotosho G.S	200	0.007163	0.06079	0.380061
14	Ikeja West	Oshogbo	250	0.008953	0.075987	0.475077
15	Aiyede	Olorunshogo G.S	60	0.002149	0.018237	0.114018
16	Aiyede	Oshogbo	115	0.004118	0.034954	0.218535
17	Oshogbo	Ganmo	75	0.002686	0.022796	0.142523
18	Oshogbo	Jebba T.S	157	0.002811	0.02386	0.149174
19	Ganmo	Jebba T.S	80	0.002865	0.024316	0.152025
20	Shiroro	Jebba T.S	244	0.004369	0.037082	0.231837
21	Shiroro	Kaduna	96	0.001719	0.01459	0.091215
22	Shiroro	Katampe	218	0.003944	0.030328	0.226244
23	Jebba T.S	Jebba G.S	8	0.000145	0.001113	0.008303
24	Jebba T.S	Kainji G.S	81	0.00145	0.01231	0.076962
25	Birnin Kebbi	Kainji G.S	310	0.005551	0.047112	0.589095
26	Kano	Kaduna	230	0.004118	0.034954	0.43707
27	Kaduna	Jos	196	0.00351	0.029787	0.37246
28	Jos	Gombe	264	0.004727	0.040121	0.501681
29	Gombe	Yola	240	0.004298	0.036474	0.456074
30	Ajaokuta	Geregu G.S	1	0.000018	0.000139	0.001038
31	Onitsha	Alaoji	138	0.004942	0.041945	0.262242
32	Onitsha	New Haven	96	0.003438	0.029179	0.182429
33	Onitsha	Okpai G.S	60	0.001085	0.008347	0.062269
34	Alaoji	Afam G.S	25	0.000452	0.003478	0.025945
35	Sapele G.S	Aladja	63	0.002256	0.019149	0.119719
36	Delta G.S	Aladja	32	0.001146	0.009726	0.06081

Table 2. Nigeria 330kV Transmission Line Bus Parameters

Bus No	Bus Name	Maximum Load Demand		Minimum Load Demand	
		MW	Mvar	MW	Mvar
2	Benin	298	144(+75)	188	91
3	Ikeja West	510	246(+75)	321	155
4	Akangba	471	228	297	144
5	Sakete	145	70	91	44
6	Aiyede	270	130	170	82
9	Oshogbo	235	114(+75)	148	72
10	Ganmo	270	130	170	82
12	Jebba T.S	412	199(+150)	260	125
14	Birnin Kebbi	112	54(+30)	71	34
16	Kano	250	121(+75)	157	76
17	Kaduna	275	133(+75)	173	84
18	Jos	141	68	89	43
19	Gombe	180	87(+100)	113	55
20	Yola	112	54	71	34
21	Katampe	300	127	189	62
22	Ajaokuta	96	46	60	29
24	Onitsha	162	76	102	48
25	Alaoji	266	124	167	78
26	New Haven	235	110	148	69
31	Aja	220	103	139	65
32	Aladja	167	81	105	51

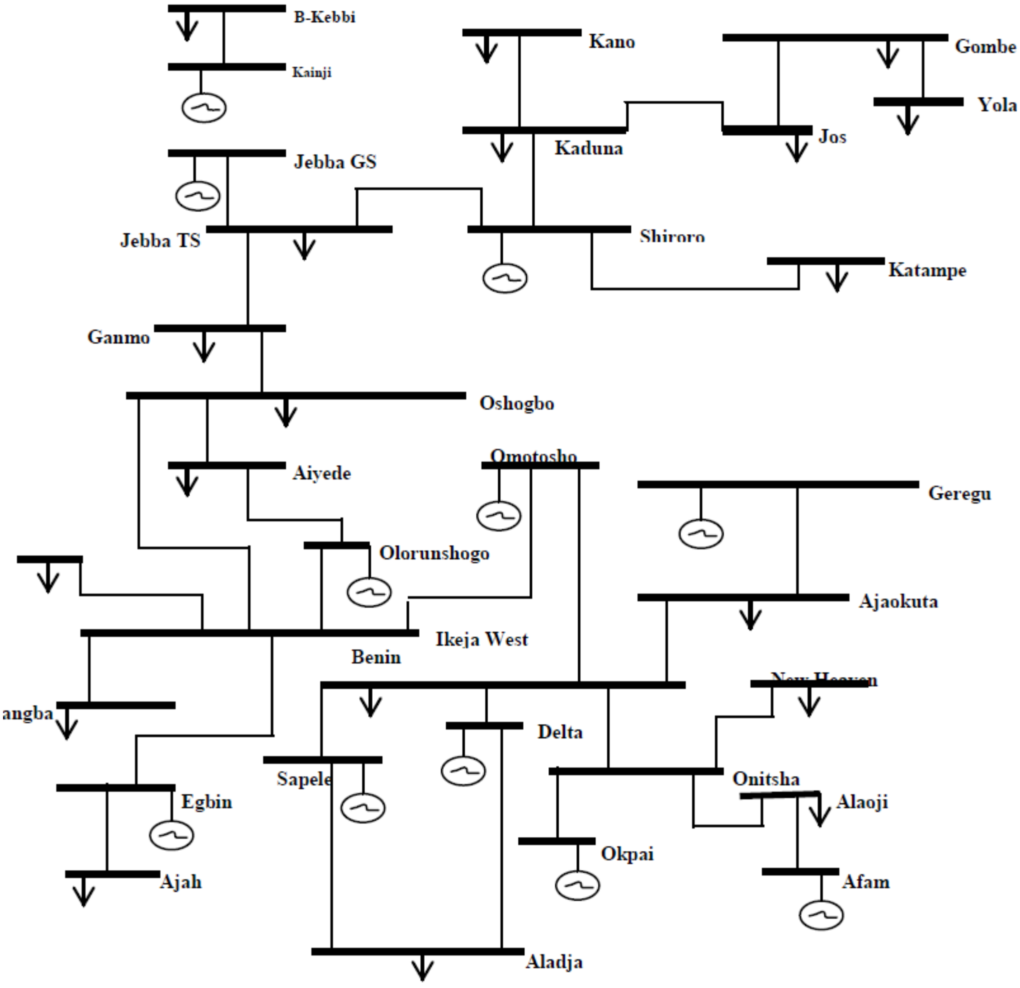

Figure 1. Single line diagram of the Nigeria 330kV transmission network

4. The Load-flow Modelling

Consider an *n*- bus power system shown in Figure 2. The transmission lines are shown by their equivalent π model with the impedances converted to per unit admittances on a common MVA buses [6].

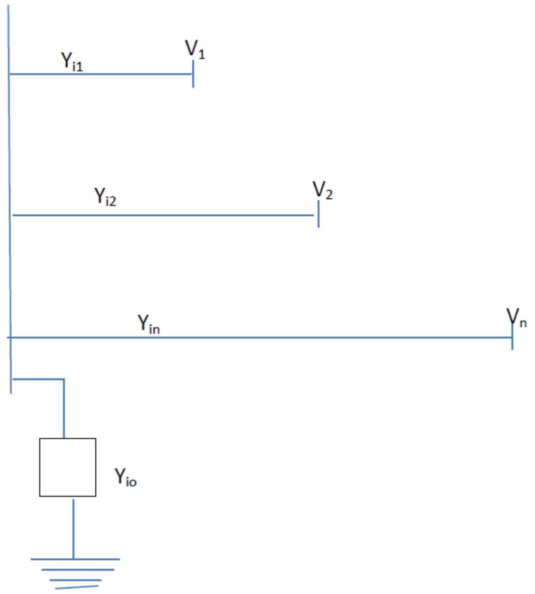

Figure 2. A typical bus of the power system

By applying Kirchhoff's Current Law (KCL) to bus i, we obtain

$$\begin{aligned} I_i &= y_{io}V_i + y_{i1}(V_i - V_1) + y_{i2}(V_i - V_2) \\ &\quad + \ldots.. + y_{in}(V_i - V_n) \\ &= (y_{io} + y_{i1} + y_{i2} + \ldots + y_{in})V_i \\ &\quad - y_{i1}V_1 - y_{i2}V_2 - \ldots - y_{in}V_n \end{aligned} \tag{1}$$

Or

$$I_i = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij}V_j, \quad j \neq i. \tag{2}$$

The real and reactive power at bus i is

$$S_i = P_i + jQ_i = V_i \; I_i^* \tag{3}$$

Or

$$I_i = \frac{P_i - jQ_i}{V_i^*} \tag{4}$$

Substituting for I_i in eqn. 2 yields

$$\frac{P_i - jQ_i}{V_i^*} = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij}V_j, \; j \neq i. \tag{5}$$

The above mathematical formulation for load flow problems results in a system of nonlinear algebraic equations which must be solved by iterative methods. The commonly used methods for solving load flow problems are Gauss-Seidel, Newton-Raphson and Fast Decoupled techniques. In this paper, Newton-Raphson techniques is used because of its quadratic convergence property and ability to handle large power network [7] which are of paramount importance in solving nonlinear equations of power flow problems.

Equation. 2 can be re-written in terms of the bus admittance matrix as

$$I_i = \sum_{j=1}^{n} y_{ij}V_j. \tag{6}$$

In the above equations, j includes bus i. expressing this equation in polar form, we have

$$I_i = \sum_{j=1}^{n} |Y_{ij}||V_j| \angle \theta_{ij} + \delta_j. \tag{7}$$

The complex power at bus i is
Substitute equation 3 into equation 7,

$$P_i - jQ_i = |V_i| \angle \delta_i \sum_{j=1}^{n} |Y_{ij}||V_j| \angle \theta_{ij} + \delta_j. \tag{8}$$

Separating the real and imaginary parts

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \, Cos(\theta_{ij} - \delta_i + \delta_j) \tag{9}$$

$$Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \, Sin(\theta_{ij} + \delta_i + \delta_j). \tag{10}$$

The load flow equations using Newton-Raphson techniques can therefore be written as

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \hline \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta n} \\ \vdots & & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} \\ \hline \frac{\partial Q_2^{(k)}}{\partial \delta n} & & \frac{\partial Q_2^{()}}{\partial \delta n} \\ \vdots & & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} \end{bmatrix} \begin{bmatrix} \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & & \vdots \\ \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \\ \hline \frac{\partial Q_2^{(k)}}{\partial |V_2|} & & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \\ \vdots & & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{bmatrix} \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_n^{(k)} \\ \hline \Delta |V_2^{(k)}| \\ \vdots \\ \Delta |V_n^{(k)}| \end{bmatrix}.$$

In a compact form, it can be written as [2]

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}=\begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta|V|\end{bmatrix} \qquad (11)$$

Where J_1, J_2, J_3 and J_4 are sub-matrices of the Jacobian matrix, which are expressed as

For J_1

Diagonal element:

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

Off-diagonal element:

$$\frac{\partial P_i}{\partial \delta_i}=-|V_i||V_j||Y_{ij}|\,Sin(\theta_i-\delta_i+\delta_j),\;\; j\neq i.$$

For J_2

Diagonal element:

$$\frac{\partial P_i}{\partial |V_i|}=2|V_i||Y_{ij}|\,Cos\theta_{ij}+\sum_{\substack{j=1\\ j\neq i}}|V_j||Y_{ij}|,\,Cos(\theta_{ij}-\delta_i+\delta_j)$$

Off-diagonal element:

$$\frac{\partial P_i}{\partial |V_j|}=|V_i||Y_{ij}|\,Cos(\theta_{ij}-\delta_i+\delta_j),\; j\neq i.$$

For J_3

Diagonal element:

$$\frac{\partial Q_i}{\partial \delta_i}=\sum_{\substack{j=1\\ j\neq i}}|V_i||V_j||Y_{ij}|Cos(\theta_{ij}-\delta_i+\delta_j)$$

Off-diagonal element:

$$\frac{\partial Q_i}{\partial \delta_j}=-|V_i||V_j||Y_{ij}|\,Cos(\theta_{ij}-\delta_i+\delta_j),\; j\neq i.$$

For J_4

Diagonal element:

$$\frac{\partial Q_i}{\partial |V_i|}=-2|V_i||Y_{ii}|\,Sin\theta_{ii}-\sum_{\substack{j1\\ j\neq i}}|V_j||Y_{ij}|,\,Sin(\theta_{ij}-\delta_i+\delta_j)$$

Off-diagonal element:

$$\frac{\partial Q_i}{\partial |V_i|}=-|V_i||v_J||Y_{ij}|\,Sin(\theta_{ij}-\delta_i+\delta_j),\; j\neq i.$$

The terms $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are the difference between the scheduled and calculated values and represents the column vector of the control variables at the PV and PQ buses and are given by

$$\Delta P_i^{(k)}=P_i^{sch}-P_i^{(k)} \qquad (12)$$

$$\Delta Q_i^{(k)}=Q_i^{sch}-Q_i^{(k)} \qquad (13)$$

$\begin{bmatrix}\Delta\delta_i\\ \Delta V_i\end{bmatrix}$ Represents the column vector of the state variables at the PV and PQ buses. Gaussian elimination or triangular factorization method can be applied to equation 11 in order to determine the unknown vectors $\Delta\delta_i$ and ΔV_i updated value of the voltage angles at all buses except slack bus [8].

The complex power that flows through the transmission line connecting any two buses *i* and *j* as a result of the injection at bus *i* and *j* respectively are S_{ij} and S_{ji}. These can be expressed mathematically as

$$S_{Li}=V_iI_{ij}^{*} \qquad (14)$$

$$S_{ji}=V_jI_{ji}^{*}. \qquad (15)$$

The power loss in line i-j is the algebraic sum of the power flow determined from equations 14 and 15, i.e.

$$S_{Lij}=S_{ij}+S_{ji}. \qquad (16)$$

5. Results and Discussion

The simulation results obtained are presented in Table 3 and Table 4. Table 3 presents the results of the voltage magnitudes and angles at various network buses while Table 4 presents the results obtained for the power flow and losses along the transmission lines within the network.

Table 3. Bus voltages and phase angle for the Nigerian 330kV Network

Bus Number	Bus Name	Voltage(pu)	Angle(degree)
1	Egbin GS.	1.0400	0.0000
2	Benin	1.0063	6.9193
3	Ikeja west	0.9811	-4.7260
4	Akangba	0.9735	-5.4148
5	Sakete	0.9623	-7.1567
6	Aiyede	**0.9471**	-13.6748
7	Olorunshogo G.S	0.9800	-6.4793
8	Omotosho G.S	1.0200	6.8160
9	Oshogbo	0.9578	-22.0787
10	Ganmo	0.9603	-27.6345
11	Shiroro G.S	0.9700	-55.7140
12	Jebba T.S	1.0026	-29.5556
13	Jebba G.S	1.0100	-29.2973
14	Birnin Kebbi	1.0302	-29.1309
15	Kainji G.S	1.0200	-26.1358
16	Kano	**0.8721**	-76.2603
17	Kaduna	**0.9046**	-67.3781
18	Jos	**0.8731**	-78.0406
19	Gombe	**0.8735**	-87.1135
20	Yola	**0.8580**	-90.1711
21	Katampe	**0.9167**	-61.3107
22	Ajaokuta	1.0199	12.0747
23	Geregu G.S	1.0200	12.1056
24	Onitsha	1.0059	9.0862
25	Alaoji	1.0145	12.9354
26	New Haven	0.9673	5.2336
27	Sapele G.s	1.0200	9.0861
28	Delta G.S	1.0200	10.2525
29	Okpai G.S	1.0200	10.9691
30	Afam G.S	1.0200	13.7384
31	Aja	1.0376	-0.2139
32	Aladja	1.0147	9.2895

Table 4. Transmission Line Power flow for the Nigerian 330kV Network

From	To	Sending End		Receiving End		Line Losses	
		P	**Q**	**P**	**Q**	**Real Power**	**Reactive Power**
1	3	1054.483	613.736	-1039.041	-495.031	15.442	118.705
1	31	220.138	102.498	-220.0000	-101.436	0.138	1.062
2	3	518.107	50.073	-504.556	54.144	13.551	104.217
2	8	1.462	-88.934	-1.319	90.145	0.143	1.211
2	9	629.904	148.23	-592.734	167.236	37.17	315.466
2	22	-310.642	4.659	313.97	23.587	3.328	28.246
2	24	-180.692	26.694	181.5	-19.835	0.808	6.859
2	27	-572.59	-112.86	575.631	136.255	3.041	23.395
2	28	-483.549	-39.526	486.961	68.492	3.412	28.966
3	4	471.876	233.916	-471	-226.469	0.876	7.447
3	5	196.119	67.181	-195	-57.681	1.119	9.5
3	7	320.102	-21.358	-318.953	31.109	1.149	9.751
3	8	-328.292	9.128	336.319	58.995	8.027	68.123
3	9	373.791	42.331	-360.628	69.391	13.163	111.722
6	7	-643.946	-55.042	653.953	139.969	10.007	84.927
6	9	373.946	-45.13	-367.432	100.418	6.514	55.288
9	10	386.215	-37.426	-381.806	74.843	4.409	37.417
9	12	499.58	-204.486	-490.65	280.282	8.93	75.796
10	12	111.806	-177.678	-110.437	189.297	1.369	11.619
11	12	-1118.996	315.278	1181.754	217.385	62.758	532.663
11	17	1264.225	409.975	-1231.955	-136.078	32.27	273.897
11	21	304.771	144.672	-300	-107.986	4.771	36.686
12	13	-489.125	-605.857	490	612.571	0.875	6.714
12	15	-503.542	-67.96	507.266	99.579	3.724	31.619
14	15	-112	38.52	112.734	-32.293	0.734	6.227
16	17	-350	-12.757	356.642	69.127	6.642	56.37
17	18	500.313	82.66	-489.284	10.941	11.029	93.601
18	19	298.284	-12.312	-292.757	59.224	5.527	46.912
19	20	112.757	26.852	-112	-20.429	0.757	6.423
22	23	-409.97	-50.208	410	50.436	0.03	0.228
24	25	-162.846	4.085	164.142	6.914	1.296	10.999
24	26	237.347	112.848	-235	-92.932	2.347	19.916
24	29	-418	-108.63	420	124.016	2	15.386
25	30	-430.142	-101.253	431	107.852	0.858	6.599
27	32	-15.631	30.191	15.656	-29.979	0.025	0.212
28	32	183.039	35.685	-182.656	-32.434	0.383	3.251
			TOTAL POWER LOSS			268.622	2247.42

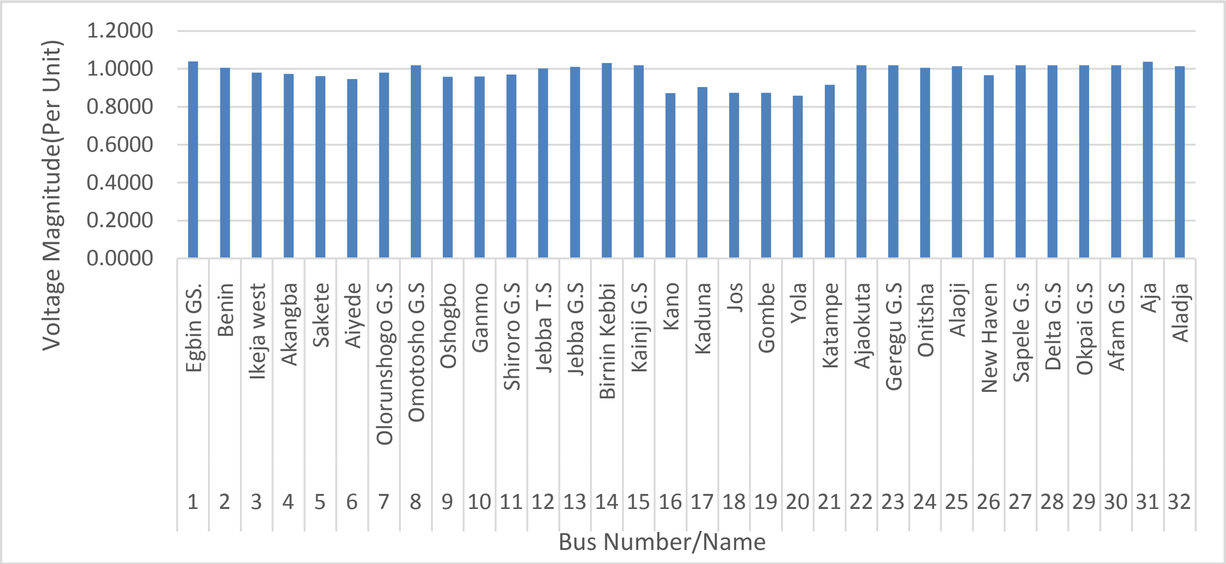

Figure 3. Bar chart showing voltage magnitude

Figure 3 is a bar chart plot which shows the graphical display of the voltage magnitude against bus number for the Nigerian 330kV grid network.

The Nigerian 330kV consisting of 32 buses was simulated based on Newton-Raphson power flow algorithm using MATLAB/SIMULINK software. The data used for the study were obtained from Power Holding Company of Nigeria (PHCN). Based on the results obtained, it was found that the total active power loss from the power flow program solutions by Newton Raphson method is 268.622MW and that of the reactive power loss is 2247.420Mvar. The results obtained also identify some weak buses with values outside the statutory limit of 0.95 pu or 313.5kV and1.05pu or 346.5kV. These weak buses include: (Kano, 0.8721pu), (Kaduna, 0.9046pu), (Jos, 0.8731pu), (Gombe, 0.8735pu), (Yola, 0.8580pu) and (Katampe, 0.9167pu). The result further showed that the losses are still very high and these weak buses are located within the Northern part of the network. This could be as a result of the fact that they are very far from the location of generating stations within the system.

6. Conclusion

In this paper, the load flow study for the Nigerian 330-kV grid network using Newton-Raphson iteration techniques was modeled using MATLAB/SIMULINK software. The result shows that the Nigerian 330kV grid network is characterized with various problems like voltage instability (voltage profile violation), problem of long transmission lines, nature of transmission lines and poor power quality, most especially, within the Northern areas of the network under consideration. Also, the result reveals that the reactive power loss in the Nigerian 330kV grid network is still very high, hence, the need for reactive power compensation. Furthermore, more substations and additional lines should be introduced into the grid network to provide more loops in the existing 330kV such that the voltage profile of the network will be greatly enhanced, especially Kano, Kaduna, Jos, Gombe, Yola and Katampe where voltage dip is severe.

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