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ASSESSMENT OF ELECTRICAL GRID FRAGILITY IN NIGERIA-31 BUS SYSTEM

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Abstract
The grid fragility is a prevalent challenge in Nigeria electricity supply industry (NESI). It has resulted in recorded incidents of voltage collapse which have been on the increase in the recent time. Meanwhile to evaluate this events; thus the nexus between voltage collapse and network capacity was explored. To actualize this, the load flow analysis was carried out on the Nigeria-31 bus system with the aid of the Newton-Raphson iteration technique. Using the relevant parameters (such as bus voltage magnitude, bus voltage angle, generated power, injected power as well as load magnitude) obtained from the analysis, the line stability index and line stability factor were obtained for every line in the network. It was discovered from the values of line stability index that Lines (26-2); (31-7); (10-11); (24-10) and (18-12) are weak and fragile while for the line stability factor, the values obtained for Lines (10-8); (11-8); (11-10); (24-10) and (18-12) indicate the fragility of some of the lines in the Nigerian Transmission Network. From this, it was established that the weakest lines were those whose values range from 0.3051 to 0.8813 for the line stability index. Correspondingly; any line that takes the value between 0.2737 and 0.9924 in respect of the line stability factor was also marked as the weakest lines in the network. Thus it was noticed that for the two line stability indices (i.e. stability factor and stability index); Line (11-10) i.e. from Oshogbo to Ikeja-West bus is the most fragile line in Nigeria-31 bus transmission network while the nearest to it are lines (24-10) i.e. from Ayede to Ikeja-West bus and (12-18) i.e. from Kaduna to Kano bus. This study is potentially sufficient for determining the lines in the transmission network that require utmost consideration for reinforcement in respect of the transmission expansion planning schemes.

Keywords: Transmission, fragility, stability index, collapse, electricity

1. Introduction

Electricity is the most crucial vehicle for socio-economic advancement in any nation. In industries, it is established that electricity contributes about 35 percent to the total cost of production. Therefore, lack of adequate electricity supply reduces the interest of investors due to unprecedented costs of production (Oluseyi, 2010). This may have its attendant problem on the increasing the rate of unemployment as well as complicate the human poverty index of a community.

Almost 50 per-cent of the Nigeria's population (precisely 76 million people) do not have access to electricity in Nigeria (Egeruoh, 2012) while the rest of the percentage do not have adequate supply of electricity. From the foregoing, it is therefore very crucial to look into steps to improve electricity in such an environment. Efforts have been made over the years to improve electricity supply in Nigeria. This has led to a number of policies in respect of the Electric Power Sector Reforms Act (Oluseyi, 2010). One of these is the restructuring and deregulation of the power sector to enhance access to electricity (Oluseyi *et al.*, 2009). The principle of deregulation involves provision of enabling environment for the investors to embark on electric power generation. With the advent of this, pressure is placed on the national grid to wheel the generated energy to the various Distribution Companies (Oluseyi *et al.*, 2012). The effects of deregulation on the grid are therefore highly profound and need to be carefully investigated (Oricha *et al.*, 2009). Several system collapse reports have been encountered in the recent times in the Nigerian national grid. Quite a number of these abnormal functioning of the transmission network has been related to poor network capacity of the transmission facilities (Samuel *et al.*, 2014) Thus, it has been quite impossible for the current Nigerian National grid to transport the recent total generated capacity to the load end. In order to record tangible improvement in power supply, the fragile Nigerian National grid has to be reinforced to ensure it has the capacity to wheel the quantum of generated electric power.

The review of the incidence of system collapse events on the transmission network have been done in past studies which revealed that in the last ten years, the Nigerian national grid has experienced an average of thirty-five system collapses per year (Awosope, 2014). Furthermore, a thorough assessment of voltage instability has been well documented for purpose of improving the phenomenon (Airoboman *et al.*, 2015).

This study, by means of variously developed stability indices, examines the grid fragility on the Nigerian Transmission Network. This is quite different from the previous approaches in a number of ways. For instance; much more than lumping the network parameters into one component while determining the fragility of the grid, this study developed a model for the investigating the extent of fragility of each line in the grid. This provides empirical information on the fragility status of lines in the entire network; thus facilitating establishing the identification of weakest buses. Hence, it aids in locating the potentially weakest buses that may threaten the system stability. Thus, this assists in prudent manipulation of the network operation for the purpose of proffering practical approach to mitigating the challenges of voltage collapse phenomenon. More importantly, this analysis of the grid fragility will serve as analytic framework to various transmission expansion planning schemes; in which case the weak line may be reinforced further to mitigate further voltage collapse in the network.

2. Materials and Methods

The primary material for this work is the bus and line data of the Nigeria-31 bus system (as it currently operates). This was collected from the Transmission Company of Nigeria (TCN). In order to evaluate this, the *MATLAB*™ Software Package (2012) would be employed. The standard approach adopted for the analysis of the transmission network is analytical combined with the simulation technique. In the case of the analytical methodology, this involves the application of the outcome of the Newton-Raphson algorithm to the well-established mathematical model for the evaluation of the line stability indices. The two main line stability indices that would be used are Line stability index and Line stability Factor. So also the same transmission network would be further evaluated using the Powerworld Simulator which is interactive power system simulation package which is used to evaluate the contingency analysis study of the transmission network.

The analysis of the Newton-Raphson load flow is carried out using the load flow equation (for N-bus system). This is expressed in polar form as follows.

$$I_i = \sum_{i=1}^{N} |Y_{ij}||V_j| \tag{1}$$

The current can thus be further simplified into real and reactive components as follows:

$$I_i = \frac{P_i - jQ_i}{V_i^*} \tag{2}$$

This can then be re-arranged as follows.

$$P_i - jQ_i = I_i V_i^* = S_i = \sum_{i=1}^{N_g} |V_i^*| \angle -\delta_i \sum_{j=N_g+1}^{N} |V_j||Y_{ij}| \angle(\delta_j + \theta_{ij}) \tag{3}$$

Separating this into the real and the imaginary parts we then obtain the equations (4) and (5); however note that the total number of buses irrespective of whether generator or load is N; hence it is taken for granted that the iteration from i=1 to N is the limit of summation as depicted in the following equations.

$$P_i = \sum_{\substack{j=1 \\ j \neq i}}^{N} |V_i^*||V_j||Y_{ij}| Cos(\delta_i - \delta_j - \theta_{ij}) \tag{4}$$

$$Q_i = \sum_{\substack{j=1 \\ j \neq i}}^{N} |V_i^*||V_j||Y_{ij}| Sin(\delta_i - \delta_j - \theta_{ij}) \tag{5}$$

The algorithm for computing involves:

Step 1: Formation of the Ybus

Step 2: Assume the initial values of bus voltage as $|V|^0$ for all load buses (PQ) buses and bus angle as δ_i^0 for all the buses except the slack bus

Step 3: Compute P_i and Q_i for each load bus using equations (4) and (5)

Step 4: Compute the scheduled errors (i.e. ΔP_i and ΔQ_i for each load bus using the equations:

$$\Delta P_i = \Delta P_i^{spec} + \Delta P_i^{calc}; i = 1,2,3 \ldots n \tag{6}$$

Where i= 1, 2, … N for PQ buses and

$$\Delta Q_i = \Delta Q_i^{spec} + \Delta Q_i^{calc}; i = 1,2,3 \ldots n \tag{7}$$

Step 5: Compute the elements of Jacobian matrix

$$\begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \tag{8}$$

Where $J_2 = J_3 = 0$

Step 6: From steps 6, 7 and 8; write the syetm equation as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & 0 \\ 0 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \dfrac{\Delta V}{V} \end{bmatrix} \tag{9}$$

Step 7: Expand the equation and thus obtain the values of $\Delta\delta_i$ and ΔV_i from equation (9) so as to modify the voltage magnitude and phase angle for each of the buses in the network (Oluseyi, 2010).

Step 8: Set up the equations for calculating the new voltage magnitude and angle as follows:

$$|V_i^{r+1}| = |V_i^r| + |\Delta V_i^r| \tag{10}$$

$$\delta_i^{(r+1)} = \delta_i^{(r)} + \Delta\delta_i^{(r)} \tag{11}$$

Step 9: Commence a new iteration cycle from Step 2 with the new values of voltage magnitude and phase angle obtained in Step 8.

Step 10: Continue this until the scheduled error is within the pre-set specified tolerance value.

$$\Delta P_i^{(r)} \prec \varepsilon;$$

and

i.e. $\Delta Q_i^{(r)} \prec \varepsilon$

The ensuing power flow solution is then employed in the subsequent sections of the work.

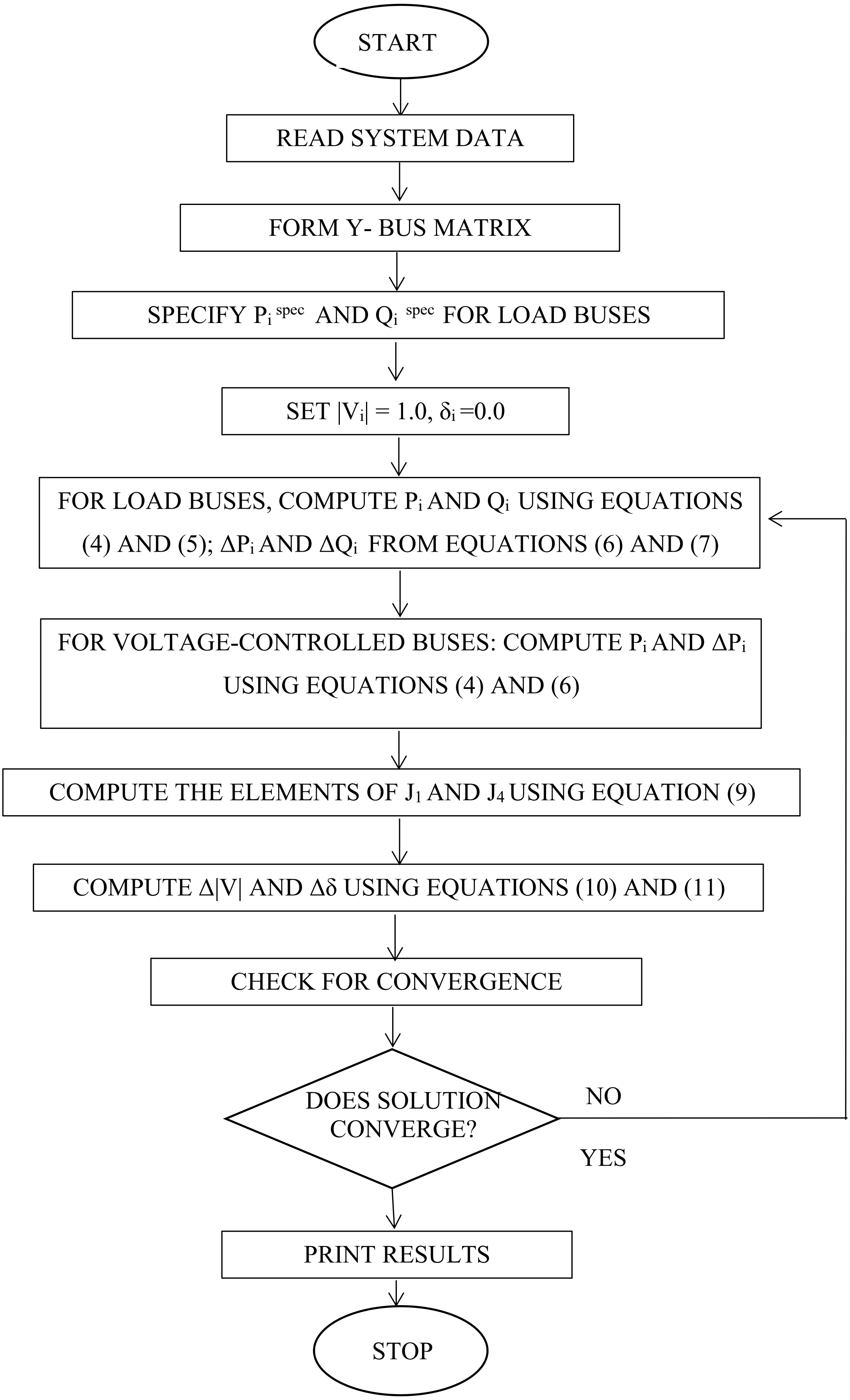

Figure 1: Flow Chart of the Newton-Raphson Load Flow Iteration Algorithm

In the case of (N-1) contingency analysis test, the powerworld simulator is arranged as shown in the flow chart shown in Figure 2.

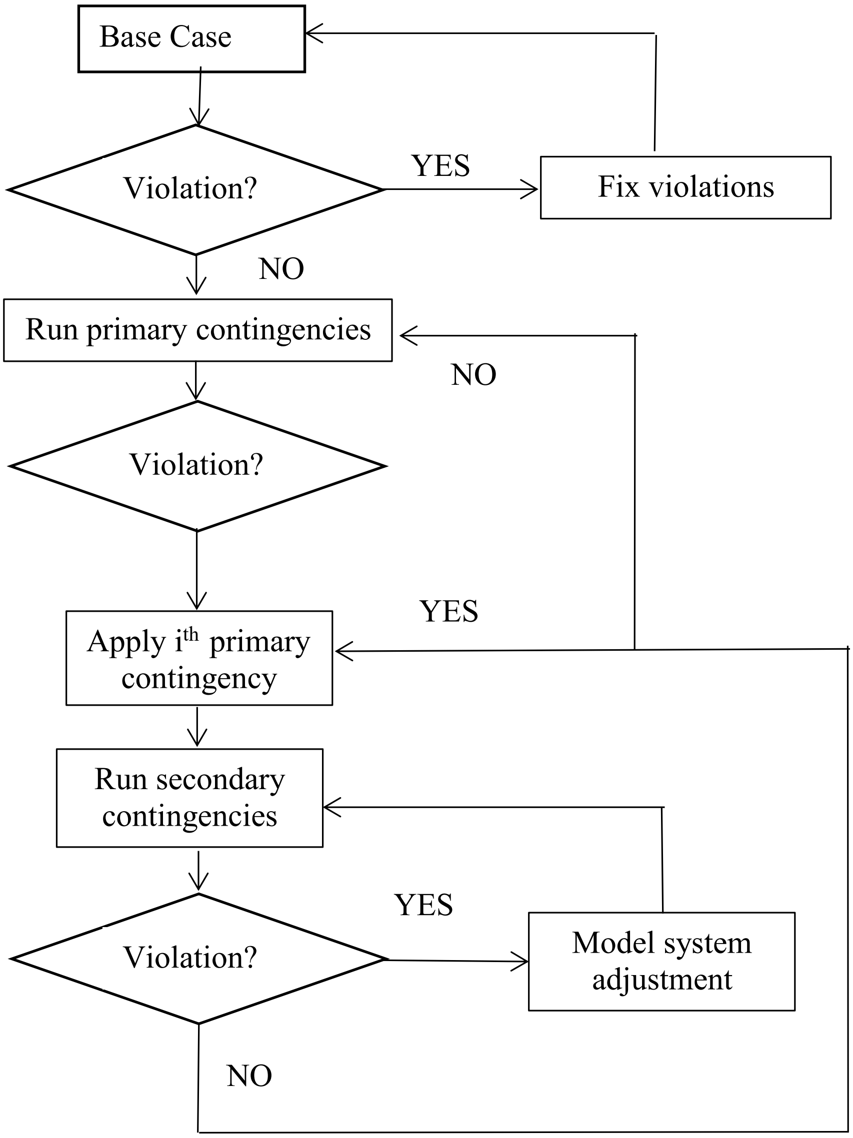

Figure 2: Flow Chart of Contingency Analysis Algorithm (Scott, 2012)

The powerworld has a menu for contingency analysis in which case the contingency analysis dialogue box is open. Then the line and bus data are then uploaded in which case the "run" mode is thus activated so as to generate the relevant results (see Figure 2) along with the pictorial display of the entire network as shown in Figure 4.

2.1 Detection of Weakest Lines Using Stability Indices

In the determination of grid fragility, there are several stability indices that can be employed (Oluseyi, 2010). In this work, the line stability index and the line stability factor shall be employed to detect the weakest lines in the Nigerian national grid. From this, the lines that should be given greater priority in respect of network reinforcement in line with previous comparative study of voltage stability indices are identified (Sinha and Hazarika, 2000). The preferred load flow study for this analysis is the Newton–Raphson load flow approach. The Newton-Raphson technique is chosen for obvious reasons, amongst which is that it has solutions for cases of divergence in iteration (Oluseyi, 2010). Thus the Newton-Raphson iterative method is used in load flow analysis and the results obtained are used to compute the above mentioned indices (Goh, *et al,* 2015).

2.2 Line Stability Index

The work of Moghavvemi and Omar (1998) on the conceptual modelling of the line stability index was adopted for this calculation. The assumption made was that the power flow through a single line. Thus by the use of the system reduction techniques to represent the entire transmission network as a single line, as shown in Figure 3, the equivalent network analysis is thus modelled as depicted equation (1) for the computation of the overall system stability index.

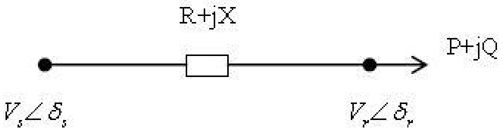

Figure 3: Diagram of a Transmission Line with 2-Bus System (Goh *et al.*, 2015)

The line stability index using this technique is given as:

$$L_{mn}=\frac{4XQ_R}{[V_s\sin(\theta-\delta)]^2} \tag{12}$$

where:
V_S is the sending end voltage
δ_S and δ_R are the phase angle at the sending and receiving buses respectively
X is the line reactance
θ is the line impedance angle

Based on the stability indices of lines, voltage collapse can be predicted. When the stability index L_{mn} is less than 1, the system is stable and when this index exceeds the value 1, the whole system loses its stability and voltage collapse occurs (Tran, 2009).

By extension, in the application to calculation of grid fragility for the purpose of this work, the line stability index is computed for every line in the transmission network rather than compressing the whole system into a single line equivalent. The lines with the stability index closest to 1 will be identified as the most fragile lines in the system.

2.3 Line Stability Factor (LQP)

For proper and effective identification of the weakest lines in the transmission network, a further analysis was performed on the network using another concept of the stability index. In this case, the Line Stability Factor (LQP) was employed while the results are compared with those obtained from the Line Stability Index earlier obtained. The stressed transmission network would obviously results in voltage collapse, thus the network is better monitored to ensure that the stability margin is not violated. This is best done by approaching the network stability analysis using voltage stability index *(*Ratra*, et al,* 2018*).* Moreover, the LQP is also formulated so as to enumerate the stability status of the transmission networks. This approach is thus applied to the currently existing Nigeria-31 bus system using Equation (2). Similarly, Figure 1 is also valid for this derivation of this calculation.

$$LQP=4\left[\left(\frac{X}{V_s^2}\right)\left(\frac{X}{V_s^2}P_s^2+Q_R\right)\right] \tag{13}$$

X is the line reactance
V_S is the voltage magnitude at the sending end
P_s is the active power at the sending end
Q_R is the reactive power at the receiving end

In similarity to the application of the Line Stability Index, the lines with the line stability factor closest to value of unity will be identified as the most fragile lines in the system. Thus the only acceptable evidence that a line is a threat to the voltage stability in a network is when the values of both its stability index and stability factor equally violate the stability margin of the network.

3. Results and Discussion

This section presents the results obtained from deploying the procedure presented in section 2. From this investigation, Table 1 shows the results obtained from the load flow analysis by applying the Newton-Raphson iteration method. Thus Table 1 is the narration of the voltage profile of the Nigerian transmission grid in which the comparison to the magnitudes and phase of the various real and reactive power quantities of each of the buses that make up the Nigeria-31 bus system are displayed.

Table 1: System Voltage Profile with Power Magnitude at Each Bus of the Nigeria-31 Bus System

Bus	V	Angle	Injection		Generation		Load	
No	(pu)	(Degree)	MW	MVar	MW	MVAr	MW	MVAr
1	1.0200	0.0000	825.4612	332.2438	332.2438	332.2438	0.0000	0.0000
2	0.9900	-2.9559	200.0000	-43.8762	-43.8762	-43.8762	0.0000	0.0000
3	1.0000	-2.3820	300.0000	11.3003	11.3003	11.3003	0.0000	0.0000
4	1.0000	-8.9140	250.0000	138.4051	138.4051	138.4051	0.0000	0.0000
5	1.0300	7.0762	490.0000	-52.6504	-52.6504	-52.6504	0.0000	0.0000
6	1.0400	7.3865	350.0000	-27.0382	-27.0382	-27.0382	0.0000	0.0000
7	1.0300	9.5870	450.0000	-35.4185	-35.4185	-35.4185	0.0000	0.0000
8	0.9953	-5.0357	-156.0000	-79.9000	-79.9000	0.0000	156.0000	79.9000
9	1.0402	4.6449	-8.6000	-5.6000	-5.6000	0.0000	8.6000	5.6000
10	0.9816	-5.6930	-429.9000	-258.4000	-258.4000	0.0000	429.9000	258.4000
11	1.0160	-0.5566	-201.0000	-136.7000	-136.7000	0.0000	201.0000	136.7000
12	1.0337	-1.1701	-166.2000	-97.8000	-97.8000	0.0000	166.2000	97.8000
13	1.0632	-6.4503	-58.4000	-28.4000	-28.4000	0.0000	58.4000	28.4000
14	0.9777	-11.2587	-144.7000	-88.4000	-88.4000	0.0000	144.7000	88.4000
15	0.9730	-10.8277	-115.2000	-42.0000	-42.0000	0.0000	115.2000	42.0000
16	0.9960	-4.8273	-82.1000	-44.5000	-44.5000	0.0000	82.1000	44.5000
17	0.9575	-12.7112	-112.6000	-50.0000	-50.0000	0.0000	112.6000	50.0000
18	0.9941	-8.0840	-184.9000	-60.0000	-60.0000	0.0000	184.9000	60.0000
19	1.0745	-10.6699	-102.9000	-17.5000	-17.5000	0.0000	102.9000	17.5000
20	1.0212	2.0303	-60.3000	-70.0000	-70.0000	0.0000	60.3000	70.0000
21	1.0058	-6.0171	-26.8000	-10.5000	-10.5000	0.0000	26.8000	10.5000
22	0.9775	-6.1333	-292.0000	-114.9000	-114.9000	0.0000	292.0000	114.9000
23	0.9977	-3.2197	-193.5000	-101.2000	-101.2000	0.0000	193.5000	101.2000
24	0.9927	-4.1225	-139.4000	-61.0000	-61.0000	0.0000	139.4000	61.0000
25	1.0003	-3.0052	-109.7000	-64.2000	-64.2000	0.0000	109.7000	64.2000
26	0.9956	-4.3557	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
27	0.9993	-4.6754	-64.3000	-44.2000	-44.2000	0.0000	64.3000	44.2000
28	0.9810	-10.9908	-119.3000	-65.7000	-65.7000	0.0000	119.3000	65.7000
29	1.0413	2.7845	-61.5000	-10.3000	-10.3000	0.0000	61.5000	10.3000
30	1.0445	4.8916	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
31	1.0401	4.9320	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

From the details of Table 1, as a representation of the voltage profile, it is evident that the Nigeria's Transmission Network as a whole is fragile requiring massive upgrades. Thus the voltage magnitudes range from 0.95 pu to 1.08 pu (under normal operating conditions) which is technically unacceptable when compared to the acceptable international standard on electricity operating policy with a permissible variation standards put at ±4 per cent of the nominal voltage magnitude.

To further buttress the earlier statement in the preceding paragraph, the measurement of the line stability indices for establishing the existing operating conditions of the Nigeria's transmission network was carried out. The results are thus presented below in Table 2. From this, it shows the values of line stability factor (LQP) and line stability index (L_{mn}) obtained for each line of the Nigerian Transmission Network. The lines with values of the stability indices closest to unity depict the most fragile lines in the system. It is highly important to juxtaposing the results obtained using the two stability indices techniques, hence, obtaining accurate results in each case. In most cases, the L_{mn} reveals larger values than the LQP for stable lines (L_{mn}, LQP$\leq$ 0.45). Whilst the contrast is the case with regard to the fragile lines.

Table 2: Line Stability Indices for the Nigerian Transmission Network

S/N	Line		LQP	L_{mn}
	From Bus	To Bus		
1	25	1	0.0863	0.0880
2	26	2	0.0213	0.4642
3	27	3	0.0063	0.0085
4	28	4	0.0831	0.0818
5	29	5	0.0322	0.0319
6	30	6	0.0134	0.0352
7	31	7	0.0253	0.6231
8	10	8	0.2737	0.1379
9	11	8	0.3132	0.2297
10	8	15	0.0850	0.0687
11	21	8	0.1830	0.1923
12	8	26	0.0005	0.0000
13	8	27	0.0037	0.0164
14	9	11	0.0782	0.0800
15	9	29	0.0138	0.0149
16	30	9	0.0003	0.0004
17	31	9	0.0002	0.0004
18	11	10	0.9924	0.8813
19	10	22	0.0133	0.0127
20	24	10	0.4379	0.4550
21	10	25	0.0311	0.0248
22	11	24	0.0878	0.0734
23	12	13	0.0949	0.0622
24	18	12	0.3339	0.3051
25	29	12	0.0515	0.0664
26	13	19	0.0551	0.0496
27	15	14	0.1823	0.1901
28	14	28	0.0103	0.0102
29	15	17	0.0647	0.0624
30	26	16	0.0334	0.0966
31	27	16	0.0138	0.0137
32	20	30	0.0112	0.0000
33	25	23	0.0084	0.0084

From observation, the five most fragile lines while juxtaposing the LQP and the L_{mn} are shown in bold prints in Table 2. It is evident from the two indices that the line from bus 11 to 10, Line (11-10) which is from Oshogbo to Ikeja-West, is the most fragile line in the Nigerian Transmission Network. Under normal operating conditions, the L_{mn} reveals a value of 0.8813 for the line from Oshogbo to Ikeja-West while the LQP has a value of 0.9924 for the same line. It is also discovered that the next two most fragile lines are the lines from Ayede to Ikeja-West, i.e. Line (24-10) and from Kaduna to Kano, i.e. Line (12–18).

The values obtained for the L_{mn} and LQP for each line are very close; indicating the accurate computation which further verifies the effectiveness of the two tests of the line stability as deployed for the Nigerian Transmission Network. In case of the line from bus Egbin to Ajah, i.e. Line (25-23), the values obtained for the two indices are in fact the same (0.0084). However, in some cases, a difficulty arises in asserting the fragility of the line where the values obtained for the two indices are contrasting as in the case of the Line (7-31). This is a rare case which can be handled by further research that is not covered in this work.

Since voltage collapse is closely related to reactive power component of the line or network; thus its consequence on the notably weak buses was determined. This provides information on the extent of the proficiency of the methods. The result is as presented in Table 3.

Table 3: Characteristic behaviour of Nigeria Transmission Line to Stability Indices at Critical Line with Variation in Reactive Power Magnitude (MVAr)

Q (MVAr)	LQP	L_{mn}
200	0.9912	0.881
210	1.0031	0.8845
220	1.0155	0.8885
230	1.0286	0.8931
240	1.0422	0.8981
250	1.0565	0.9034
260	1.0713	0.9089

Similarly, Table 4 provides information on the behaviour of the same transmission network to the phenomenon of the real power flow. The values of both the stability factor (LQP) and line stability indices (L_{mn}) are within the threshold on both sides of unity. The import of these values is quite informative in regard of the influence of the realm power flow on the system collapse. This would be further discussed later in this work.

Table 4: Characteristic behaviour of Nigeria Transmission Line to Stability Indices at Critical Line with Variation in Real Power Magnitude (MW)

P (MW)	LQP	L_{mn}
250	0.9632	0.8504
260	0.9979	0.8873
270	1.0327	0.9248
280	1.0676	0.9631
290	1.1025	1.0022
300	1.1375	1.0421
310	1.1726	1.0828

From the foregoing, Tables 3 and 4 narrated the characteristic behaviour of the most fragile line in relationship to the line stability indices, i.e. LQP and L_{mn} with varying values of real and reactive power magnitudes respectively. Table 3 shows the variations of reactive power only while Table 4 depicts that of the real power only. Further investigation was made by varying both real power and reactive power at the same time within a specific value range. From this consideration, thus Table 5 was generated; as presented.

Table 5: Characteristic behaviour of Nigeria Transmission Line to Stability Indices at Critical Line with Variations in both Real Power (MW) and Reactive Power (MVAr) Flow in the network

Q (MVAr)	P(W)	LQP	Lmn
200	250	0.9620	0.8502
210	260	1.0086	0.8905
220	270	1.0560	0.9339
230	280	1.1040	0.9804
240	290	1.1527	1.0300
250	300	1.2021	1.0828

Table 5 showed a more probable case of variations in both reactive and real power flow in the network; especially with regard to the highly fragile lines. On this table, it is observed that the LQP is more sensitive to load changes. From the table, as the load is increased to 210MW and 260MVAr, which is a meagre variation in load, it could be observed that the LQP increases above unity which is a very grievous indication that collapse would occur in the network.

With the deployment of Figure 2, the powerworld simulation is obtained as displayed in Figure 4. In the vivid pictorial illustration captured in Figure 4, the contingency analysis of the network was easily evaluated using Powerworld simulator. Thus this aided in the identification of the location of the weakest lines in the network. Hence from the Powerworld simulation of the transmission network of the Nigeria-31 bus system, it is apparently confirmed that the same lines that have been identified as the weakest buses (using the analytical technique). This is narrated pictorially and illustrated by the limited flow of power to the adjoining lines in Figure 4.

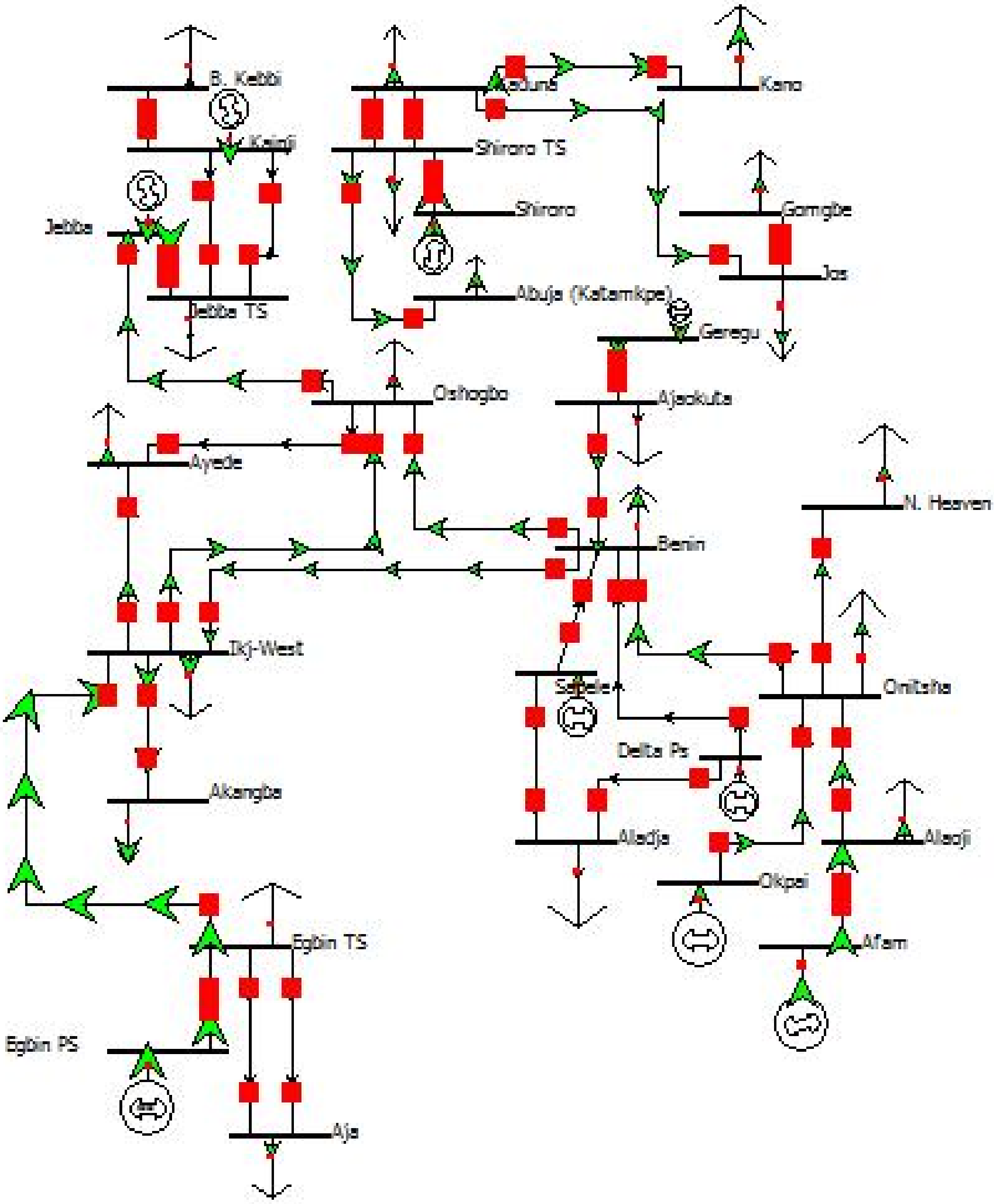

Figure 4: Powerworld Simulation of Nigeria-31 bus Transmission Network

The Nigeria- 31 bus system as presented in Figure 5 is shown below.

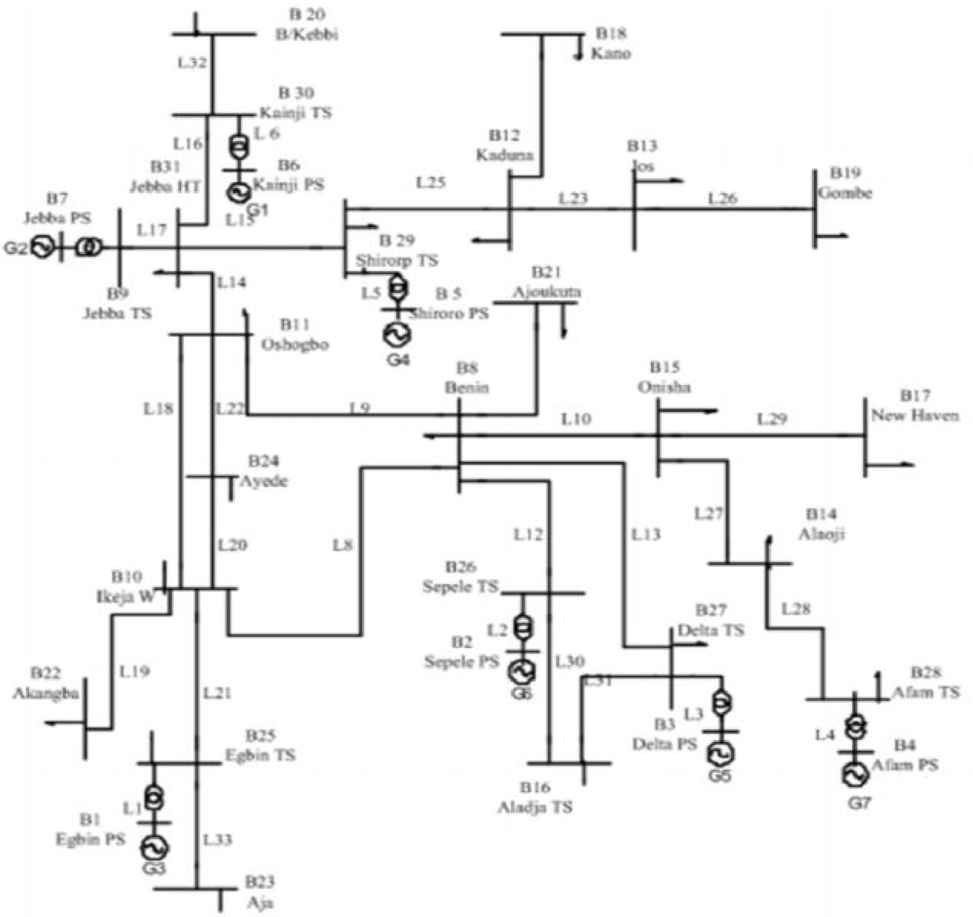

Figure 5: One Line Diagram of the Nigeria-31 Bus Transmission Network

From the outlook of Figure 4 which is developed from Figure 5, the Nigeria's transmission network is obviously weak though there are some lines that exhibit more fragility than others. From this study; a number of the buses identified to be threatened by this fragile lines would naturally not be able to supply continuous load to the load centres due to the blackout as the evidence of voltage collapse. From the outlook of Table 2 and Figure 4; some of the weakest lines in the system include Line (11-10) i.e. from Oshogbo to Ikeja-West (wherein LQP is equal to 0.9924, L_{mn} is equal to 0.8813 for normal operating conditions), so also is Line (24-10) i.e. from Ayede to Ikeja-West (LQP is equal to 0.4379, L_{mn} is equal to 0.4550 for normal operating conditions) and Line (12-18) i.e. from Kaduna to Kano in which LQP is 0.3339 while L_{mn} is 0.3054 for normal operating conditions. From the pictorial output of the Powerworld simulation as displayed in Figures 4; it is generally observed that those listed weak buses have terribly low magnitude of flow of power from sending bus to the receiving bus which further affirm the test of fragility obtained for the network. Hence, Table 6 is a narration of the influence of the contingency analysis of the Nigeria's transmission network. In which case, the critical lines were identified along with the buses that are violated in the network. This gives the summary of the fragility analysis of the network. Furthermore, when the two most fragile lines (i.e. Oshogbo to Ikeja-West and Ayede to Ikeja-West) are subjected to contingencies (as depicted in Figure 2), the buses at Kaduna, Jos, Gombe and Birnin-Kebbi are likewise violated (see Table 6).

Table 6: Violations Recorded with Contingency on Critical Lines

S/N	Critical Line	Violated Buses
1	From Oshogbo to Ikeja-West	Jos Gombe Birnin Kebbi Kaduna
2	From Ayede to Ikeja-West	Jos Gombe Birnin Kebbi Kaduna

Considering the set of violation recorded by subjecting the critical lines to contingencies, it can be concluded that the vulnerability of these lines to fragility is highly undesirable. This thus implies that any small variation in the load at the buses adjoining the critical lines makes the network to be susceptible to violation in a number of buses within the system. For instance for the case at hand, it is evident from Table 6, that at least four buses in the grid experience security margin violation. This therefore calls for an urgent upgrade of the critical lines in the system because the weakest lines would determine the overall stability status of the whole network.

4. Conclusion

From the foregoing it was established the powerworld simulator's flow analysis that that the line with least flow across it are the weakest lines. This approach was used to determine the integrity status of the network. This is as a further support to the stability indices which primarily tested the stability margin of the network. Thus, this discovery then means that the Nigeria's transmission network has violated buses as Jos, Gombe, Birnin-Kebbi and Kaduna. This is attributed to the influence of the poorly linked connection from Oshogbo to Ikeja-West and Ayede to Ikeja-West. These lines are considered as the weakest connection which suggests that they are the most critically fragile lines in the network.

In other words, the analysis has shown that two buses whose lines are adjoining the Ikeja-West bus are highly fragile (i.e. Oshogbo and Ayede). It is therefore recommended that these lines should be considered for reinforcement (using either transmission expansion programme or deployment of the flexible alternating current transmission systems (FACTS) devices such as SVC, UPFC, etc) as they are highly susceptible to voltage collapse.

In the same vein, in the Northern part of the country, i.e. the line from Kaduna to Kano should be considered as primary target for the transmission expansion programme scheme. This will improve the quantity and quality of electricity delivery to this part of the country. For a wholesome solution to the challenges of electricity supply, the frontier of this research may be further extended to consider the effects on vandalism on grid fragility whilst the study of the cost analysis of implementing remedies to fragility in the network may be considered as area of future research interest. Whilst the another simulator such as ETAP load flow software tool may be deployed to solve this problem whose output could be compared with that of the Powerworld simulator. The study has undoubtedly revealed the susceptibility of the Nigeria's transmission network to voltage collapse with empirical evidence of the locations that need to be fortified against violation induced by the fragility of the network.

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