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Assessment of Voltage Stability of the Nigerian 330 kV Network

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ABSTRACT

Ability to determine voltage stability before voltage collapse will continue to receive attention of power system operators. Several voltage stability indices to predict closeness of power system to voltage stability boundary have been proposed in literature. In this work, the most appropriate voltage stability indices for the load buses and the branches that connect them are computed for Nigeria's 33 bus, 39 line, 330 kV network to determine the components of the power system with high probability of voltage collapse. This will serve as a guide for any mitigation action to be taken before system collapse. Findings of this work show that all the buses and branches of the power system are stable with Yola, which is one of the relatively new buses on the network being the most stable while Ikeja West is the most vulnerable to voltage collapse. Similarly, the line between Oshogbo and Jebba transmission station (TS) is the most stable while Ikeja West to Benin line is the closest to point of instability. The buses and branches were ranked according to their closeness to point of instability. The results obtained in this study indicate that the Nigerian power system is entirely stable. Ikeja West bus with the lowest voltage sensitivity index of 0.0313 is the weakest bus hence will be the most likely bus that will collapse. This bus should be considered first in future compensation action that is to be carried out on the network. Transmission line between Ikeja West and Benin is the most loaded.

1. INTRODUCTION

The Nigeria National Electric Power (NNEP) system has been confronted with the problem of imbalance between demand and supply whereby the demand on it far exceeds the generation (Ebhota and Tabakov, 2018). This imbalance in demand and supply, according to Awosope, (2014) is traceable to 1970s when the Public Service Review Commission under the Chairmanship of Chief Jerome Udoji, from 1972 – 1974, improved the economic life of the workers. This made the workers to increase their electricity consumption by purchasing several sophisticated and automating machines that consumed quite a lot of energy. The power utility company, on the other hand, was not prepared for this sudden increase in consumption. This challenge has consistently left a deficit in the generated energy since that period. Such an overstretched network is prone to frequent voltage collapse.

In real-time operation of power system, it is very important that voltage stability analysis is performed whereby a stability index is used to monitor the closeness of the system to collapse and to predict the imminent danger of collapse early enough. This is with a view to alerting system operators to take necessary action to avert a voltage collapse thereby, making the power system network more secure and reliable. The terms voltage instability and voltage collapse are synonymous and are often used interchangeably. Literarily, voltage stability in a power system is the ability of the power system to maintain acceptable voltages at all bus in the system under normal condition and after being subjected to a disturbance. Voltage collapse on the other hand is the process by which the sequence of events accompanying voltage instability leads to voltage drop in a significant part of the power system.

The imbalance between power demand and the available electric power is a well-known reason for power systems to operate close to their limits of stability. The ability of a load bus to supply certain load depends on the reactive power support that the bus can receive from the system (Pradyumna et al., 2013). A bus or a line that cannot withstand its load due to inadequate reactive power support is termed a weak bus. One effective way to know the voltage instability origin is to identify weakest buses and lines in the systems. Conceptually, if a line or a bus in the system has critically unstable voltage, the whole system approaches a collapse point (Bhadoriya and Daheriya, 2014). The ability to have a prior knowledge of voltage stability level before voltage collapse is very vital information to power system operator.

Several metrics of stability called stability indices have been developed by different researchers and made available in literature (Amroune et al., 2014; Bhadoriya and Daheriya, 2014; Moradi et al., 2017). Stability indices are used to quantify how close a particular bus or line is to instability. Among such indices are, fast voltage stability index (FVSI), line stability index, voltage collapse prediction index (VCPI) and reactive power voltage stability index (RPVSI) among others.

The aim of this work is to determine whether every bus and every transmission line on the Nigerian power system is stable or not and rank the buses and lines from the least stable (or weakest) to the most stable.

2. METHODOLOGY

This work was carried out in the following mainstream sequence:

1. Obtain bus and line data for the power system: The required data were obtained from the operational records of the Transmission Company of Nigeria (TCN) and are presented in the appendix.

2. Run power flow studies: The power system can operate in one of numerous steady state voltage and power sets in the buses. Power flow analysis is the procedure used to determine these possible operational states by making use of some known bus variables of the system. The objective of power flow analysis is to obtain the system bus voltages – magnitude and angle. Once this is done, it becomes possible to estimate the amount of power flow and losses in the system lines. Power flow is basically solving the complex and nonlinear power balance equations given in Equations (1) and (2).

$$P_i = \sum_{i=I}^{N} |V_i||V_j||Y_{ij}|\cos(\delta_i - \delta_j - \theta_{ij}), \mathrm{j} = 1, \ldots, \mathrm{N} \tag{1}$$

$$Q_i = \sum_{i=I}^{N} |V_i||V_j||Y_{ij}|\sin(\delta_i - \delta_j - \theta_{ij}), \mathrm{j} = 1, \ldots, \mathrm{N} \tag{2}$$

Where: $i = 1, \ldots, \mathrm{N}$, N is the number of load buses; P_i = active power generated or injected in the bus i; Q_i = reactive power generated or injected in the bus i; $|V_i|$ = voltage magnitude on bus i; δ_i = angle of the voltage on bus i, y_{ik} = element of the nodal admittance matrix Y_{bus}. The mathematical formulation of the power flow problem results into nonlinear algebraic equations which can only be solved by iterative techniques. Among the iterative techniques, the Newton Raphson (NR) method is most often used because of, primarily, its fast convergence. The steps of the NR technique are as follows (Mander and Virdi, 2017)

Step 1: Form the nodal admittance matrix (Y_{ij}).
Step 2: Set bus N as the slack bus with voltage magnitude $|V_N|$=1 and angle δ_N =0.0. Real and reactive power are specified for the load buses and their values of voltage magnitudes and phase angles are set equal to the slack bus values. For voltage-regulated buses, voltage magnitude and real power are specified, phase angle are set equal to slack bus value. Initialize iteration counter k.
Step 3: Calculate the real Power P_i using Equation (1).
Step 4: Calculate the reactive Power Q_i using Equation (2).
Step 5: Form the Jacobian matrix J.
Step 6: Calculate the power differences ΔP_i and ΔQ_i for all i=1, 2, 3… (N-1) using Equations (3) and (4).

$$\Delta P_i = P_{i\,specified} - P^k_{i\,calculated} \tag{3}$$
$$\Delta Q_i = Q_{i\,specified} - Q^k_{i\,calculated} \tag{4}$$

Step 7: Choose the tolerance values.
Step 8: Stop the iteration if all ΔP_i and ΔQi are within the tolerance values.
Step 9: Update the values of V_i and δ_i using Equations (5) and (6).

$$\left|V_i^{(k+1)}\right| = \left|V_i^{(k)}\right| + \Delta\left|V_i^{(k)}\right| \tag{5}$$

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \tag{6}$$

3. Compute bus voltage stability indices: Voltage stability indices are used in power system to know how close the system is to voltage collapse or how much power can be supply to the load by analyzing the behavior of every bus voltage in the system with respect to the power transferred. These indices help operators in real time operation of power system or in designing and planning operation. The bus voltage of power system is more affected by reactive power than active power except in heavily loaded power system where the effect of active power on buses voltage can be noticeable (Moradi *et al.*, 2017) Therefore it is adequate to investigate bus voltage stability level by considering the variations of the bus voltage with the reactive power as in Equation (7).

$$\mathrm{VSI} = \frac{\partial \mathrm{V_i}}{\partial \mathrm{Q_j}} \tag{7}$$

The voltage sensitivity index in Equation (7) is the reactive power voltage stability index (RPVSI) and gives the variation of node i voltage magnitude due to a unit reactive power injection to node j. (Monta˜n´es et al., 2005).

The computation of RPVS considers the linearized steady state system power voltage equations are given by:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \tag{8}$$

Where J is the Jacobian

From Equation (8):

$$\Delta Q = \left(-J_3 \frac{J_2}{J_1} + J_4\right) \Delta|V| \tag{9}$$

The reactive power is less sensitive to changes in voltage phase angles and is mainly dependent on changes in voltage magnitudes. Similarly, real power change is less sensitive to the change in the voltage magnitude and is most sensitive to the change in phase angle. So, it is quite accurate to set J_2 and J_3 in Equation (9) to zero resulting in Equation (10).

$$\frac{\Delta|V|}{\Delta Q} = J_{4ij}^{-1} \tag{10}$$

The i^{th} diagonal elements of J_4^{-1} indicate the Q-V sensitivity of i^{th} load bus. The Q-V sensitivity at load bus represents the slope of the Q-V curve at given operating point. A positive Q-V sensitivity is an indicator of stable operation, the smaller the sensitivity, the more the bus is stable (Pradyumna *et al.*, 2013).

The off diagonal and diagonal elements of J_4 are computed as in Equations (11) and (12) respectively.

$$J_{4ij} = \frac{\partial Q_i}{\partial |V_j|} = |V_i||Y_{ij}|\sin(\delta_i - \delta_j - \theta_{ij}) \tag{11}$$

$$J_{4ii} = \frac{\partial Q_i}{\partial |V_i|} = -|V_i||Y_{ii}|\sin\theta_{ii} + \sum_{j=1}^{N} |V_j||Y_{ij}|\sin(\delta_i - \delta_j - \theta_{ij}) \tag{12}$$

Matrix $RPVS_{ij}$ is determined by Equation (13).

$$RPVSI_{ij} = J_{4ij}^{-1} \tag{13}$$

The sensitivity indices are computed as in Equation (14).

$$RPVS_i = diag\{J_{4ij}^{-1}\} \tag{14}$$

Every bus in power system has its unique voltage sensitivity factor. The VSIs are normalized to the same scale using Equation (15).

$$\frac{VSI_i - VSI_{min}}{VSI_{max} - VSI_{min}} \tag{15}$$

Where:

VSI_i = voltage sensitivity at bus i
VSI_{min} = minimum voltage sensitivity of the buses in the system
VSI_{max} = maximum voltage sensitivity of the buses in the system

Using the normalized voltage stability indices will give their values between 0 and 1. Bus with the score of 0 is the weakest in the system, while the score of 1 indicates bus with highest voltage stability in the power system.

Voltage stability indices of generator buses, even if computed do not indicate the weakness of the buses because they depend on the reactive power generation limit of the generator connected to such a bus. They were not computed in this work

4. Compute line indices: In this work, the line voltage stability index, symbolized Lmn to find the voltage of an interconnected system in a reduced single line network proposed by Moghavvemi and Omar, (1998) was used for weakest line identification. The Lmn index for a line is formulated from the 2-bus representation of a line. The 2-bus model of a line is illustrated in Figure 1.

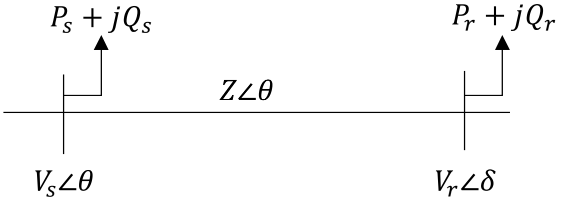

Figure 1: Model of simple branch for line voltage stability index calculation

The voltage stability index for a line is defined as follows: (Amroune et al., 2014).

$$L_{mn} = \frac{4XQ_r}{[V_s \sin(\theta-\delta)]^2} \tag{16}$$

Where: X= Line reactance, Q_r = reactive power at the receiving end, Vs= sending end voltage, θ= line impedance angle and δ= angle difference between the supply voltage and the receiving voltage.

Line indices were computed using Equation (16). The value of line index that is closed to the unity indicates that the line is closed to its stability limit. When the index is less than 1, the system is stable and when it exceeds 1, the entire system loses its stability and voltage collapse occurs. Hence the value of Lmn must be lower than 1 to maintain a stable system. The Lmn index is used to find the stability status of each line in an interconnected network, line with the higher value of Lmn index is the weaker compared to a line with the lower value of Lmn index.

Index of a line connected to a generator bus also does not indicate weakness of line because it depends on the reactive power generation limit of the generator connected to such line. They were equally not computed here.

5. Load buses and lines were ranked according to vulnerability to voltage collapse.

3. RESULTS AND DISCUSSION

Steady state load bus voltages were obtained after Newton Raphson power flow analysis. Bus voltage stability indices and their normalized values are given in Table 1. Line stability indices are given in Table 2. The system components (buses and lines) arranged according to their vulnerability to voltage collapse from most to least vulnerable are shown in Table 3.

Table 1: Bus voltage stability indices

Bus No.	Bus name	Voltage stability index	Normalized bus voltage stability index	Bus No.	Bus name	Voltage stability index	Normalized bus voltage stability index
1	Egbin	-	-	18	Gombe	0.1612	0.6284
2	Delta	-	-	19	Yola	0.2380	1.0000
3	Okpai	-	-	20	Katampe	0.0674	0.1750
4	Sapele	-	-	21	Aiyede	0.0468	0.0754
5	Afam	-	-	22	Benin	0.0427	0.0555
6	Kainji	-	-	23	Ajaokuta	0.1164	0.4119
7	Jebba	-	-	24	Makurdi	0.1045	0.3542
8	Shiroro	-	-	25	Aladja	0.0629	0.1530
9	Geregu	-	-	26	Onitsha	0.0508	0.0946
10	Ikeja-West	0.0313	0	27	New Haven	0.0600	0.1391
11	Oshogbo	0.0344	0.0154	28	Alaoji	0.0652	0.1644
12	Jebba TS	0.0344	0.0153	29	Akangba	0.0340	0.0133
13	Aja	0.0478	0.0800	30	Egbin TS	0.0378	0.0318
14	Birnin-Kebbi	0.1260	0.4584	31	Shiroro TS	0.0379	0.0323
15	Kaduna	0.0480	0.0808	32	Gamno	0.0442	0.0625
16	Kano	0.0951	0.3088	33	Maiduguri	0.6100	0.6890
17	Jos	0.0769	0.2206				

Table 2: Line stability indices

S/No	Line from to	Line stability index	Normalized line stability index	S/No	Line from to	Line stability index	Normalized line stability index
1	(1) Egbin GS (10) IK West	-	-	20	(10) IK-West (22) Benin	0.7315	1
2	(1) Egbin GS (29) Akamgba	-	-	21	(21) Ayede (11) Oshogbo	0.1795	0.2425
3	(1) Egbin GS (30) Egbin TS	-	-	22	(21) Ayede (10) IK-West	0.1001	0.1335
4	(2) Delta GS (25) Aladja	-	-	23	(17) Jos (24) Makurdi	0.1553	0.2093
5	(4) Sapele GS (25) Aladja	-	-	24	(17) Jos (18) Gombe	0.1412	0.1899
6	(6) Kainji GS (14) B/Kebbi	-	-	25	(26) Onitsha (28) Alaoji	0.3974	0.5415
7	(6) Kainji GS (12) JebbaTS	-	-	26	(26) Onitsha (27) N.Heaven	0.2629	0.3569
8	(15) Kaduna GS (31) Shiroro TS	0.1084	0.1449	27	(26) Onitsha (3) Okpai	-	-
9	(8) Shiroro GS (31) ShiroroTS	-	-	28	(29) Akangba (10) IK-West	0.0894	0.1188
10	(20 Katampe) (31) Shiroro TS	0.3175	0.4319	29	(29) Akangba (30) Egbin TS	0.2233	0.3026
11	(9) Geregu GS (23) Ajaokuta	-	-	30	(18) Gombe (19) Yola	0.1447	0.1947
12	(11) Oshogbo (12) JebbaTS	0.0028	0	31	(30) Egbin TS (13) Aja	0.0268	0.0329
13	(11) Oshogbo (22) Benin	0.6498	0.8879	32	(27) N.Heaven (28) Alaoji	0.3593	0.4892
14	(11) Oshogbo (10) IK-West	0.5396	0.7367	33	(18) Gombe (33) Maiduguri	0.1936	0.2618
15	(11) Oshogbo (32) Gamno	0.0742	0.0980	34	(28) Alaoji (5) Afam GS	-	-
16	(22) Benin (23) Ajaokuta	0.0343	0.0432	35	(32) Gamno (12) Jebba TS	0.0043	0.0021
17	(22) Benin (4) Sapele GS	-	-	36	(12) Jebba TS (7) Jebba GS	-	-
18	(22) Benin (26) Onitsha	0.4159	0.5669	37	(12) Jebba TS (8) Shiroro GS	-	-
19	(22) Benin (2) Delta GS	-	-	38	(15) Kaduna (16) Kano	0.5091	0.6948

Table 3: Buses and branches arranged from highest to lowest vulnerability to voltage collapse (a) Buses (b) Lines

(a) Buses				(b) Lines		
Bus No.	Bus name	Voltage stability index	Normalized bus voltage stability index	Line from to	Line stability index	Normalized line stability index
(10)	Ikeja West	0.0313	0.0000	(10) Ikeja West (22) Benin	0.7315	1
(29)	Akangba	0.0340	0.0133	(11) Oshogbo (22) Benin	0.6498	0.8879
(11)	Oshogbo	0.0344	0.0153	(11) Oshogbo (10) Ikeja West	0.5396	0.7367
(12)	Jebba TS	0.0344	0.0154	(15) Kaduna (16) Kano	0.5091	0.6948
(30)	Egbin TS	0.0378	0.0318	(22) Benin (26) Onitsha	0.4159	0.5669
(31)	Shiroro TS	0.0379	0.0323	(26) Onitsha (28) Alaoji	0.3974	0.5415
(22)	Benin	0.0427	0.0555	(27) New Haven (28) Alaoji	0.3593	0.4892
(32)	Gamno	0.0442	0.0625	(20) Katampe (31) Shiroro TS	0.3175	0.4319
(21)	Aiyede	0.0468	0.0754	(15) Kaduna (17) Jos	0.3034	0.4125
(13)	Aja	0.0478	0.0800	(26) Onitsha (27) New Haven	0.2629	0.3569
(15)	Kaduna	0.0480	0.0808	(29) Akangba (30) Egbin TS	0.2233	0.3026
(26)	Onitsha	0.0508	0.0946	(18) Gombe (33) Maiduguri	0.1936	0.2618
(27)	New Haven	0.0600	0.1391	(21) Aiyede (11) Oshogbo	0.1795	0.2425
(33)	Maiduguri	0.0610	0.1414	(17) Jos (24) Makurdi	0.1553	0.2093
(25)	Aladja	0.0629	0.1530	(18) Gombe (19) Yola	0.1447	0.1947
(28)	Alaoji	0.0652	0.1644	(17) Jos (18) Gombe	0.1412	0.1899
(20)	Katampe	0.0674	0.1750	(15) Kaduna (31) Shiroro TS	0.1084	0.1449
(17)	Jos	0.0769	0.2206	(21) Aiyede (10) Ikeja West	0.1001	0.1335
(16)	Kano	0.0951	0.3088	(29) Akangba (10) Ikeja West	0.0894	0.1188
(24)	Makurdi	0.1045	0.3542	(11) Oshogbo (32) Gamno	0.0742	0.0980
(23)	Ajaokuta	0.1164	0.4119	(22) Benin (23) Ajaokuta	0.0343	0.0432
(14)	Birnin Kebbi	0.1260	0.4584	(30) Egbin TS (13) Aja	0.0268	0.0329
(18)	Gombe	0.1612	0.8080	(32) Gamno (12) JebbaTS	0.0043	0.0021
(19)	Yola	0.2380	1.0000	(11) Oshogbo (12) Jebba TS	0.0028	0.00000

The bus stability indices (Table 1) are all positive indicating that all the buses of the power system are stable. A negative index indicates an unstable condition. The smaller the index, the nearer the bus to state of instability (Monta˜n´es et al, 2005). Thus, Ikeja West bus with the lowest sensitivity index of 0.0313 is the weakest bus (closest to point of instability). This is followed by Akangba with an index of 0.0340. For the lines, the Lmn indices have been computed to determine the stability of the lines. Lmn value of less than unity indicates that the line is stable, the higher the index, the weaker the line. Lmn index greater than unity indicates a voltage collapse situation (Sharma *et al.*, 2014). Thus, Ikeja West to Benin line with an index of 0.7315 is the weakest (closest to loading limit). The buses and lines have been arranged according to their weakness, from the weakest to the strongest (Table 3). The normalized indices are the bus and line indices normalized to same scale to ease comparison. Voltage stability indices depend on the loading on the power system. The loadings are never constant but continuously changing with the changing demand on the system. Because of the continual changes in the loading, stability studies carried out at different times, even on the same network, do not give the same results. It is in this regard that while this study identified Ikeja West as the weakest bus, Akwukwaegbu et al. (2017) identified Ajaokuta as the weakest bus. Enemuoh et al. (2013) and Alayande et al. (2019) had Maiduguri and Jebba TS as the weakest buses respectively. The differences are due to the differences in the loading on the network at the time of every research. In other words there are differences in the bus data used by the researchers.

4. CONCLUSION

The reactive power voltage stability indices which indicate the reactive power support requirement for a bus have been computed and normalized for the 24 load buses of Nigeria's power system and line indices also computed for the 24 line interconnecting the load buses in the network. Results obtained show that all the buses of the Nigeria national electrical power system are stable with Yola region being the most stable with RPVSI of 0.2380 while Ikeja West l is the least stable with RPVSI of 0.0313. The weakest line is Ikeja West to Benin with an Lmn index of 0.7315 while Oshogbo to Jebba transmission is the most stable with index of 0.0028. The buses and lines have been classified according to susceptibility to voltage collapse and thus a valuable working requirement for the power system operator. Practical interpretation of these results is that the power system operator should place more voltage collapse mitigation efforts on the weak components especially the Ikeja West bus and Ikeja West to Benin line which require compensation most. These results are also in line with reality because Ikeja West supplies one of the most industrialized part of the country and therefore requires reactive power support.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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APPENDIX

Table A1: Bus data expressed in per unit on 330 kV, 100 MVA base

Bus number	Bus name	Generation		Load		Voltage magnitude (pu)	Voltage angle (Radians)
		P(pu)	Q(pu)	P(pu)	Q(pu)		
1	Egbin					1.0	0.0
2	Delta GS	0.550				1.0	
3	Okpai GS	2.200				1.0	
4	Sapele GS	0.750				1.0	
5	Afam GS	4.790				1.0	
6	Kainji GS	3.230				1.0	
7	Jebba GS	3.220				1.0	
8	Shiroro GS	2.800				1.0	
9	Geregu GS	2.000					
10	Ikeja-West			3.341	3.825		
11	Oshogbo			1.781	1.103		
12	Jebba TS			0.224	0.003		
13	Aja			1.199	0.615		
14	Birnin-Kebbi			2.130	1.401		
15	Kaduna			1.080	1.487		
16	Kano			2.580	1.907		
17	Jos			1.470	0.911		
18	Gombe			1.230	0.356		
19	Yola			1.120	0.540		
20	Katampe			3.110	2.333		
21	Aiyede			2.040	0.376		
22	Benin			1.660	1.554		
23	Ajaokuta			0.400	0.090		
24	Makurdi			0.730	0.374		
25	Aladja			1.250	0.879		
26	Onitsha			1.930	1.448		
27	New Haven			1.820	1.365		
28	Alaoji			2.760	2.070		
29	Akangba			3.690	2.767		
30	Egbin TS			2.200	1.650		
31	Shiroro TS			0.800	0.375		
32	Gamno			0.270	0.130		
33	Maiduguri			0.610	0.689		

Table A2: Line data expressed in per unit on 330kV, 100MVA base

S/N	Branch from bus	To bus	Length (km)	Impedance (pu)	Half line charging susceptance
1	(1) Egbin GS	(10) IK West	62	0.0029+0.0241i	0.0109
2	(1) Egbin GS	(29) Akamgba	86	0.0040+0.0334i	0.0151
3	(1) Egbin GS	(30) Egbin TS	5	0.0005+0.0043i	0.0019
4	(2) Delta GS	(25) Aladja	32	0.0015+0.0124i	0.0056
5	(4) Sapele gs	(25) Aladja	63	0.0029+0.0245i	0.0111
6	(6) Kainji GS	(14) B.Kebbi	310	0.0145+0.1205i	0.0545
7	(6) Kainji GS	(12) JebbaTS	81	0.0038+0.0315i	0.0142
8	(31) Shiroro TS	(15) Kaduna	96	0.0045+0.0373i	0.0169
9	(8) Shiroro GS	(31) ShiroroTS	8	0.0007+0.0054i	0.0025
10	(31) Shiroro TS	(20) Katampe	144	0.0067+0.0560i	0.0253
11	(9)Geregu GS	(23) Ajaokuta	5	0.0007+0.0062i	0.0028
12	(11) Oshogbo	(12) JebbaTS	157	0.0073+0.0610i	0.0276
13	(11) Oshogbo	(22) Benin	251	0.0117+0.0976i	0.0441
14	(11) Oshogbo	(10) IK-West	252	0.0118+0.0980i	0.0443
15	(11) Oshogbo	(32) Gamno	75	0.0035+0.0292i	0.0132
16	(22) Benin	(23) Ajaokuta	195	0.0091+0.0758i	0.0343
17	(22) Benin	(4) Sapele GS	50	0.0023+0.0194i	0.0088
18	(22) Benin	(26) Onitsha	137	0.0064+0.0533i	0.0241
19	(22) Benin	(2) Delta GS	107	0.0050+0.0416i	0.0188
20	(10) IK-West	(22) Benin	280	0.0131+0.1088i	0.0492
21	(21) Ayede	(11) Oshogbo	115	0.0054+0.0447i	0.0202
22	(21) Ayede	(10) IK-West	137	0.0064+0.0533i	0.0241
23	(17) Jos	(24) Makurdi	247	0.0116+0.0960i	0.0434
24	(17) Jos	(18) Gombe	264	0.0123+0.1026i	0.0464
25	(26) Onitsha	(28) Alaoji	138	0.0065+0.0536i	0.0243
26	(26) Onitsha	(27) N.Heaven	96	0.0045+0.0373i	0.0169
27	(26) Onitsha	(3) Okpai	80	0.0037+0.0311i	0.0141
28	(29) Akangba	(10) IK-West	18	0.0008+0.0070i	0.0032
29	(29) Akangba	(30) Egbin TS	86	0.0040+0.0334i	0.0151
30	(18) Gombe	(19) Yola	188	0.0088+0.0731i	0.0331
31	(30) EgbinTS	(13) Aja	28	0.0013+0.0109i	0.0049
32	(27) N.Heaven	(28) Alaoji	138	0.0065+0.0536i	0.0243
33	(18) Gombe	(33) Maiduguri	278	0.0130+0.1081i	0.0489
34	(28) Alaoji	(5) Afam GS	25	0.0012+0.0097i	0.0044
35	(32) Gamno	(12) Jebba TS	80	0.0037+0.0311i	0.0141
36	(12) JebbaTS	(7) Jebba GS	8	0.0005+0.0039i	0.0018
37	(12) JebbaTS	(8) Shiroro GS	244	0.0114+0.0948i	0.0429
38	(15) Kaduna	(16) Kano	230	0.0108+0.0894i	0.0404
39	(15) Kaduna	(17) Jos	196	0.0092+0.0762i	0.0345