Prediction of Voltage Instability in Nigeria Interconnected Electric Power System Using V-Q Sensitivity Method

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ABSTRACT

The need to predict power system stability as it concerns voltage status is very important for the system planning, operation and control. This paper presents the prediction of voltage instability in Nigerian interconnected electric power system using V-Q sensitivity method. The method makes use of the least eigenvalue of the Jacobian matrix of the power system to calculate the V-Q sensitivity of the system. The highest sensitivity is an indication of the bus prone to voltage instability. The result from our calculations showed that Nigerian power system has the highest V-Q sensitivity of 0.1474 at the Maiduguri bus followed by Gombe, Kano and Jos with 0.1312, 0.0823 and 0.0370 respectively. It is very clear that the first bus that will collapse on the same percentage of loading will be Maiduguri followed by Gombe then Kano and Jos.

KEYWORDS: *Eigenvalue analysis, prediction, voltage instability/collapse, voltage stability, V-Q sensitivity*

I. INTRODUCTION

For many years, the demand for and consumption of energy in many countries of the world has been on the increase. The major portion of the energy needs of these nations is electric energy. In Nigeria and other industrial developing nations, the demand for supply of electrical power has been on the increase, which may be as a result of improved economic activities of the people. To satisfy the increasing demand for electricity, complex power system networks have been built. The most usual practice in electric power transmission and distribution is an interconnected network of transmission lines usually referred to as a grid system that links generators and loads to form a large integrated system that spans the entire country. In many countries of the world including Nigeria, generating stations are located thousands of kilometers apart and operate in parallel. The generating stations' output is connected and transmitted through the grid system to load centers nationwide. One of the several problems confronting the efficient performance of an interconnected system is voltage stability. Voltage stability issues are of major concern worldwide because of the significant number of black-outs that have occurred in recent times in which it was involved. For many power systems, assessment of voltage stability and prediction of voltage instability or collapse have become the most important types of analysis performed as part of system planning, operational planning and real-time operation. Voltage stability is defined as the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions, and after being subjected to a disturbance [1].

The ability to transfer reactive power from production sources to consumption sinks during steady operating conditions is a major aspect of voltage stability. The consumers of electric energy are used to rather small variations in the voltage level and the system behaviour from the operators' point of view is fairly well known in this normal operating state. Equipment control and operation are tuned towards specified set points giving small losses and avoiding power variation due to voltage sensitive loads. Once outside the normal operating voltage band many things may happen of which some are not well understood or properly taken into account today. A combination of actions and interactions in the power system can start a process which may cause a completely loss of voltage control. It is known that to maintain an acceptable system voltage profile, a sufficient reactive support at appropriate locations must be found. Nevertheless, maintaining a good voltage profile does not automatically guarantee voltage stability. On the other hand, low voltage although frequently associated with voltage instability is not necessarily its cause [2] and [3]. Voltage stability studies of a power system is now essential and is intended to help in the classification and the understanding of different aspects of power system stability [4].

Voltage stability evaluation requires the determination of:

(i) The parameters and a stress test that establish the structural causes of voltage collapse and instability in each load area (exhaustion of reactive reserves in a reactive reserve basin).

(ii) A method of identifying each load area (voltage collapse and instability area) that has a unique voltage collapse and instability problem, and

(iii) A measure of proximity to voltage collapse for each load area (a measure of reactive reserve or voltage control areas with zero reserves in the reactive reserve basin)

One of the operating goals of an electric power system is to attend the power demand keeping the system's voltages as well as the frequency close to rated values. Deviation from these nominal conditions may result in abnormal performance of or even damage to the supplied equipment. An unacceptable voltage level means voltage instability. The voltage instability, also known as voltage collapse of power systems appears when the attempt of load dynamics to restore power consumption is just beyond the capability of the combined transmission and generator system [5]. The problem is also a main concern in power system operation and planning. It is characterized by a sudden reduction of voltage on a set of buses of the system. In the initial stage the decrease of the system voltage starts gradually and then decreases rapidly.
The following can be considered the main contributing factors to the problem [6]:

1. Stressed power system; i.e., high active power loading in the system.
2. Inadequate reactive power resources.
3. Load characteristics at low voltage magnitude and their difference from those traditionally used in stability studies.
4. Transformers tap changer response to decreasing voltage magnitudes at the load buses.
5. Unexpected and or unwanted relay operation may occur during conditions with decreased voltage magnitudes.

So, there is a requirement to have an analytical method, which can predict the voltage collapse problem in a power system. As a result, considerable attention has been given to this problem by many power system researchers. A number of techniques have been proposed in the literature for the analysis of this problem [7]. In this paper, a V-Q sensitivity method has been used to predict voltage instability of Nigerian 330kV, 30bus interconnected electric power system.

II. POWER FLOW PROBLEM

The power flow or load flow is widely used in power system analysis. It plays a major role in planning the future expansion of the power system as well as helping to run existing systems to run in the best possible way. The network load flow solution techniques are used for steady state and dynamic analysis programme [3] and [4]. The solution of power flow predicts what the electrical state of the network will be when it is subject to a specified loading condition. The result of the power flow is the voltage magnitude and the angle of each of the system nodes. These bus voltage magnitudes and angles are defined as the system state variables. That is because they allow all other system quantities to be computed such as real and reactive power flows, current flows, voltage drops, power losses, etc … power flow solution is closely associated with voltage stability analysis. It is an essential tool for voltage stability evaluation. Much of the research on voltage stability deals with the power-flow computation methods. The power flow problem solves the complex matrix equation:

$$I=YV=\frac{S^*}{V^*} \qquad (1)$$

The Newton-Raphson method is the most general and reliable algorithm to solve the power-flow problem. It involves interactions based on successive linearization using the first term of Taylor expansion of the equation to be solved. From equation (1), we can write the equation for node k (bus k) as derived in [8].

$$P_K = |V_k|\sum_{m=1}^{n}|V_m|\left[G_{km}\cos(\delta_k-\delta_m)+B_{km}\sin(\delta_k-\delta_m)\right] \quad (2)$$

$$Q_k = |V_k|\sum_{m=1}^{n}|V_m|\left[G_{km}\sin(\delta_k-\delta_m)-B_{km}\cos(\delta_k-\delta m)\right] \quad (3)$$

This mismatch power at bus k is given by:

$$\Delta P_k = p_k^{sch} - p_k \qquad (4)$$

$$\Delta Q_k = Q_k^{sch} - Q_k \qquad (5)$$

The P_k and Q_k are calculated from Equation (2) and (3)

The Newton – Raphson method solves the partitioned matrix equation:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = J \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \qquad (6)$$

Where,

ΔP and ΔQ = mismatch active and reactive power vectors.

ΔV and ΔΘ = unknown voltage magnitude and angle correction vectors.

J = Jacobian matrix of partial derivative terms

III. EIGENVALUE ANALYSIS

The Eigenvalue analysis mainly depends on the power-flow Jacobian matrix of equation (6). Gao, Morison and Kundur [9] proposed this method in 1992. It can predict voltage collapse in complex power system networks. It involves mainly the computing of the smallest eigenvalues and associated eigenvectors of the reduced Jacobian matrix obtained from the load flow solution. The eigenvalues are associated with a mode of voltage and reactive power variation which can provide a relative measure of proximity to voltage instability. The analysis is expressed as follows:

Equation (6) can be rewritten as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \qquad (7)$$

By letting $\Delta P = 0$ in Equation (7)

$$\Delta P = 0 = J_{11} \Delta \theta + J_{12} \Delta V , \ \Delta \theta = - J_{11}^{-1} J_{12} \Delta V \qquad (8)$$

and

$$\Delta Q = J_{21} \Delta \theta + J_{22} \Delta V \qquad (9)$$

Substituting Equation (8) in Equation (9):

$$\Delta Q = J_R \Delta V \qquad (10)$$

Where

$$J_R = \left[J_{22} - J_{21} J_{11}^{-1} J_{12} \right] \qquad (11)$$

J_R is the reduced Jacobian matrix of the system.

Equation (10) can be written as

$$\Delta V = J_R^{-1} \Delta Q \qquad (12)$$

IV. V – Q SENSITIVITY ANALYSIS

The relationship between system voltage stability and eigenvalues of the J_R matrix is best understood by relating the eigenvalues with the V-Q sensitivities of each bus (which must be positive for stability). J_R can be taken as a symmetric matrix and therefore the eigenvalues of J_R are close to being purely real. If all the eigenvalues are positive, J_R is positive definite and the V-Q sensitivities are also positive, indicating that the system is voltage stable.

V – Q sensitivity analysis calculates the relation between voltage change and reactive power change from equation (12).

$$\Delta V = J_R^{-1} . \Delta Q$$

ΔV incremental change in bus voltage magnitude (vector)

ΔQ incremental change in bus reactive power injection (vector)

J_R reduced Jacobian matrix

The elements of the inverse of the reduced Jacobian matrix J_R are the V – Q sensitivities. The diagonal components are the self sensitivities $\frac{\partial V_i}{\partial Q_i}$ and the nondiagonal elements are the mutual sensitivities $\frac{\partial V_k}{\partial Q_i}$

The sensitivities of voltage controlled buses are equal zero. Positive sensitivities: stable operation, the smaller the sensitivity the more stable the system. As stability decreases, the magnitude of the sensitivity increases, becoming infinite at the stability limit (maximum loadability).

Negative sensitivities: unstable operation. The system is not controllable, because all reactive power control devices are designed to operate satisfactorily when an increase in Q is accompanied by an increase in V.

V. SYSTEM DESCRIPTION OF NIGERIAN 330KV, 30-BUS INTERCONNECTED ELECTRIC POWER SYSTEM

The electrical utility is probably the largest and most complex industry in the world. The electrical engineer, who researches in this industry, will encounter challenging problems in designing future power systems to deliver increasing amounts of electrical energy in a safe, clean and economical manner [10].

The transmission network in Nigeria is characterised by several outages leading to disruption in the lives of the citizenry. According to Anil et al [11], the level of disruption is a function of the dependency of people on electricity, which can be very high for a developed country and not as much as developing countries. In Nigeria, the available energy generated is not enough to meet the demands of the users leading to constant load shedding and blackouts. The Nigerian power stations are mainly hydro and thermal plants. Power Holding Company of Nigeria.(PHCN) generating plants sum up to 6200MW out of which 1920MW is hydro and 4280MW is thermal-mainly gas fired[12].The transmission grid system in Nigeria is predominantly characterised by radial, fragile and very long transmission lines, some of which risk total or partial system collapse in the event of major fault occurrence and make voltage control difficult. These lines include Benin-Ikeja West (280Km) Oshogbo-Benin (251km), Oshogbo-Jebba (249km) Jebba-Shiroro (244km), Birnin-Kebbi-Kainji (310km), Jos-Gombe (265Km) and Kaduna-Kano (230km) [13].These lines experience high voltages under light load conditions and very low voltages under high loading conditions [12]. The Nigerian Electricity Network comprises 11,000km Transmission lines (330kV and 132kV), the sub-transmission line (33kV) is 24,000km, the distribution line (11kV) is 19000km, while the substations are 22,500 [14].

VI. SYSTEM DISTURBANCES/COLLAPSES IN NIGERIAN INTERCONNECTED POWER System

Electricity supply situation in Nigeria is inadequate and unstable; the problems cut across generation, transmission and distribution/commercial operation. Voltage instability and collapse are the major issues in today's electric power operations. Table 1 shows the system disturbances/collapse in Nigerian Power System from 2000 to 2011. Transmission and generation faults and their effects caused most of the voltage collapse.

Table 1 Summary of System Disturbances from January to December (2000 to 2011)

S/N	Years (Jan-Dec)	No. of Disturbances	Cause of Collapse
1.	2011	19	Transmission
2.	2010	42	Generation/Transmission
3.	2009	39	Generation/Transmission
4.	2008	42	Generation/Transmission
5.	2007	27	Generation/Transmission
6.	2006	30	Generation/Transmission
7.	2005	36	Generation/Transmission
8.	2004	52	Generation/Transmission
9.	2003	53	Generation/Transmission
10.	2002	41	Generation/Transmission
11.	2001	19	Generation/Transmission
12.	2000	11	Generation/Transmission

Source [15]

VII. SAMPLE SYSTEM SIMULATION, RESULTS AND ANALYSIS

The V-Q sensitivities analysis method has been successfully applied to Nigerian power systems. A power flow program based on Matlab is developed to:

1. Calculate the power flow solution
2. Analyze the voltage stability based on eigenvalue analysis
3. Generate the V-Q sensitivities to predict voltage instability or collapse

The Nigerian 330kV, 30Bus Interconnected Power System (NIPS) is shown in the appendix, the model is achieved using elements arrangement. The data required for the simulation are as follows: Line data represented in Table 2; while Table 3 represents load distribution.
The calculated voltage profile of the Power Holding Company of Nigeria (PHCN) 330kV, 30bus interconnected network system is shown in figure 1.

Table 2 Line Data for Nigeria Integrated Power System (NIPS)
Length 1KM

S/N	ID	Name	From	To	R(1), Ohm	X(1), Ohm	C(1), uF	B(0), Us
1.	373	L373	B11	B6	13.26402	21.75822	0.000245	0.077
2.	389	L389	B6	B8	0.835	6.52	0.0012	0.377
3.	405	L405	B12	B8	0.7623	5.5466	0.0034	1.068
4.	413	L413	B20	B28	2.2869	16.63992	0.001685	0.529
5.	421	L421	B9	B8	5.21631	39.26934	0.001751	0.55
6.	429	L429	B19	B29	5.21631	39.2693	0.00175	0.55
7.	437	L437	B3	B9	0.20691	1.60083	1.8e-005	0.006
8.	445	L445	B17	B9	1.0291	7.7265	0.0014	0.44
9.	453	L453	B24	B26	2.05821	15.45291	0.000693	0.218
10.	461	L461	B17	B18	10.08414	76.79628	0.000864	0.271
11.	469	L469	B17	B19	7.81001	66.30921	0.000743	0.233
12.	477	L477	B19	B20	12.82842	96.57252	0.001082	0.34
13.	485	L485	B2	B8	0.20691	1.60083	1.8e-005	0.006
14.	493	L493	B12	B13	4.61736	35.19648	0.000396	0.124
15.	501	L501	B12	B14	9.62676	80.3682	0.000904	0.284
16.	509	L509	B13	B14	5.0094	38.3328	0.000496	0.156
17.	517	L517	B14	B21	2.9948	22.5423	0.004	1.257
18.	541	L541	B22	B21	2.0854	15.6925	0.0028	0.88
19.	549	L549	B29	B26	2.0854	15.6925	0.0028	0.88
20.	557	L557	B21	B1	0.5391	4.0239	0.00072	0.226
21.	573	L573	B21	B23	2.9294	22.0523	0.00098	0.308
22.	589	L589	B23	B24	5.79348	44.15895	0.000497	0.156
23.	597	L597	B24	B5	1.06722	8.03682	9.02e-005	0.028
24.	605	L605	B10	B14	0.6534	5.31432	0.000211	0.066
25.	613	L613	B10	B14	0.6534	5.31432	0.000211	0.066
26.	621	L621	B10	B16	0.3267	2.40669	0.000108	0.034
27.	629	L629	B10	B15	3.29967	24.78564	0.000278	0.087
28.	637	L637	B14	B15	0.35937	145.0548	0.000122	0.038
29.	645	L645	B14	B15	0.35937	145.0548	0.000122	0.038
30.	661	L661	B1	B25	2.70072	20.26629	0.000227	0.071
31.	669	L669	B1	B7	2.85318	21.75822	0.000245	0.077
32.	677	L677	B7	B25	1.11078	8.37441	9.38e-005	0.029
33.	685	L685	B4	B10	0.60984	4.82427	0.000884	0.278
34.	732	L732	B23	B26	3	20	0.000332	0.104
35.	829	L829	B30	B9	0.5391	4.0239	0.00072	0.226
36.	175409	L175409	B11	B27	1.4265	10.879	0.00049	0.154

Source [11]

Table 3 Load Distribution for Nigeria Integrated Power System (NIPS)

S/N	ID	Name	LF Type	P, MW	Q, MVAR
1.	182	Load 11	PQ	56.4	42.3
2.	207	Load 14	PQ	332	249
3.	201	Load 13	PQ	133	97.5
4.	213	Load 10	PQ	80	60
5.	286	Load 16	PQ	95	71.25
6.	298	Load 25	PQ	20	15
7.	292	Load 15	PQ	228	171
8.	316	Load 23	PQ	86	64.5
9.	310	Load 24	PQ	264.8	198
10.	304	Load 26	PQ	90	67.5
11.	334	Load 9	PQ	109.6	82.2
12.	322	Load 21	PQ	124.2	93.3

13.	340	Load 17	PQ	390	0
14.	364	Load 19	PQ	65	48.75
15.	370	Load 20	PQ	132.8	99.6
16.	764	Load 18	PQ	130	60
17.	779	Load 12	PQ	144.9	108.68
18.	773	Load 8	PQ	7.9	5.93
19.	175351	Load 22	PQ	20	15
20.	175420	Load 27	PQ	56.4	42.3
21.	175457	Load 30	PQ	130	60
22.	175482	Load 29	PQ	83.45	61.22
23.	175506	Load 28	PQ	80	60

Source [11]

The voltage profile of all buses of the PHCN 30 Bus system as obtained from the load flow result. To have clear indication of voltage collapse on the system loading the V-Q sensitivities calculation was carried out using the system eigenvalues. For a 30bus network with 7generator buses the expected eigenvalues will be 23 since voltage stability is load dependent we expect the eigenvalues at the 23 load buses. Table 4 is the calculated eigenvalues while Figure 2 is the plot of the eigenvalues. From Table 4, all the eigenvalues are positive and this is an indication that the system is stable. For the determination of the buses in the system that will collapse with system loading, the least eigenvalue of 3.4951 will be used. .

Table 4 PHCN 30 Bus system eigenvalues

S/N	Eigenvalue	S/N	Eigenvalue
1.	3.4951	13.	183.4425
2.	12.0129	14.	194.8132
3.	21.1896	15.	198.2067
4.	23.1243	16.	214.9579
5.	34.6424	17.	223.3135
6.	49.2926	18.	289.0459
7.	51.1237	19.	420.3368
8.	58.8551	20.	495.4999
9.	107.3404	21.	1104.0739
10.	120.5424	22.	1215.5813
11.	128.6551	23.	1449.9396
12.	131.8992	- -	- - - - - -

Table 5 The V-Q Sensitivities for the Network System

S/N	ID	Name	Sensitivity, Mvar
1.	175463	N175463-maiduguri-B28	0.1474
2.	53	B-53-Gombe-B20	0.1312
3.	148	N148-Kano-B18	0.0823
4.	45	N45-Jos-B19	0.0370

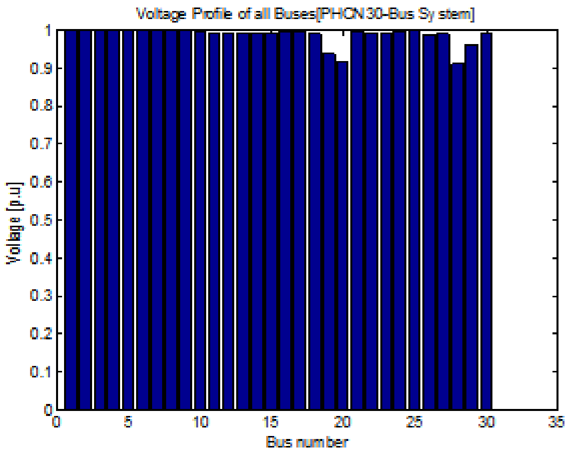

Figure 1 Voltage Profile of (PHCN) 30-Bus System

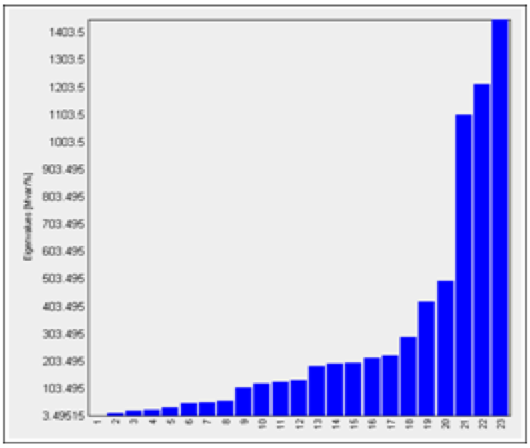

Figure 2 The eigenvalues of the 23 buses

The calculated V-Q sensitivities are represented in Table 5, while Figure 3 is V-Q sensitivities graph representation. The bus with highest sensitivity of 0.1474 is Maiduguri followed by Gombe, Kano and Jos with 0.1312, 0.0823 and 0.0370 respectively. It is now clear that the first bus that will collapse on the same percentage of loading will be Maiduguri followed by Gombe then Kano before Jos.

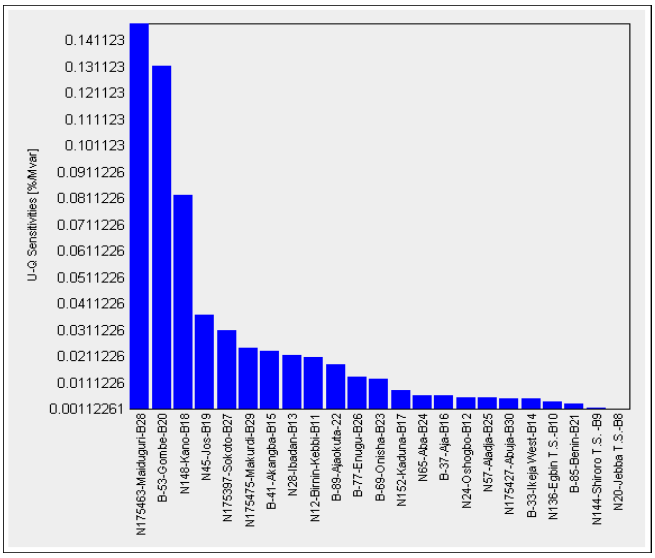

Figure 3 The V-Q sensitivities of all Buses

VIII. CONCLUSION

Voltage instability or collapse is a common feature in Nigerian interconnected electric power system. The problem cut across generation, transmission and distribution. Prediction of power system stability as it concerns voltage state is very important for the system planning, operation and control. In this work, V-Q sensitivity was carried out on the Nigerian 330kV 30Bus interconnected power system. .The calculation was done using the least eigenvalue of the Jacobian matrix. The calculated values shows that Nigerian power system has the highest V-Q sensitivity of 0.1474 at the Maiduguri bus followed by Gombe, Kano and Jos with 0.1312, 0.0823 and 0.0370 respectively. It is very clear that the first bus that will collapse on the same percentage of loading will be Maiduguri followed by Gombe then Kano and Jos . V-Q sensitivity is a good method for the prediction of voltage instability of an interconnected power system, it is used in combination with eigenvalue analysis.

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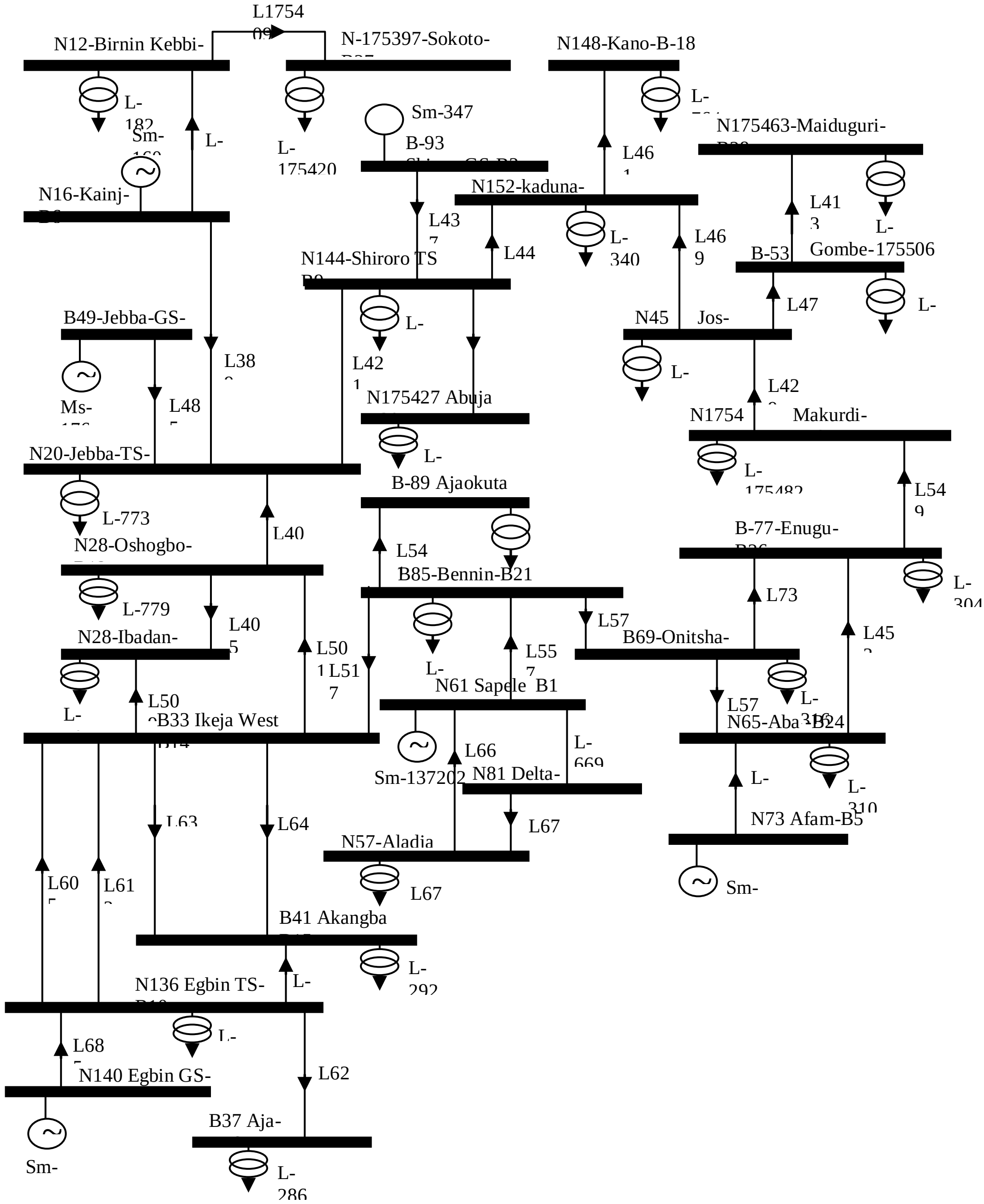

N12-Birnin Kebbi-
L1754
N-175397-Sokoto-
N148-Kano-B-18
Sm-347
B-93
N175463-Maiduguri-
N16-Kainj-
N152-kaduna-
L46
L41
N144-Shiroro TS
L43
L44
L46
9
B-53
Gombe-175506
B49-Jebba-GS-
L38
L42
N175427 Abuja
N45
Jos-
L47
Ms-
L48
N1754
Makurdi-
N20-Jebba-TS-
B-89 Ajaokuta
L-773
N28-Oshogbo-
L40
L54
B85-Bennin-B21
B-77-Enugu-
L54
L-779
N28-Ibadan-
L40
5
L50
L51
7
L57
B69-Onitsha-
L73
L45
L55
7
N61 Sapele B1
L50
B33 Ikeja West
L66
Sm-137202
N81 Delta-
L57
N65-Aba B24
L-
310
N73 Afam-B5
L64
L67
N57-Aladia
L67
L60
L61
B41 Akangba
N136 Egbin TS-
L68
N140 Egbin GS-
L62
B37 Aja-
Sm-
L-
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