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Enhancing the Voltage Stability of the Nigerian 330KV 48-Bus Power System Network Using Modal/Eigenvalue Analysis

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Abstract
This study is based on the application of modal analysis on the 48 bus 330KV Nigerian Network using PSAT MATLAB Toolbox. The Modal/Eigenvalue analysis technique was used to investigate the stability of the 48-bus Nigerian power network system. The modal method calculates the smallest eigenvalue and all the associated eigenvectors of the Jacobian matrix using the steady state mode. The magnitude of the smallest eigenvalue estimates the proximity of the system to the voltage instability. The participation factor can be employed to identify the bus that provides the highest contribution to the instability of the system. The 48-bus Nigerian network was simulated under static loads and changing loads and Modal/Eigenvalue analysis was performed on the system under each of these conditions. It was found that increase in loads at the three selected weakest buses reduced the stability of the system. Results obtained in this study proved that reactive power compensators were able to drastically improve the stability profile of the 48 bus Nigerian network and even rescue the system at the event of voltage instability especially the ones caused by change in loads.
Keywords: Modal, voltage stability, eigenvalue, participation factors. MATLAB Toolbox, PSAT
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1. INTRODUCTION

Electric power supply plays a key role in the development and technological advancement of a nation. The need for steady and adequate supply of electrical power in Nigeria has risen tremendously, partly due to increase in population, industrial activities and increase in the use of electrical powered gadgets. In order to meet this challenge, systematic power system networks have been developed and are being modified on a continuous basis.

The grid system is usually the platform that provides interconnection of network of transmission lines that connects electrical power generating systems to load in a pattern of expanded integrated system that covers an entire country. Due to proximity of fuel for and other requirement for generation, generating stations are usually situated thousands of kilometers from one another and function in pairs. The power obtained from generating stations uses the grid system to transmit energy to load centers so that electrical energy can be accessible to consumers/customers.

Usually, there are always difficulties in the planning, operation, formation and co-ordination of a dense interconnection of national electric power system networks. Adequate knowledge and engineering skills and experience are required to properly handle these challenges adequately.

The stability of power system is a principal factor in power system network. Variation in load can generate a small but significant disturbance in a power network. Faults can also generate bigger proportion of disturbance to a power network causing variation in the power flow swing of the system. A stable power swing means the swiftness of the system to restore synchronous operation after a disturbance incidence on the system. Alternatively, a system that has unstable power swing may result in the alteration of synchronization with sets of machines functioning at a different synchronous speed [7]. One of the several problems facing the efficient performance of an interconnected system is voltage stability [3]. For the Nigerian power systems, evaluation of voltage stability and forecast of voltage instability assessment is executed as an aspect of system scheduling, operational planning and real-time control. The Nigerian national grid suffers from serious cases of voltage instability or voltage collapse in a frequent manner which greatly affects the socio-economic activities of the Nation [2].

Considering this situation, there is a need to explore an analytical approach, which can envisage the voltage collapse problem in a power system. Consequently, significant consideration has been given to this challenge by several power system scholars. The dynamic analysis is chiefly vital in the last stages of the voltage collapse. Dynamic voltage stability is evaluated by observing the eigen-value of the linearized system as a power system is increasingly loaded. Instability occurs when a pair of complex eigen-value crosses to the right half plane. This system represents the dynamic voltage instability [3].

This paper uses the MATLAB software environment to model an interconnected power system networks using power system analysis toolsbox (PSAT) and simulated for voltage stability evaluation using Modal Analysis Technique, and also simulation of the solution to the instability due to load by using Static Var Systems was done. The method of improvement of voltage stability used by this thesis is the enhancement of a method to recalculate the out-of-step protection settings to suit the prevalent operating condition of some of the generators of the Nigeria 48 bus power system network.

1.1 REVIEW OF PREVIOUS STUDIES

In the past three decades, intense efforts have been geared towards analyzing and solving the problem of voltage stability in power system network. Different methods have been used to analyze, predict, identify and find solution to voltage instability and collapse. Newton based algorithms have a problem in handling a large number of inequality constraints. Linear programming methods are fast and reliable, but the main disadvantage is associated with the piecewise linear cost approximation. Nonlinear programming methods have a difficulty of convergence and algorithm complexity.

[5] Proposed analysis and the use of modal based method in the estimation of voltage stability of bulk power system and utilize the power system Jacobian matrix to calculate the eigenvalues required for the analysis of the voltage stability of the power system network. This method employs the negative or positive eigenvalues state to rate the stability of the system. This method was used to determine the components of the system that contribute to instability through the use of the participating factors. The method was implemented on IEEE 14 bus system and the various eigenvalues were calculated and the one with the lowest magnitude value used to estimate the participation factors that indicate buses that will contribute highest to voltage instability of the system.

Theoretically and in practice there are several mathematical methods to optimize the distribution of the generated power dispatching. The application of the artificial intelligence has proved its efficacy when applied to the optimization of objective functions [4].

[5] Carried out a research on voltage stability evaluation for system collapse improvement in Nigeria Electric Power System (NEPS) reduced to 33 bus systems using modal analysis. The Q-V curves were computed for the weakest buses of this identified critical mode in the NEPS reduce to 33 Bus systems as supported and compared with the results obtained by modal analyses technique.

[6] Proposed modelling and simulations of steady-state stability problems in MATLAB environment are performed using author developed computational tool implementing both conventional and more advanced numerical approaches. The performance obtain was compared with the Simulink-based library Power System Analysis Toolbox (PSAT) in terms of solution accuracy, CPU time and possible limitations.

2.THE POWER FLOW PROBLEM AND MODAL ANALYSIS

2.1 Power Flow Problem Formulation

Power flow analysis is essential in the coordination of power system to guarantee that power systems are run properly. One advantage of the Newton-Raphson method (NR) is the speed of convergence especially in very large power system networks. Another factor that makes Newton-Raphson method powerful is the adaptability of this method in most power system modelling software like MATLAB. The power flow equation is derived in polar form because in the power flow problem analysis, real power and voltage magnitude are stated for the voltage-controlled buses (Samuel et al., 2014).

The expression for current flow in a power system network in polar form is given as [4]

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

To determine the real power at a given bus *i* is

$$P_i = V^* I_i + jQ_i \quad (2)$$

Equation 2 can be rearranged in polar form using equation 1 as

$$P_i = |V_i|\angle(-\delta_i) \sum_{j=1}^{n} |Y_{ij}|\,|V_i|\angle(\theta_{ij} + \delta_j) + jQ_i \quad (3)$$

Equation 3 can be separated- the real and the imaginary portion for easy estimation in a network and are obtained in Equation 4 and 5 respectively.

$$P_i = \sum_{j=1}^{n} |Y_{ij}||V_i||V_j| \cos(\theta_{ij} + \delta_j - \delta_i) \quad (4)$$

$$Q_i = -\sum_{j=1}^{n} |Y_{ij}||V_i||V_j| \sin(\theta_{ij} + \delta_j - \delta_i) \quad (5)$$

The real and the reactive component of the power in equations (4) and (5) can be expanded using Taylor series to produce a pattern of linear equations involving a Jacobian matrix which exhibits clear link relating small variation real power with voltage angle and also the variation of voltage magnitude with variation in reactive power.

This can be simplified as

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ |\Delta V| \end{bmatrix} \quad (6)$$

ΔP and ΔQ represent differences between specified values and calculated values respectively, ΔV and $\Delta\delta$ represent voltage magnitude and voltage angle respectively in incremental forms and sub-matrices J_1 through J_4

form the Jacobian matrix [5].

2.2 Modal Analysis

The modal (eigenvalue) analysis can be used essentially as a formidable analytical tool to investigate both proximity and mechanism of voltage instability [3]. The process of voltage collapse is a dynamic occurrence, but static power network solution methods can still be utilized to generate criteria which are good markers of voltage stability margin and can ascertain weak buses of the system.

Modal analysis method is capable of calculating voltage collapse or instability in power system networks. The major aspect of this technique involves the estimation of the smallest eigenvalues and related eigenvectors of the reduced Jacobian matrix acquired from performing load flow analysis. Eigenvalues have a great deal of relationship with the mode of voltage and reactive power variation, and are employed to estimate voltage instability in a power network system. After execution of modal analysis, the participation factors are usually utilized to easily identify the weakest connections or buses in the system. The participation factor values can adequately be used to determine the weakest bus in the system. The participation factor values are usually obtained from the eigen-vectors analysis of eigenvalues.

Modal analysis $\Delta V/\Delta Q$ is an important method for forecasting voltage collapse and determination of the stability margin in power system. By solving linearized power flow equation, the ΔP and ΔQ matrix is obtained in equation 6 from the previous power flow solution [4].

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\theta \\ |\Delta V| \end{bmatrix} \quad (7)$$

Considering $P\Delta = 0$, the reduced Jacobian matrix as obtained in equation 7 is expressed as:

$$\Delta J_L = [J_4 - J_3 J_1^{-1} J_2] \quad (8)$$

$$\Delta Q = J_L \Delta V \quad (9)$$

$$\Delta V = J_L^{-1} \Delta Q \quad (10)$$

Putting

$$J_L = \xi \Lambda \eta \quad (11)$$

where

ξ is right eigenvector matrix

η is left eigenvector matrix

Λ is diagonal eigenvalue matrix

Then, inverting equation 11 produces

$$J_L^{-1} = \xi \Lambda^{-1} \eta \quad (12)$$

And substituting equation 12 in equation 11 gives

$$\Delta V = \xi \Lambda^{-1} \eta \Delta Q \quad (13)$$

$$\Delta V = \sum_i \frac{\xi_i \eta_i}{\delta_i} \Delta Q \quad (14)$$

where η_i is the ith row of the left eigenvector of *JR*, and ξ_i is the i^{th} column of the right eigenvector. The i^{th} mode of the Q-V response is defined by the i^{th} eigenvalue δ_i, and the corresponding right and left eigenvectors ξ_i and η_i. Equation (13) can be presented as

$$\eta \Delta V = \Lambda^{-1} \eta \Delta Q \quad (15)$$

By defining $v = \Lambda^{-q}$ as the vector of modal voltage changes and as the vector of modal reactive power changes, the first-order equations can be broken down as

$$v = \Lambda^{-1} q \quad (16)$$

Therefore, for the i^{th} mode, we have

$$v_i = \frac{1}{\delta_i} q_i \quad (17)$$

At the instant where $\delta_i > 0$, the i^{th} modal voltage and the i^{th} modal reactive power changes align in the same direction, indicating voltage stability of the system; whereas $\delta_i < 0$ denotes the instability of the system. The magnitude of δ_i signifies an average level of instability of the i^{th} modal voltage. The smaller the magnitude of a positive δ_i, the nearer the i^{th} modal voltage to experience instability. The system voltage collapse when $\delta_i = 0$, and is as a result of changes in the modal reactive power that causes an infinite change in the modal voltage.

A system voltage is assumed to be stable if the eigenvalues of J_R are all positive. However, in the analysis of dynamic systems the eigenvalues with negative real parts are stable. The interaction 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. The system is considered voltage unstable if one or more of the eigenvalues is found to be negative. A zero eigenvalue of J_R means that the system is on the point of voltage instability. In essence, small eigenvalue of J_R determines the proximity of the system to

being voltage unstable [4]. There is no need to evaluate all the eigenvalues of JR of a large power system because it is known that once the minimum eigenvalues become zero the system Jacobian matrix becomes singular and voltage instability occurs. Therefore, the eigenvalues that are vital are the critical eigenvalues of the reduced Jacobian matrix J_R. This implies that the smallest eigenvalues of J_R are taken to be the least stable nodes of the system. The rest of the eigenvalues are not considered because these nodes are considered to be vital in the determination of stability of the system. After the minimum eigenvalues and the corresponding eigenvectors have been calculated the participation factor can be utilized to identify the weakest bus in the system.
The relative contribution of the power at bus k in mode i is given by the bus participation factor [3]

$$P_{ki} = \xi_{ki}\eta_{ki} \quad (18)$$

Participation factors show the most critical nodes which can lead the system to instability. Generally, the higher the magnitude of the participation factor of a bus in a specific mode, the easier the solution that can be applied on that bus in stabilizing the node.

The flowchart developed for outlining the steps followed in the modal/eigenvalue analysis of the power system network is shown in Figure 1 below.

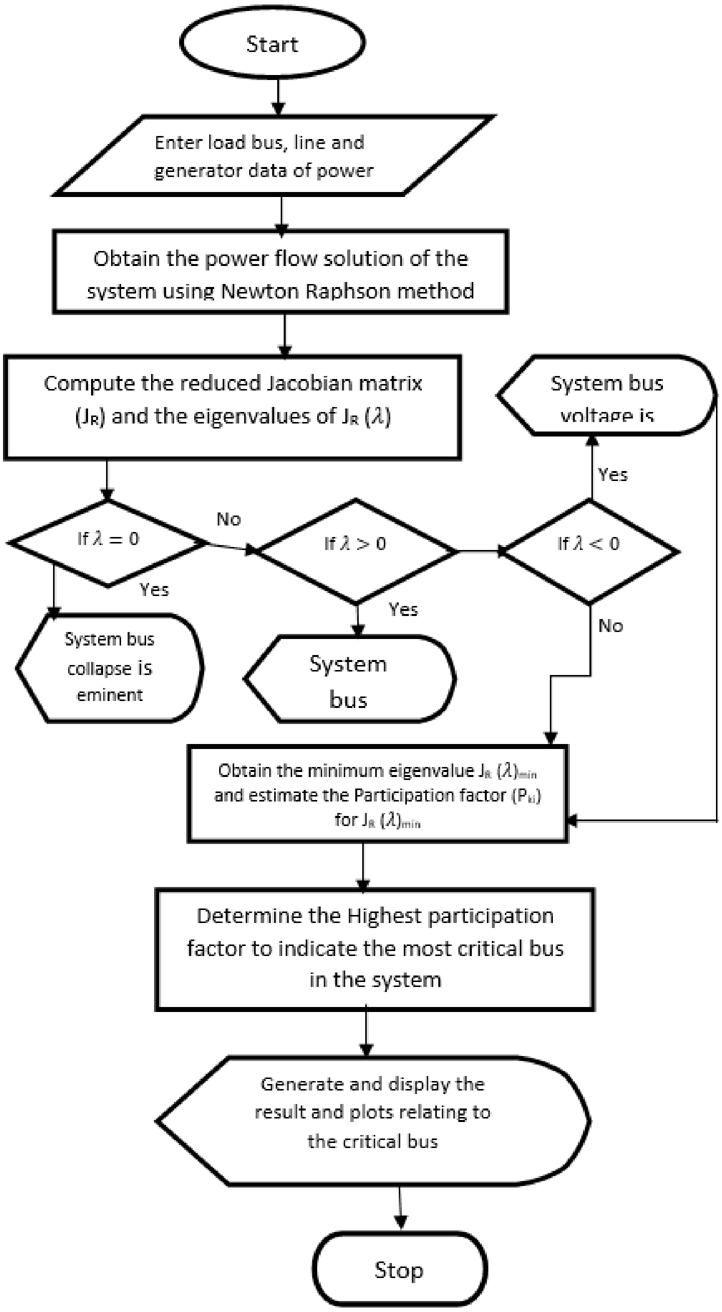

Figure 1: Algorithm for the modal analysis method of stability analysis (Courtesy of Modern power system Analysis by D.P.Kothari and I.J. Nagrath)

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2.3 The 330KV 48-Bus Nigerian Power System Network and Data

The Nigerian 48 bus power system network configuration and one-line diagram is depicted as shown in Figure 2. For the study of the system to be actualized 330KV 48 bus system of Nigeria transmission network, the Egbin power station was selected as the slack bus. Data gathering from TCN were centred on 2018 operational reports. Line data, load data, the generators and other system constituents were also collated and assembled.

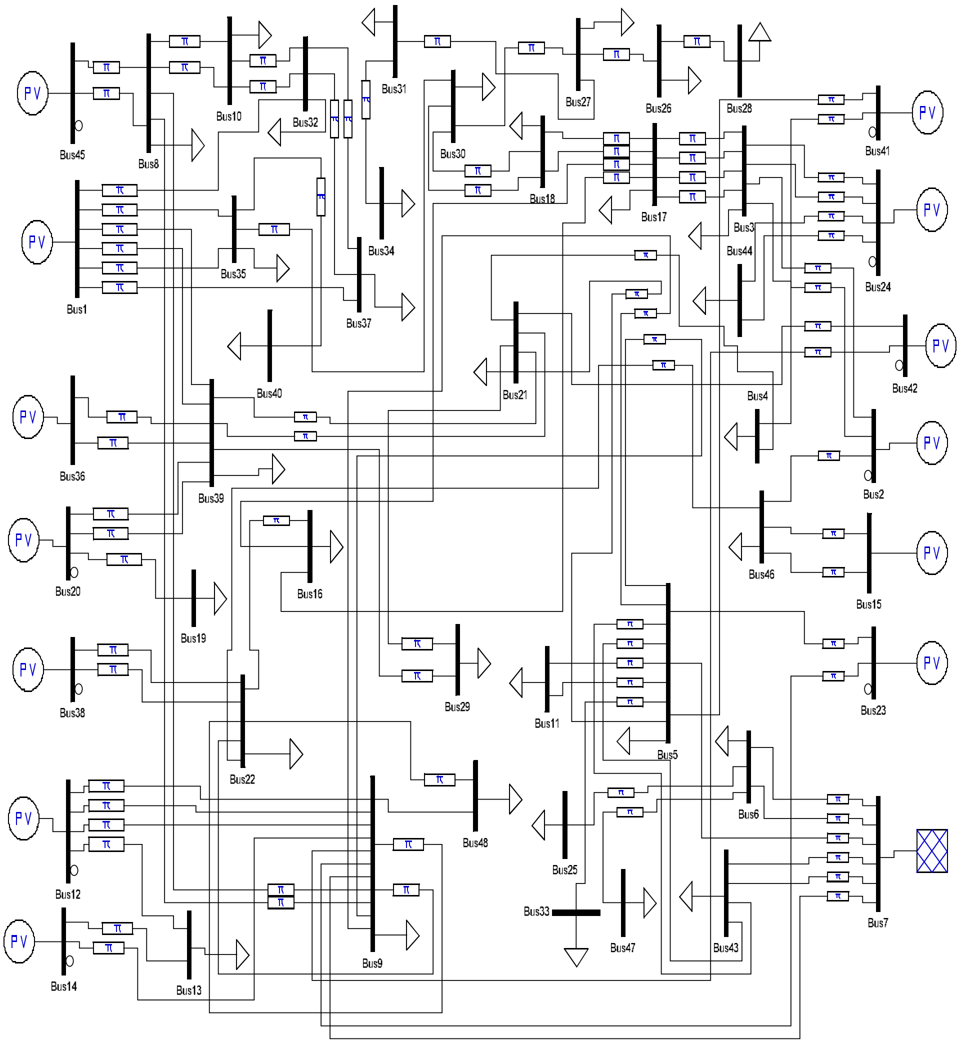

Figure 2: Main Model of the Nigerian 48-bus 330KV Power System Network using PSAT.

The data for the power flow analysis and modal analysis involves the bus data, transmission line data (impedance of lines), voltages and transformer/load data obtained from Transmission Company of Nigeria (TCN) are as presented in Tables 1 to 2 respectively.

Table 1: System Bus data of the 330kV, 48-bus Network (Source: Transmission Company of Nigeria, 2018)

S/No	Bus Name	Volts Mag. (p.u.)	Angle (Deg.)	Bus Type/ Code	Bus Loads		Generation			
					P (MW)	Q (Mvar)	P (MW)	Q (Mvar)	Q_{min}	Q_{max}
1	Shiroro G/S	1.000	0	P-V (2)	150	70	270	220	-200	200
2	Afam G/S	1.000	0	P-V (2)	315	157.5	650	590	-210	222
3	Ikot Ekpene	1.020	0	P-Q (3)	321	160.5	0	0	0	0
4	Ayede	0.932	0	P-Q (3)	275	206	0	0	0	0
5	Ikeja West	0.986	0	P-Q (3)	635	474	0	0	-150	0
6	Aja	1.040	0	P-Q (3)	300	205	0	0	0	0
7	Egbin G/S	1.050	0	Slack (1)	0	0	0	0	-200	210
8	Ajaokuta	1.026	0	P-Q (3)	230	115	0	0	0	0
9	Benin	1.000	0	P-Q (3)	383	150	0	0	-150	0
10	Lokoja	1.020	0	P-Q (3)	300	150	0	0	0	0
11	Akangba	0.970	0	P-Q (3)	300	250	0	0	0	0
12	Sapele G/S	0.979	0	P-V (2)	120	50	160	90	-180	200
13	Aladja	1.046	0	P-Q (3)	100	70	0	0	0	0
14	Delta G/S	1.050	0	P-V (2)	107	53	460	250	-100	120
15	Alaoji G/S	1.010	0	P-V (2)	65	33	120	95	-75	80
16	New Haven	1.050	0	P-Q (3)	180	130	0	0	0	0
17	Ugwuaji	1.097	0	P-Q (3)	39	25	0	0	0	0
18	Makurdi	1.060	0	P-Q (3)	84	50	0	0	-75	0
19	Birnin Kebbi	1.010	0	P-Q (3)	146	85	0	0	0	0
20	Kainji G/S	1.050	0	P-V (2)	7	5	282	-65	-180	200
21	Osogbo	0.966	0	P-Q (3)	200	150	0	0	-75	0
22	Onitsha	1.005	0	P-Q (3)	184	134	0	0	-75	0
23	Omotosho G/S	1.050	0	P-V (2)	18	15	664	300	-150	150
24	Odukpani G/S (Calabar)	1.058	0	P-V (2)	10	7	240	150	-120	200
25	Alagbon	1.000	0	P-Q (3)	260	120	0	0	0	0
26	Damaturu	1.050	0	P-Q (3)	50	20	0	0	0	0
27	Gombe	1.045	0	P-Q (3)	320	170	0	0	-100	100
28	Maidugiri	0.996	0	P-Q (3)	10	5	0	0	0	0
29	Ganmo	1.073	0	P-Q (3)	150	90	0	0	0	0
30	Jos	0.970	0	P-Q (3)	70	50	0	0	-75	0
31	Yola	1.087	0	P-Q (3)	100	50	0	0	-75	0
32	Gwagwalada	1.060	0	P-Q (3)	150	70	0	0	0	0
33	Sakete	1.003	0	P-Q (3)	50	20	0	0	0	0
34	Jalingo	1.007	0	P-Q (3)	80	50	0	0	0	0
35	Mando (Kaduna)	1.040	0	P-Q (3)	170	120	0	0	-75	0
36	Jebba G/S	1.065	0	P-V (2)	20	0	360	160	-110	150
37	Katampe (Abuja)	1.000	0	P-Q (3)	290	145	0	0	-75	0
38	Okpai G/S	1.000	0	P-V (2)	10	5	450	150	-150	190
39	Jebba	1.040	0	P-Q (3)	15	5	0	0	-150	0
40	Kumbotso (Kano)	1.000	0	P-Q (3)	240	130	0	0	-75	0
41	Olorunsogo P/S	1.020	0	P-V (2)	20	10	626	300	-150	150
42	Ihovbor G/S	1.050	0	P-V (2)	8	3	225	110	-70	90
43	Okearo	0.999	0	P-Q (3)	220	70	0	0	-75	0
44	Adiabor	0.905	0	P-Q (3)	140	90	0	0	0	0
45	Geregu G/S	1.050	0	P-V (2)	20	5	415	200	-200	210
46	Alaoji	1.010	0	P-Q (3)	400	150	0	0	-75	0
47	Lekki	1.000	0	P-Q (3)	10	2	0	0	0	0
48	Asaba	0.998	0	P-Q (3)	2	0	0	0	0	0

Table 2 System Line Data of 330kV, 48-bus Grid Network (Source: Transmission Company of Nigeria, 2018)

S/N	CODE	FROM (BUS NAME) / TO (BUS NAME)	LINE IMPEDANCE		SUSCEPTANCE B (siemens)	LINE LENGTH (KM)
			R (Ω)	X (Ω)		
1	K1J	Kainji/Jebba Line 1	3.159	26.811	0.0368	81
2	K2J	Kainji/Jebba Line 2	3.159	26.811	0.0368	81
3	K3R	Kainji/Birnin Kebbi	12.090	102.610	0.0096	310
4	B8J	Jebba G.S/Jebba T.S 1	0.315	2.424	0.4057	8
5	B9J	Jebba G.S/Jebba T.S 2	0.315	2.424	0.4057	8
6	J3R	Jebba/Shiroro Line 1	9.516	80.764	0.0122	244
7	J7R	Jebba/Shiroro Line 2	9.516	80.764	0.0122	244
8	J1H	Jebba/Osogbo Line 1	6.123	51.967	0.0189	157
9	J2H	Jebba/Osogbo Line 2	6.123	51.967	0.0189	157
10	J3G	Jebba/Ganmo Line	3.393	28.797	0.0342	87
11	H3G	Osogbo/Ganmo	2.730	23.170	0.0426	70
12	H2A	Osogbo/Ayede	4.485	38.065	0.0259	115
13	H1W	Osogbo/Ikeja West	9.828	83.412	0.0118	252
14	H7V	Osogbo/Ihovbor	8.814	74.806	0.0132	226
15	V7B	Ihovbor/Benin	0.195	1.655	0.5959	5
16	M2S	Mando/Jos	7.683	65.207	0.0151	197
17	SIE	Jos/Gombe	10.335	87.715	0.0112	265
18	M6N	Mando/Kumbotso	8.970	76.130	0.0129	230
19	R1M	Shiroro/Mando Line 1	3.744	31.766	0.0310	96
20	R2M	Shiroro/Mando Line 2	3.744	31.766	0.0310	96
21	R4B	Shiroro/Katampe Line 1	5.674	43.632	0.0225	144
22	R5G	Shiroro/Gwagwalada	4.680	39.720	0.0248	120
23	G5B	Gwagwalada/Katampe	1.560	13.240	0.0745	40
24	N6W	Egbin/Ikeja West Line 3	2.443	18.786	0.0523	62
25	N7K	Egbin/Okearo Line 1	2.176	18.469	0.0534	55.8
26	N8K	Egbin/Okearo Line 2	2.176	18.469	0.0534	55.8
27	K7W	Okearo /Ikeja West Line 1	1.088	9.235	0.1068	27.9
28	K8W	Okearo/ Ikeja West Line 2	1.088	9.235	0.1068	27.9
29	W3L	Ikeja West/Akangba 1	0.6762	5.739	0.1719	17.34
30	W4L	Ikeja West/Akangba 2	0.6762	5.739	0.1719	17.34
31	M5W	Omotosho/Ikeja West	6.304	48.480	0.0203	160
32	R1W	Olorunsogo/Ikeja West	3.034	23.331	0.0421	77
33	NW1BS	Ikeja West/Sakete	2.730	23.170	0.0426	70
34	R2A	Olorunsogo/Ayede	2.340	19.860	0.0497	60
35	B6N	Benin/Egbin	8.502	72.158	0.0137	218
36	B11J	Benin/Ajaokuta Line 1	7.995	67.855	0.0145	205
37	B12J	Benin/Ajaokuta Line 2	7.995	67.855	0.0145	205
38	B1T	Benin/Onitsha Line1	5.343	45.347	0.0217	137
39	B2T	Benin/Onitsha Line2	5.343	45.347	0.0217	137
40	B5M	Benin/Omotosho G/S	4.680	39.720	0.0248	120
41	S3B	Sapele/Benin Line 1	2.028	17.212	0.0573	52
42	S4B	Sapele/Benin Line 2	2.028	17.212	0.0573	52
43	S5B	Sapele/Benin Line 3	2.028	17.212	0.0573	52
44	S4W	Sapele/Aladja	2.457	20.853	0.0473	63
45	R1J	Geregu/Ajaokuta line 1	0.195	1.655	0.5959	5
46	R2J	Geregu/Ajaokuta line 2	0.195	1.655	0.5959	5
47	G3B	Delta/Benin	2.053	17.427	0.0566	52.65
48	T3H	Onitsha/New Haven	3.744	31.776	0.0157	96

S/N	CODE	FROM (BUS NAME) / TO (BUS NAME)	LINE IMPEDANCE		SUSCEPTANCE B (siemens)	LINE LENGTH (KM)
			R (Ω)	X (Ω)		
49	K1T	Okpai/Onitsha Line 1	2.184	18.536	0.0532	56
50	K2T	Okpai/Onitsha Line 2	2.184	18.536	0.0532	56
51	T4A	Onitsha/Alaoji	5.382	45.678	0.0216	138
52	F1A	Afam/Alaoji Line 1	1.123	9.533	0.1035	28.8
53	F2A	Afam/Alaoji Line 2	1.123	9.533	0.1035	28.8
54	N3J	Egbin/Aja Line 1	0.552	4.242	0.2318	14
55	N4J	Egbin/Aja Line 2	0.552	4.242	0.2318	14
56	J1L	Ajaokuta/Lokoja Line 1	1.482	12.578	0.0784	38
57	J2L	Ajaokuta/Lokoja Line 2	1.482	12.578	0.0784	38
58	L6G	Lokoja/Gwagwalada line 1	6.240	52.960	0.0186	160
59	L7G	Lokoja/Gwagwalada line 2	6.240	52.960	0.0186	160
60	H1U	New Haven/Ugwuaji line 1	0.273	2.317	0.4257	7
61	H2U	New Haven/Ugwuaji line 2	0.273	2.317	0.4257	7
62	D1B	Odukpani/Adiabor line 1	0.690	5.859	0.1683	17.7
63	D2B	Odukpani/Adiabor line 2	0.690	5.859	0.1683	17.7
64	F1E	Afam/Ikot Ekpene line 1	2.457	20.853	0.0473	63
65	F2E	Afam/Ikot Ekpene line 2	2.457	20.853	0.0473	63
66	A1K	Alaoji/Ikot Ekpene line 1	2.145	18.205	0.0542	55
67	A2K	Alaoji/Ikot Ekpene line 2	2.145	18.205	0.0542	55
68	K1U	Ikot Ekpene/Ugwuaji line 1	3.861	32.769	0.0301	99
69	K2U	Ikot Ekpene/Ugwuaji line 2	3.861	32.769	0.0301	99
70	K3U	Ikot Ekpene/Ugwuaji line 3	3.861	32.769	0.0301	99
71	K4U	Ikot Ekpene/Ugwuaji line 4	3.861	32.769	0.0301	99
72	E1Y	Gombe/Yola line	9.360	79.440	0.0124	240
73	B3D	Benin/Asaba line	5.343	45.347	0.0217	137
74	D3T	Asaba/Onitsha line	0.799	6.785	0.1454	20.5
75	A1S	Makurdi/Jos line 1	10.374	88.046	0.0112	266
76	A2S	Makurdi/Jos line 2	10.374	88.046	0.0112	266
77	U1A	Ugwuaji/Makurdi line 1	6.123	51.967	0.0189	157
78	U2A	Ugwuaji/Makurdi line 2	6.123	51.967	0.0189	157
79	J1E	Aja/Lekki 330kV line	0.468	3.972	0.2483	12
80	J1B	Aja/Alagbon 330kV line	1.014	8.606	0.1123	26
81	L7A	Alaoji G/S / Alaoji T/S 330kV line 1	0.195	1.655	0.5959	5
82	L8A	Alaoji G/S / Alaoji T/S 330kV line 2	0.195	1.655	0.5959	5
83	D1K	Odukpani/Ikot Ekpene line 1	1.443	12.247	0.0805	37
84	D2K	Odukpani/Ikot Ekpene line 2	1.443	12.247	0.0805	37
85	B5W	Benin/Ikeja West	11.032	84.840	0.0116	280
86	G1W	Delta/Aladja	1.248	10.592	0.0931	32
87	E1D	Gombe/Damaturu	6.240	52.960	0.0186	160
88	D1M	Damaturu/Maidugiri	10.140	86.060	0.0115	260
89	Y1G	Yola/Jalingo	5.460	46.340	0.0213	140

2.4 MATLAB PSAT Toolbox

The system data is used in MATLAB code or modelled in PSAT in order to model the power system network under study. The capacity of these systems to handle the system analysis involved in this study cannot be overemphasized.

Using MATLAB scripts and PSAT software tool in MATLAB, the admittance matrix is estimated and saved. The load flow analysis is carried out using the Newton-Raphson method. Load flow data together with machine data is employed to model the dynamic performance of the system as a system of linear equations using small signal stability. Small disturbances represented as load changes are implemented sequentially on the system by working on the load data and executing a load flow calculation. The process is repeated until the system is ascertained to be unstable by modal analysis from the eigenvalue and eigenvector estimation procedure. Eventually, participation factors are then estimated which will signify the state's effects on each of the modes; consequently, depicting the most critical mode.

The power system steady state and dynamic model is reproduced in PSAT tool in a MATLAB software as shown in Figure 3 Then by using the transient stability module which is presented in Figure 4, plots of eigenvalues, participation factors, and other transient stability analysis are used to display load or bus transient performance. Predefined power system compensators models with their corresponding parameter inputs are used to ascertain locations by participation factor analysis to stabilize the system. The plots will also be used to show the impact of the power system compensators or SVCs on controlling the system and bringing the system out of instability.

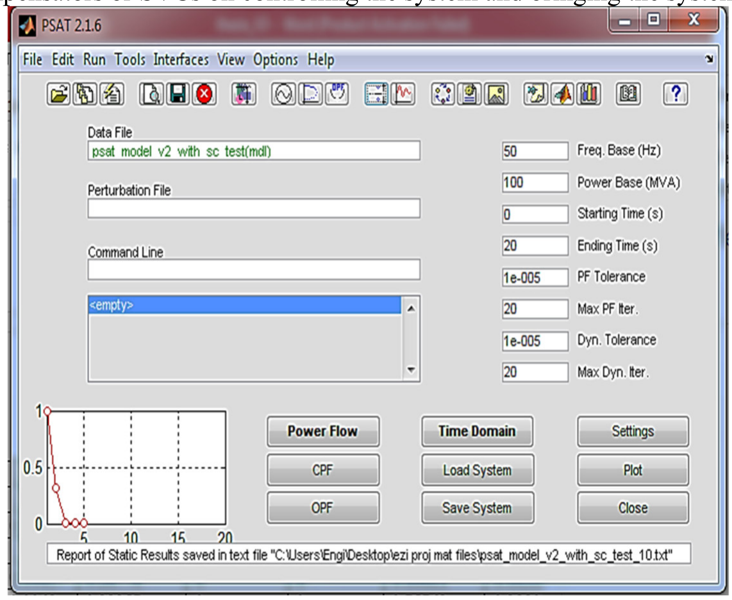

Figure 3 PSAT software tool interface

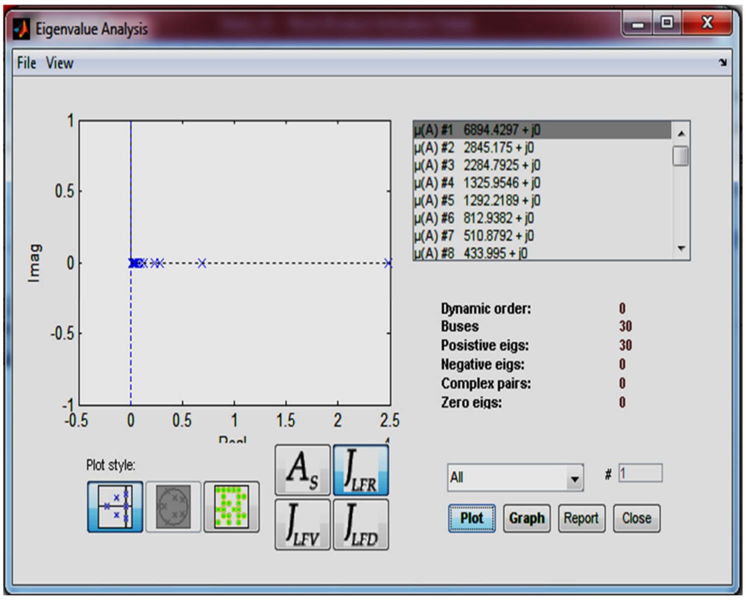

Figure 4 PSAT interface for plotting Eigenvalues, participation factors and other dynamic analysis

3. RESULTS AND DISCUSSION

As soon as the identification of the electrical system put under test is complete and the description of the simulation software codes, a system analysis and simulation will successively be carried out. The analysis and simulation process of the 48 Bus Nigerian power System Network contains several steps. The first step is to perform our test and analysis on the original 48 bus Nigerian power network without inserting any disturbance, and then identify the weak buses that are susceptible to instability. The next step is to simulate small disturbances by introducing load changes to the buses which are closer to instability compared to others and performing stability analysis on the network to see whether voltage instability or collapse will occur and subsequently introduce compensators at the critical buses and generation sources of these buses and monitor the improvement on the network. Then on this network load is added on the two weakest buses and analysis performed until the system become unstable then introduce compensators on this unstable system in order to ascertain the effectiveness of compensators in bringing the system out of instability caused by change in load at the weaker buses.

3.1 Main Case Modal of the 48 bus 330kV Nigerian Network

The various tests were performed on the model of the 48 bus 330KV Nigerian Network consisting of fifteen power generating systems. The power flow analysis of the model was carried out using PSAT in MATLAB Simulink environment. Table 3 shows the load flow results showing the voltage, phase angle, real power of the generators, reactive power of the generators, real power of load, and reactive power of load at the various buses.

Table 3: Main Case Model Power Flow Result of the three highest and three lowest voltage profile

Bus	V (p.u.)	Phase (rad)	P gen (p.u.)	Q gen (p.u.)	P load (p.u.)	Q load (p.u.)
Bus12	0.979	0.01882	2.9376	-217.8541	1.56	0.65
Bus14	1.05	0.01813	24.081	112.6464	1.2776	0.63282
Bus23	1.05	0.02131	48.379	84.1565	0.04212	0.0351
Bus31	0.98871	-0.00335	0	0	1.118	0.559
Bus34	0.98679	-0.10691	0	0	0.7544	0.4715
Bus36	1.065	0.0022	0.004	107.9533	0	0

Making reference to Table 3 and Figure 5, the voltages at the PQ buses all falls within the acceptable level of ±5% with the bus value at bus 34 (Jalingo) having the lowest with PU voltages of 0.98679 which signify that the system voltages are relatively stable as required from the system when no disturbance is applied to the system. Utilizing the results for the load flow analysis, the eigenvalues were computed with their corresponding largest participation factor to identify the most significant state on that bus. A display of the table of the results and the required plot of the modes is shown in Table 4 and Figure 6.

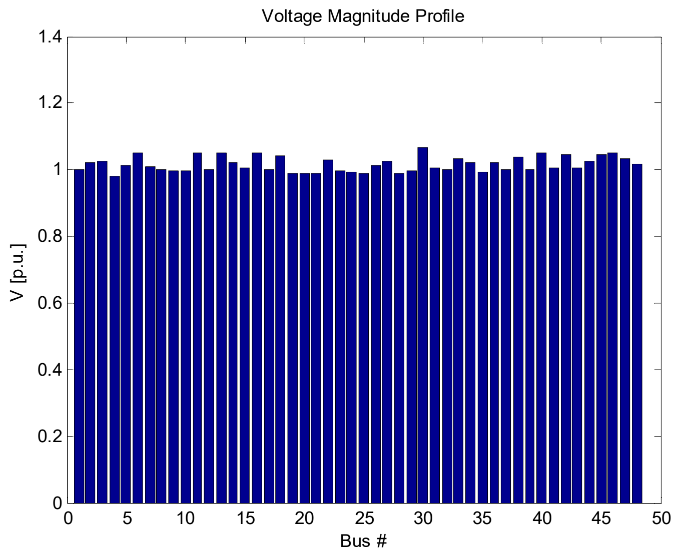

Figure 5: Angle profiles of all buses of the main case model of the 48 bus Nigerian power network system

Table 4 Three highest and three lowest Eigenvalues of the standard Jacobian matrix of the Main Case Modal of the 48 bus 330KV Nigerian Network

Most Associated Bus	Real part	Imaginary Part
Bus21	35015.2337	0
Bus9	23434.2254	0
Bus3	17919.4067	0
Bus34	6.2181	0
Bus28	165.0059	0
Bus25	727.8858	0

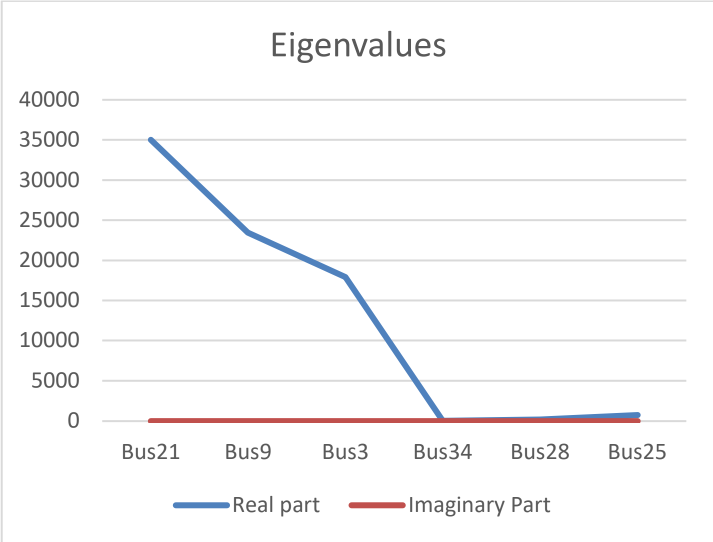

Figure 6: Three highest and three lowest eigenvalues of the main case model of the 48 bus Nigerian power network system

The observations from Table 4 indicate that all the eigenvalues are stable with the lowest obtained at Jalingo bus whose eigenvalue is 6.2181 is the most critical node. The participating factors computed for this weakest bus are shown in Table 5. Table 5 showed that bus 34 has the highest participation factor of 0.999. The implication of this outcome indicates that the bus 34 offers the highest contribution to the voltage instability of the network.

Table 5: Participation factors at the smallest eigenvalue for the main case model

Bus	Participation factor
Bus1, Bus 10, Bus11, Bus12, Bus13 Bus15, Bus16 Bus17, Bus19, Bus2, Bus20, Bus1, Bus22, Bus23, Bus24, Bus25, Bus27, Bus29, Bus3, Bus28, Bus32, Bus33, Bus35, Bus36, Bus36, Bus37, Bus38, Bus39, Bus4, Bus40, Bus41, Bus42, Bus43, Bus44, Bus45, Bus46, Bus47, Bus48, Bus5, Bus6, Bus7, Bus8, Bus9	0
Bus18	1.00E-05
Bus26	8.00E-05
Bus27	8.00E-05
Bus30	1.00E-05
Bus31	0.00019
Bus34	0.99954

3.2 Main Case Modal of the 48 bus 330KV Nigerian Network with added load at the two weakest Buses

The various tests were performed on the model of the 48 bus 330KV Nigerian Network consisting of fifteen power generating systems. The power flow analysis of the model was carried out using PSAT in MATLAB Simulink environment. Table 6 shows the load flow results showing the voltage, phase angle, real power of the generators, reactive power of the generators, real power of load, reactive power of load at the various buses.

Table 6: Power Flow Result of the Main Case Model with added load for three buses with the highest voltage profile and three buses with the lowest voltage profile

Bus	**V (p.u.)**	**Phase (rad)**	**P gen (p.u.)**	**Q gen (p.u.)**	**P load (p.u.)**	**Q load (p.u.)**
Bus28	0.63458	-0.45581	0	0	1.8987	1.1867
Bus31	0.97051	-0.03111	0	0	1.118	0.559
Bus34	0.97092	-0.03029	0	0	0.7656	1.4201
Bus14	1.05	0.01303	24.081	112.6723	1.2776	0.63282
Bus20	1.05	-0.00282	8.1526	50.6585	0.00602	0.0043
Bus23	1.05	0.01688	48.379	84.1684	0.04212	0.0351

Making reference to Table 6 and Figure 7, the voltages at the PQ buses falls within the acceptable level of

±5% except at bus 28 (Maidugiri) having the lowest with PU voltages of 0.63458 which signify that the system is experiencing voltage instability at bus 34 from the system when a disturbance is applied to the system's three weakest buses. Utilizing the results for the load flow analysis, the eigenvalues were computed with their corresponding largest participation factor to identify the most significant state on that bus. A display of the table of the results and the required plot of the modes is shown in Table 7 and Figure 8.

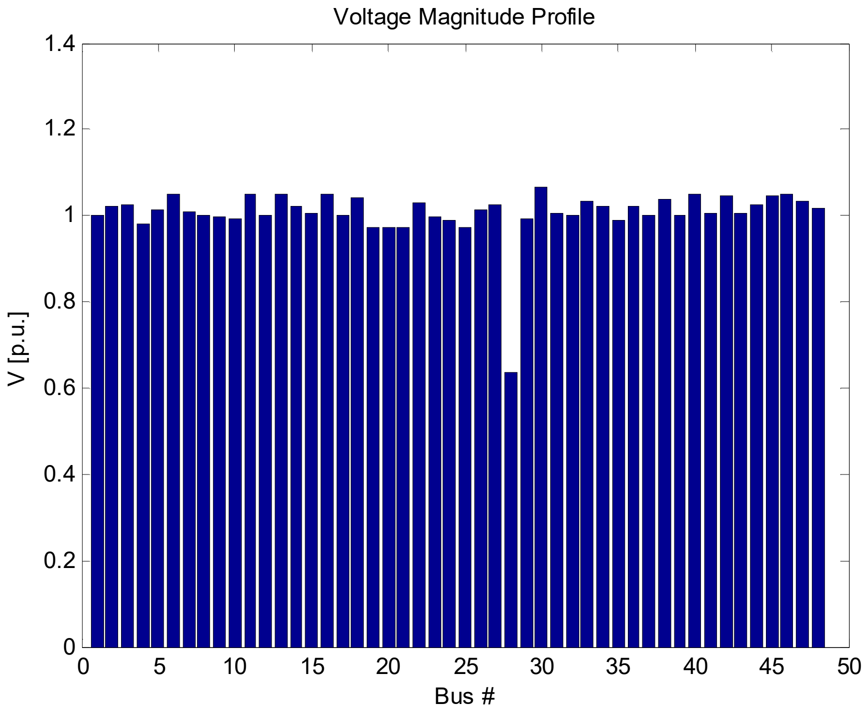

Figure 7: Angle profiles of all buses of the main case model of the 48 bus Nigerian power network system with added load at two weakest buses

Table 7 Three highest and three lowest Eigenvalues of the standard Jacobian matrix of the Main Case Modal of the 48 bus 330kV Nigerian Network with added load disturbances at weakest buses

Most Associated Bus	Real part	Imaginary Part
Bus21	35015.7528	0
Bus9	23433.9648	0
Bus3	17889.3353	0
Bus34	1.4423	0
Bus28	160.4958	0
Bus25	727.8858	0

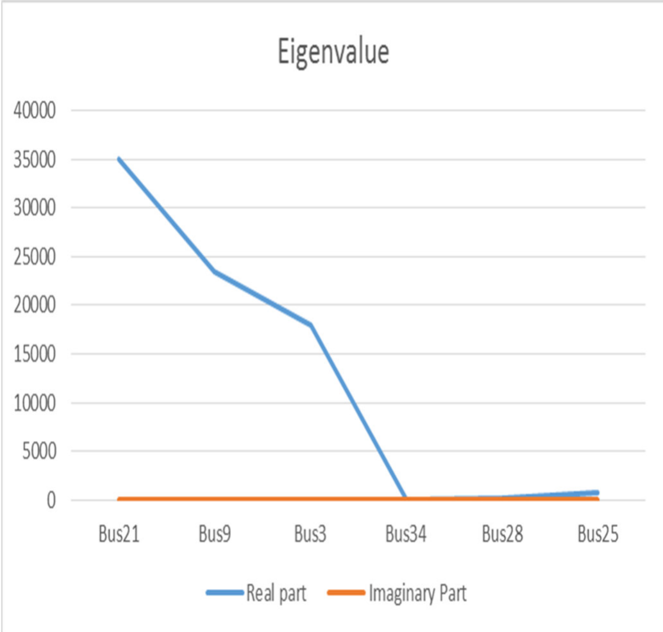

Figure 8: Eigenvalues of all buses for the main case model of the 48 bus Nigerian power network system with added load disturbances at weakest buses

For second case of the model with added load at the three weakest buses identified from the first model from Figure 8 all the eigenvalues are positive, this is an indication that the system is stable but has a less stability profile than the main case observed from the characteristics of the eigenvalues.

Referring to Table 7 and Figure 8, observation made shows that the system is stable but tending towards instability since all the mode λ is located on the left half of the imaginary plane, but the smallest eigenvalue experienced a drop from 6.2181 in Table 4 to 1.4423 in Table 7 when compared to the main model without load added at the weakest buses. Hence the system will move to a state of collapse with the addition of more constant PQ loads at the weak bus and the instability will continue to increase with addition of loads to this bus. Further increase of load at the weak buses can lead to power system collapse. The participating factors computed for this identified critical mode are shown in Table 8.

Table 8: Participation factors at the smallest eigenvalue for the main case model with added loads at weak buses

Bus	Participation factor
Bus1, Bus10, Bus11, Bus12, Bus13, Bus14, Bus15, Bus16, Bus17, Bus19, Bus2, Bus20, Bus21, Bus22, Bus23, Bus24, Bus25, Bus28, Bus29, Bus3, Bus32, Bus33, Bus35, Bus36, Bus37, Bus38, Bus39, Bus4, Bus40, Bus41, Bus42, Bus43, Bus44, Bus45, Bus46, Bus47, Bus48, Bus5, Bus6, Bus7, Bus8, Bus9,	0
Bus18	1.00E-05
Bus26	8.00E-05
Bus27	8.00E-05
Bus30	1.00E-05
Bus31	0.00019
Bus34	0.99954

3.3 Effect of using Compensators on the Model of the 48 bus 330KV Nigerian Network with added load

Various tests were performed on the model of the 48 bus 330kV Nigerian Network with added load at critical points and the effect of the application of compensators on the network observed. The power flow analysis of the model was carried out using PSAT in MATLAB Simulink environment. Table 9 and shows the load flow results showing the voltage, phase angle, real power of the generators, reactive power of the generators, real power of load, reactive power of load at the various buses.

Table 9: Power Flow Result of the Main Case Model with added load using compensators for three buses with the highest voltage profile and three buses with the lowest voltage profile

Bus	V (p.u.)	Phase (rad)	P gen (p.u.)	Q gen (p.u.)	P load (p.u.)	Q load (p.u.)
Bus12	0.979	0.01344	2.9376	-217.9362	1.56	0.65
Bus31	0.98696	-0.03523	0	0	1.118	0.559
Bus27	0.98803	-0.03251	0	0	23.1936	12.3216
Bus14	1.05	0.01275	24.081	112.6143	1.2776	0.63282
Bus20	1.05	-0.00326	8.1526	50.6589	0.00602	0.0043
Bus23	1.05	0.01684	48.379	84.099	0.04212	0.0351

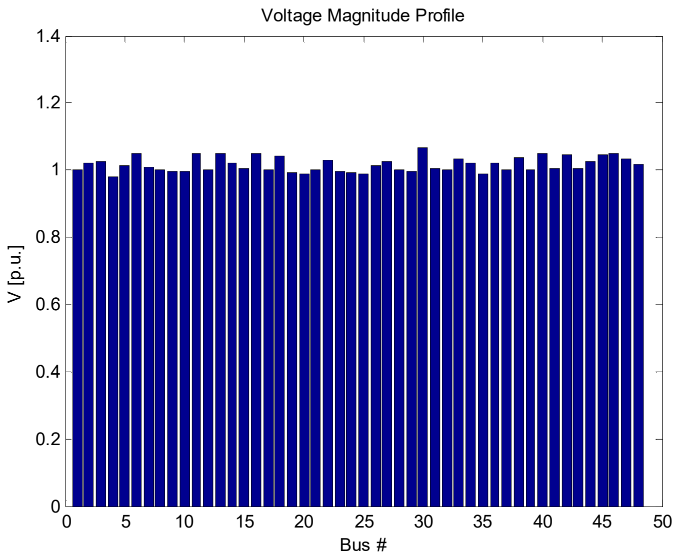

Figure 9: Angle profiles of all buses of the main case model of the 48 bus Nigerian power network system with added load at two weakest buses

Making reference to Table 9 and Figure 9, the voltages at the PQ buses falls within the acceptable level of ±5% at all the buses with bus 12 now having the lowest per unit voltage profile of 0.979 which signify that the compensators have improved the voltage stability compared to the system when a disturbance is applied to the system's three weakest buses. Utilizing the results for the load flow analysis, the eigenvalues were computed with their corresponding largest participation factor to identify the most significant state on that bus. A display of the table of the results and the required plot of the modes is shown in Table 10 and Figure 10. From Table 10 all the eigenvalues are positive this is an indication that the system is stable.

Table 10 Three highest and three lowest Eigenvalues of the standard Jacobian matrix of the Main Case Modal of the 48 bus 330KV Nigerian Network with added load and application of compensators

Most Associated Bus	Real part	Imaginary Part
Bus21	35015.7919	0
Bus9	23434.7444	0
Bus3	17915.1652	0
Bus31	488.7831	0
Bus40	972.7492	0
Bus25	727.8858	0

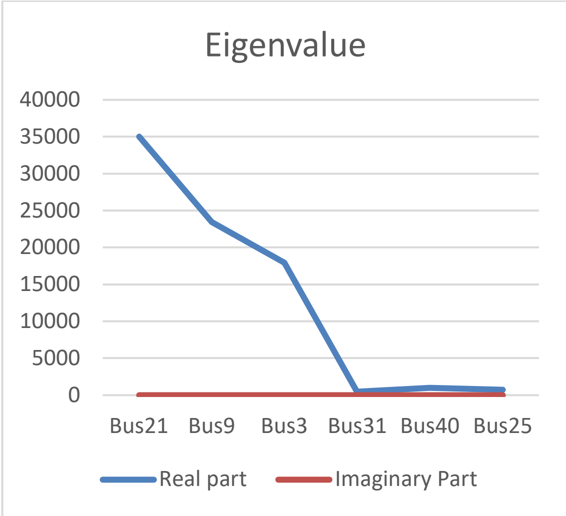

Figure 10: Eigenvalues of all buses for the main case model of the 48 bus Nigerian power network system with added load disturbances at weakest buses

Referring to Table 10 and Figure 10, observation made shows that the system is stable but tending toward instability since all the mode λ is located on the left half of the imaginary plane, but the smallest eigenvalue experienced an improvement from 1.4423 in Table 7 to 488.7831 in Table 10 when compare to the main model without added load at weakest buses. Hence the system disturbances caused by change in PQ loads at the weak bus cause instability but placing compensators on sources linked with the weak buses can minimize the effect of these disturbances. The participating factors computed for this identified critical mode are shown in Table 11.

Table 11: Participation factors at the smallest eigenvalue for the main case model

Bus	Participation factor
Bus1, Bus10, Bus11, Bus12, Bus13, Bus14, Bus15, Bus19, Bus2, Bus20, Bus21, Bus23, Bus24, Bus25, Bus28, Bus29, Bus3, Bus32, Bus33, Bus36, Bus37, Bus38, Bus39, Bus4, Bus41, Bus42, Bus43, Bus44, Bus45, Bus47, Bus5, Bus6, Bus7, Bus8,Bus34	0
Bus3	0.00312
Bus9	1e-005
Bus16	0.00571
Bus17	0.01148
Bus18	0.04402
Buss22	0.00027
Bus26	0.08038
Bus27	0.22669
Bus30	0.07755
Bus31	0.49694
Bus35	0.01635
Bus40	0.03686
Bus46	2e-005
Bus48	0.00059

4. CONCLUSION

Application of Modal Analysis on the 48 bus 330KV Nigerian Network has been explored and tested using PSAT MATLAB Toolbox. The Modal/Eigenvalue analysis technique was used to investigate the stability of the 48-bus Nigerian power network system. The method calculates the smallest eigenvalue and all the associated eigenvectors of the reduced Jacobian matrix using the steady state mode. The magnitude of the smallest eigenvalue gives us a measure of how close the system is to the voltage instability. Then, the participation factor was used to identify the weakest link or point or bus to the system associated to the minimum eigenvalues.

The 48-bus Nigerian network was simulated under changing loads condition until the system was driven to point of instability and Modal/Eigenvalue analysis was performed on the system under each of these conditions.

Results obtained in this study proved that compensators were able to drastically improve the voltage stability profile of the 48 bus Nigerian network and even rescue the system at the event of voltage instability especially ones caused by change in loads.

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In addition to working at Voice of Nigeria, Engla is deeply involved in solar energy system solutions and mechatronics.