© OCT 2025 | IRE Journals | Volume 9 Issue 4 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I4-1711275-2724

Vulnerability Assessment of Nigerian 48-Bus 330 kV Transmission Network to Cascading Failure Using Eigenvalue-Based Modal Analysis

FABIAN C. OREKE[1], CHRISTOPHER O. AHIAKWO[2], SEPRIBO L. BRAIDE[3], HACHIMENUM N. AMADI[4]
[1,2,3,4]*Electrical Engineering Department, Rivers State University, Nigeria*

Abstract - This study presents a vulnerability assessment of Nigeria's 48-bus 330 kV transmission network to cascading failures under multiple contingency scenarios using eigenvalue-based modal analysis. A high-fidelity simulation model was developed in NEPLAN, comprising 48 buses, 67 transmission lines, and multiple generating stations. Modal analysis was employed to diagnose voltage instability by evaluating participation factors associated with the system's lowest-frequency oscillation modes. The results reveal that northeastern buses, including Jalingo (0.2056), Maiduguri (0.1982), Yola (0.1925), Damaturu (0.1548), and Gombe (0.1227), exhibit dominant modal participation, indicating heightened vulnerability to reactive power disturbances. Transmission corridors such as Makurdi–Jos (1.000), Jos–Gombe (0.6875), and Ugwaji–Makurdi (0.3467) demonstrated strong modal sensitivity, suggesting their critical role in fault propagation pathways. Generator participation analysis identified Okpai GS (1.0000) and Shiroro GS (0.4357) as key dynamic influencers, underscoring their strategic importance in system stability. The findings highlight the grid's susceptibility to cascading failures, particularly in weakly meshed Northeastern regions with limited reactive power support. Modal analysis proves to be an effective diagnostic tool for identifying instability-prone elements and guiding targeted resilience interventions. The study recommends strategic deployment of reactive compensation devices and topology reconfiguration to mitigate instability and cascading failure risks and enhance grid robustness under multi-contingency conditions.

Keywords: Cascading Failure, Eigenvalue, Modal Analysis, Vulnerability Assessment, Nigerian 48-Bus 330kV Transmission Network

I. INTRODUCTION

Nigeria's national power grid has experienced frequent collapses, resulting in significant annual economic losses of approximately $29 billion (Reuters, 2024). Between 2010 and 2023, the Nigerian national grid experienced a total of 223 system collapses, comprising 158 total collapses and 65 partial collapses, which underscores the grid's fragility and heightened vulnerability to failure (Ekeng *et al.,* 2024). These frequent disruptions are primarily attributed to aging infrastructure, particularly transmission lines and substations that have exceeded 40 years of service, system overload, and underinvestment in maintenance and modernization efforts.

The Nigerian national grid is beset by numerous operational and structural deficiencies, including a persistently poor voltage profile across much of the network, particularly in the Northern region, and a deteriorating, radial, and fragile grid configuration. These structural weaknesses are compounded by inadequate dispatch and control infrastructure, which contributes to frequent system collapses (Aribi *et al.,* 2015).

Furthermore, the increasing energy demand and the extensive transmission of electricity across geographically dispersed regions push the transmission lines to operate near or beyond their voltage stability limits. Such operational stress induces power flow fluctuations, particularly in congested corridors, resulting in increased transmission losses. In severe cases, these conditions can trigger cascading outages, which may ultimately result in a complete system collapse (Ahiakwo *et al*., 2022).

Aging infrastructure and assets that have exceeded their design lifespan pose a significant risk to power system reliability due to their increased likelihood of sudden failure, often resulting from deteriorated physical conditions (Banafa & Biswal, 2019). Such failures can either directly initiate cascading outages or act as hidden vulnerabilities that exacerbate the impact of other disturbances. Among the various types of power system disruptions, cascading failures are widely recognized as the most severe and complex threats to grid stability and reliability (Guo, *et al.,* 2023).

According to the North American Electric Reliability Corporation (NERC, 2023), a cascading failure is defined as "the uncontrolled successive loss of system elements triggered by an incident at any location." These failures represent a chain reaction of outages triggered by an initial fault, which propagates through the system due to mechanisms such as overloading, angular instability, and voltage collapse (Bialek *et al.*, 2016).

Based on historical records of cascading failures, various causes have been identified, including natural disasters, equipment failures, overloading, and human factors. (Veloza & Santamaria, 2016). Although they occur infrequently, their consequences are often catastrophic, resulting in widespread blackouts, significant economic losses, social disruptions, environmental damage, and even threats to human life.

Tackling cascading failures, one of the main mechanisms causing widespread blackouts of the power network, has been widely recognized as a crucial aspect in increasing resilience to extreme events (Panteli &Mancarella, 2017).

Therefore, evaluating the risk of cascading failures is essential for ensuring the robustness and adaptability of modern power systems. Such assessments enable proactive identification of vulnerability pathways, inform strategic reinforcement planning, and ensure the grid's resilience under evolving load and contingency conditions.

II. MATERIALS AND METHOD

2.1 Materials Used

The materials utilized in this study include: Generating station data, transmission line data, transmission station load data, the Nigerian 330kV grid network diagram, and NEPLAN software. The data comprises 14 PV generators, 60 transmission lines consisting of thirty-four (34) single circuits, twenty-four (24) double circuits, one (1) triple circuit, and one (1) quadruple circuit. 34 load buses, bus rated voltage, impedance, and susceptance of transmission line, load MW, and Mvar. Egbin G/S is taken as the slack bus. These data were collected from the Transmission Company of Nigeria (TCN) as shown in Tables 2.1 and 2.2, respectively.

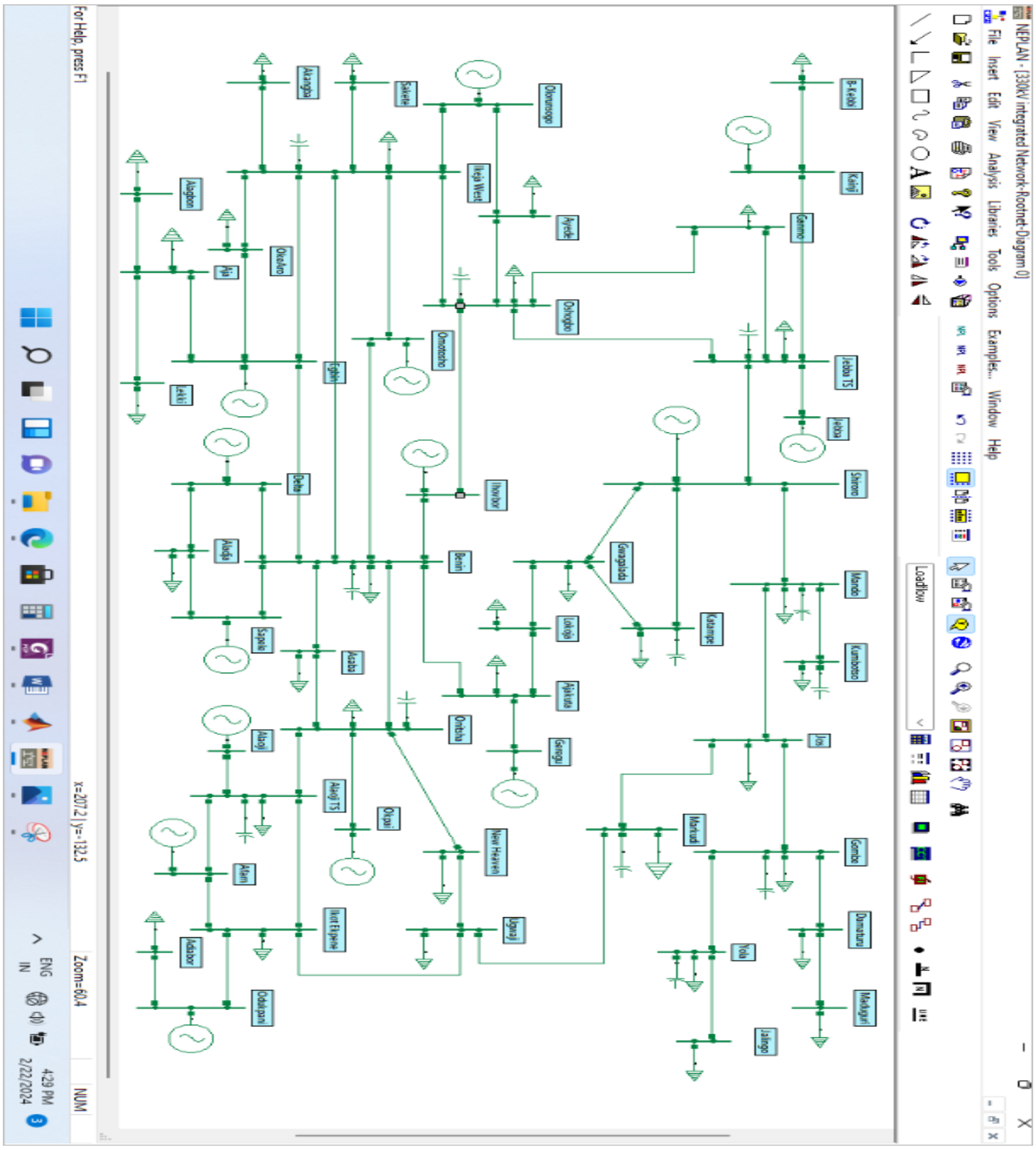

Figure 2.1: *Single-Line Diagram of the Nigerian 48-Bus 330 kV Transmission Network* in NEPLAN Software

Table 2.1: 330KV System 48 Bus Data

Bus ID	Bus Name	Bus Type	Bus Loads		Generation			
			P_L (MW)	Q_L (MVar)	Install. (MW)	Avail. (MW)	Q_{max}	Q_{min}
1	Adiabor	P-Q	140	90	0	0	0	0
2	Afam G/S	P-V	295	157.5	800	590	222	-210
3	Aja	P-Q	300	205	0	0	0	0
4	Ajaokuta	P-Q	230	115	0	0	0	0
5	Akangba	P-Q	300	250	0	0	0	0
6	Aladja	P-Q	100	70	0	0	0	0
7	Alagbon	P-Q	260	120	0	0	0	0
8	Alaoji	P-Q	400	150	0	0	0	-75
9	Alaoji G/S	P-V	113.8	53	240	95	80	-75
10	Asaba	P-Q	185.7	169.5	0	0	0	0
11	Ayede	P-Q	275	206	0	0	0	0
12	Benin	P-Q	383	150	0	0	0	-150

13	Birnin Kebbi	P-Q	146	85	0	0	0	0
14	Damaturu	P-Q	50	20	0	0	0	0
15	Delta G/S	P-V	497	253	620	250	120	-100
16	Egbin G/S	Slack	0	0	1300	0	0	0
17	Ganmo	P-Q	150	90	0	0	0	0
18	Geregu G/S	P-V	396	150	562	200	210	-200
19	Gombe	P-Q	320	170	0	0	0	-100
20	Gwagwalada	P-Q	150	70	0	0	0	0
21	Ihovbor G/S	P-V	8	3	225	110	90	-70
22	Ikeja West	P-Q	635	474	0	0	0	-150
23	Ikot Ekpene	P-Q	321	160.5	0	0	0	0
24	Jalingo	P-Q	80	50	0	0	0	0
25	Jebba	P-Q	15	5	0	0	0	-150
26	Jebba G/S	P-V	336	160	482	160	150	-110
27	Jos	P-Q	70	50	0	0	0	-75
28	Kainji G/S	P-V	414	205	500	265	200	-180
29	Katampe	P-Q	290	145	0	0	0	-75
30	Kumbotso	P-Q	` 240	130	0	0	0	-75
31	Lekki	P-Q	15.19	8.3	0	0	0	0
32	Lokoja	P-Q	300	150	0	0	0	0
33	Maidugiri	P-Q	80	30	0	0	0	0
34	Makurdi	P-Q	84	50	0	0	0	-75
35	Mando	P-Q	170	120	0	0	0	-75
36	New Haven	P-Q	180	130	0	0	0	0
37	Odukpani G/S	P-V	116	47	226	150	200	-120
38	Okearo	P-Q	220	70	0	0	0	-75
39	Okpai G/S	P-V	294	105	300	150	190	-150
40	Olorunsogo G/S	P-V	90	30	300	126	150	-150
41	Omotosho G/S	P-V	100.1	45	480	200	150	-150
42	Onitsha	P-Q	184	134	0	0	0	-75
43	Osogbo	P-Q	200	150	0	0	0	-75
44	Sakete	P-Q	50	20	0	0	0	0
45	Sapele G/S	P-V	50	25	120	90	200	-180
46	Shiroro G/S	P-V	207	95	450	220	200	-200
47	Ugwuaji	P-Q	39	25	0	0	0	0
48	Yola	P-Q	100	50	0	0	0	-75

Source: Transmission Company of Nigeria

Table 2.2: 330kV Grid Line Data

S/N	From Bus	To Bus	Length (km)	Line Type	R (Ω)	X (Ω)	B (S)	C (uF)
1	Afam	Ikot Ekpene	63	2	8.064	56.435	0.00032	0.00101
2	Afam	Alaoji	28.8	2	3.686	25.799	0.00015	0.00046
3	Aja	Lekki	12	1	0.768	5.375	0.00003	0.00010
4	Aja	Alagbon	26	1	1.664	11.645	0.00007	0.00021
5	Ajaokuta	Lokoja	38	2	4.864	34.040	0.00019	0.00061
6	Alaoji	Ikot Ekpene	55	2	7.040	49.269	0.00028	0.00088
7	Alaoji G/S	Alaoji	5	2	0.640	4.479	0.00003	0.00008
8	Asaba	Onitsha	20.5	1	1.312	9.182	0.00005	0.00016
9	Benin	Egbin	218	1	13.952	97.642	0.00055	0.00174
10	Benin	Ajaokuta	205	2	26.240	183.639	0.00104	0.00328
11	Benin	Onitsha Line	137	2	17.536	122.725	0.00070	0.00219
12	Benin	Omotosho	120	1	7.680	53.748	0.00031	0.00096

© OCT 2025 | IRE Journals | Volume 9 Issue 4 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I4-1711275-2724

S/N	From Bus	To Bus	Length (km)	Line Type	R (Ω)	X (Ω)	B (S)	C (uF)
		G/S						
13	Benin	Asaba	137	1	8.768	61.362	0.00035	0.00110
14	Benin	Ikeja West	280	1	17.920	125.412	0.00071	0.00224
15	Damaturu	Maidugri	260	1	16.640	116.454	0.00066	0.00208
16	Delta	Benin	52.65	1	3.370	23.582	0.00013	0.00042
17	Delta	Aladja	32	1	2.048	14.333	0.00008	0.00026
18	Egbin	Ikeja West	62	1	3.968	27.770	0.00016	0.00050
19	Egbin	Okearo	55.8	2	7.142	49.986	0.00028	0.00089
20	Egbin	Aja	14	2	1.792	12.541	0.00007	0.00022
21	Geregu	Ajaokuta	5	2	0.640	4.479	0.02540	0.00008
22	Gombe	Yola	240	1	15.360	107.496	0.60980	0.00192
23	Gombe	Damaturu	160	1	10.240	71.664	0.40660	0.00128
24	Gwagwalada	Katampe	40	1	2.560	17.916	0.10160	0.00032
25	Ihovbor	Benin	5	1	0.320	2.240	0.01270	0.00004
26	Ikeja West	Akangba	17.34	2	2.221	15.537	0.08820	0.00028
27	Ikeja West	Sakete	70	1	4.480	31.353	0.17790	0.00056
28	Ikot Ekpene	Ugwuaji	99	4	25.344	177.676	1.00650	0.00317
29	Jebba	Shiroro Line	244	2	31.258	219.077	1.24060	0.00390
30	Jebba	Osogbo Line	157	2	20.122	141.016	0.79830	0.00251
31	Jebba	Ganmo	87	1	5.568	38.979	0.22100	0.00070
32	JebbaG.S	Jebba	8	2	1.024	7.166	0.04070	0.00013
33	Jos	Gombe	265	1	16.960	118.694	0.67340	0.00212
34	Kainji	Birnin Kebbi	310	1	19.840	138.849	0.78870	0.00248
35	kainjiG.S	Jebba	81	2	10.368	72.140	0.40970	0.00130
36	Lokoja	Gwagwalada	160	2	20.480	143.328	0.81320	0.00256
37	Makurdi	Jos	266	2	34.029	238.296	1.35290	0.00426
38	Mando	Jos	197	1	12.608	88.246	0.50060	0.00158
39	Mando	Kumbotso	230	1	14.720	102.997	0.58440	0.00184
40	New Haven	Ugwuaji	7	2	0.896	6.271	0.03560	0.00011
41	Odukpai	Adiabor	17.7	2	2.266	15.841	0.08990	0.00028
42	Odukpani	Ikot Ekpene	37	2	4.736	33.127	0.18810	0.00059
43	Okearo	Ikeja West	27.9	2	3.571	24.987	0.14170	0.00045
44	Okpai	Onitsha	56	2	7.168	50.973	0.28810	0.00090
45	Olorunsogo	Ikeja West	77	1	4.928	35.488	0.20170	0.00062
46	Olorunsogo	Ayede	60	1	3.840	27.684	0.15250	0.00048
47	Omotosho	Ikeja West	160	1	10.240	71.664	0.40660	0.00128
48	Onitsha	New Haven	96	1	6.144	42.998	0.24390	0.00077
49	Onitsha	Alaoji	138	1	8.832	61.813	0.35060	0.00110
50	Osogbo	Ganmo	70	1	4.480	31.353	0.17790	0.00056
51	Osogbo	Ayede	115	1	7.360	51.509	0.29220	0.00092
52	Osogbo	Ikeja West	252	1	16.128	112.871	0.64030	0.00202
53	Osogbo	Ihovbor	226	1	14.464	101.225	0.57430	0.00181
54	Sapele	Benin	5	3	9.984	69.997	0.39780	0.00125
55	Sapele	Aladja	63	1	4.032	28.218	0.15970	0.00050
56	Shiroro	Mando	96	2	12.288	86.396	0.48920	0.00154
57	Shiroro	Katampe	144	1	9.216	64.198	0.36470	0.00115
58	Shiroro	Gwagwalada	120	1	7.680	53.748	0.30500	0.00096
59	Ugwuaji	Makurdi	157	2	20.096	141.997	0.80320	0.00251
60	Yola	Jalingo	140	1	8.960	62.706	0.35570	0.00112

Source: Transmission Company of Nigeria

2.2 Method

Eigenvalue-based Modal analysis was employed as a diagnostic tool to assess the vulnerability of the Nigerian 48-bus 330kV Transmission Network to cascading failures under multiple contingency scenarios. The method identifies critical nodes and weak buses where initial faults may propagate into widespread failures. It utilizes the eigenvalues and eigenvectors derived from the reduced Jacobian matrix obtained from Newton-Raphson power flow calculations, linking system stress to potential instability cascades.

Modal analysis was adopted in this study due to its ability to characterize the sensitivity of bus voltages to reactive power disturbances, which is a critical mechanism through which localized instabilities can escalate into widespread cascading failures. This modal framework was applied before each contingency scenario simulation, the reduced Jacobian was recalculated based on pre-contingency system conditions, and eigenvalues and participation factors were used for ranking contingencies based on severity and identifying vulnerable elements most involved in instability modes.

$$P_i = \sum_{k=1}^{n}|Y_{ik}||V_i||V_k|\cos(\delta_k + \theta_{ik} - \delta_i) \quad (2.1)$$

$$Q_i = -\sum_{k=1}^{n}|Y_{ik}||V_i||V_k|\sin(\delta_k + \theta_{ik} - \delta_i) \quad (2.2)$$

where;

Y_{ik}: the admittance matrix

P_i: the injected real power

Q_i: the injected reactive power

δ_i: phase angle

Expanding (2.1) and (2.2) in Taylor's series, neglecting higher order terms, we have;

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \begin{bmatrix} \begin{vmatrix} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} \end{vmatrix} & \begin{vmatrix} \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \end{vmatrix} \\ \begin{vmatrix} \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} \end{vmatrix} & \begin{vmatrix} \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{vmatrix} \end{bmatrix} \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_n^{(k)} \\ \Delta |V_2^{(k)}| \\ \vdots \\ \Delta |V_n^{(k)}| \end{bmatrix} \quad (2.3)$$

The Jacobian matrix gives the linearized relationship between small changes in voltage angle $\Delta\delta_i^{(k)}$ and magnitude $\Delta|V_i^{(k)}|$ with a small change in real $\Delta P_i^{(k)}$ and reactive power $\Delta Q_i^{(k)}$ respectively.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_3 \\ J_2 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \quad (2.4)$$

where;

J_1, J_2, J_3, J_4 are the elements of the Jacobian matrix

2.2.1 Formulation of the Reduced Jacobian Matrix

The reduced Jacobian matrix J_R is obtained by simplifying the Newton-Raphson equations for steady-state power flow with the assumption of constant real power (ΔP =0). This yields:

$$0 = J_{11}\,\Delta\theta + J_{12}\,\Delta V \quad (2.5)$$

$$\Delta Q = J_{21}\,\Delta\theta + J_{22}\,\Delta V \quad (2.6)$$

From (2.5), making $\Delta\theta$ subject of the equation we have;

$$\Delta\theta = [-J_{12}J_{11}^{-1}\Delta V] \quad (2.7)$$

Substituting (2.7) into (2.5)

$$\Delta Q = J_{21}[-J_{12}J_{11}^{-1}\Delta V] + J_{22}\,\Delta V \quad (2.8)$$

$$\Delta Q = \Delta V[J_{22} - J_{21}J_{11}^{-1}J_{12}] \quad (2.9)$$

$$J_R = [J_{22} - J_{21}J_{11}^{-1}J_{12}] \quad (2.10)$$

$$\Delta Q = J_R\Delta V \quad (2.11)$$

$$\Delta V = J_R^{-1}\Delta Q \quad (2.12)$$

This equation provides a linearized model relating voltage variation to reactive power injection, capturing voltage sensitivity under changing operating conditions, especially during contingencies

2.2.2 Eigenvalue-Based Critical Mode Detection

To assess stability margins, modal decomposition J_R is performed

$$J_R = \lambda\phi\xi \quad (2.13)$$

$$J_R^{-1} = \lambda^{-1}\phi\xi \quad (2.14)$$

Where;

ϕ: right eigenvector matrix of J_R

ξ: left eigenvector matrix of J_R

λ: diagonal eigenvalue matrix of J_R

Substituting (2.14) into (2.12)

$$\Delta V = \lambda^{-1}\phi\xi\Delta Q \quad (2.15)$$

$$\Delta V = \frac{\phi_i\xi_i}{\lambda_i}\Delta Q \quad (2.16)$$

$$\phi_i\xi_i = 1 \quad (2.17)$$

$$\Delta V = \frac{1}{\lambda_i}\Delta Q \quad (2.18)$$

This section presents the results of the vulnerability assessment of the Nigerian 330kV transmission network to cascading failures triggered by multiple contingencies.

© OCT 2025 | IRE Journals | Volume 9 Issue 4 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I4-1711275-2724

Table 3.1: Most Critical Mode

S/N	EigenValue Mvar/%
1	2.783
2	20.3888
3	27.1716
4	72.9833
5	113.9135
6	125.6806

Table 3.1 presents the most critical mode eigenvalues derived from the modal analysis of the Nigerian 48-bus 330 kV transmission network, highlighting the system's vulnerability to cascading failures under multiple contingencies. The eigenvalues 2.783 Mvar/%, 20.3888 Mvar/%, 27.1716 Mvar/%, 72.9833 Mvar/%, 113.9135 Mvar/%, and 125.6806 Mvar/% represent the sensitivity of the particular modes to reactive power disturbances. In stability studies, the lowest eigenvalue is typically of greatest concern, as it indicates the weakest mode, characterized by poor voltage control and a higher likelihood of initiating cascading failures during a contingency. Therefore, the eigenvalue of 2.783 Mvar/% is accepted as the critical threshold for this study. While mid-range values, such as 20.39 Mvar/% and 27.17 Mvar/%, suggest moderate sensitivity, often linked to inter-area oscillations or weakly damped modes, and higher eigenvalues, such as 72.98 to 125.68 Mvar/%, indicate stronger modal observability and control, they are less critical for initiating cascading failures. The assessment highlights the bus or area that is most vulnerable to voltage instability, requiring immediate reinforcement, such as FACTs devices, to improve system resilience and minimize the risk of cascading outages across the network.

Figure 3.1 below illustrates the bus participation factors corresponding to the system's most critical mode, characterized by the lowest eigenvalue of 2.783 Mvar/%, as identified in Table 3.1. These factors quantify the relative contribution of each bus to voltage instability and its susceptibility to cascading failure under this mode.

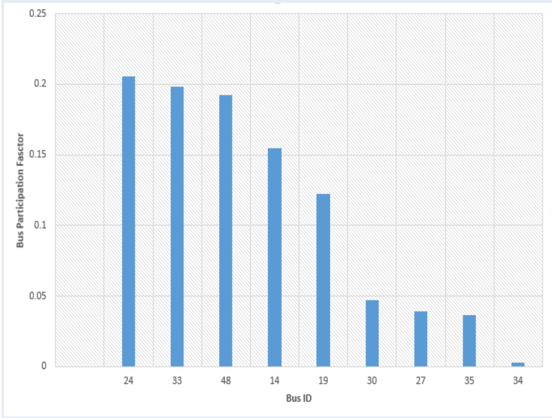

Figure 3.1: Plot of Bus Participation Factor

As illustrated in Figure 3.1, among the identified buses, Bus 24 (Jalingo) exhibited the highest participation factor at 0.2056, indicating a dominant contribution to the critical mode of voltage instability, closely followed by Bus 33 (Maiduguri) with a participation factor of 0.1982, and Bus 48 (Yola) at 0.1925. The high values highlighted buses with the most vulnerable nodes within the network, making them likely initiators of cascading failures under multiple fault contingencies. Additionally, Bus 14 (Damaturu) and Bus 19 (Gombe) showed notable influence, with participation factors of 0.1548 and 0.1227, respectively. However, buses such as Kumbotso, Jos, Mando, and Makurdi exhibited lower participation levels, suggesting a comparatively reduced impact on the system's dynamic response under this mode of disturbance.

Figure 3.2 below illustrates the branch participation factors corresponding to the system's most critical mode, characterized by the lowest eigenvalue of 2.783 Mvar/%, as identified in Table 3.1. It quantifies the relative contribution of each transmission line to voltage instability and its susceptibility to cascading failure under this mode.

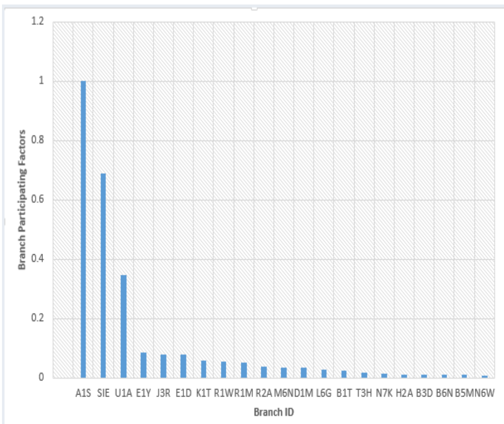

Figure 3.2: Plot of Branch Participation Factors

As shown in Figure 3.2 above, the branch connecting Markudi - Jos (Branch ID: A1S) recorded the highest participation factor of 1.0000, indicating its dominant sensitivity to voltage instability and its potential role as a trigger point for cascading failures. This was followed by the Jos-Gombe branch (SIE) with a participation factor of 0.6875, and the Ugwaji-Markudi line (U1A), which contributed 0.3467. These high values highlight branches that are particularly vulnerable and likely to propagate disturbances during multiple contingency events.

Several other branches, including Gombe-Yola (E1Y), Shiroro -Jebba TS (J3R), and Gombe-Damaturu (E1D), also demonstrated moderate influence, with participation values ranging between 0.0787 and 0.0845. Lines such as Okpai- Onitsha (K1T), Olorunsogo - Ikeja West (R1W), and Shiroro - Mando (R1M) exhibited slightly lower but still notable contributions.

In contrast, branches like Egbin – Ikeja West (N6W), Egbin - Benin (B6N), and Omotosho - Benin (B5M) had relatively low participation factors, suggesting a reduced impact on the system's dynamic behavior under the considered mode.

Figure 3.3 below shows the generators' participation factors corresponding to the system's most critical mode, characterized by the lowest eigenvalue of 2.783 Mvar/%, as identified in Table 3.1.

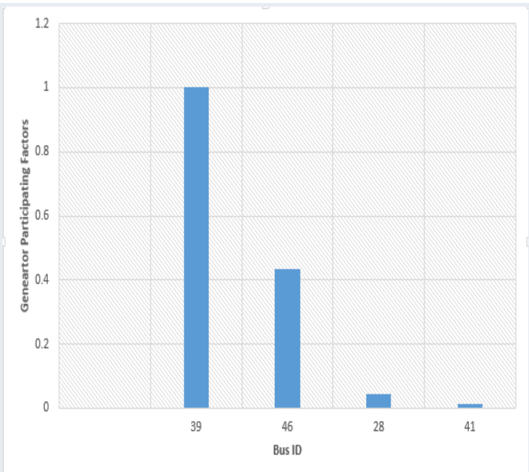

Figure 3.3: Plot of Generator Participation Factors

As illustrated in Figure 3.3, Okpai GS (Bus 39) exhibited the highest participation factor of 1.0000, indicating it is the most dominant contributor to the observed mode of instability. This suggests that any disturbance at or near this generator could significantly impact the overall system's voltage stability, particularly under multiple contingencies.

Shiroro GS (Bus 46) follows with a moderate participation factor of 0.4357, reflecting a considerable yet secondary influence on the system dynamics. In contrast, Kainji GS (Bus 28) and Omotosho GS (Bus 41) recorded significantly lower participation factors of 0.0434 and 0.0125, respectively. These values suggest that their impact on the identified critical mode is minimal compared to Okpai and Shiroro.

III. CONCLUSION

The findings highlight the grid's susceptibility to cascading failures, particularly in the Northeastern region with limited reactive power support. Modal analysis proves to be an effective diagnostic tool for identifying instability-prone elements and guiding targeted resilience interventions. The study recommends strategic deployment of reactive compensation devices and topology reconfiguration to mitigate cascading outage risks and enhance grid robustness under multi-contingency conditions.

REFERENCES

[1] Ahiakwo, C. O., Idoniboyeobu, D. C., Braide, S. L., & Onita, C. L. (2022). Investigation of voltage stability of the Nigerian 330kV transmission network using Newton Newton-Raphson method. *International Journal of Research in Engineering and Science, 10*(6), 122–129. https://www.researchgate.net/publication/361101209

[2] Aribi, F., Nwohu, M. N., Sadiq, A. A., &Ambafi, J. G. (2015). Voltage profile enhancement of the Nigerian North-East 330kV power network using STATCOM. *International Journal of Advanced Research in Science, Engineering and Technology, 2*(1), 330–336. Available from IJARSET.

[3] Banafer, M., & Biswal, M., "Investigation of Power System Cascading Failure and the Causes," *2nd International Conference on Energy, Power and Environment: Towards Smart Technology,* ICEPE 2018, 2019.

[4] Bialek, J., Ciapessoni, E., Cirio, D., Cotilla-Sanchez, E., Dent, C., Dobson, I., Henneaux,

P., Hines, P., Jardim, J., Miller, S., Panteli, M., Papic, M., Pitto, A., Quiros-Tortos, J., & Wu, D. (2016). Benchmarking and validation of cascading failure analysis tools. *IEEE Transactions on Power Systems*, *31*(6), 4887–4900. https://doi.org/10.1109/tpwrs.2016.2518660

[5] Ekeng, L., Ahiakwo, C., Amadi, H., &Obuah, E. (2024). Voltage collapse in Nigeria Power system- causes and remedies. *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)*, *19*(1), 54–63. https://www.iosrjournals.org

[6] Guo, Z., Sun, K., Su, X., & Simunovic, S. (2023). A review on simulation models of cascading failures in power systems. *iEnergy*, *2*(4), 284–296. https://doi.org/10.23919/ien.2023.0039

[7] NERC (2023). Glossary of terms used in NERC reliability standards. North American Electric Reliability Corporation (NERC). Available at https://www.nerc.com/pa/Stand/Glossary%20of%20Terms /Glossary_of_Terms.pdf

[8] Panteli, M., & Mancarella, P. (2017). Modeling and evaluating the resilience of critical electrical power infrastructure to extreme weather events. *IEEE Systems Journal, 11*(3), 1733–1742. https://doi.org/10.1109/JSYST.2015.2389272

[9] Reuters. (2024). *Why Nigeria's power grid is failing*. Retrieved from https://www.reuters.com/world/africa/why-nigerias-power-grid-is-failing-2024-12-11

[10] Transmission Company of Nigeria (TCN). (2021). *Transmission network status and performance report*. Retrieved from https://www.tcn.org.ng

[11] Veloza, O. P., & Santamaria, F. (2016). Analysis of major blackouts from 2003 to 2015: Classification of incidents and review of main causes. *The Electricity Journal*, *29*(7), 42–49. https://doi.org/10.1016/j.tej.2016.08.006