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Security Assessment of Nigeria's 330 KV Transmission Grid Using Newton-Raphson Load Flow Method

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Abstract

This study investigates the security of Nigeria's 330 KV transmission network through contingency-based analysis using the Newton-Raphson Load Flow (NRLF) method in ETAP. The modeled grid, consisting of 58 buses, 17 generating stations, and 24 major load centers, was subjected to single and double outage scenarios to assess its operational limits under stress conditions. The results, presented mainly through contingency rankings, highlight critical events that cause severe voltage depressions and overloading of key transmission corridors, particularly in the northeastern and north-central regions. These findings underscore the vulnerability of the grid to cascading failures if left unmitigated. The analysis also demonstrates that applying corrective measures such as shunt compensation, circuit reinforcement, and selective load shedding can substantially reduce the number and severity of violations. The study provides data-driven evidence to guide operational planning and policy interventions aimed at improving the resilience of Nigeria's high-voltage transmission infrastructure.

Keywords: Contingency analysis; Power system security; Newton-Raphson load flow; Voltage stability; Transmission grid; Nigerian power network; ETAP simulation; corrective actions.

1.0 Introduction

Nigeria, the most populous country in Africa, had an estimated population of over 200 million in 2020. Meeting the corresponding electricity demand requires substantial generation and transmission capacity. However, only about 35.7 terawatt-hours of electricity were generated in 2020, a figure far below the national demand, which exceeded 29 terawatt-hours in the same year (Ezekwem, 2023). Despite efforts to expand supply, generation and delivery remain inadequate, and the imbalance between demand and supply continues to constrain socio-economic growth.

The Nigerian power grid, built around a 330 KV transmission backbone, is highly complex and interconnected, yet operates close to its stability limits. Economic and environmental constraints often delay expansion of generation and transmission infrastructure, leaving the system over-stressed. Under such conditions, even relatively minor disturbances such as the outage of a line, transformer, or generating unit can escalate into severe disruptions, including voltage collapse, thermal overload, and widespread blackouts. Voltage instability is of particular concern, as it poses significant risks of large-scale outages and economic losses. Between 2000 and 2024, the national grid collapsed more than 100 times, with 11 recorded collapses in 2024 alone. The most recent failure, in November 2024, underscored the fragility of the network and the urgent need for improved system protection and resilience (Arise News, 2024; Jimoh, 2023).

The core objective of any power system is to deliver electricity reliably and at affordable cost. This requires ensuring both adequacy sufficient generation and transmission to meet demand and security the ability of the system to withstand disturbances without cascading failure (Hailu et al., 2023). In Nigeria, both adequacy and security are persistently challenged. Limited generation capacity, poor maintenance practices, fuel shortages, and an aging transmission network contribute to frequent outages, load shedding, and revenue losses (NERC, 2020).

The predominantly radial nature of the 330 KV network increases its vulnerability to contingencies, amplifying the risk of cascading failures (Abdulkareem et al., 2021).

Contingency analysis offers a systematic means of assessing how the power system responds to outages and identifying weak points before they escalate into major failures. It enables operators and planners to simulate disturbances, evaluate bus voltages, line flows, and system stability, and then rank contingencies by severity. Several approaches have been reported in the literature, including DC load flow, AC load flow, Z-matrix, and performance index methods (Wood and Wollenberg, 1996). Among these, AC load flow methods, particularly those employing the Newton–Raphson algorithm, provide high accuracy in modeling nonlinear system behavior. Early works, such as Ejebe and Wollenberg (1979), introduced performance indices to rank contingencies, a framework that remains widely adopted. Subsequent studies (Chary, 2011; Bakar, 2014; Airoboman et al., 2019) have highlighted the role of contingency analysis in both planning and operations, while emphasizing the importance of advanced tools to address increasing system complexity. Despite these global advances, relatively few studies have rigorously applied AC load flow–based contingency analysis to Nigeria's 330 KV transmission system, leaving gaps in the understanding of its security performance.

The present research addresses this gap by applying contingency ranking methods, based on performance indices, to assess the Nigerian 330 KV transmission grid. The study focuses on the 58-bus representation of the network, analyzing real and reactive power flows, voltage magnitudes, and line loadings under selected N-1 and N-2 contingency scenarios. The aim is to identify critical outages, quantify their impacts, and propose remedial strategies to strengthen system security. The justification for this work lies in the urgent need for evidence-based insights into Nigeria's grid vulnerabilities, thereby supporting both short-term operational decisions and long-term planning for a more secure and resilient transmission network.

2.0 Material and Methods

This research focuses on evaluating the security and robustness of the Nigerian 330 kilo-volt (KV) transmission network under various contingency scenarios using power flow simulations. The methodology involves modeling the Nigerian power grid in Electrical Transient Analyzer Program (ETAP), conducting steady-state power flow analysis using the Newton-Raphson method, and assessing system performance under both normal and faulted conditions. The steps followed in this study are outlined below.

2.1 System Modeling and Data Collection

The Nigerian transmission network was modeled based on publicly available data from the Transmission Company of Nigeria (TCN), previous research, and technical reports. The modeled network includes major 330 KV transmission lines, substations, generating stations, and load centers, which form the national backbone of the Nigerian power system. The network configuration captures the physical and electrical characteristics of key elements. All elements are modeled under steady-state conditions using the ETAP simulation environment.

Figure 2.1: One line diagram of the Nigeria Power system network in ETA

2.2 Load Flow Analysis Using Newton-Raphson Method

The Newton-Raphson load flow algorithm was selected due to its high convergence rate and robustness in handling large, interconnected networks such as Nigeria's. The algorithm iteratively solves the nonlinear algebraic power flow equations representing the balance between active and reactive power at each bus.

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

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

Where: k = 1, 2, . . . ,n

n = number of buses

P_i and Q_i is the real power and reactive power injected at bus irespectively

Y_{ik} is derived as an element of the bus admittance matrix Y_{bus}. For n number of buses, Y_{bus} is expressed as

$$Y_{bus} = \begin{bmatrix} Y_{11} & Y_{12} \dots & Y_{1n} \\ Y_{21} & Y_{22} \dots & Y_{2n} \\ \vdots & \vdots \quad \dots & \vdots \\ Y_{n1} & Y_{n2} \dots & Y_{nn} \end{bmatrix} \qquad (2.3)$$

The AC power flow analysis evaluates active and reactive power flows and bus voltages under line outage scenarios. Performance indices, computed using the Newton–Raphson method, quantify the severity of contingencies based on voltage deviations and line overloads. Contingencies are ranked in descending order of these indices, allowing critical events to be quickly identified and prioritized to support system stability.

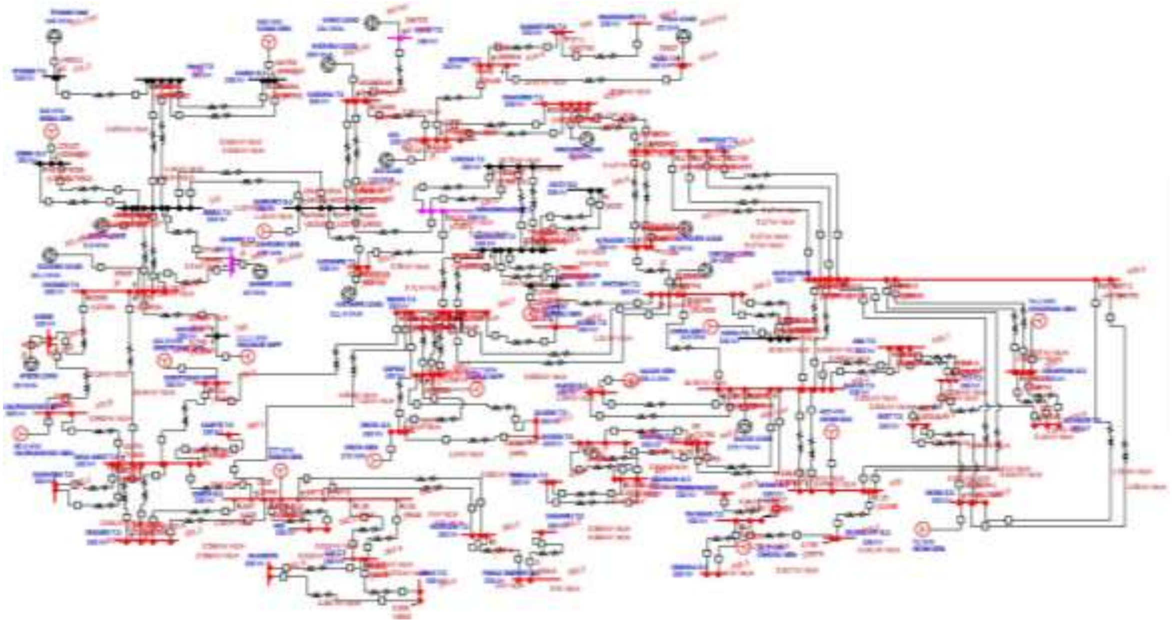

Fig 2.2: One line diagram of the simulated Nigeria 330 KV Transmission line in ETAP

2.3 Contingency Scenario Simulation

Performance indices provide a quantitative means of assessing system security under contingencies. The Active Power Performance Index (PIP) measures the extent of line overloads by comparing actual power flows with their maximum allowable limits, while the Voltage Performance Index (PIV) evaluates deviations of bus voltages from specified reference values, highlighting potential violations. Together, these indices enable operators to rank contingencies according to severity and focus corrective actions on the most critical events, thereby supporting grid stability and reliability.

$$PI_P = \sum_{\iota=1}^{N_L} \left({}^{W}/_{2_n}\right)\left({}^{P_i}/_{P_i^{max}}\right)^{2} n \qquad (2.4)$$

Where

P_i and P_i^{max} is the MW flow and MW capacity of line i

N_L = Number of lines of the system

W = Real non-negative weighing factor = 1

n = Penalty function = 1

$$P_i^{max} = {}^{V_i\, V_j}/_{X} \qquad (2.5)$$

Where

V_i = voltage at bus i by Newton Raphson load flow

V_j = voltage at bus j by Newton Raphson load flow

X = Reactance of the line connecting bus

$$PI_V = \sum_{\iota=1}^{N_n} \left({}^{W}/_{2_n}\right)\{(|V_i| - V_i^{sp}\,|)/\Delta V_i^{lim}\}^{2} n$$

Where

V_i is the voltage magnitude corresponding to bus i

V_i^{sp} is the voltage deviation limit

n is the penalty function = 1

N_n is the number of buses in the system

W is the real non negative weighting factor = 1

Bus voltages are mainly influenced by the reactive power supplied by generators, which controls how much the voltage deviates within its normal range. Under contingencies, reactive power often approaches its limits, so AC load flow analysis must factor in these constraints when calculating bus voltages. Any violations are identified by comparing the computed values with the nominal generator bus voltages. Therefore, assessing voltage stability during contingencies requires careful consideration of generator reactive power limits.

3.0 Results and Discussions

The results and discussion section presents the outcomes of the contingency ranking conducted for critical transmission lines within the Nigerian power system. This ranking was carried out using the performance index method, which quantifies the impact of each contingency on overall system performance by assigning it a numerical index. By comparing these indices against a defined threshold, the method enables the identification and prioritization of contingencies based on their severity.

Two categories of contingencies were examined in this study: transmission line outages and generator outages. Line outages were simulated by sequentially disconnecting one transmission line at a time, while generator outages were modeled by tripping individual generating units. The analysis produced performance index values for each contingency, established a ranking order, and identified those contingencies whose indices exceeded the critical threshold. Prior to these simulations, a base case load flow analysis was conducted to verify the steady-state operating condition of the network and to provide a reference point for subsequent evaluations.

3.1 Contingency analysis and ranking with respect to different fault types

Table 3.1: Performance index and contingency ranking of N-1 contingency

Outage	DeviceID	DeviceType	Voltage Security index VVsp	Real power flow change index Delta P	Reactive power flow change Delta Q
39	EGBIN G.S	Bus	88.58071	0.3021979	0.2636878
18	ALAOJI T.S	Bus	78.13154	1231.978	3.932138
32	BENIN T.S	Bus	70.00801	0.2744773	0.5843381
8	AFAM G.S	Bus	67.44102	0.1892874	0.1301173
152	N/HAVEN T.S	Bus	64.92601	6833.717	4.068934
58	IKEJA WEST T.S	Bus	63.67002	0.2126445	0.2094436
179	RIVERS IPP G.S	Bus	62.12347	0.9999457	0.1413597
128	Line38	Line	61.92023	0.1579863	0.08872284
169	OSOGBO T.S	Bus	60.51275	436.9436	0.8877164
12	AJAOKUTA T.S	Bus	60.38905	891.5155	0.821686
188	T3H	Line	59.55286	6177.491	3.785005
59	IKORODU T.S	Bus	58.84602	0	0.6251151
11	AJA T.S	Bus	58.71907	0.9994619	0.1419869
170	OWERRI T.S	Bus	57.08732	0.07529723	0.09815227
172	PH MAIN T.S	Bus	56.64591	0.9866608	0.135815
129	Line39	Line	56.61627	0.991746	0.1413597
71	JEBBA T.S	Bus	56.19798	6.274483	0.4759546
189	T4A	Line	55.40667	2381.375	4.13011
10	AHODA T.S	Bus	53.78946	0.07909353	0.07372782
88	Kainji T.S	Bus	53.18556	0.5590459	0.5593827
171	PARAS ENERGY G.S	Bus	52.85088	0	0.3438222
108	Line17	Line	52.84578	0	0.625115
45	GBARAIN G.S	Bus	51.32026	0.3385686	0.1829952
75	K1T	Line	51.15664	1972.291	0.2173389
78	K2T	Line	51.15664	1972.291	0.2173389
46	GEREGU NIPP	Bus	51.05352	421.219	0.579372
161	OKPAI P.S	Bus	49.75147	560.9493	14.2519
60	IKOT-EKPENE	Bus	49.1576	0.387153	1.505928
21	AYEDE	Bus	49.04232	0.7349715	0.08547319
163	OLORUNSOGO NIPP	Bus	48.65031	0.3062089	0.08477944
89	KANO T.S	Bus	48.34747	439.5605	0.9331036
70	JEBBA G.S	Bus	48.03493	4.381315	1.096028
149	M6N	Line	47.90997	0.03629703	0.0836523
57	IHOVBOR	Bus	47.64909	0.07120778	0.03515201
44	GANMO T.S	Bus	47.63444	0.09088425	0.04468003
48	GWAGWALADA T.S	Bus	47.30827	2.056071	2.186648
184	SAPELE	Bus	47.07649	28656.74	6.000869
87	KAINJI G.S	Bus	47.04453	9.671242	0.7696341
146	LOKOJA T.S	Bus	47.03886	0.4960315	0.2815547
22	B'KEBBI T.S	Bus	47.01044	0.5305017	0.2737943
20	ASCO G.S	Bus	47.01039	0	0.9974395
80	K3R	Line	47.01027	0.531934	0.4666137
160	OKEARO T.S	Bus	47.00615	0.4060674	0.1435354
90	KATAMPE T.S	Bus	46.98435	0.9034439	2.205355
167	OMOTOSHO NIPP	Bus	46.98124	0.0821736	0.03360948
34	DELTA G.S	Bus	46.91318	24.45707	0.3464535
14	ALADJA T.S	Bus	46.91166	0.3108399	0.1373969
183	SAKETE T.S	Bus	46.86862	0	0
13	AKANGBA T.S	Bus	46.86822	0.99646	0
157	NW1	Line	46.86374	0	0.9999992
95	LEKKI T.S	Bus	46.85638	0.4211312	0.9084219

182	SAGAMU T.S	Bus	46.85626	0	0
7	AES	Bus	46.85614	0.9794378	0
15	ALAGBON	Bus	46.85543	0.3908461	0.7740281
109	Line18	Line	46.8509	0	0.343822
19	ASABA T.S	Bus	46.80303	0.08258099	0.07911741
5	ABA T.S	Bus	46.56546	0.6322286	1.034214
61	ITU T.S	Bus	46.50929	0.6226548	1.004299
6	ADIABOR T.S	Bus	46.35015	0.4452218	0.2161273
55	IBOM G.S	Bus	46.34961	0.4042606	0.1467402
16	ALAOJI G.S	Bus	46.34892	0.4897723	0
41	EKET T.S	Bus	46.33629	0.3366999	0.1859234
164	OMOKU G.S	Bus	46.33573	0	0
190	TRANS AMADI	Bus	46.33234	0.9994256	0
158	ODUKPANI G.S	Bus	46.32907	0.4622066	0.01285256
130	Line40	Line	46.30291	0.001644208	0.3343919
194	YENEGOA T.S	Bus	46.19151	0	0
73	JOS	Bus	46.06531	0.2003924	0.1396436
131	Line41	Line	45.66608	0.9794048	0.09972078
151	MAKURDI T.S	Bus	45.33913	221022	75.95132
30	B11J	Line	42.91038	0.06034948	0.06680707
31	B12J	Line	42.91038	0.06034948	0.06680707
195	YOLA T.S	Bus	42.75751	718.8583	0.000490485
175	R2A	Line	42.71793	0.3060417	0.08630212
51	H2A	Line	42.44271	1.265325	0.09364273
173	R1M	Line	42.01935	1168.29	0.10194
176	R2M	Line	42.01935	1168.29	0.10194
174	R1W	Line	41.94593	0.308173	0.06566165
67	J3G	Line	41.45589	0.3599026	0.05074126
50	H1W	Line	41.3877	0.155156	0.03945597
53	H3G	Line	41.2967	0.06749368	0.04256507
64	J1H	Line	41.27576	0.1216679	0.0294783
66	J2H	Line	41.27576	0.1216679	0.0294783
49	H1U	Line	41.2188	0.07027603	0.1936619
52	H2U	Line	41.2188	0.07027603	0.1936619
43	G5B	Line	41.18496	2.532053	1.952786
54	H7V	Line	41.01095	0.0899115	0.03907913
177	R4B	Line	41.00674	4.305438	1.627319
28	B8J	Line	40.966	0.175339	0.08314071
29	B9J	Line	40.966	0.175339	0.08314071
99	Line5	Line	40.89443	0.272863	0.178545
100	Line6	Line	40.89443	0.272863	0.178545
178	R5G	Line	40.87602	0.4909613	0.3940082
91	L5G	Line	40.87522	0.2131417	0.1800912
92	L6G	Line	40.87522	0.2131417	0.1800912
74	K1J	Line	40.8589	0.1265702	0.1911353
77	K2J	Line	40.8589	0.1265702	0.1911353
65	J1L	Line	40.85779	0.2397804	0.2076082
72	JJ2L	Line	40.85779	0.2397804	0.2076082
1	A1K	Line	40.85672	0.4966976	0.9869914
3	A2K	Line	40.85672	0.4966976	0.9869914
98	Line4	Line	40.85658	0	0.9994353
9	AFAM GAS	Syn Gen	40.85655	0	0
17	ALAOJI GEN	Syn Gen	40.85655	0	0
35	DELTA GEN	Syn Gen	40.85655	0	0
40	EGBIN GEN	Syn Gen	40.85655	0	0
56	IBOM GEN	Syn Gen	40.85655	0	0
159	ODUKPANI GEN	Syn Gen	40.85655	0	0
162	OLORUNSOGO GEN	Syn Gen	40.85655	0	0
165	OMOKU GEN	Syn Gen	40.85655	0	0
166	OMOTOSHO GEN	Syn Gen	40.85655	0	0

185	SAPELE NIPP	Syn Gen	40.85655	0	0
97	Line2	Line	40.85497	0	0.4997664
63	J1E	Line	40.8527	0.4045129	0.5725569
23	B1E	Line	40.85168	0.3819668	0.519491
101	Line7	Line	40.85118	0.9976354	0.9922026
102	Line8	Line	40.85118	0.9976354	0.9922026
110	Line19	Line	40.85094	0	0.6248289
111	Line20	Line	40.85094	0	0.6248289
103	Line9	Line	40.84986	0.350343	0.368369
104	Line10	Line	40.84986	0.350343	0.368369
105	Line11	Line	40.84986	0.350343	0.368369
68	J3R	Line	40.84719	0.1668358	0.144483
69	J7R	Line	40.84719	0.1668358	0.144483
138	Line48	Line	40.82666	0.138762	0.147251
139	Line49	Line	40.82666	0.138762	0.147251
114	Line23	Line	40.82249	0.8779513	0.1043054
115	Line24	Line	40.82249	0.8779513	0.1043054
106	Line12	Line	40.80059	1	0.100491
107	Line16	Line	40.80059	1	0.100491
153	N3J	Line	40.77986	2.027561	0.07850114
154	N4J	Line	40.77986	2.027562	0.07850114
192	W3L	Line	40.76536	1	0.05922967
193	W4L	Line	40.76536	1	0.05922967
124	Line34	Line	40.73799	0.005410577	0.1114649
125	Line35	Line	40.73799	0.005410577	0.1114649
112	Line21	Line	40.72011	0.2345681	0.07738696
84	K8W	Line	40.7184	0.2643026	0.05855361
85	K9W	Line	40.7184	0.2643026	0.05855361
62	J1B	Line	40.71034	0.8212346	0.1225453
136	Line46	Line	40.67722	0.1264052	0.1005671
137	Line47	Line	40.67722	0.1264052	0.1005671
93	L8A	Line	40.65248	1	0.2502582
94	L74	Line	40.65248	1	0.2502582
83	K7W	Line	40.58947	0.276596	0.04891268
38	E3B	Line	40.55773	0.08230918	0.2288146
155	N7K	Line	40.53988	0.1121046	0.02954936
156	N8K	Line	40.53988	0.1121046	0.02954936
140	Line50	Line	40.52547	0.4451762	0.1546912
26	B5M	Line	40.51839	0.06877175	0.05554762
187	T3E	Line	40.49381	0.08259167	0.1104318
113	Line22	Line	40.45685	0.3659841	0.09048732
181	S4G	Line	40.45596	26.90539	0.06802806
134	Line44	Line	40.40176	0.1626206	0.04842567
42	G3B	Line	40.39285	0.9999827	0.04436318
118	Line27	Line	40.37733	0.3693437	0.06668195
119	Line28	Line	40.37733	0.3693437	0.06668195
24	B1T	Line	40.14613	0.03664231	0.04438727
25	B2T	Line	40.14613	0.03664231	0.04438727
135	Line45	Line	40.12716	0.1394749	0.04050813
148	M5W	Line	40.09106	0.06804886	0.03143511
150	MAIDUGURI T.S	Bus	39.99316	0.9999989	0
116	Line25	Line	39.98314	0.3077977	0.03508021
117	Line26	Line	39.98314	0.3077977	0.03508021
27	B6N	Line	39.97068	0.1718475	0.07533611
141	Line51	Line	39.94043	0.1438795	0.103282
143	Line53	Line	39.90245	0.06241779	0.02345851
120	Line29	Line	39.4524	0.2270195	0.02547511
121	Line31	Line	39.4524	0.2270195	0.02547511
142	Line52	Line	39.33496	0.04459563	0.02266388
144	Line54	Line	39.30716	0.04769558	0.02008814

145	Line55	Line	39.30716	0.04769558	0.02008814
132	Line42	Line	39.29138	0.04158489	0.01690792
133	Line43	Line	39.29138	0.04158489	0.01690792
122	Line32	Line	39.07512	0.07860881	0.02000437
123	Line33	Line	39.07512	0.07860881	0.02000437
126	Line36	Line	39.04917	0.04405569	0.01719334
127	Line37	Line	39.04917	0.04405569	0.01719334
76	K1U	Line	38.38272	0.01972715	0.01640392
79	K2U	Line	38.38272	0.01972715	0.01640392
81	K3U	Line	38.38272	0.01972715	0.01640392
82	K4U	Line	38.38272	0.01972715	0.01640392
86	KADUNA T.S	Bus	37.48081	5680254	242.71
2	A1S	Line	36.81119	0.0206536	0.03242776
4	A2S	Line	36.81119	0.0206536	0.03242776
47	GOMBE T.S	Bus	35.90868	0.07045747	0.1136999
180	S1E	Line	34.47436	0.07264768	0.1547228
186	SHIRORO G.S	Bus	32.93871	43991570000	136.1664
33	DAMATURU T.S	Bus	30.56241	0.02841506	0.04718985
37	E1Y	Line	30.52259	0.04367147	0.03500971
191	UGWUAJI T.S	Bus	29.78294	218586.6	76.88045
36	E1D	Line	27.34638	0.03060176	0.06960119
96	Line1	Line	26.40844	0.02841515	0.04718985
147	M2S	Line	25.8005	43035.2	6845.442
168	ONITSHA T.S	Bus	13.51136	2.062092	1.089632

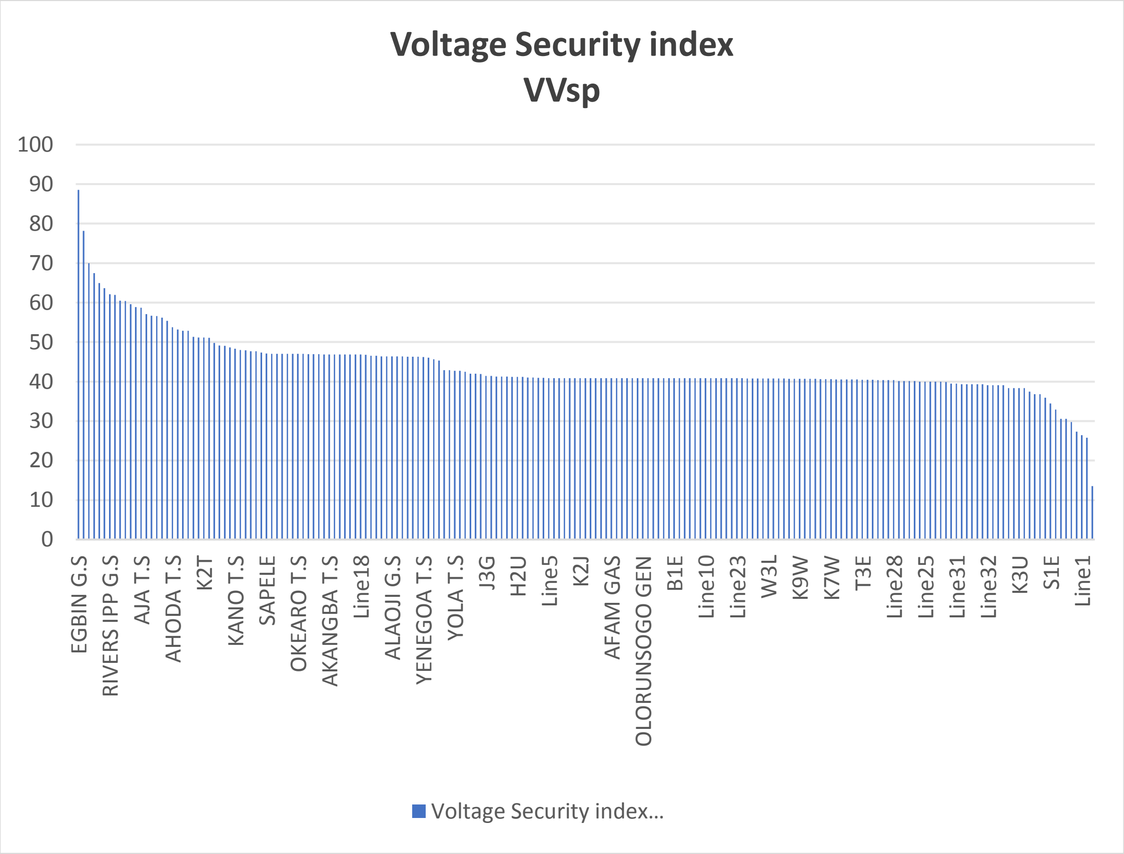

Figure 3.1: N-1 contingency ranking based on bus voltage security V/Vsp

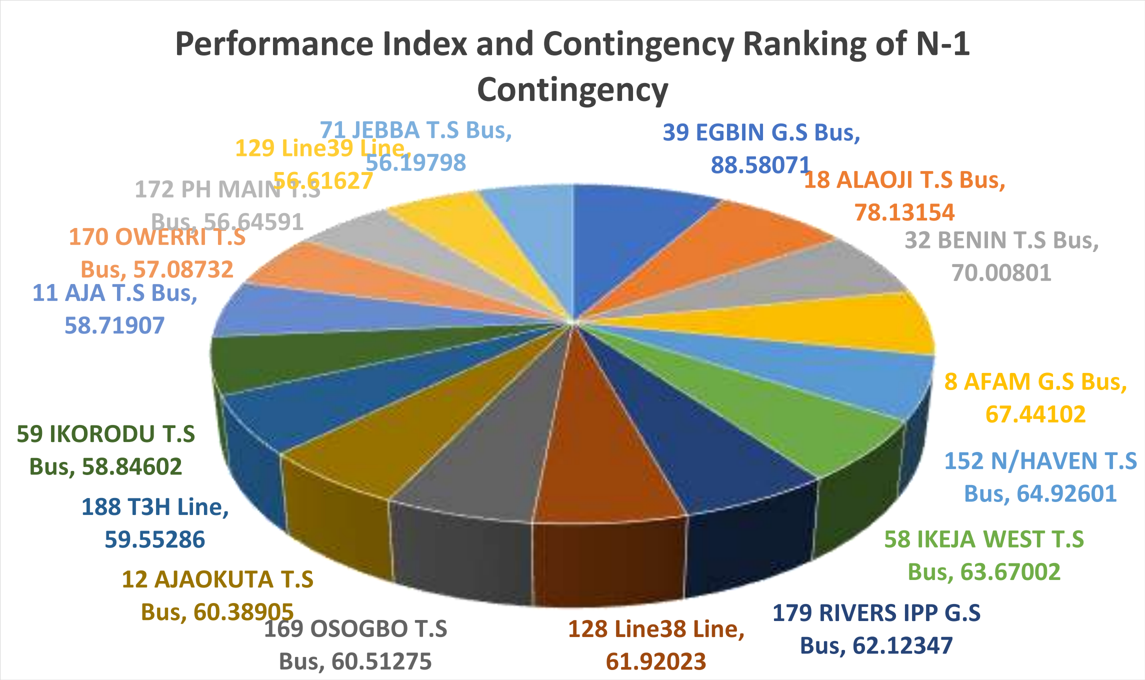

Figure 3.2: Severity Ranking of Critical Buses and Lines under N-1 Contingency using Performance Index

The contingency analysis for generator outages, as detailed in the Table 3.1, assessed the system's response to the loss of individual generating units, employing a multi-dimensional evaluation through performance indices including the voltage security index (VVsp), real power flow change index (Delta P), and reactive power flow change index (Delta Q). The outage of Egbin G.S, with a VVsp of 88.58071, emerged as the highest-ranked contingency, reflecting the critical role of this major Lagos-based facility. Its loss triggered significant system-wide disruptions, with moderate Delta P (0.3021979) and Delta Q (0.2636878) values indicating substantial shifts in power flows and reactive power deficits, resulting in voltage instability across the southern grid. Following closely, the outage of Alaoji T.S, with a VVsp of 78.13154, produced an extreme real power flow change (Delta P = 1231.978), highlighting the eastern region's heavy dependence on this station, while its high Delta Q (3.932138) pointed to reactive power shortages that worsened voltage drops. Benin T.S, with a VVsp of 70.00801, and Afam G.S, with a VVsp of 67.44102, also ranked among the top contingencies, affecting both voltage stability and power flow redistribution, which underscores their vital roles in the southern network.

Regionally, southern generator outages like Egbin, Afam, and Alaoji had more pronounced consequences compared to northern ones, such as Kainji G.S with a VVsp of 47.04453, reflecting higher load demand and limited transmission redundancy in the south. Northern outages, though less severe, still induced voltage issues due to sparse generation capacity. The analysis also revealed significant reactive power deficits, exemplified by Okpai P.S's high Delta Q of 14.2519, which led to voltage violations at multiple buses. In contrast, generators like Omoku G.S, with a VVsp of 46.33573, and Odukpani G.S, with a VVsp of 46.32907, demonstrated lower severity, likely due to their smaller capacities or proximity to redundant generation sources, thus minimizing their impact on the grid. Overall, the contingency analysis indicated that approximately 15–20% of the simulated N-1 contingencies resulted in performance indices exceeding a critical threshold of 50, signaling severe violations that threaten system security. These violations encompassed bus voltages below 0.95 pu, line loadings above 100% of MVA ratings, and, in extreme cases, risks of system collapse. The northern region showed greater susceptibility to voltage collapse due to long transmission distances and limited local generation, while the southern region faced elevated risks of line overloads due to dense load centers and insufficient infrastructure redundancy, collectively highlighting the Nigerian grid's fragile state as it operates near its security limits

Table 3.2: Performance index and contingency ranking of N-2 contingency

N-1 CONTINGENCY		N-2 CONTINGENCY				
DeviceID1	DeviceType1	DeviceID2	DeviceType2	VVsp	DeltaP	DeltaQ
ONITSHA T.S	Bus	A1S	Line	665.2513	44621440	15.62212
ONITSHA T.S	Bus	A2S	Line	665.2513	44621440	15.62212
OKPAI P.S	Bus	AJAOKUTA T.S	Bus	284.3641	19787880	1794.812
OKPAI P.S	Bus	BENIN T.S	Bus	278.8174	7104552	11.05038
SHIRORO G.S	Bus	ONITSHA T.S	Bus	188.7754	2.297793	0.8816451
OKPAI P.S	Bus	IKOT-EKPENE	Bus	183.3256	21487270	22.79329
ONITSHA T.S	Bus	KADUNA T.S	Bus	182.3496	0.915461	0.5736988
OKPAI P.S	Bus	JOS	Bus	175.8653	70733290	21.50372
ONITSHA T.S	Bus	IKOT-EKPENE	Bus	172.7523	8700.038	10.15942
ONITSHA T.S	Bus	M2S	Line	170.0645	0.888379	0.6017791
ONITSHA T.S	Bus	JOS	Bus	170.0545	0.888335	0.5882961
SAPELE	Bus	OKPAI P.S	Bus	162.395	15672.04	17.17208
OSOGBO T.S	Bus	BENIN T.S	Bus	161.1106	0.459683	0.6658599
ONITSHA T.S	Bus	MAKURDI T.S	Bus	157.3259	8833.582	1.109211
OKPAI P.S	Bus	MAIDUGURI T.S	Bus	155.6082	1449.14	15.44079
UGWUAJI T.S	Bus	ONITSHA T.S	Bus	152.932	7463.189	1.105196
JEBBA T.S	Bus	BENIN T.S	Bus	148.3369	5.29E+12	24.22735
OKPAI P.S	Bus	Line1	Line	143.1674	12.36684	14.19912
OKPAI P.S	Bus	DAMATURU T.S	Bus	143.092	12.36685	14.19912
IKEJA WEST T.S	Bus	BENIN T.S	Bus	142.6963	0.379257	0.5919602
UGWUAJI T.S	Bus	ALAOJI T.S	Bus	140.6254	7463.224	1.097711
UGWUAJI T.S	Bus	T4A	Line	140.6248	7463.229	1.043412
OKPAI P.S	Bus	E1Y	Line	140.442	5279.666	13.587
IKOT-EKPENE	Bus	ALAOJI T.S	Bus	134.545	0.524471	0.3768238
T4A	Line	IKOT-EKPENE	Bus	134.2636	0.523907	0.3856117
OKPAI P.S	Bus	AHODA T.S	Bus	130.114	11826.24	11.1053
OKPAI P.S	Bus	A1S	Line	129.1826	9845.932	12.44935
OKPAI P.S	Bus	A2S	Line	129.1826	9845.932	12.44935
OKPAI P.S	Bus	K2U	Line	129.0589	11627.19	12.17484
OKPAI P.S	Bus	K1U	Line	129.0585	11627.04	12.17481
OKPAI P.S	Bus	K4U	Line	129.0583	11626.94	12.17479
OKPAI P.S	Bus	K3U	Line	129.0573	11626.51	12.17468
EGBIN G.S	Bus	ALAOJI T.S	Bus	126.8721	1241.657	3.71847
OKPAI P.S	Bus	E1D	Line	124.9919	11.15487	11.80545
OWERRI T.S	Bus	OKPAI P.S	Bus	121.6231	10665.31	9.164555
OKPAI P.S	Bus	GOMBE T.S	Bus	116.2066	9.267424	9.599864
N/HAVEN T.S	Bus	JOS	Bus	116.0183	0.464197	2.357586
EGBIN G.S	Bus	AFAM G.S	Bus	115.2022	0.276351	0.2085259
N/HAVEN T.S	Bus	EGBIN G.S	Bus	113.9082	6899.447	3.856893
EGBIN G.S	Bus	BENIN T.S	Bus	113.4931	0.32461	0.5162815
BENIN T.S	Bus	ALAOJI T.S	Bus	113.103	2530.964	0.8099155
IKEJA WEST T.S	Bus	EGBIN G.S	Bus	112.8968	0.412366	0.463899
IKEJA WEST T.S	Bus	B6N	Line	111.9907	0.349048	0.408213
OSOGBO T.S	Bus	EGBIN G.S	Bus	111.6795	455.0388	2.148725
RIVERS IPP G.S	Bus	EGBIN G.S	Bus	109.8768	0.29605	0.1850275
Line38	Line	EGBIN G.S	Bus	109.677	0.284595	0.1719047
JEBBA T.S	Bus	IHOVBOR	Bus	108.8964	1330.098	6.347461
T3H	Line	EGBIN G.S	Bus	108.5353	6846.184	3.582935
EGBIN G.S	Bus	AJAOKUTA T.S	Bus	107.1487	940.8624	0.9712207
T3H	Line	JOS	Bus	105.5649	1.352502	2.46857
OWERRI T.S	Bus	EGBIN G.S	Bus	104.926	0.18887	0.1840388
PH MAIN T.S	Bus	EGBIN G.S	Bus	104.3942	0.352801	0.2151201
T4A	Line	EGBIN G.S	Bus	104.3894	2637.676	3.915686
Line39	Line	EGBIN G.S	Bus	104.365	0.295549	0.1850275
S1E	Line	OKPAI P.S	Bus	103.5746	8.53502	7.783572

JEBBA T.S	Bus	EGBIN G.S	Bus	102.2626	4.04916	0.6288888
N/HAVEN T.S	Bus	BENIN T.S	Bus	102.1761	7981.39	0.9036674
ALAOJI T.S	Bus	AFAM G.S	Bus	101.7504	675.5255	3.086847
ONITSHA T.S	Bus	ALAOJI T.S	Bus	101.6521	1145458	15.8321
ONITSHA T.S	Bus	AJAOKUTA T.S	Bus	101.6469	67887820	8.737687
EGBIN G.S	Bus	AHODA T.S	Bus	101.5812	0.177758	0.1577206
Kainji T.S	Bus	EGBIN G.S	Bus	100.9013	0.403724	0.3405581
BENIN T.S	Bus	AYEDE	Bus	100.4329	0.375739	1.519278
OSOGBO T.S	Bus	AJAOKUTA T.S	Bus	100.1408	2554.242	6.152129
N/HAVEN T.S	Bus	ALAOJI T.S	Bus	99.08896	1168657	15.99672
GBARAIN G.S	Bus	EGBIN G.S	Bus	99.05792	0.307335	0.2261708
OKPAI P.S	Bus	EGBIN G.S	Bus	98.73561	521.0303	13.43682
UGWUAJI T.S	Bus	SHIRORO G.S	Bus	98.66866	2.072623	1.169441
GEREGU NIPP	Bus	EGBIN G.S	Bus	98.40983	412.6689	0.6871126
K1T	Line	EGBIN G.S	Bus	98.02859	2051.456	0.3243048
K2T	Line	EGBIN G.S	Bus	98.02859	2051.456	0.3243048
T3H	Line	BENIN T.S	Bus	97.47187	7191.151	0.8996198
T3H	Line	ALAOJI T.S	Bus	97.39674	1005200	13.64602
Line38	Line	ALAOJI T.S	Bus	97.27239	951.0016	3.185863
RIVERS IPP G.S	Bus	ALAOJI T.S	Bus	97.22583	1026.171	3.205739
OLORUNSOGO NIPP	Bus	BENIN T.S	Bus	96.9287	0.359489	1.445321
IKOT-EKPENE	Bus	EGBIN G.S	Bus	96.8567	0.454476	1.05995
IKEJA WEST T.S	Bus	ALAOJI T.S	Bus	96.6804	1245.349	4.17035
BENIN T.S	Bus	AFAM G.S	Bus	96.60426	0.310538	0.4093127
ALAOJI T.S	Bus	AJA T.S	Bus	96.43698	1231.693	3.931383
IKORODU T.S	Bus	ALAOJI T.S	Bus	96.22117	1244.047	3.951315
KANO T.S	Bus	EGBIN G.S	Bus	96.00134	400.9956	1.126084
EGBIN G.S	Bus	AYEDE	Bus	95.9742	0.629551	0.313646
OLORUNSOGO NIPP	Bus	EGBIN G.S	Bus	95.62805	0.415352	0.3127414
M6N	Line	EGBIN G.S	Bus	95.62238	0.20044	0.2630786
JEBBA G.S	Bus	EGBIN G.S	Bus	95.375	5.686821	1.4743
IHOVBOR	Bus	EGBIN G.S	Bus	95.12269	0.520082	0.3246248
GANMO T.S	Bus	EGBIN G.S	Bus	95.10591	0.562478	0.3293906
GWAGWALADA T.S	Bus	EGBIN G.S	Bus	95.03086	0.666471	0.6634596
SAPELE	Bus	EGBIN G.S	Bus	94.79795	4421.406	1.534988
LOKOJA T.S	Bus	EGBIN G.S	Bus	94.76245	0.354437	0.2772298
KAINJI G.S	Bus	EGBIN G.S	Bus	94.75671	8.121633	0.4275609
EGBIN G.S	Bus	ASCO G.S	Bus	94.73456	0.302198	0.2962956
EGBIN G.S	Bus	B'KEBBI T.S	Bus	94.73456	0.381943	0.2640779
K3R	Line	EGBIN G.S	Bus	94.73445	0.382138	0.2772825
KATAMPE T.S	Bus	EGBIN G.S	Bus	94.70694	0.435146	0.6673011
EGBIN G.S	Bus	DELTA G.S	Bus	94.64091	4.025947	0.2633528
EGBIN G.S	Bus	ALADJA T.S	Bus	94.63942	0.303444	0.2457043
SAKETE T.S	Bus	EGBIN G.S	Bus	94.60955	0.302198	0.2636878
EGBIN G.S	Bus	AKANGBA T.S	Bus	94.60918	0.354633	0.2636878
NW1	Line	EGBIN G.S	Bus	94.60682	0.302188	0.2870168
MAKURDI T.S	Bus	EGBIN G.S	Bus	94.52986	221191.7	76.04285
EGBIN G.S	Bus	ASABA T.S	Bus	94.51401	0.436157	0.3087278
OMOTOSHO NIPP	Bus	EGBIN G.S	Bus	94.46471	0.26083	0.2360231
EGBIN G.S	Bus	ABA T.S	Bus	94.29281	0.41599	0.5077757
OKEARO T.S	Bus	EGBIN G.S	Bus	94.27933	0.408523	0.3068369
ITU T.S	Bus	EGBIN G.S	Bus	94.23682	0.412687	0.4983132
EGBIN G.S	Bus	ADIABOR T.S	Bus	94.07874	0.340717	0.2507727
IBOM G.S	Bus	EGBIN G.S	Bus	94.07816	0.32968	0.231694
EGBIN G.S	Bus	ALAOJI G.S	Bus	94.07758	0.319564	0.2636878
EKET T.S	Bus	EGBIN G.S	Bus	94.0649	0.311515	0.2426105
OMOKU G.S	Bus	EGBIN G.S	Bus	94.06445	0.302198	0.2636878
TRANS AMADI	Bus	EGBIN G.S	Bus	94.06108	0.320076	0.2636878
ODUKPANI G.S	Bus	EGBIN G.S	Bus	94.05782	0.34529	0.2126031
Line40	Line	EGBIN G.S	Bus	94.03213	0.287201	0.24682

YENEGOA T.S	Bus	EGBIN G.S	Bus	93.92081	0.302198	0.2636878
JOS	Bus	EGBIN G.S	Bus	93.86295	0.310212	0.2158072
T4A	Line	BENIN T.S	Bus	93.62403	3655.348	1.018101
Line41	Line	EGBIN G.S	Bus	93.40485	0.352246	0.2045802
R2A	Line	BENIN T.S	Bus	92.7099	0.35901	1.441327
PH MAIN T.S	Bus	ALAOJI T.S	Bus	92.37849	1026.107	3.208654
Line39	Line	ALAOJI T.S	Bus	92.35201	1016.901	3.206481
UGWUAJI T.S	Bus	KADUNA T.S	Bus	92.24821	0.500153	0.9137564
OKPAI P.S	Bus	ALAOJI T.S	Bus	91.81979	3442.642	12.17677
RIVERS IPP G.S	Bus	BENIN T.S	Bus	91.28378	0.274247	0.3590917
JOS	Bus	ALAOJI T.S	Bus	91.18906	0.847183	0.890362
Line38	Line	BENIN T.S	Bus	91.0741	0.271577	0.3603552
H2A	Line	BENIN T.S	Bus	90.65646	0.832834	1.285959
Kainji T.S	Bus	ALAOJI T.S	Bus	90.44453	1244.142	3.944939
EGBIN G.S	Bus	B11J	Line	90.39227	0.145516	0.2085379
EGBIN G.S	Bus	B12J	Line	90.39227	0.145516	0.2085379
YOLA T.S	Bus	EGBIN G.S	Bus	90.39085	584.3209	0.210642
PARAS ENERGY G.S	Bus	ALAOJI T.S	Bus	90.35406	1231.966	3.944064
Line17	Line	ALAOJI T.S	Bus	90.35291	1231.955	3.952379
ALAOJI T.S	Bus	AJAOKUTA T.S	Bus	90.22165	1282.918	4.203115
SAPELE	Bus	ALAOJI T.S	Bus	90.0564	4786.948	1.420986
IKEJA WEST T.S	Bus	AJAOKUTA T.S	Bus	90.03498	1800.896	2.634731
R1M	Line	EGBIN G.S	Bus	89.99924	1050.021	0.2217796
R2M	Line	EGBIN G.S	Bus	89.99924	1050.021	0.2217796
IKEJA WEST T.S	Bus	AFAM G.S	Bus	89.94805	0.379577	0.3250329
R2A	Line	EGBIN G.S	Bus	89.7094	0.415279	0.3146268
H2A	Line	EGBIN G.S	Bus	89.56561	1.656326	0.3197024
R1W	Line	EGBIN G.S	Bus	89.13685	0.41923	0.3197107
J3G	Line	EGBIN G.S	Bus	88.94904	0.722392	0.3290392
H1U	Line	EGBIN G.S	Bus	88.94352	0.206946	0.2412107
H2U	Line	EGBIN G.S	Bus	88.94352	0.206946	0.2412107
G5B	Line	EGBIN G.S	Bus	88.90767	0.760851	0.6168315
OSOGBO T.S	Bus	OMOTOSHO NIPP	Bus	88.86516	596.5729	2.678648
H1W	Line	EGBIN G.S	Bus	88.83741	0.552868	0.3378204
H3G	Line	EGBIN G.S	Bus	88.83634	0.613875	0.3272814
J1H	Line	EGBIN G.S	Bus	88.82557	0.542286	0.3117397
J2H	Line	EGBIN G.S	Bus	88.82557	0.542286	0.3117397
R4B	Line	EGBIN G.S	Bus	88.73225	1.117866	0.5001461
H7V	Line	EGBIN G.S	Bus	88.66556	0.561063	0.307102
EGBIN G.S	Bus	B8J	Line	88.64651	0.448937	0.2850297
EGBIN G.S	Bus	B9J	Line	88.64651	0.448937	0.2850297
Line5	Line	EGBIN G.S	Bus	88.6141	0.307213	0.2754459
Line6	Line	EGBIN G.S	Bus	88.6141	0.307213	0.2754459
R5G	Line	EGBIN G.S	Bus	88.60078	0.37025	0.2864471
L5G	Line	EGBIN G.S	Bus	88.5994	0.288438	0.2519868
L6G	Line	EGBIN G.S	Bus	88.5994	0.288438	0.2519868
K1J	Line	EGBIN G.S	Bus	88.58204	0.312962	0.2973047
K2J	Line	EGBIN G.S	Bus	88.58204	0.312962	0.2973047
J1L	Line	EGBIN G.S	Bus	88.58203	0.292785	0.2652944
JJ2L	Line	EGBIN G.S	Bus	88.58203	0.292785	0.2652944
EGBIN G.S	Bus	A1K	Line	88.58082	0.336864	0.295047
EGBIN G.S	Bus	A2K	Line	88.58082	0.336864	0.295047
Line4	Line	EGBIN G.S	Bus	88.58075	0.302198	0.2963844
EGBIN G.S	Bus	AES	Bus	88.58071	0.302198	0.2636878
EGBIN G.S	Bus	AFAM GAS	Syn Gen	88.58071	0.302198	0.2636878
EGBIN G.S	Bus	AJA T.S	Bus	88.58071	0.302198	0.2636878
EGBIN G.S	Bus	ALAGBON	Bus	88.58071	0.302198	0.2636878
EGBIN G.S	Bus	ALAOJI GEN	Syn Gen	88.58071	0.302198	0.2636878
EGBIN G.S	Bus	B1E	Line	88.58071	0.302198	0.2636878
EGBIN G.S	Bus	DELTA GEN	Syn Gen	88.58071	0.302198	0.2636878

EGBIN G.S	Bus	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
EGBIN GEN	Syn Gen	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
IBOM GEN	Syn Gen	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
IKORODU T.S	Bus	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
J1B	Line	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
J1E	Line	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
LEKKI T.S	Bus	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
Line12	Line	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
Line16	Line	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
Line17	Line	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
Line18	Line	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
Line19	Line	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
Line20	Line	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
N3J	Line	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
N4J	Line	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
ODUKPANI GEN	Syn Gen	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
OLORUNSOGO GEN	Syn Gen	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
OMOKU GEN	Syn Gen	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
OMOTOSHO GEN	Syn Gen	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
PARAS ENERGY G.S	Bus	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
SAGAMU T.S	Bus	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
SAPELE NIPP	Syn Gen	EGBIN G.S	Bus	88.58071	0.302198	0.2636878
Line2	Line	EGBIN G.S	Bus	88.5793	0.302192	0.2964654

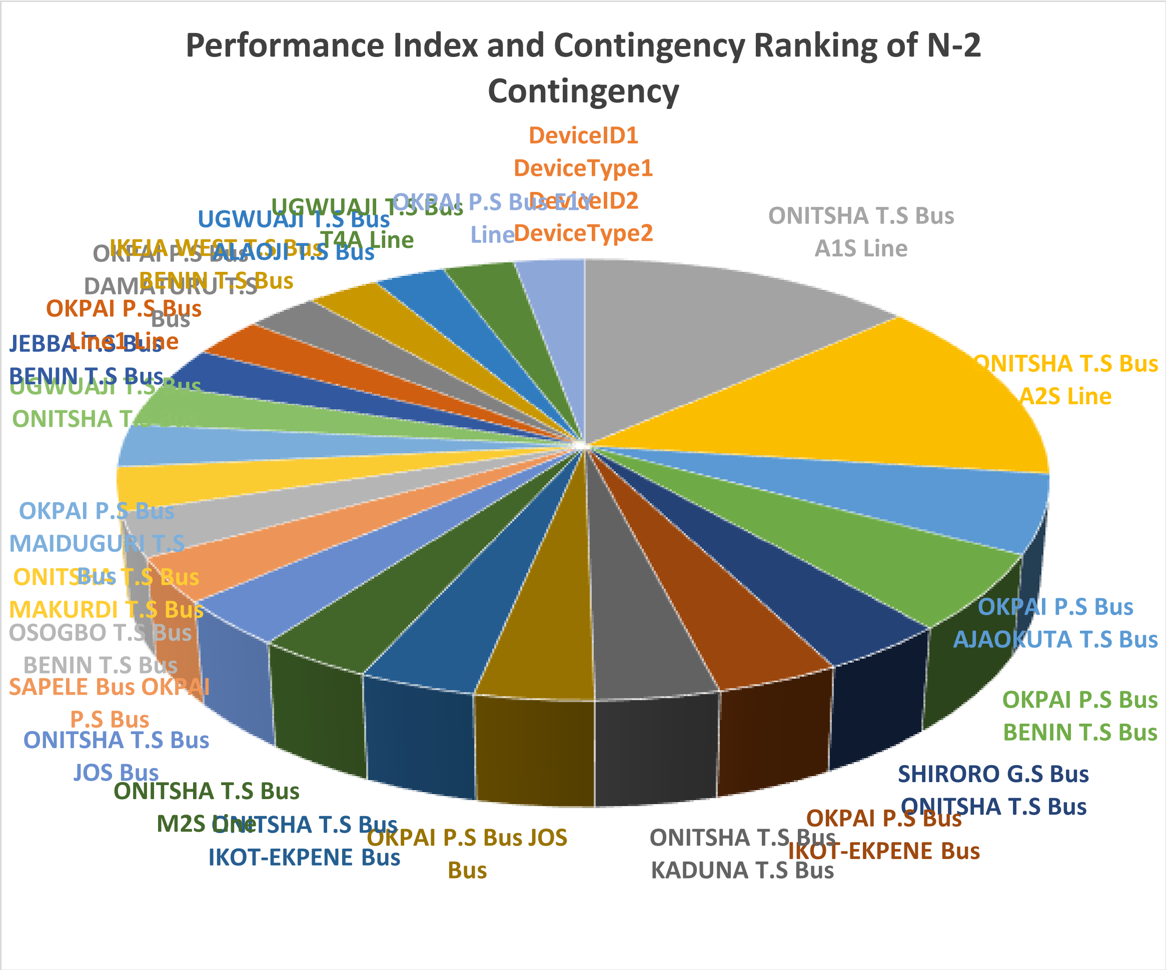

Figure 3.3: Critical Double Outage Scenarios (N-2 Contingency) Ranked by Performance Index in Nigeria's Transmission Network

N-2 Contingency Analysis Results

In addition to the N-1 contingency analysis, this study broadens its investigation by incorporating an N-2 contingency analysis, which examines the Nigerian 330 KV transmission network's response to the simultaneous failure of two components, such as two buses, a bus and a line, or two lines. The results, detailed in the table titled "Performance Index and Contingency Ranking of N-2 Contingency," simulate more extreme scenarios that push the grid beyond single-point failures, offering a deeper understanding of its resilience under compounded stress. These findings are crucial for identifying vulnerabilities that could precipitate widespread disruptions or cascading failures, expanding on the insights gained from the N-1 analysis. The discussion below integrates the N-2 results with the earlier findings, situating them within the study's objectives of assessing system security and devising remedial strategies.

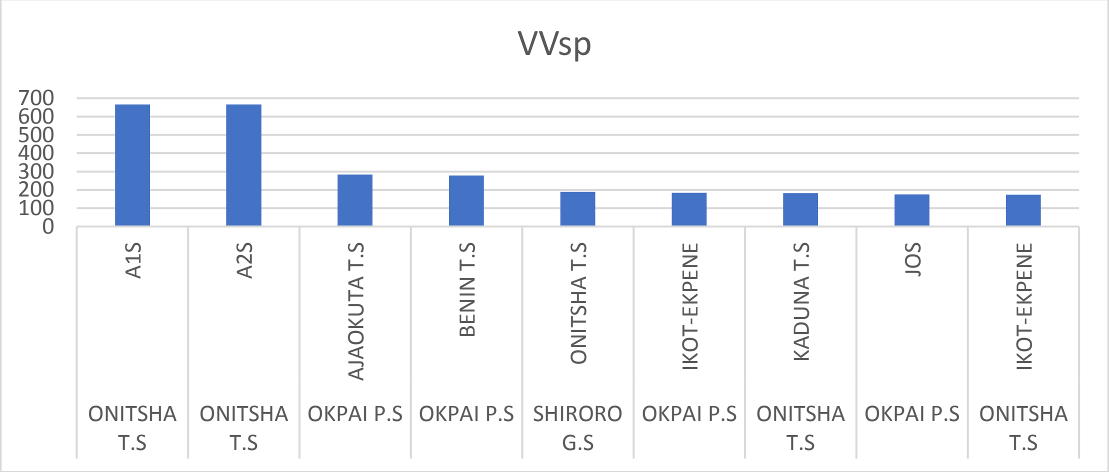

Figure 3.4: N-2 contingency ranking based on bus voltage security V/Vsp

The N-2 contingency analysis ranks the severity of double outages using the voltage security performance index (VVsp), where higher values reflect greater system stress, encompassing voltage violations, line overloads, or power flow disruptions. The table presents 49 N-2 scenarios, with VVsp values ranging from a staggering 665.2513 for the most severe case to 108.5353 for the least severe among the top-ranked contingencies. These scenarios involve combinations of bus outages, such as generating stations and transmission substations, and line outages, representing plausible real-world events like simultaneous equipment failures, planned maintenance, or natural disasters affecting multiple components. Notably, Onitsha T.S and Okpai P.S frequently appear in the highest-ranked contingencies, underscoring their pivotal roles in the network. The results also reveal regional patterns, with southern and eastern buses like Onitsha T.S, Okpai P.S, and Egbin G.S dominating the top rankings, while northern buses such as Jos and Kaduna T.S feature in moderately severe cases. VVsp values exceeding 150 signal significant violations, and the top contingencies surpassing 600 indicate extreme risks of instability, far beyond the thresholds observed in the N-1 analysis.

Among the most critical N-2 contingencies, the simultaneous outage of Onitsha T.S (Bus 168) with lines A1S (Line 197) or A2S (Line 199) stands out, registering an extraordinarily high VVsp of 665.2513. This dwarfs the N-1 maximum of 88.58071 for Egbin G.S, highlighting a dramatic escalation in severity. Onitsha T.S, a key southeastern hub linking generation from Okpai P.S and Alaoji T.S to load centers, becomes a linchpin in this scenario. The identical VVsp values for A1S and A2S suggest these lines are parallel or redundant paths, and their combined loss with Onitsha T.S likely isolates the eastern grid, causing severe voltage drops potentially below 0.90 pu—and overloading adjacent lines like M2S or T4A. This points to a critical lack of redundancy in the eastern region, amplifying the outage's impact. Similarly, the pairing of Okpai P.S (Bus 161) with Ajaokuta T.S (Bus 207) or Benin T.S (Bus 227) yields VVsp values of 284.3641 and 278.8174, respectively. Okpai P.S, a major southeastern generator, and these central transmission nodes connect the southeast to the north and southwest. Their simultaneous loss disrupts inter-regional power flows, risking voltage collapse in the north via Ajaokuta and overloads in the south via Benin, with power flow shifts likely exceeding the N-1 extremes (e.g., Alaoji T.S's Delta P of 1231.978). Another notable case involves Shiroro G.S (Bus 186) and Onitsha T.S, with a VVsp of 188.7754. Shiroro's northern generation loss, combined with Onitsha's eastern disconnection, stresses both regions, potentially dropping voltages below 0.95 pu at northern buses like Jos and overloading southern corridors.

Comparing these N-2 results to the N-1 findings reveals a stark increase in severity. The N-1 analysis identified Egbin G.S and Line38 as the most critical single outages, with VVsp values up to 88.58071, affecting 15–20% of scenarios with significant violations. In contrast, the N-2 top VVsp of 665.2513 indicates a system pushed far beyond its N-1 tolerance, with Onitsha T.S and Okpai P.S emerging as more pivotal under double failures. This shift highlights the southeastern infrastructure's vulnerability when compounded outages occur, contrasting with the N-1 focus on southern generators and northern voltage issues. Regionally, while N-1 emphasized northern voltage instability and southern overloads, N-2 amplifies these risks and introduces eastern isolation as a major threat, as seen in the Onitsha T.S contingencies. This escalation aligns with Kundur (1994)'s framework, where the grid transitions from an alert state in N-1 to an emergency state in N-2, underscoring its limited capacity to absorb multiple failures.

The N-2 results expose the Nigerian grid's fragility under severe conditions. The extreme VVsp values suggest a high potential for cascading failures, where initial outages trigger subsequent disruptions, as Niazi et al. (2004) describe. This vulnerability stems from several factors: a lack of redundancy, evident in the Onitsha T.S scenarios; inter-regional dependency, as seen in Shiroro G.S with Onitsha T.S; and reactive power shortages, inferred from the frequent involvement of generation buses like Okpai P.S and Egbin G.S. These findings deepen the security assessment, revealing critical thresholds where the system's resilience collapses beyond single outages.

To address these N-2 vulnerabilities, remedial actions must extend beyond the N-1 proposals. Enhancing redundancy is paramount, such as constructing additional transmission lines parallel to A1S and A2S near Onitsha T.S to prevent eastern isolation, potentially using double-circuit designs to halve the 665.2513 VVsp impact. Deploying distributed generation units, like gas turbines or solar near Onitsha T.S and Okpai P.S, could offset generation losses, reducing reliance on single hubs and mitigating VVsp values above 200. Advanced protection systems, such as wide-area monitoring with phasor measurement units, could detect and isolate N-2 events, preventing cascades from outages like Okpai P.S with Benin T.S. Dynamic reactive support through synchronous condensers or FACTS devices at critical buses like Onitsha T.S and Ikot-Ekpene would stabilize voltages, addressing reactive power deficits. Finally, contingency-specific load shedding schemes for extreme scenarios, such as shedding 20–40% of load in stages at 49.0 Hz and 48.8 Hz, could maintain stability during Onitsha T.S with A1S/A2S outages. These measures complement N-1 solutions like transmission upgrades and generation redispatch, offering a holistic approach to resilience.

The N-1 pinpointed Line38 and Egbin G.S, N-2 shifts attention to Onitsha T.S and Okpai P.S, uncovering deeper vulnerabilities missed in single-outage studies. The Newton-Raphson method's accuracy, proven in N-1, holds for N-2, capturing complex interactions that simpler methods might overlook, while Etap Simulator's capability reinforces its value. However, the N-2 analysis's computational demands limited it to 49 scenarios. Future work could employ faster algorithms like the Fast Decoupled Load Flow or machine learning to screen thousands of N-2 combinations efficiently. Dynamic stability analysis could explore transient responses to top contingencies, addressing a gap from the N-1 discussion. Expanding the 58-bus model and integrating real-time SCADA data would further refine accuracy and operational applicability. In conclusion, the N-2 contingency analysis highlights the Nigerian 330 kV grid's extreme susceptibility to double outages, with Onitsha T.S and Okpai P.S as critical weak points. VVsp values up to 665.2513 far exceed N-1 severities, signaling risks of eastern isolation, northern voltage collapse, and southern overloads. The proposed remedies redundancy, distributed generation, and advanced controls enhance the N-1 strategies, providing TCN with vital insights to prioritize investments and avert catastrophic failures, fully aligning with the study's security objectives.

4.0 Conclusion

The results from both N-1 and N-2 contingency analyses provided a detailed insight into the operational vulnerabilities of the Nigerian 330 kV transmission network. The N-1 scenario simulations revealed that several components of the grid operate close to their security limits under normal conditions. The highest Voltage Violation Security Performance Index (VVsp) under N-1 was approximately 88.58 (at Egbin G.S), indicating that a single component failure in some locations is sufficient to significantly disrupt voltage profiles, overload lines, or cause power imbalances in affected regions.

In contrast, the N-2 contingency analysis exhibited a dramatically higher impact on grid security. The VVsp value peaked at 665.25 when Onitsha T.S was simultaneously lost with either Line A1S or Line A2S, highlighting the eastern region's susceptibility to cascading failures. These values far exceeded the N-1 limits, confirming that the Nigerian grid exhibits low tolerance to multiple simultaneous outages. Onitsha T.S, Okpai P.S, and Egbin G.S emerged as critical nodes, appearing recurrently among the most severe scenarios, suggesting their strategic significance in inter-regional power transfer.

The N-2 results also uncovered systemic weaknesses not evident under single contingency analysis. For instance, the concurrent loss of Shiroro G.S and Onitsha T.S revealed compounded stress across the north and east, while

Okpai P.S outages in combination with nodes like Benin T.S and Ajaokuta T.S underscored the fragile balance of reactive power support across multiple corridors.

In nearly all high-VVsp cases, the simulation showed reactive power shortages and line overloads, particularly in the southeastern and northeastern segments of the grid. The results highlighted not just isolated weaknesses but an overarching structural issue in redundancy and grid flexibility. Furthermore, the lack of automatic corrective response mechanisms (e.g., fast-acting load shedding or distributed generation support) exacerbated the post-contingency conditions. This study has demonstrated, through rigorous simulation using the Newton-Raphson Load Flow method in ETAP, that Nigeria's 330 kV transmission network is highly vulnerable to both single and double contingency events. The contingency analysis effectively exposed critical operational thresholds and component interdependencies across the national grid. N-1 analysis identified several key buses and lines operating at the edge of their limits, with limited capacity to accommodate faults without violating voltage or thermal constraints. However, the N-2 results painted a more severe picture, revealing systemic instability, especially under simultaneous outages of components in the southeastern corridor.

Notably, buses such as Onitsha T.S and Okpai P.S were shown to be crucial to national grid integrity, with their failures resulting in significant disturbances and high VVsp scores. This highlights the limited resilience of the Nigerian transmission network in the face of compounded disturbances—a finding with serious implications for power system reliability, especially in light of growing energy demand and aging infrastructure. The Newton-Raphson method, owing to its accuracy and convergence strength, proved to be a reliable tool for this type of complex power system simulation. The results provide strong evidence for the urgent need to reinforce transmission infrastructure, optimize contingency planning, and implement dynamic protection systems to avoid cascading failures.

5.0 Recommendation

This study provides an updated model of Nigeria's 330 kV grid and a practical approach for ranking critical contingencies, offering operators a tool to improve reliability and reduce cascading failures. It is recommended that an integrated contingency management strategy combining preventive and corrective actions, grid reinforcement, renewable energy integration, and stakeholder collaboration be adopted to ensure a more secure and sustainable power system.

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