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Critical Contingency Analysis: Enhancing Stability in Nigeria's 330kv Grid

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ABSTRACT: This study presents a contingency ranking analysis for the Nigerian 330kV power system using ETAP software. The network model, consisting of 65 buses, 120 transmission lines, 16 generators, and 14 loads, was evaluated to identify critical contingencies affecting system performance. Results indicate that the outage of the M2S line poses the most significant threat to grid stability, while the SAPELE NIPP generator failure has negligible impact. Recommendations focus on enhancing system resilience through load management, network restructuring, and renewable energy integration. Limitations of the study include model simplification and software dependency, suggesting areas for future research expansion.

KEYWORDS: Nigerian power grid, contingency ranking, ETAP, 330kV transmission, system stability.

I. INTRODUCTION

Nigeria is the most populous country in Africa. As of 2020, the nation's population amounted to just over 200 million. To meet the electrical energy needs of individuals in Nigeria, a high volume of production is expected. In 2020, around 35.7 thousand gigawatt hours of electricity were generated. This was very low in comparison to the level of electricity demand, which exceeded 29 terawatt hours in the same year. Moreover, the amount of energy that was supplied reached roughly 35 gigawatt hours in 2020. Visibly, more investments in electricity production are needed to bridge the existing demand and supply gap in the country (Ezekwem, 2023).

The electrical power system is a complex network of interconnected components designed to deliver electricity to consumers. To ensure its reliable operation, sophisticated control systems are employed to maintain system parameters within acceptable limits. However, the system's complexity makes it susceptible to various disturbances and stresses. As the demand for electricity continues to grow, power systems are facing significant challenges. The expansion of transmission and generation infrastructure is often hindered by economic and environmental factors, leading to overloaded and weakened systems. This situation increases the risk of voltage instability and other power quality issues. The combination of increased load demand and limited infrastructure capacity can push power systems closer to their stability limits. Voltage instability, in particular, is a major concern as it can lead to widespread power outages and significant economic losses. To address these challenges, innovative solutions and advanced technologies are required to enhance the resilience and efficiency of power systems. From the year 2000 to 2024, the Nigerian power grid has collapsed over 100 times. As of now, the Nigerian power grid has collapsed 11 times in 2024. The most recent collapse occurred on November 7, 2024, which was the second collapse in that week alone(Arise News, 2024). The frequent collapses have raised significant concerns about the reliability and stability of the power system in Nigeria. It's a challenging situation for many Nigerians, as these collapses lead to widespread power outages and disruptions to daily life and businesses. In view of these, the total number of system collapses per year is quite alarming and indicates that the transmission system is stressed. This has serious implications for system protection and eliminates the critical service of providing customers with reliable, continuous power (Jimoh, 2023).

The primary objective of an electrical power system is to reliably deliver electricity to consumers at an affordable cost. This involves ensuring both the adequacy and security of the system. Adequacy refers to the system's ability to meet the demand for electricity, both in terms of power and energy. It involves having sufficient generation and transmission capacity to supply the required amount of electricity. Security refers to the system's ability to withstand disturbances without compromising its performance. It involves maintaining system stability and avoiding cascading failures that can lead to widespread blackouts. In deregulated power markets, the focus on economic efficiency can sometimes compromise security. As a result, power systems may be operated closer to their limits, increasing the risk of disturbances and blackouts. Power system disturbances, such as sudden outages of transmission lines, generators, or transformers, can have severe consequences. These disturbances can lead to cascading failures, resulting in widespread blackouts that can cause significant economic losses and social disruption. (Hailu et al., 2023).

The Nigerian power system is one of the most challenged in Africa, with frequent outages, low generation capacity, high losses, and poor quality of service (Airoboman et al., 2019). The transmission network, which consists of mainly 330-kV lines, is radial and vulnerable to contingencies that can cause cascading failures and blackouts (Abdulkareem et al., 2021). Therefore, there is a need to improve the reliability and security of the transmission system by identifying and ranking the critical lines that can affect the system performance under different fault scenarios. Contingency analysis is a complementary tool for assessing the impact of potential failures of power system equipment on the system security and stability. It is useful for planning and operating the system in a secure and reliable manner.

Contingency ranking for critical transmission lines in Nigeria power system is relevant because it provides valuable insights into the current state and future needs of the transmission network. It can help to identify the weak points and bottlenecks in the network, as well as the optimal locations and sizes of reactive power compensation devices. It can also help to evaluate the effectiveness of existing protection schemes and suggest possible improvements or alternatives. Furthermore, it can support the development of contingency plans and emergency control strategies to mitigate the consequences of severe faults and prevent widespread outages.

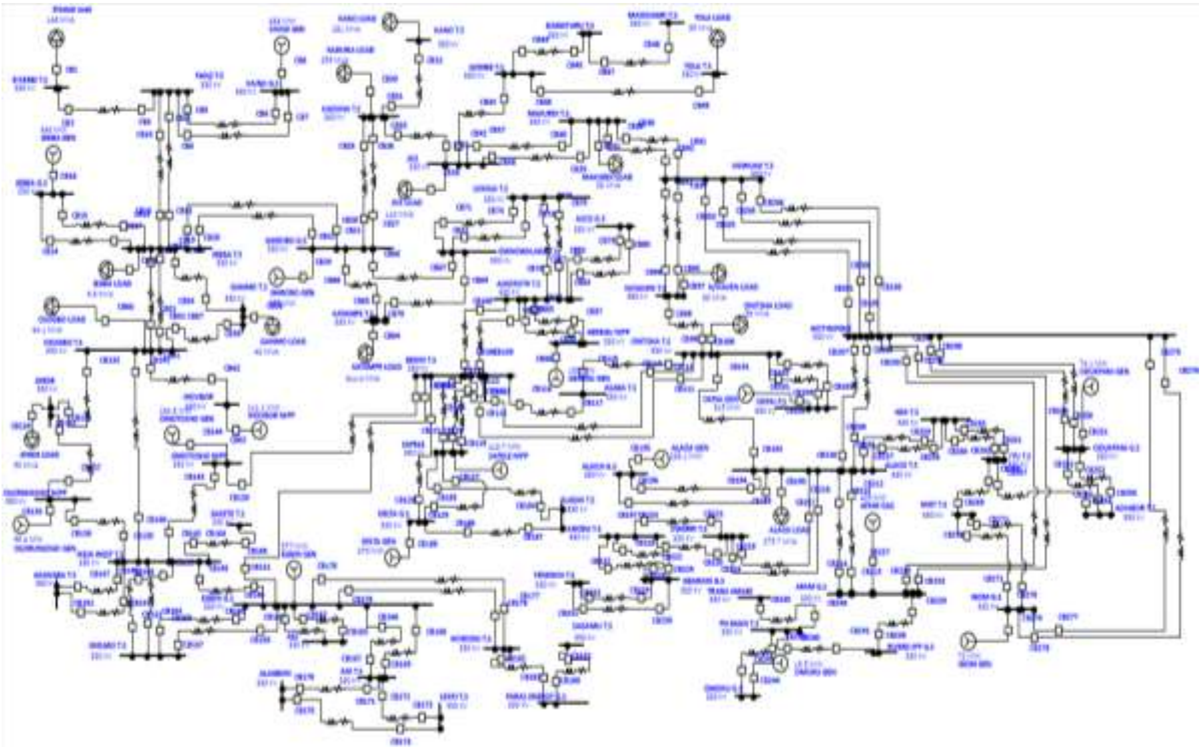
The Nigerian power system faces numerous challenges that hinder its performance and reliability. Insufficient generation capacity, poor maintenance, and fuel shortages contribute to frequent load shedding and blackouts, significantly impacting economic activities and social welfare. Moreover, the transmission network suffers from high technical and non-technical losses due to aging infrastructure, inadequate protection, and theft. This results in a substantial loss of energy and revenue. The system's vulnerability to contingencies, such as line or generator outages, leads to frequent interruptions in power supply. Consequently, the system exhibits a low reliability index, characterized by high interruption frequencies and durations (NERC, 2020).

To mitigate the impacts of contingencies, which are both unpredictable and inevitable within electrical networks, a thorough power system security assessment is imperative. Power system security encompasses strategies intended to maintain system operation despite the failure of one or more elements. The assessment of security levels is executed through two primary approaches: deterministic and probabilistic (Risk-Based). Deterministic methods assess security by considering the impact of the most severe yet plausible contingency, whereas probabilistic methods employ the risk concept, integrating both the likelihood and magnitude of contingency effects.

This research focuses on evaluating the security of the Nigerian 330kV transmission grid by employing the Performance Indices Contingency Ranking Assessment method.

II. CONTINGENCY RANKING APPROACH

The application of AC power flow solutions in contingency analysis is pivotal as it provides comprehensive data on active and reactive power flows, as well as bus voltage magnitudes. In the context of power system contingency ranking, the focus is on line outage scenarios. The severity of each contingency is quantified using a performance index (PI), which is calculated through the Newton-Raphson load flow method for each potential outage.



One line diagram of the Nigeria Power system network

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

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

Where: k = 1, 2, . . . ,n
n = number of buses

P_i and $Q_i$is the real powerand 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

$$Y_{bus} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{bmatrix}$$

The AC power flow solution delivers detailed insights into the active and reactive power flows and the voltage magnitudes at various buses within the power system. Each line outage scenario is analyzed to determine its impact on the overall system. The performance indices are computed using the Newton-Raphson load flow method, reflecting the severity of the contingencies based on factors such as line overloads and voltage deviations. Contingencies are then ranked in descending order of their performance index values, starting with the highest PI. This ranking helps prioritize the most critical contingencies that require immediate attention to maintain system stability and reliability.

Performance indices such as the Active Power Performance Index (PIP) measure the degree of line overloads by comparing the actual power flow to the maximum allowable flow. The Voltage Performance Index (PIV) assesses the deviation of bus voltages from their specified reference values, indicating potential voltage limit violations. By employing these indices, power system operators can effectively rank and address the most severe contingencies, ensuring the stability and reliability of the power grid.

Active Power performance index (PIP)
This index is used to measure the degree of line over loads.

$$PI_P = \sum_{i=1}^{N_L} \left(\frac{W}{2n}\right)\left(\frac{P_i}{P_i^{max}}\right)^{2n}$$

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 weighting factor = 1
n = Penalty function = 1

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$$P_i^{max} = \frac{V_i V_j}{X}$$

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

Voltage performance index (PIV)
This is the index which determines the out of limit bus voltages

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

Where
V_i is the voltage magnitude corresponding to bus i
V_i^{sp} is the specified volatage magnitude corresponding to bus i
ΔV_i^{lim} is the voltage deviation limit
n is the penalty function = 1
N_n isd the number of buses in the system
W is the real non negative weighting factor = 1

The voltage levels at busbars are predominantly affected by the reactive power output from generation units, which dictates the extent of voltage deviations when reactive power remains within specified bounds. During contingency scenarios, reactive power may near its operational limits, prompting the AC load flow analysis to account for these constraints in computing busbar voltages. Consequently, voltage violations are detected by comparing the calculated voltages against the nominal voltages at generator buses. Thus, voltage stability assessments under contingency conditions necessitate consideration of the reactive power limits of generators.

Contingency Ranking For Different Scenarios In The Nigerian Power System

The result and discussion of this study presents and analyzes the findings of the contingency ranking for critical transmission lines in Nigeria power system. The contingency ranking was performed using the performance index method, which is a technique that assigns a numerical value to each contingency based on its impact on the power system performance. The performance index method can rank the contingencies according to their severity by comparing their performance indices with a predefined threshold value. The contingency ranking was performed for two types of contingencies: line outage and generator outage. The line outage contingency was simulated by opening one transmission line at a time. The generator outage contingency was simulated by tripping one generator at a time. The contingency ranking results include the performance index value for each contingency, the ranking order of the contingencies, and the critical contingencies that exceed the threshold value. Before the contingency analysis, the base load flow analysis was performed to ascertain the steady state operation of the system.

III. CONTINGENCY ANALYSIS AND RANKING WITH RESPECT TO DIFFERENT FAULT TYPES

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

DeviceID1	Device Type	VVsp	Change in Power(P)	Change in Power (Q)	Ranking
M2S	Line	25.8005	43035.2	6845.442	1
T3H	Line	59.55286	6177.491	3.785005	2
T4A	Line	55.40667	2381.375	4.13011	3
K1T	Line	51.15664	1972.291	0.2173389	4
K2T	Line	51.15664	1972.291	0.2173389	5
R1M	Line	42.01935	1168.29	0.10194	6
R2M	Line	42.01935	1168.29	0.10194	7
S4G	Line	40.45596	26.90539	0.06802806	8
R4B	Line	41.00674	4.305438	1.627319	9
G5B	Line	41.18496	2.532053	1.952786	10
N4J	Line	40.77986	2.027562	0.07850114	11
N3J	Line	40.77986	2.027561	0.07850114	12
H2A	Line	42.44271	1.265325	0.09364273	13
L8A	Line	40.65248	1	0.2502582	14
L74	Line	40.65248	1	0.2502582	15
Line12	Line	40.80059	1	0.100491	16
Line16	Line	40.80059	1	0.100491	17

W3L	Line	40.76536	1	0.05922967	18
W4L	Line	40.76536	1	0.05922967	19
G3B	Line	40.39285	0.9999827	0.04436318	20
Line7	Line	40.85118	0.9976354	0.9922026	21
Line8	Line	40.85118	0.9976354	0.9922026	22
Line39	Line	56.61627	0.991746	0.1413597	23
Line41	Line	45.66608	0.9794048	0.09972078	24
Line23	Line	40.82249	0.8779513	0.1043054	25
Line24	Line	40.82249	0.8779513	0.1043054	26
J1B	Line	40.71034	0.8212346	0.1225453	27
K3R	Line	47.01027	0.531934	0.4666137	28
A1K	Line	40.85672	0.4966976	0.9869914	29
A2K	Line	40.85672	0.4966976	0.9869914	30
R5G	Line	40.87602	0.4909613	0.3940082	31
Line50	Line	40.52547	0.4451762	0.1546912	32
J1E	Line	40.8527	0.4045129	0.5725569	33
B1E	Line	40.85168	0.3819668	0.519491	34
Line27	Line	40.37733	0.3693437	0.06668195	35
Line28	Line	40.37733	0.3693437	0.06668195	36
Line22	Line	40.45685	0.3659841	0.09048732	37
J3G	Line	41.45589	0.3599026	0.05074126	38
Line9	Line	40.84986	0.350343	0.368369	39
Line10	Line	40.84986	0.350343	0.368369	40
Line11	Line	40.84986	0.350343	0.368369	41
R1W	Line	41.94593	0.308173	0.06566165	42
Line25	Line	39.98314	0.3077977	0.03508021	43
Line26	Line	39.98314	0.3077977	0.03508021	44
R2A	Line	42.71793	0.3060417	0.08630212	45
K7W	Line	40.58947	0.276596	0.04891268	46
Line5	Line	40.89443	0.272863	0.178545	47
Line6	Line	40.89443	0.272863	0.178545	48
K8W	Line	40.7184	0.2643026	0.05855361	49
K9W	Line	40.7184	0.2643026	0.05855361	50
J1L	Line	40.85779	0.2397804	0.2076082	51
JJ2L	Line	40.85779	0.2397804	0.2076082	52
Line21	Line	40.72011	0.2345681	0.07738696	53
Line29	Line	39.4524	0.2270195	0.02547511	54
Line31	Line	39.4524	0.2270195	0.02547511	55
L5G	Line	40.87522	0.2131417	0.1800912	56
L6G	Line	40.87522	0.2131417	0.1800912	57
B8J	Line	40.966	0.175339	0.08314071	58
B9J	Line	40.966	0.175339	0.08314071	59
B6N	Line	39.97068	0.1718475	0.07533611	60
J3R	Line	40.84719	0.1668358	0.144483	61
J7R	Line	40.84719	0.1668358	0.144483	62
Line44	Line	40.40176	0.1626206	0.04842567	63
Line38	Line	61.92023	0.1579863	0.08872284	64
H1W	Line	41.3877	0.155156	0.03945597	65
Line51	Line	39.94043	0.1438795	0.103282	66
Line45	Line	40.12716	0.1394749	0.04050813	67
Line48	Line	40.82666	0.138762	0.147251	68
Line49	Line	40.82666	0.138762	0.147251	69
K1J	Line	40.8589	0.1265702	0.1911353	70

K2J	Line	40.8589	0.1265702	0.1911353	71
Line46	Line	40.67722	0.1264052	0.1005671	72
Line47	Line	40.67722	0.1264052	0.1005671	73
J1H	Line	41.27576	0.1216679	0.0294783	74
J2H	Line	41.27576	0.1216679	0.0294783	75
N7K	Line	40.53988	0.1121046	0.02954936	76
N8K	Line	40.53988	0.1121046	0.02954936	77
H7V	Line	41.01095	0.0899115	0.03907913	78
T3E	Line	40.49381	0.08259167	0.1104318	79
E3B	Line	40.55773	0.08230918	0.2288146	80
Line32	Line	39.07512	0.07860881	0.02000437	81
Line33	Line	39.07512	0.07860881	0.02000437	82
S1E	Line	34.47436	0.07264768	0.1547228	83
H1U	Line	41.2188	0.07027603	0.1936619	84
H2U	Line	41.2188	0.07027603	0.1936619	85
B5M	Line	40.51839	0.06877175	0.05554762	86
M5W	Line	40.09106	0.06804886	0.03143511	87
H3G	Line	41.2967	0.06749368	0.04256507	88
Line53	Line	39.90245	0.06241779	0.02345851	89
B11J	Line	42.91038	0.06034948	0.06680707	90
B12J	Line	42.91038	0.06034948	0.06680707	91
Line54	Line	39.30716	0.04769558	0.02008814	92
Line55	Line	39.30716	0.04769558	0.02008814	93
Line52	Line	39.33496	0.04459563	0.02266388	94
Line36	Line	39.04917	0.04405569	0.01719334	95
Line37	Line	39.04917	0.04405569	0.01719334	96
E1Y	Line	30.52259	0.04367147	0.03500971	97
Line42	Line	39.29138	0.04158489	0.01690792	98
Line43	Line	39.29138	0.04158489	0.01690792	99
B1T	Line	40.14613	0.03664231	0.04438727	100
B2T	Line	40.14613	0.03664231	0.04438727	101
M6N	Line	47.90997	0.03629703	0.0836523	102
E1D	Line	27.34638	0.03060176	0.06960119	103
Line1	Line	26.40844	0.02841515	0.04718985	104
A1S	Line	36.81119	0.0206536	0.03242776	105
A2S	Line	36.81119	0.0206536	0.03242776	106
K1U	Line	38.38272	0.01972715	0.01640392	107
K2U	Line	38.38272	0.01972715	0.01640392	108
K3U	Line	38.38272	0.01972715	0.01640392	109
K4U	Line	38.38272	0.01972715	0.01640392	110
Line34	Line	40.73799	0.005410577	0.1114649	111
Line35	Line	40.73799	0.005410577	0.1114649	112
Line40	Line	46.30291	0.001644208	0.3343919	113
AFAM GAS	Syn Gen	40.85655	0	0	114
ALAOJI GEN	Syn Gen	40.85655	0	0	115
DELTA GEN	Syn Gen	40.85655	0	0	116
EGBIN GEN	Syn Gen	40.85655	0	0	117
IBOM GEN	Syn Gen	40.85655	0	0	118
Line2	Line	40.85497	0	0.4997664	119
Line4	Line	40.85658	0	0.9994353	120
Line17	Line	52.84578	0	0.625115	121
Line18	Line	46.8509	0	0.343822	122
Line19	Line	40.85094	0	0.6248289	123

Line20	Line	40.85094	0	0.6248289	124
NW1	Line	46.86374	0	0.9999992	125
ODUKPANI GEN	Syn Gen	40.85655	0	0	126
OLORUNSOGO GEN	Syn Gen	40.85655	0	0	127
OMOKU GEN	Syn Gen	40.85655	0	0	128
OMOTOSHO GEN	Syn Gen	40.85655	0	0	129
SAPELE NIPP	Syn Gen	40.85655	0	0	130

Fig. 1: N-1 contingency ranking based on bus voltage security V/Vsp

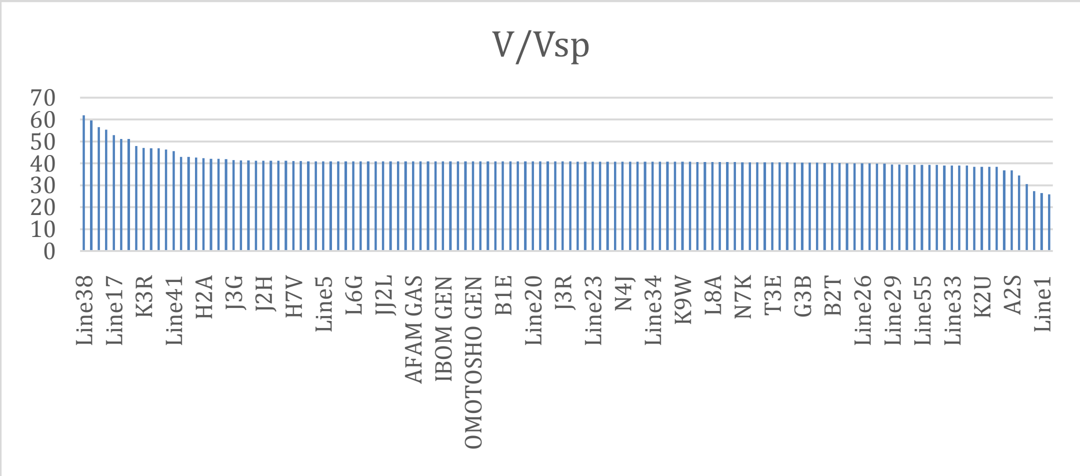
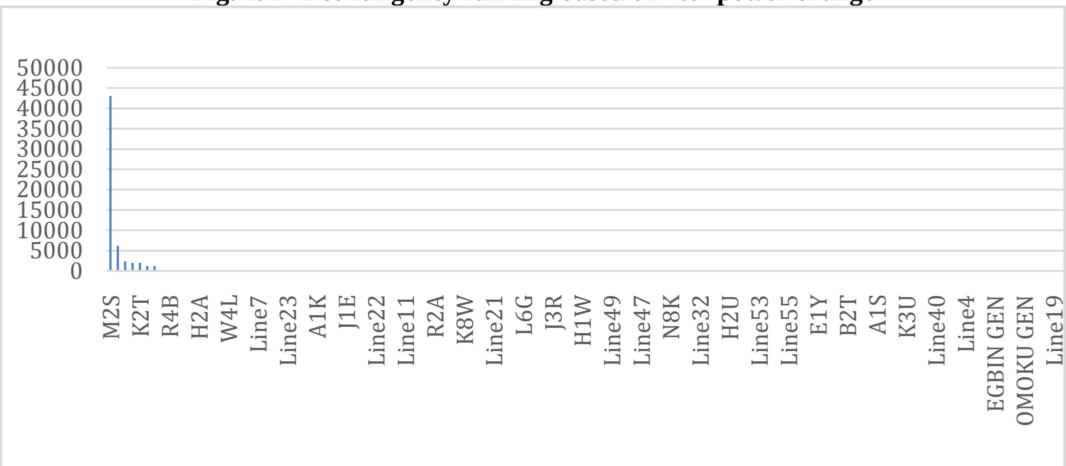


Fig. 2: N-1 contingency ranking based on real power change



A fast screening or ranking algorithm was used to perform contingency analysis and ranking on the Nigeria 330kV power system. The algorithm selected a ranked contingency list for detailed studies. The contingencies were ordered by their ranking, with the most severe contingency ranked 1 and the least ranked 130. Table 1 shows the variation of the performance index with their ranking. The result indicates that the component contingency has different impacts on the real power. The contingency ranked number one (1), which corresponds to the line M2S outage, is the most severe contingency. The generator outage at SAPELE NIPP is the least impactful component outage, according to the performance index.

IV. CONCLUSION

This study has conducted a comprehensive contingency ranking for the Nigerian 330kV transmission system using ETAP software, providing insights into the network's behavior under various fault conditions. By modeling a system with 65 buses, 120 transmission lines, 16 generators, and 14 loads, we identified the outage of the M2S line as the most severe contingency, significantly affecting bus voltages and power flow stability. Conversely, the failure of the SAPELE NIPP generator had negligible impact, demonstrating the system's resilience to certain generator outages. Our analysis ranked the critical contingencies, highlighting lines M2S, T3H, T4A, K1T, and K2T as prime areas for operator vigilance due to their influence on voltage regulation and power transfer. This study contributes a detailed system model and a methodology for mitigating cascading failures, offering a framework for identifying potential line and bus overloads post-contingency, which can guide preventive maintenance and operational strategies to maintain system integrity.

From this research, we advocate for the implementation of both preventive measures like load shedding, generation rescheduling, and reactive power compensation, alongside corrective actions such as network reconfiguration to manage the effects of critical contingencies. The development of a comprehensive contingency management plan, which includes not only the identification and ranking but also the evaluation, mitigation, and restoration of power system operations, is crucial. We also recommend expanding the transmission network to enhance power transfer capabilities and incorporate renewable energy to diversify the generation mix, thereby reducing line losses and improving system stability. However, the study's reliance on a simplified model and a single simulation tool suggests the need for validation with more detailed models and comparative software analyses. Future research should extend this to other voltage levels and regions within Nigeria, exploring probabilistic methods and real-world testing to refine our understanding and application of contingency analysis in electrical power systems.

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