

Performance Evaluation of Power Transmission Network through Risk-Based Security Assessment Using Linear Approximation Method

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ABSTRACT

The persistent power failure in the transmission network has jeopardized business and industrial activities in the country as a result of low power margin and low sensitivity in the network. This situation if unchecked can affect the system frequency and stability, and eventual lead to total collapse of the network. Modal analysis was employed to diagnose voltage instability. The concept of risk that considers both the probability of occurrence and the security of the contingency, sensitivity of voltage with respect to active power and reactive power, the variance of the load uncertainty was used to achieve the probability of distribution. Continuous severity function was adopted to quantify the severity because its uniformity quantifies the severity of the contingencies. The Nigerian 330kv transmission grid was used to illustrate the proposed method and the risk indices were evaluated after a contingency was simulated. The voltage magnitude of 2.783 Mvar/% is accepted as the critical threshold for this study. While mid-range values, such as 20.39 Mvar/% and 71.02 Mvar/%, suggest moderate sensitivity, often linked to inter area oscillations or weakly damped modes, and higher values, such as 72.98 to 125.68 Mvar/%, indicate stronger modal inference and control, they are less critical for initiating cascading failures. The result reveals that some northern Nigeria buses, and some buses at the transmission corridor including Damaturu (29Mvar), Jaligo (50Mvar), Jos (50Mvar), Maidugiri (30Mvar), Yola (50Mvar), Makurdi (50Mvar), Sakete (20Mvar) and Uguwaji (35 Mvar), exhibit dominant modal participation, indicating heightened vulnerability to reactive power disturbances. The calculated risk indices reflect a quantitative measure of the system low voltage security levels. They are efficient means of quickly identifying and investigating situations that cause high risk to the network. 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 reduce the risk of cascading outages across the network. Hence, continuous intelligent monitoring of the network through hazard detection and predicting devices are suggested.

KEYWORDS

Security-assessment, contingency, risk-based index, sensitivity, stability

I. INTRODUCTION

Bulk electricity generated from the power plants are usually conveyed to the substations through the transmission network. Nigeria national grid system is an interconnection of 9,454km length of 330KV transmission line made of 22 generating stations through a network of fifty-nine (59) buses and sixty-seven (67) transmission lines of either dual or single circuit lines with 48 load buses and four control centres (one national control centre at Oshogbo and three supplementary control centres at Benin, Shiroro and Egbin). The Nigeria 330KV transmission network covers a total length of 9,454km with total installed transformer capacity of 7688MVA and average available capacity of 7364MVA. Optimal power flow is used to determine the optimal system operating point at the lowest total generation cost while enforcing a variety of operational constraints such as the limit of bus voltages, line flows, real power generator and reactive power generator of all bus. A system operating limit is defined as the value (such as MW, MVar, Amperes, Frequency or Volts) that satisfies the most limiting of the prescribed operating criteria for a specified system configuration to ensure operation within acceptable reliability criteria. System operating limits are usually based upon certain operating criteria though they are not limited to the following: Facility ratings (applicable pre- and post-contingency equipment or facility rating), Voltage stability ratings (applicable pre and post-contingency voltage stability limit) and Transient stability ratings (applicable pre and post- contingency stability limits) and System voltage limits (applicable pre and post-contingency voltage limits). Over the years, Nigeria transmission network has been regulated by government through the Transmission Company of Nigeria (TCN).

However, the network is currently undergoing deregulation process to meet-up the energy need and competitive market environment. In recent time, Nigerian transmission network system has operated in highly stressed and unpredictable conditions which usually cause frequent collapse in network, resulting in significant annual economic losses of approximately \$29 billion (Reuters, 2024). Between 2010 and 2023 the Nigerian national grid experience a total 226 system collapses, comprising 158 total collapse and 68 partial collapses which underscores the grid's fragility and heightened vulnerability to failure. This frequent disruption are primarily attributed to aging infrastructure particularly transmission lines and sub stations that have exceeded 40 years of service, system over load and under investment in maintenance and modernization efforts. The Nigerian national grid is beset by numerous operational and structural deficiencies, including a persistently poor voltage profile across most 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. Furthermore, the increasing energy demands and the extensive transmission of electricity across geographically dispersed regions push the transmission line to operate near or beyond their voltage stability limits. Such operational stress induces power flow fluctuations, particularly in congested corridors, resulting in increased transmission loss. In several cases, these ultimately results in a complete system collapse.

Aging infrastructure and assets that have exceeded their desired lifespan pose a significant risk to power system reliability due their increased likelihood of sudden failure, often resulting to deteriorated physical conditions. Such failures can either directly initiate cascading outages or act as hidden vulnerability that exacerbates the impact of other

disturbances. Among the various types of power system disruptions, cascading failures are widely recognized as the most severe and requiring urgent attention otherwise, the network becomes more vulnerable. The need to monitor the system's security level had increased, and is frequently driving operators to make serious decisions whether or not to take action, which action to take and to what extent. In order to address the decisions making problem, security analysis must be carry out on the power system network. Power system security is the ability of the power system to withstand one or more component outages with minimal disruption of service or its quality. The determination of security level for a given operating condition has been done traditionally using deterministic criteria. Under deterministic criteria, an operating condition is secure if it can withstand the effect of each, and every contingency in a pre-specified contingency set. However, with industry's emphasis on economic competition and with the associated increased network vulnerability, there is a growing alternative approach based on the concept of risk assessment, within the context of operational decisions making. This method considers both probability and impact of the contingency. The impact can be measured in terms of the voltage and current violations, Energy Not Served (ENS), or cost.

A. *Problem statement*

The intermittent grid collapse witnessed in the transmission network is as a result of its vulnerability to extensive damage due to natural hazards, as evident in recent occurrences such as hurricanes, earthquakes, floods, tornados etcetera. These natural hazards have led to huge direct losses such as damage to power system network and indirect losses such as power outages, as well as social disruptions. Not only that, the networks are operated under highly stressed and unpredictable conditions due to aging infrastructure, which usually cause frequent collapse in network, resulting in significant annual economic losses. Several research works were carried out at different occasions to ascertain the probability of contingencies and its remedial actions to mitigate its effects. Modal analysis was employed to diagnose voltage instability by evaluating participation factors associated with the system 's lowest-frequency oscillation modes, yet adequate stability was not achieved in the network. Hence, the need for the introduction of a fundamental engineering technique known as linear approximation, which uses tangent line at specific points to approximate complex nonlinear function, and evaluate risk-based security assessment of Nigeria's 48-bus 330kv transmission network vulnerability to cascading failures under multiple contingency scenarios. And the fragility function assessment of the grid network hazard using artificial intelligence (AI), is suggested.

B. *Aim of the Study*

The aim of this work is to identify, assess and mitigate risk where possible and to continually monitor the network to avoid other risk or threats emerging.

C. *Objective off the Study*

The objectives of this work include:

- Identifying, assessing threats and vulnerabilities of Nigerian's transmission network.

- Employing modal analysis for diagnosing voltage instability by evaluating participation factors associated with the system's lowest-frequency oscillation modes.
- Developing 'risk' concept that considers both the probability of occurrence and the security of the contingency.
- Developing risk assessment strategy that will be utilized in the identification of potential threats, and prompt eradication.
- Using linear approximation method for calculating risk-based indices under multiple contingency scenarios.

D. Significance/Impact of the study

The significance of this study includes the following:

- It enhances constant power supply.
- It encourages investors to build industries and factories.
- It brings development in the country.
- It contributes to the regional energy development.
- It enhances the economic growth of the country.

E. The scope of the work

This work is limited to the evaluation of the operational performance of power transmission network through risk-based security assessment, using linear approximation method. A case study of Nigerian, 48 bus 330kv transmission network.

II. LITERATURE REVIEW

Risk assessment is a crucial and systematic process of identify, analysing, and mitigate hazards such as component or equipment failures, renewable integration issues, natural disasters, and their likes, using probability methods. Power transmission system in Nigeria has long been regulated by government, though currently undergoing deregulation process, yet operated in highly stressed and unpredictable conditions, which usually cause frequent collapse in network, resulting in significant annual economic losses. The frequent disruption in power supply due to incessant grid collapse is primarily attributed to aging infrastructure, system over load and under investment in maintenance, are recognized as the most severe and complex threats to grid stability and reliability.

These failures represent a chain reaction of outages triggered by an initial fault, which propagates through risk during operation of the transmission network, due to mechanisms such as overloading, angular instability, and voltage collapse.

Based on historical records of cascading failures, various causes have been identified, including natural disasters, equipment failures, overloading, and human factors. 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 cascaded failures is a major way of preventing blackouts in the power transmission network. This has been widely recognized as a crucial aspect in increasing resilience to the extreme events.

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.

A. *Severity factor*

The severity factor quantifies the contingency impact for the operational risk assessment (ORA). In the ORA studies, a severity factor is explicitly involved. The impact of a contingency can be broad and different for different stakeholders. The impact of transmission system operation (TSO), can be in the form of low voltage, extreme loading or low frequency. For the network users, the impact can be in the form of expected number and duration of interruptions. For any of the stakeholders and even for the society as a whole, the impact can be in form of loss associated with the contingency. Merging all these impacts and stakeholders into one single value would overly simplify the issues and limit the amount of feedback that the ORA can give to the TSOs.

It is therefore necessary to define a range of severity factor, each addressing one of the impacts for one of the stakeholders. When performing risk assessment for a transmission system, three things are involved. The first is the scope of the risk assessment. The second depends on the time window considered and on the specific circumstances. The third has close relationship with the first. Different kinds of risk assessment can be performed for the transmission system, for instance: technical risk, economical risk, social risk, or environmental risk. Another classification of risk assessment for transmission system is based on the time window considered, with the main ones being a window of many years generally known as ("reliability assessment")

B. *Risk quantification*

Risk can be quantified as the probability of something adverse happening, multiplied by the impact of that, referred to as risk level or degree of risk. This approach can be used to quantify the operational risk of the transmission system, by multiplying the probability of contingency case with a severity factor (quantifying the impact) for that contingency case. Probability is an objective mathematical concept that can be calculated, though not always with high accuracy.

C. *Operational risk conceptualization*

What distinguishes ORA from other types of risk assessment of the transmission network system is the short time window. The risk assessment is performed for a short time spanned under a predefined operating condition. This time span, referred to as the lead time T_{lead} , can be from few hours to few days. The operational risk of a transmission system can be defined as the product of the probability of contingencies and a severity factor, summed over all contingencies.

D. Component outage

To calculate the probability of component outage $P(c)$ in operational risk assessment (ORA), components that are involved in the contingency case, it is important to consider common-mode outages and other dependent outages, not just single outages. The basic parameters for most component outage models are the instantaneous failure rate and instantaneous repair rate. Both rates vary at different time scales and most times considered constant within the lead time. The instantaneous failure rate depends on the environmental condition, the component loading, and the component history including age and historic loading. The instantaneous repair rate depends on the failure, the possibility to repair the component, and the weather conditions.

E. Threat Identification

A key part of the threat analysis is determining the threat actions associated with each threat source. These factors govern the probability and impact of a given threat-source to exploit vulnerability. Threat identification requires a balanced focus on various things that might happen and creating a playback to play out a scenario. Some of the threats in the transmission network includes; Aging infrastructure, poor maintenance culture, system overloading and under investment in maintenance and modernization efforts.

F. List of identified hazards and control measure

Hazards in the transmission network are potential dangers or causes of damage to the network. However, their causes and effects can be mitigated through some of the following measures highlighted in table 2.1 below.

Table: 1. Potential hazards and the mitigation measures

S/N	HAZARD	CONTROL MEASURE
1.	Work station Setup	Good work layout and management
2.	Restricted Assess	Provision of safety sign and symbols
3.	Bites and Stings	Environmental Fumigation
4.	Powered Equipment	Maintenance and provision of PPE
5.	Vehicles	Proper and regular maintenance
6.	Electrical	Use of PPE and permit to work
7.	Lifting and carrying	Use of mechanical aid
8.	Working at height	Egress, safety line and edge Protection
9.	Food	Good personal hygiene
10.	Mobile and fixed plant	Periodic maintenance
11.	Working in remote areas	Provision of shelter and security

G. *Transmission line fault classification*

Transmission line faults classification are crucial to the dependability of the electrical system because they must be detected quickly to prevent cascading outages, halting industrial operations, or causing blackouts. Thus, in order to isolate the faulted equipment, detection must be quick and efficient. While they are in use, electrical networks, machines, and equipment frequently experience different kinds of problems. When a defect arises, the machine's characteristic values (such as impedance) may shift from their current values to different values until the issue is fixed. There is need to know the types of faults that exist in this regard. Thus, transmission line faults are classified into two main categories as follows:

1. *Symmetrical Faults*

A fault is stated to occur when all phases are impacted while the system is still balanced and symmetrical. In these forms, these are identified as:

- Line to line to line to ground fault (L-L-L-G).
- Line to line to line fault (L-L-L).

2. *Unsymmetrical Faults*

An unsymmetrical fault state is considered to have developed when the load in a three-phase power supply displays uneven characteristics on each of the three phases. These are noted on the relevant forms as:

- Line to line (L-L).
- Line to ground (L-G), also known as Line to line ground (L-L-G)

Table 1 shows a summary of the faults found in transmission lines, indicating their types, short form of identification, category and probability of occurrence.

Table 2: Fault types, category and occurrence probability

S.No	Type of Faults	Short Form	Symmetrical or Unsymmetrical	Probability of Occurrence
1	Three phase line to ground fault	3LG	Symmetrical	2 - 3%
2	Three phase line to line fault	3LL	Symmetrical	< 1%
3	Single line to ground fault	1LG	Unsymmetrical	70 - 80%
4	Line to line fault	1LL	Unsymmetrical	15 - 20%
5	Double line to Ground fault	2LG	Unsymmetrical	< 10%

H. *Probability*

In the context of power system security, probability is the likelihood that a contingency can cause security violations and the simplest way of obtaining probability for a contingency is based on the system operator's experience (Ni, M. et al., 2003). However, modern probabilistic and statistical techniques for deriving contingency probability distribution through the collection and analysis of historical data produce results that are more reliable. The techniques worked out a single risk index after considering the likelihood and severity of each contingency.

The risk index quantifies the degree of risk of the current operating conditions when the system experiences a contingency. In simplified terms, risk index is the product of contingency likelihood and its severity. In mathematical terms;

$$\text{Risk Index} = \text{Probability} \times \text{Impact} \quad (1)$$

Contingencies are modeled to be Poisson distributed since they are rare events, and a widely used expression for Poisson distribution is,

$$P_r(x) = 1 - e^{-\lambda} \quad (2)$$

Where, x: is the number of occurrence. λ : is the mean number of events during a given unit of time.

I. *Impact*

Severity provides a quantitative evaluation of what would happen to the power system in the specified condition in terms of impact, consequence, or cost. Severity functions are used to uniformly quantify the severity of network condition in terms of performance indicators and they should reflect the consequences of the contingency and loading conditions in terms of network parameters that are understandable to system operators. In general, there are three types of severity functions: discrete, continuous and percentage of violation of the severity function.

III. **METHODOLOGY**

This research work adopted linear approximation method for evaluating the risk indices of low voltage security based on sensitivity method of probabilistic contingency analysis, because sensitivity techniques are quick and easy ways of computing any possible violations of operating limits. In addition, when applied to linear systems they are efficient even when the systems are very large. The linear approximation method requires the probability of voltage distribution, probability of contingency, and the severity function evaluate the severity of the contingency.

A. *Procedure*

The process of evaluation of transmission network performance through risk-based assessment, commenced by determining the following;

(i). Probability of Voltage Distribution: This was achieved through the calculation of the standard deviation from variance-covariance matrix and sensitivities of voltage with respect to active (P) and reactive (Q) power are required to evaluate the probability of voltage distribution. The sensitivities were obtained from the Jacobian matrix (J) of the basic load flow problem, by simply inverting the Jacobian matrix using special techniques. Newton Raphson load flow algorithm was used due to its inherent advantages of accuracy and fast convergence. However, only the stressed buses sensitivities are evaluated and they are located at the particular stress row of J-1.

The complex power at stressed buses can be expressed in equation 3 to 7,

$$P_i - jQ_i = |V_i| \angle \delta_i \sum_{j=1}^n |Y_{ij}| |V_j| \angle \theta_{ij} + \delta_j.$$

Separating the real and imaginary parts

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

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

The terms $\Delta P_i(k)$ and $\Delta Q_i(k)$ are the difference between the scheduled and calculated values and represents the column vector of the control variables at the PV and PQ buses and are given by

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)}$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)}$$

$\Delta \delta_i$
 ΔV_i Represents the column vector of the state variables at the PV and PQ buses.

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

Where J1 J2 J3 and J4 are sub-matrices of the Jacobian matrix written in a compact form, The load flow equations using Newton-Raphson techniques can therefore be written as

$$\begin{array}{cccc} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \dots & \frac{\partial P_2^{(k)}}{\partial \delta_n} & \frac{\partial P_2^{(k)}}{\partial |V_2|} & \dots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & & \vdots & \vdots & & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & & \frac{\partial P_n^{(k)}}{\partial \delta_n} & \frac{\partial P_n^{(k)}}{\partial |V_2|} & & \frac{\partial P_n^{(k)}}{\partial |V_n|} \end{array}$$

$$\frac{\partial Q_2^{(k)}}{\partial \delta_n} \dots \frac{\partial Q_2^{(k)}}{\partial \delta_n} \frac{\partial Q_2^{(k)}}{\partial |V_2|} \dots \frac{\partial Q_n^{(k)}}{\partial |V_n|}$$

$$\frac{\partial Q_n^{(k)}}{\partial \delta_2} \dots \frac{\partial Q_n^{(k)}}{\partial \delta_n} \frac{\partial Q_n^{(k)}}{\partial |V_2|} \dots \frac{\partial Q_n^{(k)}}{\partial |V_n|}$$

Assuming that the stressed voltage/ bus is ith bus, then the probability distribution of VI will be;

$$P_r(V_i) = \frac{1}{\sigma V_i \sqrt{2\pi}} e^{-\frac{(V_i - \mu V_i)^2}{2\sigma^2 V_i}}$$

Where;

$P_r(V_i)$ = the probability distribution of V_i

σV_i = the standard deviation of V_i

μV_i = the mean deviation of V_i

B. Probability of contingency

In probability of Contingency, the events of contingency (E_i) are modeled to be Poisson distributed since they are rare events. The formula for Poisson distribution is given as,

$$P_r E_i = \sum_{x=1}^{\infty} P_r(x) = 1 - P_r(x=0) = 1 - e^{-\lambda_i}$$

Where

It is the occurrence rate of contingency per time interval and E_i is the ith contingency.

C. Low Voltage Severity Function

We adopt continuous severity function because it measures the extent of the violation and it can be composing easily. The continuous severity evaluates to 1.0, for each bus at the deterministic limits (0.95 pu) and increases linearly as voltage magnitude fall below limits. Figure 1 shows an illustration of continuous severity function.

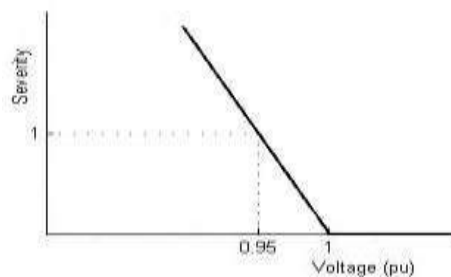


Figure 1. The illustration of continuous severity function for low voltage

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

B. Line Data

Table: 4 - 330KV System 48 Bus Data

Bus ID	Bus Name	Bus Type	Bus Loads		Generation			
			PL (MW)	QL (MVar)	Install. (MW)	Avail. (MW)	Qmax	Qmin
13	Adiabor	P-Q	140	90	0	0	0	0
14	Afam G/S	P-V	295	157.5	800	590	222	-210
15	Aja	P-Q	300	205	0	0	0	0
16	Ajaokuta	P-Q	230	115	0	0	0	0
17	Akangba	P-Q	300	250	0	0	0	0
18	Aladja	P-Q	100	70	0	0	0	0
19	Alagbon	P-Q	260	120	0	0	0	0
20	Alaoji	P-Q	400	150	0	0	0	-75

21	Alaoji G/S	P-V	113.8	53	240	95	80	-75
22	Asaba	P-Q	185.7	169.5	0	0	0	0
23	Ayede	P-Q	275	206	0	0	0	0
24	Benin	P-Q	383	150	0	0	0	-150
27	Birnin Kebbi	P-Q	146	85	0	0	0	0
28	Damaturu	P-Q	50	20	0	0	0	0
29	Delta G/S	P-V	497	253	620	250	120	-100
30	Egbin G/S	Slack	0	0	1300	0	0	0
31	Ganmo P-Q	P-Q	150	90	0	0	0	0
32	Geregu G/S	P-V	396	150	562	200	210	-200
33	Gombe P-Q	P-Q	320	170	0	0	0	-100
34	Gwagwalada	P-Q	150	70	0	0	0	0
35	Ihovbor G/S	P-V	8	3	225	110	90	-70
36	Ikeja West	P-Q	635	474	0	0	0	-150
37	Ikot Ekpene	P-Q	321	160.5	0	0	0	0
38	Jalingo	P-Q	80	50	0	0	0	0
39	Jebba	P-Q	15	5	0	0	0	-150
40	Jebba G/S	P-V	336	160	482	160	150	-110
28	Jos	P-Q	70	50	0	0	0	-75
49	Kainji G/S	P-V	414	205	500	265	200	-180
50	Katampe	P-Q	290	145	0	0	0	-75
51	Kumbotso	P-Q	240	130	0	0	0	-75
52	Lekki	P-Q	15.19	8.3	0	0	0	0
53	Lokoja	P-Q	300	150	0	0	0	0
54	Maidugiri	P-Q	80	30	0	0	0	0
55	Makurdi	P-Q	84	50	0	0	0	-75
56	Mando	P-Q	170	120	0	0	0	-75
57	New Haven	P-Q	180	130	0	0	0	0
58	Odukpani G/S	P-V	116	47	226	150	200	-120
59	Okearo	P-Q	220	70	0	0	0	-75
60	Okpai G/S	P-V	294	105	300	150	190	-150
61	Olorunsogo G/S	P-V	90	30	300	126	150	-150
62	Omosho G/S	P-V	100.1	45	480	200	150	-150
63	Onitsha	P-Q	184	134	0	0	0	-75
64	Osogbo	P-Q	200	150	0	0	0	-75
65	Sakete	P-Q	50	20	0	0	0	0
66	Sapele G/S	P-V	50	25	120	90	200	-180
67	Shiroro G/S	P-V	207	95	450	220	200	-200
68	Ugwuaji	P-Q	39	25	0	0	0	0
69	Yola	P-Q	100	50	0	0	0	-75

C. Line Data

Table: 5 - Table 2.2: 330kV Grid Line Data

S/N	From Bus	To Bus	Length (km)	Line Type	R (Ω)	X (Ω)	B (S)	C (μ F)
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	Omosho	120	1	7.680	53.748	0.00031	0.00096
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

The Nigerian 330kV transmission grid has been used as a case study system to evaluate the performance of the proposed method. The study system single line diagram is shown in figure 2. The line data and bus data are shown in tables I and II respectively. A line outage was simulated to evaluate the system risk indices and the simulation was done by simply removing the line information from the line data. The load mean values were assumed to be the same as the base case forecast values and 2% load standard deviate/on was assumed and MATLAB software was used for it.

V. RESULTS

The results obtained after simulating a contingency on line 17- 18 and assuming a standard deviation of 2% are recorded in table III. Table III shows the stressed buses (buses with voltages below 1.0 p.u.) and the low voltage risk indices of the stress buses. Figure 3 graphically represents the low voltage risk indices.

Table: 6 - Stressed buses and their risk indices

BUS NO	VOLTAGE MAGNITUDE (PU)	RISK INDICES
2	0.689	6.2142

3	0.976	0.5016
11	0.121	17.6011
12	0.901	2.0044
13	0.987	0.2858
14	0.168	16.6395
15	0.631	7.4041
16	0.888	2.2353
19	0.618	7.6477
Total Risk Indices		60.5347

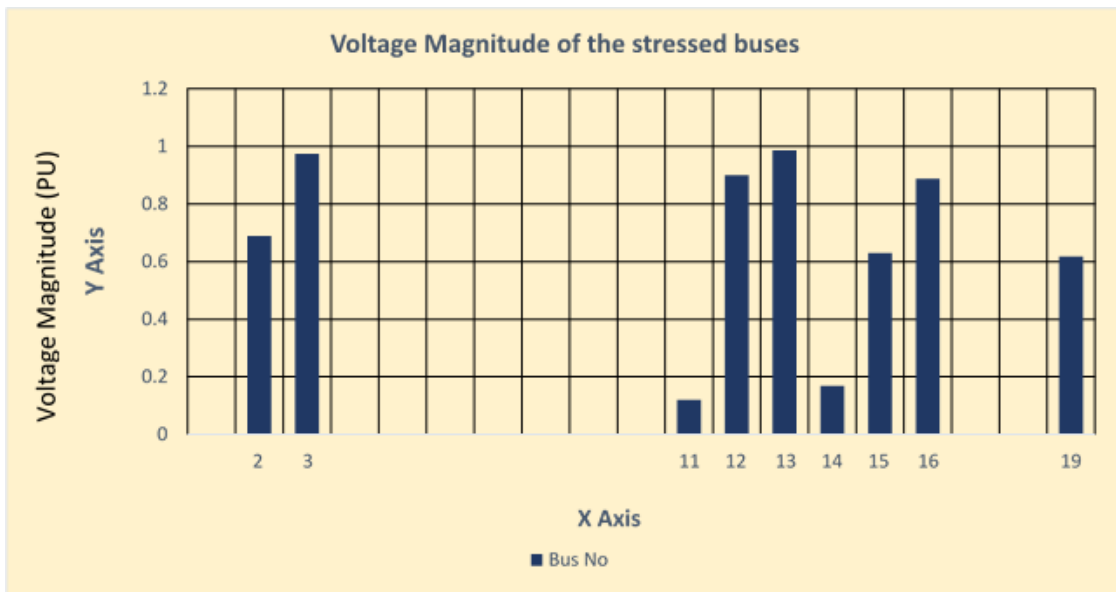


Figure 3: Graphical representation of voltage magnitude

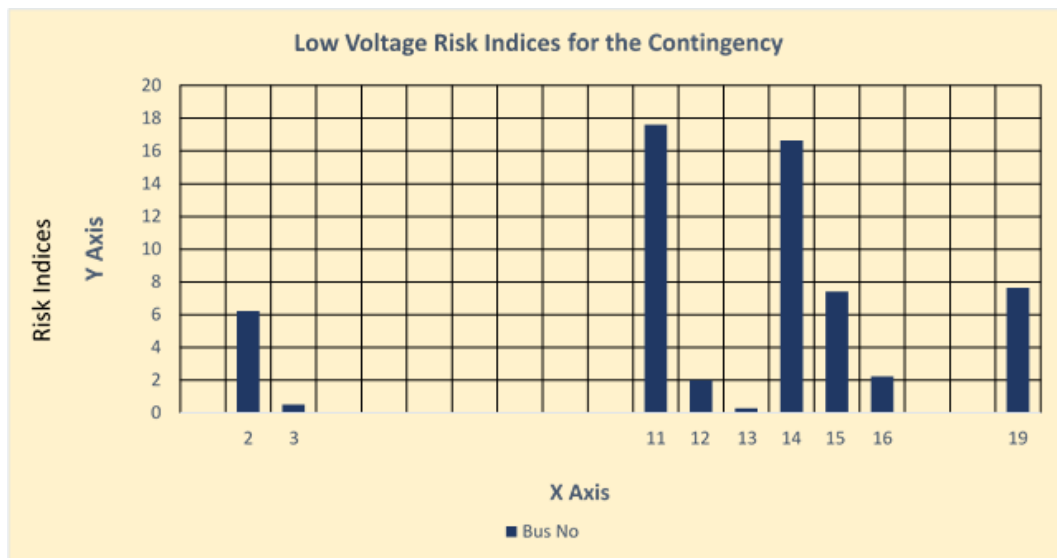


Figure: 4. Low Risk Indices

VI. DISCUSSION OF RESULT

The risk indices in table III reflect the quantitative measurement of security level hence, they facilitate decisions making in determining operating limits associated with static voltage problems. Ultimately, this involves selecting a risk level to delineate between acceptable and unacceptable operating regions. The threshold value selection can be based on experience, existing criteria, and optimization of cost. Furthermore, a decisions making algorithm can be used to select the threshold risk index level from these criteria and it is advantageous to the conservatism of the operational decision makers (ODM); the system operators, engineers and their managers. The risk index is a leading indicator of security level in that the assessment provides a uniform security measurement for the near future operating condition based on the current information. The results shown in table III enable the system operator/engineers to quickly identify and investigate high-risk scenarios. In addition, risk index gives useful information of insecurity beyond the threshold value and can be used in pricing power system security.

A. Findings

During the period of this research work, the following risks were identified.

- The workstation has poor infrastructural design, thereby limiting the operational efficiency of the network.
- Most of the north east and central buses, including Jalingo, Maidugry, Yola, Damaturu, and Gombe, exhibit dominant modal participation, indicating heightened vulnerability to reactive power disturbances.
- 3 Most of the equipment used in the transmission sub-stations are aged and require immediate replacement.
- It was also discovered that the maintenance work are not regular, rather corrective maintenance approach was majorly adapted.

VII. CONCLUSION

The outcome of the study highlights the grid's susceptibility to cascading failures, more especially in the North-east and central part of Nigeria, with limited reactive power support. The modal analysis, probabilistic and scenario-based hazard analysis, component vulnerability, proves to be effective diagnostic tools 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.

RECOMMENDATION

From the studies, the following recommendations were made;

- The concept of risk that considers both the probability of occurrence and the security of the contingency should be optimized in risk assessment of power system network as contained in the work.

- Sensitivity based method of probabilistic contingency analysis should be adopted for the evaluation of the technique, due to its efficiency in computing possible violation of operating limits as provided.
- Modal analysis be made a standard for diagnosing voltage instability through the evaluation of participation factors as provided.
- Again it is recommended that the sensitivity of voltage with respect to active power and reactive power, be used to achieve the probability of distribution as revealed.

Continuous severity function was adopted to quantify the severity because its uniformity quantifies the severity of the contingencies. It is therefore, recommended that power system network managers, control system engineers, and researcher in electrical power system should consider the tropical-based system reliability modal, probabilistic and scenario-based hazard analysis be carried out on 50 bus, and fragility functions be provided in the model hazard grid using artificial intelligence (AI).

Data Collection the data used for this study were obtained from Transmission Company of Nigeria (TCN) and are presented in Table 1 and Table 2. Computer software programme known as MATLAB/SIMULINK was used in conducting the simulation.

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