Integrated reliability assessment of medium voltage networks incorporating voltage and reactive power performance indices

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ABSTRACT

Energy system operation relies on synchronous protection and safety, with stable networks able to handle disruptions without abrupt changes. Due to the complexity of modern electrical systems, contingency analysis is essential for addressing issues in power system analysis. This study presents a comprehensive method for identifying the initial causes of cascading system failures in power systems. Case studies utilizing IEEE test systems with various cascade models demonstrate the effectiveness of this approach. The analysis aids in evaluating the possible impacts on the system and informs preventive strategies to avoid failures. This study integrates voltage stability and reactive power performance indices to create a framework for assessing the reliability of a medium-voltage power network operating at 33 kV. It evaluates N-1 and N-2 contingencies due to line and generator outages to identify and rank critical network components. In contrast to traditional reliability evaluations, the approach identifies weaknesses connected to voltage that impact system resilience. The proposed approach enables improved ranking of severe contingencies beyond conventional methods, supporting targeted reinforcement and enhancing voltage stability and overall system reliability.

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1. INTRODUCTION

Contingency analysis has long been a cornerstone of power system security assessment, providing an essential framework for evaluating the operational impacts of equipment outages [1]-[3]. Contingency refers to the failure or disconnection of a system element, and contingency analysis aims to assess the impact on operational parameters such as bus voltages and line flows. In an electric power system, a contingency is an unforeseen circumstance that arises briefly [4]. This brief period may put the electric power system's components at risk and result in an outage [5]. The discharge of generation, transmission, and distribution to the load is all considered releases of elements in the electric power system [6]. It is common practice to solve load flow problems in a particular power system using conventional computational approaches [7]-[9].

Modern power systems rely on the reliable functioning of medium voltage (MV) distribution networks, necessitating robust evaluation frameworks focused on voltage stability and static security [10]. A key aspect of these evaluations is contingency analysis, which traditionally utilizes alternating current (AC) power flow solutions to simulate outage scenarios (e.g., N-1, N-2) and evaluate subsequent violations of operational constraints like branch flows and bus voltage magnitudes [11]. Methods such as the Newton-Raphson load flow are commonly employed to rank contingencies based on performance indices (PIs), active/apparent power performance indices, and including the voltage performance index (VPI) [11]-[17].

However, existing contingency assessment methodologies often exhibit critical limitations. The use of AC power flow methods in analyzing outage scenarios has been examined in [10]. The impact of generator and transmission line outages on power flows, utilizing distribution factors, has been explored in [18], [19]. The concentric relaxation method was introduced by the authors in [20] for contingency evaluation. A zero-mismatch method is given for fast power flow solutions [21]. The choice of weighting coefficients for performance indices for contingency ranking is discussed [22]. An iterative approach for calculating eigenvalues under outage conditions for the purpose of contingency ranking was proposed in [23].

Stanelyte and Radziukynas [24] employed a decoupled load flow analysis combined with a compensation technique to determine post-outage voltages, with rankings established based on a performance index. First, they often overlook the link between voltage and reactive power issues, considering them separately, which can lead to inaccuracies in networks with high X/R ratios due to decoupled power flow assumptions [11]-[13], [25], [26]. Second, while traditional PIs effectively identify limit violations, they often fail to provide a comprehensive, integrated metric that simultaneously quantifies voltage deviation and reactive power inadequacy, creating a gap in holistic reliability evaluation. Recent studies have begun exploring composite indices [18], [19], yet a unified framework integrating voltage stability and reactive power reserve sufficiency specifically for integrated MV network reliability assessment remains underdeveloped.

This research introduces an integrated reliability assessment technique for medium voltage networks, highlighting the development of a combined voltage and reactive power performance index (VRPI). This index offers a comprehensive view of system health by synergistically assessing post-contingency scenarios, moving beyond traditional, segmented indices. The specific objectives of this research are: i) To develop a unified VRPI that monitors reactive power margin violations and anomalies in voltage magnitude during emergencies; ii) Incorporate the VRPI into standard frameworks for N-1 and N-2 contingency analysis in medium voltage networks; and iii) Numerical simulation validates the suggested strategy's superiority over traditional PI-based techniques in detecting key contingencies and potential weaknesses.

This study proposes a contingency analysis framework designed to assess both N-1 and N-2 outage scenarios across the power system. A core contribution is the development of an ETAP-based algorithm for the 33-Bus system that employs load flow calculations in conjunction with a voltage-reactive power performance index (VRPI) to systematically filter and rank contingency events. This combined methodology enhances the ability to anticipate and prioritize the operational impacts of potential equipment failures.

2. METHOD

The contingency analysis program uses a computer-generated simulation of critical infrastructure, a network model to simplify an influence system's real parts and linkages. ETAP is commonly used for precise measurements, incorporating association information and electrical attributes of the instrumentality due to transmission line ohmic resistance. The rule contingency analysis uses network data and network parameters to model and compute the consequences of removing instrumentality from the power system. The network model is commonly used in security analysis applications to accurately depict the entire power system. With fewer electrical components and buses, it simplifies the design, allowing for more precise results and condensed or simplified representations of the power system.

The system redesign for load balancing, power loss reduction, and breakdown restoration in an N-1 and N-2 contingency scenario is the main topic of this work. It takes into account a distribution network's branches, switches, feeders, buses, loads, and generators. Companies must provide additional connectivity to maintain resilience, enabling the stream to employ various methods to reach the same customer as required [8], [9]. The network strategically places switches to operate in either closed or open mode when there are additional connections. For fixed-line customers to continue receiving service in the event of an N-1 emergency, redundancy in the distribution network is essential.

A series of switch state changes could be triggered to power the affected area. To locate a solution that efficiently restores power throughout the affected area, the available switch installations are found using a one-line power grid transformation technology. Operating constraints must be followed by this solution, guaranteeing a backup plan supported by a switching approach [3]-[5]. Line and generator contingencies are the most common types of contingencies, leading to two main categories of violations.

Low voltage violations are common on buses, indicating less than ideal voltage. The operational voltage variation typically falls between 0.95 and 1.05 p.u., with low voltage below 0.95 p.u. and high voltage above 1.05 p.u. Voltage issues in the capabilities network are mostly caused by reactive power. This paper discusses line boundaries for MVA violations, a contingency where a road's MVA rating exceeds the designated threshold. It discusses the alarm condition and corrective actions for lines exceeding 80-90% of the limit.

The degree of line overloading is measured by the active power performance index [11].

$$PI_p = \sum_{i=0}^{N} \left(\frac{W}{2n}\right)\left(\frac{P_i}{P_{i,max}}\right) \tag{1}$$

Where $P_{i,\,max}$ and Pi represent line I's MW capacity and MW flow, respectively. N is the system's line count. W-real non-negative weighting factor 1. N-Penalty function = 1.

$$P_{imax} = \frac{V_i V_j}{X} \tag{2}$$

At bus I, Vi is the load flow voltage. V_j represents the voltage at bus j by R load flow. X is the line linking the bus's reactance.

The voltage performance index is used to determine the out-of-limit bus voltages [11].

$$PI\ v = \sum_{i=0}^{N} \llbracket\left(\frac{W}{2n}\rrbracket\right)\left\{\frac{|V_i|-|V_{isp}|}{\Delta Vi\ lim}\right\} 2n \tag{3}$$

Where: The voltage magnitude associated with bus I is denoted by V_i;. V_{isp} - voltage magnitude specified in relation to bus I; ΔV_i lim -voltage deviation limit; n -function penalty =1; N - The system's bus count; W - real non-negative weighting factor = 1.

Reactive power limits, which might result in aberrant voltages as power injection voltage (PIV) rises, are taken into account while calculating bus voltages in the AC load flow analysis. Reactive power may exceed its limitations in a contingency situation, resulting in a discrepancy between actual and predicted levels. To ensure correct voltage analysis, this study takes into account the generators' reactive power restrictions [11]. The established formula is (4).

$$PI\ v = \sum_{i=0}^{N} \llbracket\left(\frac{W}{2n}\rrbracket\right)\left\{\frac{|V_i|-|V_{isp}|}{\Delta Vi\ lim}\right\} 2n + \sum\left(\frac{W}{2n}\right)\left\{\frac{Q_i}{Q_{imax}}\right\} \wedge 2n \tag{4}$$

Where: Q_i is the reactive power at bus I; Q_{imax} -reactive power limit at bus I; N -number of generating units; W -real non-negative weighting factor = 1. The workflow of this research work is shown in Figure 1.

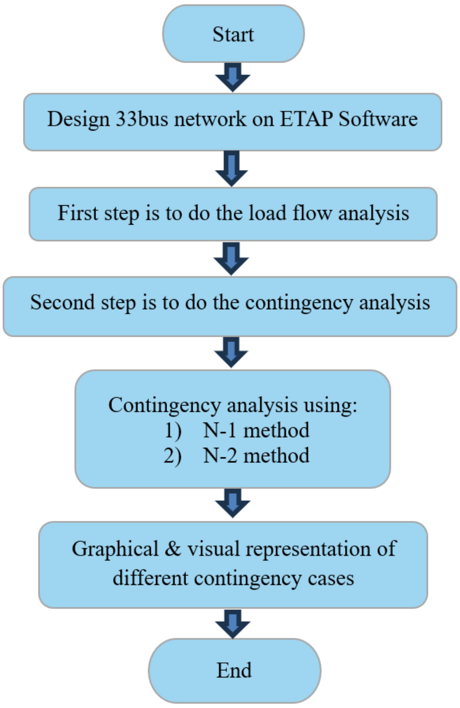

Figure 1. Flow diagram of this research

The flow diagram illustrates the sequential steps undertaken in the research using ETAP software for power system analysis. It begins with launching the ETAP software, followed by conducting a Load Flow Analysis to establish the system's steady-state performance. Next, a contingency analysis is performed, focusing on system behavior under fault conditions using both N-1 and N-2 methods. The results from these simulations are then analyzed through graphical and visual representations to evaluate system stability and reliability under various contingency scenarios. The process concludes upon completing the assessment of all contingency cases.

3. RESULTS AND DISCUSSION

3.1. Load flow analysis in terms of contingency

Examining the load flow in Figure 2 with three cases: a) when all the sources (all the generators, PV array, and lines) are active, b) when the transformer and lines are in active mode, and c) when the PV array and lines are active. Load flow analysis in Figure 2 of the 33-bus system under three operating conditions: The load flow analysis is performed for a 33-bus system under three different source configurations. The graphical results reveal that when all sources (generators, PV array, and lines) are active, the system experiences minimal real power loss. However, when either the generator alone or both the generator and PV array are offline, as indicated by the blue and red lines, respectively, real power losses increase significantly. This demonstrates the critical role of both the generator and PV in maintaining system efficiency and minimizing losses.

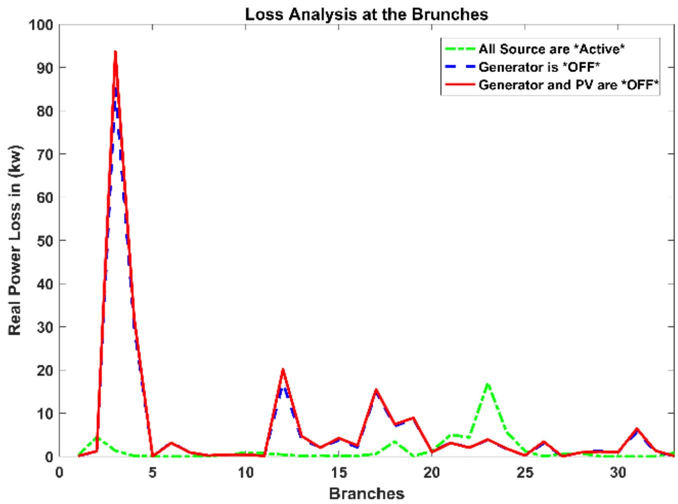

Figure 2. Load flow analysis according to the different cases on different branches

3.2. Contingency analysis using the N-1 method

The software used for the simulation purpose is named ETAP software. The 33-bus network is designed for contingency analysis purposes. The main source of this network is grid power, which is 33 kV as an input. This grid power supplies the voltages to the other components of this network through transmission lines. Based on different situation here 6 cases are analyzed on the basis of the N-1 contingency analysis method. They are:

- Case-1: When only the Bus-2 is off
- Case-2: When only the Bus-29 is off
- Case-3: When only the generator Bus (Bus-30) is off
- Case-4: When only the Bus-31 is off
- Case-5: When only the Bus-32 is off
- Case-6: When only the transmission Line-2 is off

Based on these cases, the performance index of this network can be determined. They are shown in Table 1. Bus-30, with a generator source, was significantly influenced by N-1 contingency analysis due to its higher performance index rating, voltage regulation, active power, and reactive power.

From Figure 3, six N-1 contingency cases were analyzed based on bus voltages, with Case-3 showing the most severe voltage violations. Bus-30 exhibited the largest voltage drop, indicating its critical vulnerability during this outage scenario. After computing the PIVQ, the algorithm will determine whether the value corresponds to a Class I, Class II, or Class III category for each potential system failure. Based on this classification, the PIVQ will be prioritized accordingly: i) Class I (most critical) outages are addressed first; ii) Followed by Class II (critical); and iii) Finally, Class III (non-critical) outages. The class structure is presented in Table 2. Using the ETAP software after getting the load flow analysis, for N-1 contingency with the necessary cases. Table 3 shows the following data.

Table 1. Performance index for the N-1 contingency analysis method

Case	Type	$\frac{V}{V_{sp}}$	ΔP	ΔQ	$\frac{S}{S_{sp}}$	Combined
Bus-2	Bus	12.39	6.18	8.14	0	26.71
Bus-29	Bus	13.16	193.22	32.08	0.03	238.50
Bus-30	Bus	17.15	392.34	55.72	0.11	465.32
Bus-31	Bus	12.81	196.59	19.45	0.01	228.85
Bus-32	Bus	12.56	94.93	10.16	0	117.66
Line-2	Branch	0.37	39.84	31.01	0.01	71.24

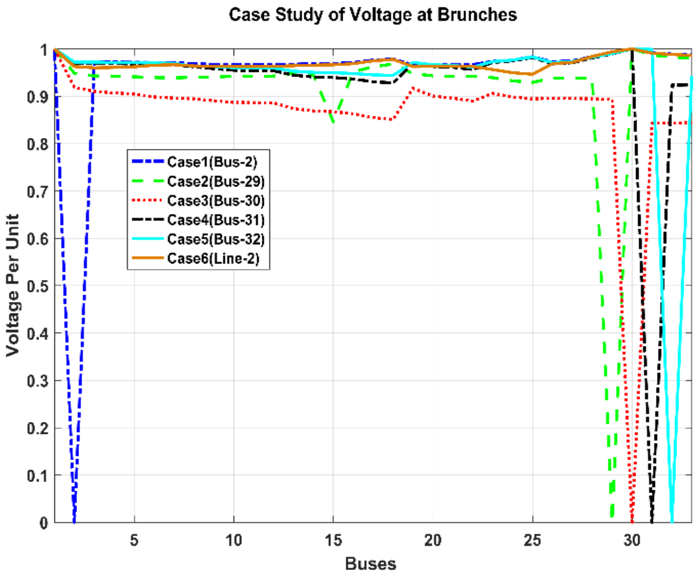

Figure 3. Voltage regulation in different branches on the basis of N-1 contingency analysis

Table 2. Standard value for PIVQ analysis

Class/rank	I (most critical)	II (critical)	III (non-critical)
PI range	>10	5-10	<5

Table 3. Contingency analysis data using the N-1 method

Out of operation	ID	Condition	% Post-contingency	% Violation	Type
Bus-2	Bus-2	Undervoltage	0	90	Most-critical
Bus-29	Bus-29	Undervoltage	0	90	Most-critical
Bus-30	Bus-14	Undervoltage	84.79	5.21	Most-critical
	Bus-15	Undervoltage	84.63	5.37	Most-critical
	Bus-16	Undervoltage	84.18	5.82	Most-critical
	Bus-17	Undervoltage	83.33	6.67	Most-critical
	Bus-18	Undervoltage	82.96	7.04	Most-critical
	Bus-30	Undervoltage	0	90.00	Most-critical
	Bus-31	Undervoltage	82.12	7.88	Most-critical
	Bus-32	Undervoltage	82.17	7.83	Most-critical
	Bus-33	Undervoltage	82.29	7.71	Most-critical
Bus-31	Bus-31	Undervoltage	0	90	Most-critical
Bus-32	Bus-32	Undervoltage	0	90	Most-critical

Figure 4 shows the N-1 contingency corresponding to the outage of Bus-2. This scenario examines the effects of a single-bus disconnection on voltage stability and power flow redistribution across the 33 kV network, forming a reference case for subsequent contingency analyses. The graphic illustrates the malfunction that occurred at Bus-30 within the system, as displayed in ETAP when a fault is detected on a bus or component.

Visualization of Bus-30 outage: The diagram highlights the critical significance of Bus 30, as the impact of its malfunction on the overall system is greater than initially expected. A yellowish hue indicates a relatively healthy system state, where the extent of violation is minimal. In contrast, a red coloration signifies a severe violation, suggesting that the affected buses are critically compromised, potentially leading to system failure or shutdown.

The visual representation in Figure 5 indicates that Bus-30 is marked with a red cross, signifying that it is either out of service or has experienced a fault. Analysis of the N-1 contingency performance index further confirms that the impact of Bus-30's failure is significant, with severe consequences for the stability and operation of the entire network.

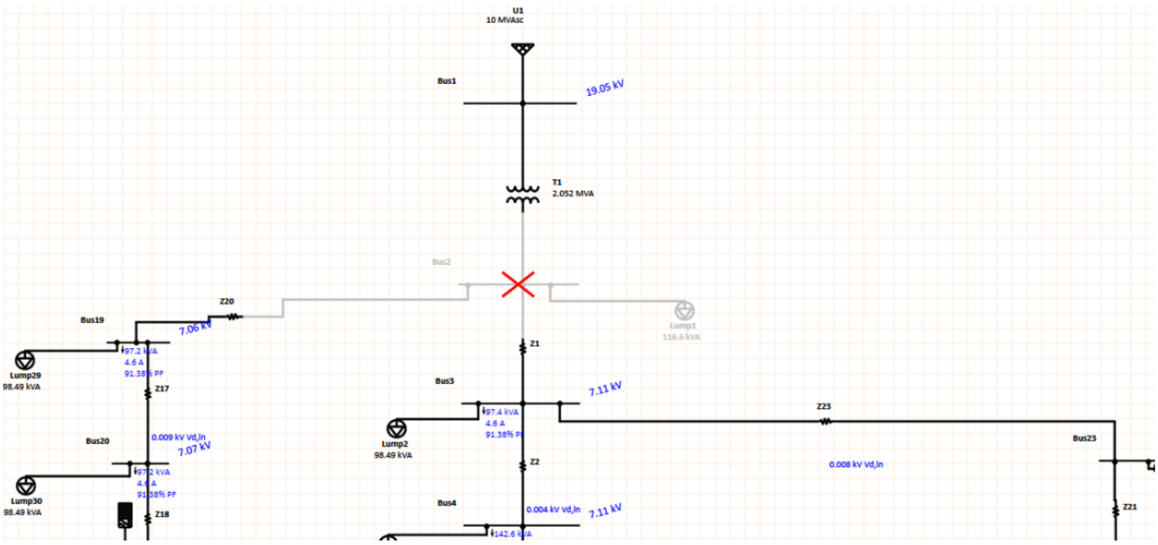

Figure 4. Only the Bus-2 is off

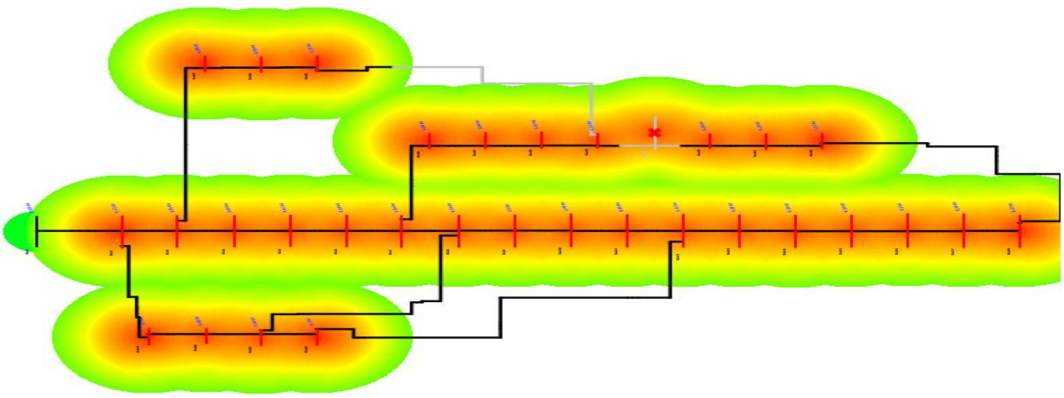

Figure 5. Visual view of Bus-30 outage

3.3. Contingency analysis using N-2 method

An N-2 contingency refers to a scenario in which faults occur simultaneously at two or more components, resulting in their unavailability or removal from operation. Based on different situation here 4 cases are analyzed on the basis of the N-2 contingency analysis method in Table 4. They are:

- Case-1: When Transformer 1 & Line 1 are off
- Case-2: When Transformer 2 & Line 2 are off
- Case-3: When Line 1 & Line 2 are off
- Case-4: When Line 1 & Bus 30 are off

The N-2 contingency analysis revealed that Bus-30 was significantly impacted. Specifically, the simultaneous outage of Bus-30 and Line-2 poses a greater threat to system stability compared to other components. As shown in Table 4, both Bus-30 and Line-2 exhibit higher performance index values, along with elevated levels of active power, reactive power, and voltage regulation.

As part of the N-2 contingency analysis, five distinct scenarios were evaluated, focusing on bus voltage profiles. A healthy system typically maintains voltage within the acceptable range of 0.95 to 1.05 per unit. As illustrated in Figure 6, Case 2 exhibits the most severe voltage violations, indicating a critical system condition. The graph also demonstrates that Bus-30 and Line-2 experience the most significant deviations from nominal voltage levels, highlighting their greater vulnerability compared to other buses. Using the ETAP software after getting the load flow analysis, for N-2 contingency with the necessary cases. Table 5 shows the following data.

Table 4. Performance index for the N-2 contingency analysis method

Case	Type	$\frac{V}{V_{sp}}$	ΔP	ΔQ	$\frac{S}{S_{sp}}$	Combined
Bus-30 and Line-2	Bus/branch	17.20	405.38	53.71	0.11	476.40
Transformer-1 and Line-1	Transformer/branch	0.63	79.36	36.00	0	115.99
Transformer-2 and Line-2	Transformer/branch	1.03	131.43	45.26	0	177.72
Line-1 and Line-2	Branch	0.76	116.90	36.29	0.01	153.96
Line-1 and Bus-30	Branch	51.19	168.61	35.10	0.08	254.98

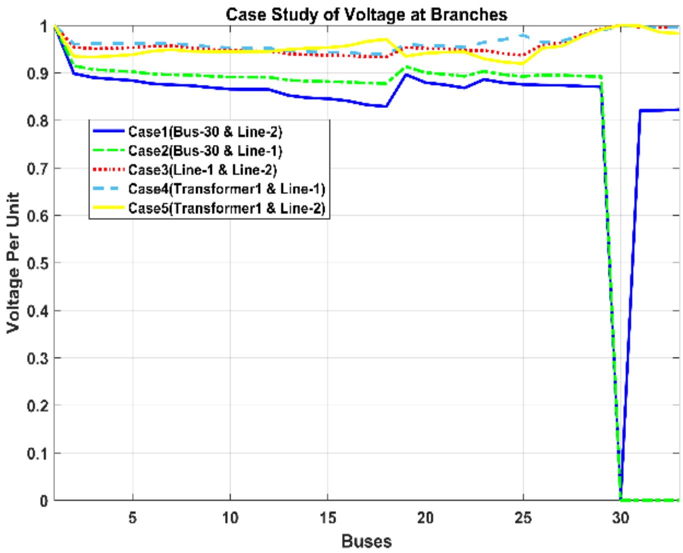

Figure 6. Voltage regulation in different branches based on N-2 contingency analysis

Table 5. Contingency analysis data using the N-2 method

Out of operation	ID	Condition	% post-contingency	% violation	Type
Bus-30 and Line-2	Bus-14	Undervoltage	84.73	5.27	Most-critical
	Bus-15	Undervoltage	84.56	5.44	Most-critical
	Bus-16	Undervoltage	84.11	5.89	Most-critical
	Bus-17	Undervoltage	83.26	6.74	Most-critical
	Bus-18	Undervoltage	82.9	6.1	Most-critical
	Bus-30	Undervoltage	0	90	Most-critical
	Bus-31	Undervoltage	82.05	7.95	Most-critical
	Bus-32	Undervoltage	82.1	7.9	Most-critical
	Bus-33	Undervoltage	82.23	7.77	Most-critical
Bus-30 and Line-1	Bus-30	Undervoltage	0	90	Most-critical
	Bus-31	Undervoltage	0	90	Most-critical
	Bus-32	Undervoltage	0	90	Most-critical
	Bus-33	Undervoltage	0	90	Most-critical

Figure 7 presents the N-2 contingency corresponding to the simultaneous outage of Line-1 and Bus-30. This case examines the combined impact of multiple component failures on voltage stability and network reliability, offering a stringent test of system resilience. Visualization of Line-1 and Bus-30 Outage: when a fault occurs at Bus-30 and Line-2, the critically affected system looks like the given Figure 8.

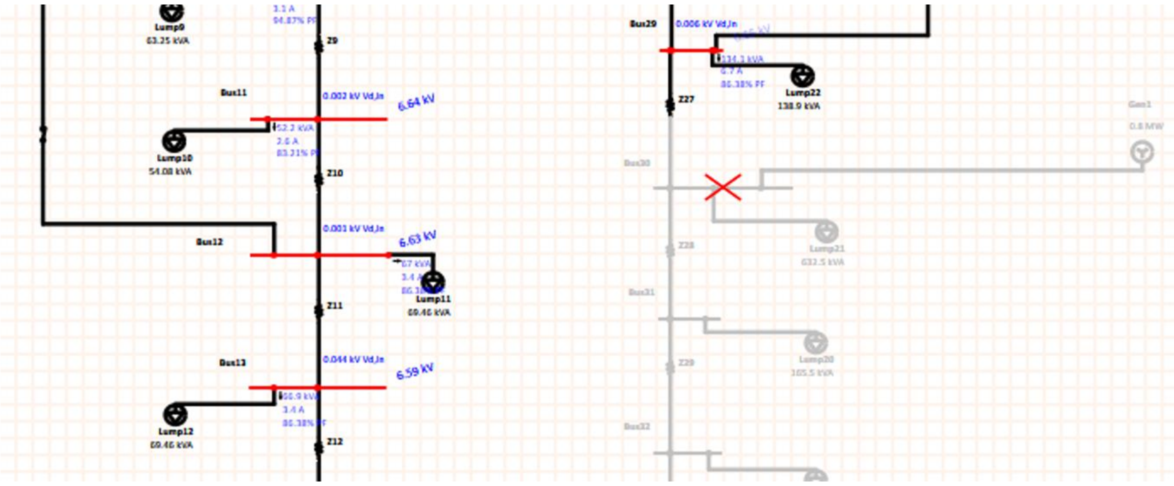

Figure 7. Line 1 and Bus-30 are off

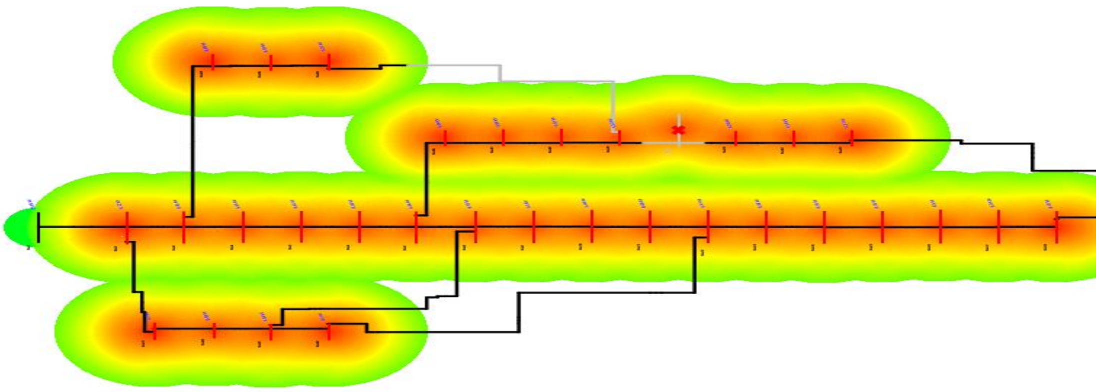

Figure 8. Visual view of Bus-30 and Line-2 are outage

4. CONCLUSION

This study investigated the reliability and vulnerability of a 33 kV distribution network using N-1 and N-2 contingency analyses. The N-1 analysis revealed that critical buses such as Bus-30, Bus-31, and Bus-32 are highly sensitive to single-component failures, with significant voltage drops and high combined severity indices. The most severe single contingency, the outage of Bus30, caused ΔP of 392.34 MW, ΔQ of 55.72 MVAR, and a combined index of 465.32, affecting adjacent buses below operational voltage thresholds. N-2 analysis, simulating simultaneous outages, further increased system instability. The most critical case, concurrent loss of Bus-30 and Line-2, produced a combined index of 476.40, with voltage at several buses dropping below 85%, indicating risk of voltage collapse and load disconnection. The study's novelty lies in integrating voltage and reactive power performance indices with contingency-based reliability assessment, enabling more accurate identification and ranking of severe contingencies than conventional reliability-only approaches. Practically, the results guide network reinforcement, including voltage support device placement, feeder reconfiguration, and improved redundancy, enhancing system resilience. Limitations include the reliance on steady-state analysis and deterministic assumptions, without accounting for dynamic responses, protection actions, load shedding, or renewable generation variability. Future work should extend this framework to dynamic and probabilistic assessments to capture realistic system behavior under contingencies.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [DAR], upon reasonable request.

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