ANALYSIS OF ELECTRICAL NETWORK RELIABILITY IN MULTI-OUTAGE SCENARIOS

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Abstract:

As the demand for electricity grows and power networks expand, ensuring stability and reliability has become more important than ever. Modern power systems are complex, and failures can cause major problems, including overheating, voltage drops, and widespread blackouts. Whether a single part of the system fails or multiple failures happen at once, the impact can be serious. To keep the power grid running smoothly, it is important to find weak points in the system and take steps to prevent failures before they occur. This study analyses the reliability of an electrical network under multi-outage scenarios using a contingency assessment approach. The IEEE 30-bus system is used as a case study, and simulations are performed using specialized software to evaluate the impact of generator and transmission line failures.
The analysis shows how power flow changes under different failure conditions and highlights system vulnerabilities related to load stress and voltage stability. By identifying these weaknesses, appropriate measures can be implemented to prevent the negative effects of sudden generator and transmission line outages, ensuring system stability and reducing the risk of widespread failures.

1 Introduction

Power system reliability is crucial for a stable and secure energy supply, consisting of two main aspects: adequacy and security. Adequacy ensures that sufficient generation capacity is available to meet demand, including reserves for unexpected outages. Security focuses on maintaining system stability by regulating voltage levels, current flows, and power distribution within safe limits, even during disturbances. As electrical power systems form the backbone of modern infrastructure, assessing their reliability is essential to prevent disruptions that could impact industrial, commercial, and residential sectors [1][2]. Contingency analysis is a crucial aspect of power system operations that focuses on evaluating the system's response to potential component failures, such as the outage of generators or transmission lines [3][4]. This analysis helps in identifying vulnerabilities and preparing appropriate mitigation strategies to ensure that the system remains stable and secure [5][6]. By simulating various outage scenarios, contingency analysis provides operators with the necessary information to prevent cascading failures and maintain continuous operation. The importance of contingency analysis has been underscored by several high-profile power outages and system failures. For instance, the 1965 blackout in the northeastern United States [7], the 2003 blackouts in Algeria [8], and the 2012 blackouts in India [9] highlighted the devastating impact of inadequate contingency planning. These events have driven the need for robust contingency analysis to identify and address system vulnerabilities proactively, ensuring that power systems can withstand and quickly recover from unexpected disturbances [10][11]. Existing research on contingency analysis in electrical power systems has explored various methods

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and tools to ensure system stability and security, focusing on identifying vulnerabilities and guiding mitigation strategies [12][13]. Tools like the Power World simulator is extensively used for their comprehensive capabilities, including economic dispatch, power transfer distribution factor (PTDF) computation, and security-constrained optimal power flow (SCOPF) analysis [14]. The Newton-Raphson method is another key technique for accurate power flow solutions [15]. Additionally ,One of the contingency analysis methods is the 1P1Q (Performance Contingency Index) method, which identifies the most severe contingencies in an electric power system. This method helps engineers address issues and determine appropriate actions when contingencies occur. The 1P1Q method ranks contingency severity by calculating performance indices for power flow and voltage [16].Despite these advancements, there are gaps such as the need for faster and more efficient computational techniques to handle the complexity of modern power systems. This study addresses these gaps by developing models that integrate advanced computational techniques and multiple analytical tools, aiming to enhance the accuracy and efficiency of contingency analysis, providing more reliable insights into system vulnerabilities, and supporting robust mitigation strategies [17][18]. Effective contingency analysis requires accurate power system modelling. This includes detailed representations of system components such as generators, transmission lines, and loads. The model must account for system topology, component parameters, and operational constraints.

The modelling process typically involves load flow analysis, which determines the steady-state operating conditions of the power system under normal and contingency scenarios, and the use of sensitivity factors, such as Line Outage Distribution Factors (LODF), to estimate the impact of specific outages on line flows and system stability [19][20]. The primary objectives of this study are to develop and validate models for effective contingency analysis in electrical power systems, identify critical vulnerabilities and evaluate the severity of potential outages, propose and test mitigation strategies to enhance system stability and security, and utilize advanced tools, such as the Power World simulator and linear sensitivity factors like the Line Outage Distribution Factor (LODF), to improve the accuracy and efficiency of contingency analysis. This paper focuses on testing these objectives using the IEEE 30-bus system within the PowerWorld simulator. The study will demonstrate the effectiveness of the proposed models and methodologies in identifying and mitigating system vulnerabilities. By providing detailed insights into the power system's behavior under various contingency scenarios, this research aims to enhance the overall reliability and security of electrical grids. The structure of this paper includes a comprehensive literature review, a detailed description of the methodology, results from the simulation and analysis, a discussion of the findings, proposed mitigation strategies, and concluding remarks with recommendations for future research. The remainder of this paper discusses contingency analysis and power system realisability, followed by the methodology outlining the IEEE 30-bus system model and simulations. The results section analyzes outage impacts on power flow and voltage stability, while proposed mitigation strategies focus on infrastructure reinforcements and reactive power support. Finally, the conclusion summarizes key findings and suggests future research directions to enhance grid resilience.

2 Theoretical investigation

2.1 Contingency Analysis in Power Systems

Contingency analysis is a crucial part of power system operations, assessing potential impacts from component failures, like transmission line or generator outages, on grid stability. By identifying weaknesses in the system, contingency analysis helps operators proactively plan for faults, thereby enhancing system resilience and security [21-23].

2.2 Sensitivity Factors

One of the essential tools in contingency analysis is the use of linear sensitivity factors, which help quantify the impact of system changes, such as outages or shifts in power flows, on other network elements. The Line Outage Distribution Factor (LODF) is particularly useful for predicting how the power flow will redistribute when a specific line goes out of service [22,24,26].

2.3 Line Outage Distribution Factor (LODF)

The Line Outage Distribution Factor (LODF) quantifies the change in power flow on a line j due to the outage of another line k. Mathematically, the LODF for line j with respect to the outage of line k is defined as:

$$LODF_{j,k} = \frac{\Delta P_j}{P_k} \tag{1}$$

where:

- ΔP_j is the change in power flow on line jjj due to the outage of line k,
- P_k is the pre-outage power flow on line k [22,25-26].

This factor is crucial in contingency analysis as it predicts how power flow will redistribute across other lines when a line fails, enabling operators to anticipate and mitigate potential overloads [24,26].

2.4 Calculation of LODF Using Power Transfer Distribution Factors (PTDFs)

The LODF can also be calculated using Power Transfer Distribution Factors (PTDFs), which represent the effect of a power injection or withdrawal on a line's flow. The LODF calculation enables an estimation of redistributed flow on adjacent lines when an outage occurs, allowing better contingency planning and proactive control measures [21,23-25]

the LODF can be computed as:

$$LODF_{j,k} = \frac{PTDF_{j,mn} - PTDF_{k,mn}}{1 - PTDF_{k,mn}} \tag{2}$$

Here, $PTDF_{k,mn}$ represents the PTDF for line k for the same power injection and withdrawal. This equation helps quantify the relative redistribution of flow to line j when line k is outaged.

2.5 Application of LODF in Contingency Analysis

The LODF values are essential in contingency analysis, as they enable operators to:

- Predict overloads: Calculate potential overloads on specific lines if a nearby line fails.
- Plan corrective actions: Implement re-dispatching or load-shedding strategies based on the predicted flow redistribution.
- Prioritize contingencies: Rank critical outages by assessing lines with high LODF values that would likely contribute to cascading failures.

3 Results and discussion

This study utilizes the IEEE 30-bus test system and PowerWorld Simulator to perform a comprehensive contingency analysis, highlighting the critical importance of understanding the impacts of generator and transmission line outages. By simulating these outages, the analysis identifies key vulnerabilities in the power system, such as overloads and voltage stability issues. This approach underscores the necessity of contingency analysis in maintaining grid reliability, stability, and resilience, ensuring the effective and safe operation of the electrical grid under various stress conditions. The IEEE 30-bus test case represents a simple approximation of the American Electric Power system as it was in December 1961. The equivalent system has 15 buses, 2 generators, and 3 synchronous condensers. The 11 kV and 1.0 kV base voltages are guesses, and may not reflect the actual data. The model actually has these buses at either 132 or 33 kV; what is worth mentioning is that the 30-bus test case does not have line limits [27].

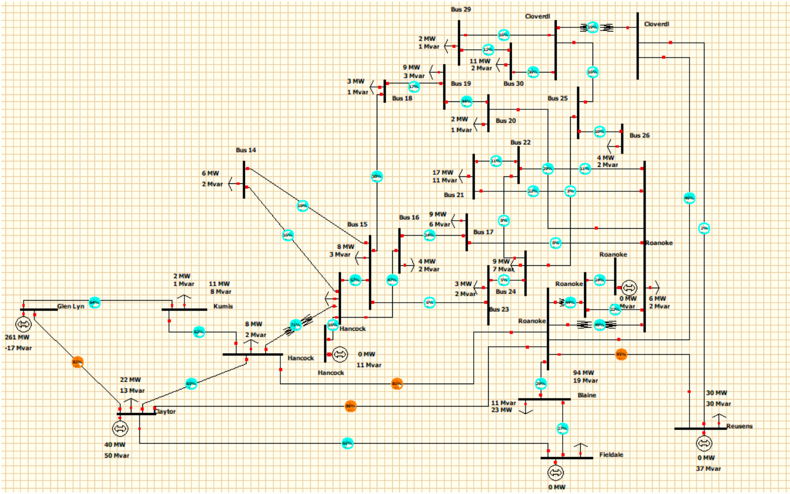

Figure 1. IEEE 30 bus system.

This simulation examines the IEEE 30-bus system using PowerWorld Simulator to assess the impacts of different outage scenarios. The study analyses both separate and combined (multi) outages of a generator and a transmission line.

3.1 OPEN Generator G_5 Fieldale U1

Table 1. Contingency analysis results for the IEEE 30-bus system when the generator G_5FieldaleU1 is open.

Label	Violations	Max Branch %
G_000001U1	1	136.4
G_000002U1	1	104.5
G_000005U1	**0**	
G_000008U1	1	119
G_000011U1	0	
G_000013U1	0	

The table 1 presents contingency analysis results for the IEEE 30-bus system when the generator G_5FieldaleU1 is out of service. It reveals significant branch loading issues, particularly with G_000001U1, which experiences 136.4% loading, indicating severe thermal stress and potential failure risk. G_000002U1 and G_000008U1 also show high loadings at 104.5% and 119%, respectively, each with one violation, pointing to critical stress points. Conversely, G_000005U1, the generator taken out of service, shows no violations. These findings suggest the need for capacity upgrades, load redistribution, and enhanced voltage support to mitigate risks and maintain grid stability under such contingencies.

3.2 OPEN line "L_2 Claytor-5FieldaleC1

Table 2. Achieved result for STT and GMAW processes.

Category	Element	Value	Limit	Percent
Branch MVA	Claytor (2) -> Hancock (4) CKT 1 at Claytor	75.84	65	116.68
Branch MVA	Claytor (2) -> Roanoke (6) CKT 1 at Claytor	103.78	65	159.66
Branch MVA	Hancock (4) -> Roanoke (6) CKT 1 at Hancock	119.16	90	132.4
Branch MVA	Blaine (7) -> Fieldale (5) CKT 1 at Blaine	99.95	70	142.78
Bus Low Volts	Fieldale (5)	0.9	0.9	

The table presents results from a contingency analysis of the IEEE 30-bus system when the transmission line "L_2 Claytor-5FieldaleC1" is out of service, revealing significant operational vulnerabilities. The analysis shows severe branch MVA violations with Claytor to Roanoke at 159.66%, Blaine to Fieldale at 142.78%, Hancock to Roanoke at 132.4%, and Claytor to Hancock at 116.68%. These overloads indicate significant thermal stress, posing high risks of overheating and line failures. Additionally, the voltage at Fieldale is at the minimum acceptable limit of 0.9 pu, suggesting potential voltage stability issues. To mitigate these risks, capacity upgrades for the overloaded lines, strategic load redistribution, and enhanced reactive power support at Fieldale are recommended. Implementing real-time monitoring systems is essential for prompt corrective actions. Addressing these technical issues is crucial for maintaining grid reliability, stability, and resilience under contingency conditions.

3.3 Contingency scenario involving the outage of generator and line

The provided table outlines the state of the power system under the contingency scenario involving the outage of generator "G_5FieldaleU1" and line "L_2 Claytor-5FieldaleC1". The table categorizes violations into Branch MVA and Bus Low Volts, highlighting the critical stress points within the IEEE 30-bus system.

Table 3. result of contingency scenario involving the outage of generator and line.

Category	Element	Value	Limit	Percent	Nom kV Assoc.
Branch MVA	Claytor (2) -> Hancock (4) CKT 1 at Claytor	85.23	65	131.12	132
Branch MVA	Claytor (2) -> Roanoke (6) CKT 1 at Claytor	117.27	65	180.42	132
Branch MVA	Hancock (4) -> Roanoke (6) CKT 1 at Hancock	129.66	90	144.07	132
Branch MVA	Blaine (7) -> Fieldale (5) CKT 1 at Blaine	111.27	70	158.96	132
Branch MVA	Roanoke (6) -> Blaine (7) CKT 1 at Roanoke	155.35	130	119.5	132
Bus Low Volts	Fieldale (5)	0.65	0.9		132
Bus Low Volts	Roanoke (6)	0.87	0.9		132
Bus Low Volts	Blaine (7)	0.76	0.9		132
Bus Low Volts	Reusens (8)	0.87	0.9		132
Bus Low Volts	Bus 19 (19)	0.9	0.9		33
Bus Low Volts	Bus 24 (24)	0.89	0.9		33
Bus Low Volts	Bus 25 (25)	0.88	0.9		33
Bus Low Volts	Bus 26 (26)	0.86	0.9		33
Bus Low Volts	Cloverdl (27)	0.88	0.9		33
Bus Low Volts	Cloverdl (28)	0.87	0.9		132
Bus Low Volts	Bus 29 (29)	0.86	0.9		33
Bus Low Volts	Bus 30 (30)	0.84	0.9		33

The provided graph visually represents the flow of power and the associated overload percentages on various transmission lines within the IEEE 30-bus system under a specific contingency scenario:

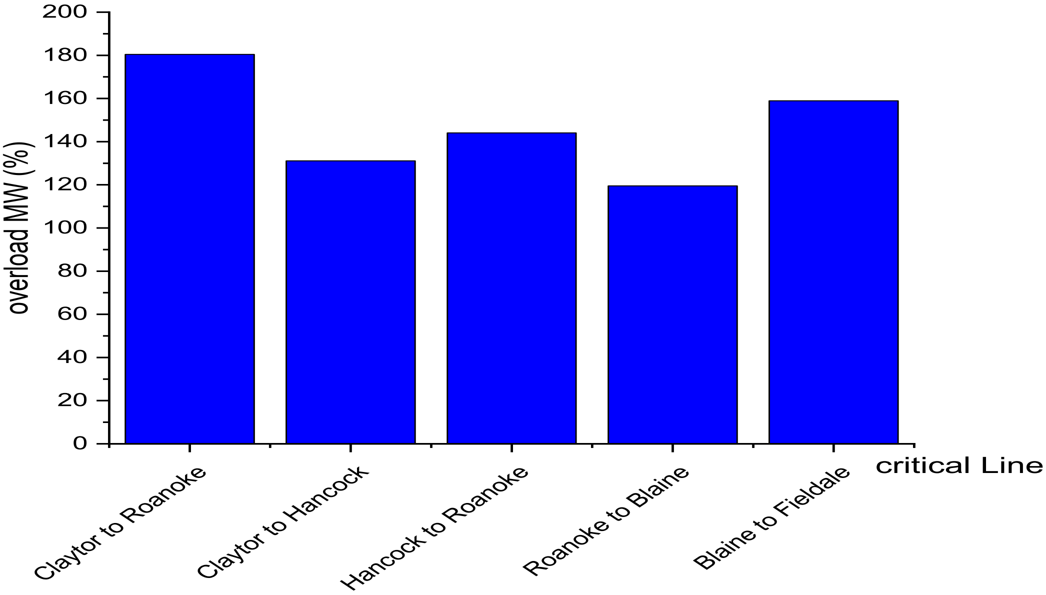

Figure 2. Overload Percentages of Critical Transmission Lines in the IEEE 30-Bus System Under Contingency.

The provided graph represents the overload percentages for various transmission lines in the IEEE 30-bus system under a specific contingency scenario.
The diagram highlights the following critical overload percentages:
Claytor to Roanoke: 180.42%
Claytor to Hancock: 131.12%
Hancock to Roanoke: 144.07%
Roanoke to Blaine: 119.5%
Blaine to Fieldale: 158.96%

3.3.1 Analysis

Severe Overloads:

-The line from Claytor to Roanoke shows the highest overload at 180.42%. Such a high percentage indicates that the line is carrying nearly double its rated capacity, posing a severe risk of thermal damage and potential failure.

- The Blaine to Fieldale line is also critically overloaded at 158.96%, which can lead to similar risks of overheating and line tripping.
- The lines Claytor to Hancock (131.12%) and Hancock to Roanoke (144.07%) are significantly overloaded, indicating high-stress zones that require immediate attention to prevent failures.
- These lines are critical for maintaining the stability of the network, and their overloads suggest potential weak points in the system.

Moderate Overload:

The Roanoke to Blaine line, although less severe, still operates above its capacity at 119.5%. This moderate overload can exacerbate under additional stress or contingencies.

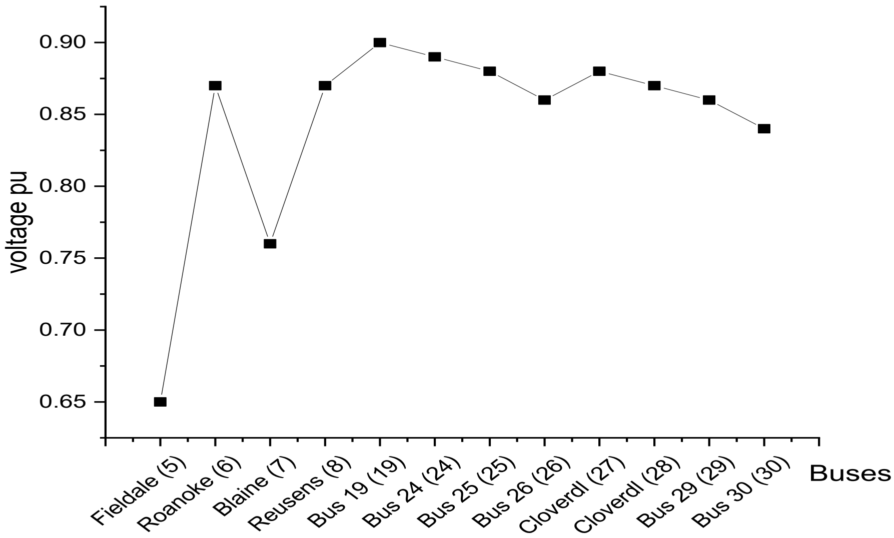

Figure 3. Bus Voltage Levels Below Acceptable Limit in the IEEE 30-Bus System Under Contingency.

The provided bar chart illustrates the voltage levels of various buses in the IEEE 30-bus system that are below the acceptable limit of 0.9 per unit. Each bar represents the voltage level of a specific bus, with the red dashed line indicating the minimum acceptable voltage threshold.

3.3.2 Analysis and Commentary:

The chart highlights several buses experiencing undervoltage conditions, which can compromise the stability and reliability of the power system. Key observations include:

Severely Affected Buses:

Bus 30 has the lowest voltage level, significantly below the 0.9 per unit limit. Such low voltage can lead to voltage collapse if not addressed promptly.
Other buses like Bus 29 and Bus 26 also exhibit voltage levels well below the acceptable threshold, indicating potential risks to connected loads and overall system stability.

Moderately Affected Buses:

Fieldale, Roanoke, and Blaine show voltage levels around 0.875 per unit. While these are closer to the limit, they still pose concerns for maintaining stable voltage profiles across the network.
Bus 24 and Cloverdale (27), though slightly higher, remain below the 0.9 per unit mark, suggesting the need for voltage support measures.

Less Affected Buses:

Bus 19 is the closest to the acceptable limit but still falls short. It indicates that even minor voltage deviations need monitoring and corrective actions to prevent further degradation.

3.4 Comparative the results

Table 4. Comparison of System Performance Under Separate and Multi-Outage Scenarios.

Parameter	Separate Outages	Multi-Outage
	-Both scenarios independently show significant but manageable overloads.	-The multi outage results in extreme overloads and severe thermal stress, indicating a high risk of system failure.
Severity of Overloads	-Certain lines experience high stress, but the overall system can potentially remain stable with targeted interventions	- The cumulative impact is much more significant, showing that the system's resilience is heavily compromised when both a line and a generator are out of service simultaneously
Voltage Stability	-Voltage at Fieldale remains at the limit during the line outage, indicating potential but manageable stability issues.	-The voltage at Fieldale remains critical, with the added stress of multi outages exacerbating the risk of voltage collapse.
System Resilience	- The system shows localized vulnerabilities, but overall stability can be maintained with appropriate measures.	- The system's resilience is severely compromised, indicating a need for comprehensive upgrades and strategic interventions to handle such high-stress scenarios.

3.5 Recommendations

For Separate Outages:

- Implement targeted capacity upgrades and load redistribution to alleviate stress on overloaded lines.
Enhance voltage support measures at critical buses to maintain stability.

For Multi Outage:

- Conduct a thorough review of the system's capacity and resilience, focusing on the most stressed lines.
- Develop robust contingency plans, including automated protection schemes and dynamic load balancing, to prevent cascading failures.
- Invest in real-time monitoring and advanced control systems to enable rapid response to extreme conditions.

Addressing these vulnerabilities through strategic planning and infrastructure enhancements is crucial for maintaining grid reliability, stability, and resilience under both individual and multi outage scenarios.

4 Conclusion

The contingency analysis simulation of the IEEE 30-bus system using PowerWorld Simulator provides critical insights into the system's vulnerabilities under different outage scenarios. The analysis reveals that separate outages of either a generator or a transmission line result in significant but manageable overloads and localized stress points. However, when both a generator and a transmission line are simultaneously out of service, the system faces extreme overloads, severe thermal stress, and a higher risk of cascading failures. These conditions underscore the need for comprehensive capacity upgrades, strategic load redistribution, and enhanced voltage support to mitigate risks. Implementing real-time monitoring systems is crucial for prompt corrective actions. This simulation demonstrates the indispensable role of contingency analysis in enhancing grid reliability, stability, and resilience, ensuring efficient and safe operation under various contingency conditions. The results indicate that while single outages cause stress within operational limits, multi-outages push the system beyond stability thresholds, leading to extreme overloads and voltage collapses. Key vulnerabilities, such as the Claytor to Roanoke line exceeding 180% of its capacity and Fieldale's voltage dropping to 0.65 pu, highlight the need for urgent infrastructure reinforcements and real-time monitoring. Without preventive measures, cascading failures and large-scale blackouts become highly probable.

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