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Review paper

Steady-State Security and Power System Contingency Analysis: A Review

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Abstract: This paper comprehensively reviewed the contingency analysis and its relation to blackouts. It explored the causes and impacts of blackouts in interconnected power systems, emphasizing the need for effective contingency planning and analysis to mitigate their occurrence and minimize their effects. The study critically examined existed literature, research studies, and practical approaches related to contingency analysis in the context of blackouts. By synthesizing and analyzing these sources, Contingency analysis is a crucial feature in modern Energy management system (EMS), ensuring static security in power systems by analyzing overloads and voltages outside allowed limits. Contingency analysis system (CAs) with corrective action schemes struggle to differentiate safe operating regimes from hazardous ones, posing significant power system risks. The power system operator must always be aware of the system's status. The paper provided a holistic consideration of the subject matter. Additionally, it highlights key findings, emerging trends, and future directions for research and practical implementation in contingency analysis and blackout management.

Keywords: Contingency analysis, blackout failures, static security assessment, catastrophic events, and steady-state security.

1. Introduction

In the past decade, power system blackouts have caused severe consequences, including infrastructure damage, communication breakdowns, economic repercussions, and public safety concerns.

Analyzing blackout effects covers power system operation, synchronization loss, and restoring out-of-sync generation challenges. Additionally, blackouts indicate vulnerable areas in power system networks, prompting extensive research to address incidents and develop strategies for secure network operation [1]. Therefore, ensuring economic and reliable power systems is crucial to prevent transmission line overloading, which can cause outages and complete blackouts. Operators must always monitor the system's state and initiate necessary corrective action if required [2].

Contingency analysis (CA) is crucial for designing and managing power systems, assessing static security through overloads and over/under voltage [3-4]. However, standard CA with corrective action schemes cannot differentiate between safe and potentially hazardous voltage stability regimes, posing significant threats to electrical systems [5]. In general, contingency analysis is crucial for power system security, as it helps calculate violations and predict the effects of outages like conductors and apparatus failures. This approach helps maintain the facility's security and dependability by analyzing the system's state in case of contingencies and requiring necessary actions to maintain the system's security [6].

Ensuring a system's security and reliability is crucial for its performance and performance under specific conditions. Security refers to the system's ability to maintain predetermined parameters in case of component failure, such as generators, transformers, or transmission lines [7].

This study focuses on a thorough overview of contingency analysis for power system security and catastrophic events mitigation. It provides a thorough review of the contingency analysis of the power system to forecast line and generator outages and how to maintain the system's security and dependability [8]. Finally, contingency analysis study helps to strengthen the initial basic plan. It is also helpful to develop system operators to improve their ability to resolve problems. It especially helps the busy power system operators. Therefore, this paper has been divided into eight sections including the introduction. The second section discussed the contingency in electrical power system network, and contingency analysis methods. The type of violations has been discussed in section three. Section four discussed in detail the steady-state security assessment in power system. The importance of remedial action schemes in mitigating catastrophic events has been discussed in section five. The application of artificial intelligence in power system contingency and steady-state assessment has been covered in section six. Finally, section seven covered the conclusion.

2. Contingency in the power system

Contingency refers to the sudden loss or failure of power system components or a specific sequence of events. Contingencies such as unexpected line outages may lead to voltage collapse blackouts. A contingency assessment is necessary to determine line severity and alert operators to susceptible lines using contingency ranking for corrective actions. Contingency analysis is a simulation technique examining the impact of generating and transmission unit failures on MVA flows and bus voltage magnitudes, determining the optimal course of action in a given situation [4].

A scalar performance index (PI) ranks the contingencies [9]. The PI's two main responsibilities are:

1. The distinction between genuine critical outages and non-critical ones, and
2. The estimation of the relative severity of critical failures [10].

Power systems require redundancy for failure scenarios, with contingency analysis being a crucial component in modern energy management [11-12-13]. Contingency analysis involves accurate system performance estimations from streamlined conditions to determine stability after disruptions [14]. One of the most crucial duties for the planning and operation engineers of bulk power systems is contingency analysis.

Line Outage Distribution Factor (LODF) is a crucial linear sensitivity variable that identifies major contingencies and suggests preventive and remedial measures.

- LODFs represent flow change due to second-line failure [15].
- Typically, Calculate the difference between pre-contingency flow and MW flow.
- LODFs rely on presumptive network architecture but are independent of flows.

PTDFs reveal linearized power transfer effects, impacting stability research due to increasing load demand without investments in generation and gearboxes, requiring faster, dependable technologies [16-17].

Contingency analysis measures seriousness of contingencies and predicts system violations, aiding network design, maintenance, and extension activities in identifying network flaws [18-19]. Increasing transmission capacity, transformer rating, and circuit breaker rating can all counteract the deficiencies [20].

Contingency analysis enables sensitive system operation, preventing power system issues from escalating into significant issues [21–22]. Therefore, Computers use CA programmers to simulate power systems, detecting outages and overloads [23].

Correctness procedure and solution speed pose challenging methodological issues in contingency analysis, ensuring system security and potential outage consequences for operators [20].

Rising demand, development constraints, and power sector transformation make managing and controlling the system increasingly challenging [24–25]. As operators drive these systems close to their stability limit, this has led to frequent power system stability violations, according to [23]. This move has consequently caused several voltage collapse incidents with large costs for both the utilities and the consumers [26–27]. Power systems need to be monitored to warn operators of potential emergencies or defects that point to voltage instability [28-29].

Kundur [30], Voltage stability refers to a power system's ability to maintain stable voltage magnitudes on all network buses under normal conditions and after disturbances. A network is considered voltage unstable if a disturbance causes a gradual decrease in voltage on at least one bus. [31]. Voltage collapse may occur due to a perturbation affecting the entire network or a portion [29].

Increased load demand, improper voltage control, reactive power incongruity, system loss, and faulty on-load tap changing transformers may cause disturbances. [32, 33]. Voltage collapse could happen whether the perturbation causes a decreased voltage profile throughout the entire network or only a portion of it [34]. Dynamic analysis uses time-domain simulations for voltage stability assessment, but online methods require extensive computations and time-consuming computations, making them unsuitable for online voltage stability analysis [35–36].

2.1. Contingency analysis

A failure in a power system can cause outages, affecting the entire system's operation. It can prevent safe and reliable operation. Contingency refers to unexpected events in a power supply, such as a generator, transmission line, or transformer going down. Power systems must be secure for their use [37–38]. Contingency analysis evaluates the impact of contingencies and alerts system operators to critical situations. These situations can be overloaded transformer and/or transmission lines and voltage violation at system buses [39]. Typically, three main phases the contingency analysis procedure can be divided into, these phases are:

- **Contingency identification**: it is a list of all contingencies that could adversely affect the security of the electrical network.
- **Contingency selection and ranking**: in the second phase the list of contingencies is filtered out and only contingencies that pose a real threat to the overall security of electrical network are selected. Typically, this phase includes two algorithms, one of these algorithms is aiming to identify the critical contingencies, which results in new list with less contingencies. The second algorithm, on the other hand, aims to rank these contingencies based on the severity they pose to the security of power system.
- **Contingency evaluation**: the last phase includes initiating corrective action to alleviate contingencies adverse effects [39].

2.1.1 Voltage-reactive performance index ($PIVQ$)

The voltage-reactive power performance index assesses contingency from voltage limit abuse and generator violation at nodes, ensuring sternness and reliability. The PIVQ index can be mathematically formulated as follows:

$$\sum_{i=1}^{N_B}\left(\frac{W_{Li}}{M}\right)\left[\frac{\left|V_i-V_i^{SP}\right|}{\Delta V_i^{lim}}\right]^M+\sum_{i=1}^{N_G}\left(\frac{W_{Gi}}{M}\right)\left[\frac{Q_i}{Q_i^{max}}\right]^M \quad (1)$$

Where:

$\Delta V_i^{lim} = V_i - V_i^{max} for V_i > V_i^{max} and\ V_i^{max} - V_i\ for\ V_i - V_i^{min}$

where N_B, and N_G are the number of buses and the number of generation units, respectively. V_i, V_i^{Sp}, V_i^{max}, V_i^{min}, W_{Gi}, W_{Vi}, Q_i, and Q_i^{max} represent voltage, specified voltage, the voltage maximum, the voltage minimum, the real non-negative weighting factor of generation units, the real non-negative weighting factor at other each bus, the generated reactive power, the maximum allowable generated reactive power.

2.1.2 Line MVA performance index($PIMVA$)

System stress is measured using scalar performance indices, such as load bus voltage violations or gearbox line overloads. Critical contingencies may be non-critical depending on different loading conditions, impacting the system's performance significantly.

$$PI_{MVA} = \sum_{i=1}^{N_L}\left(\frac{W_{Li}}{M}\right)\left[\frac{S_i^{post}}{S_i^{max}}\right]^M \quad (2)$$

where S_i^{post} is the post-contingent MVA flow of line, S_i^{max} is the MVA rating of line I, N_L is the number of lines in the system, W_{Li} is the real non-negative weighting factor, M is the order of the exponent for penalty function.

Contingency analysis (CA) is a security analysis application in power utility control centers, identifying overloads and problems arising from contingencies in an EMS system, contrasting with SCADA systems [20].

Contingency analysis is an abnormal condition in electrical networks that stresses the entire system or a specific area due to generator trips, changes in generation, load values, or transmission line openings. It provides tools for organizing, producing, analyzing, and reporting contingencies and related violations [40].

CA is used as to study as off-line tool of contingency events, and as an online tool to display to operators what would be the consequences of future outages.

- Security is determined by the ability of the system to withstand equipment failure.
- Weak elements are those that present overloads in the contingency conditions (congestion).
- Standard approach is to perform a single (N-1) contingency analysis simulation.
- A ranking method will be demonstrated to prioritize transmission planning.
  [41].

2.2 Contingency analysis methods

Contingencies are hazardous disruptions that occur during steady power system operation. A load flow study is crucial for understanding, expanding, and planning a power system [42]. It determines steady-state operating conditions, including voltage magnitudes, phase angles, line flows, generator power generation, and power loss. These operational conditions [43-44] are crucial for ensuring the power system's effective functioning and future development.

Analyzing contingencies using methods like reduced load flow, full AC load flow analysis, or sensitivity factors is challenging for online applications in large power systems due to computational requirements [45-46]. Online contingency analysis challenges the trade-off between speed and accuracy using conventional methods [47-48].

2.2.1. Important methods used in contingency analysis

- AC load flow-based methods
- DC load flow-based method.

- Z-bus-based contingency analysis.
- Performance Index-based method.

2.2.1.1. AC load flow-based methods

Computers can solve nonlinear algebraic equations in power flow problems, calculating voltage magnitude and phase angle at each bus in a power system. A single-line schematic is developed as input for computer-based solutions, involving information on buses, gearbox lines, and transformers. Four variables, voltage magnitude, phase angle, net real power, and reactive power, are connected to each bus [49]. In a power transmission network, there are three types of buses, these buses are named as follows.

– Generator Bus or Voltage Controlled Bus (P, V bus)
– Load Bus (P, Q bus)
– Slack Bus (Swing Bus or Reference bus)

2.2.1.2 DC Load Flow-Based Method

The DC load flow-based method simplifies AC load flow analysis by assuming a constant power factor, making it suitable for online applications. However, it may not accurately describe the system's dynamic behavior due to the absence of reactive power effects [50-51].

2.2.1.3. Z-Bus-Based Contingency Analysis

Z-bus-based methods transform power systems into equivalent impedance matrices, simplifying contingency analysis by representing system behavior in voltage deviations and branch currents. They offer a balance between accuracy and computational efficiency, suitable for both offline and online applications [52].

2.2.1.4. Performance Index-Based Method

Performance index-based methods quantify system performance and assess contingencies using specific indices like voltage stability, power losses, and line overloading. They prioritize and rank contingencies, enabling efficient identification of critical contingencies by system operators [53].

Each of these methods has advantages and limitations, and their applicability depends on the requirements, system size, and computational resources available. System operators and engineers must carefully choose the appropriate method based on the desired accuracy, computational efficiency, and online or offline application needs.

3. Violation types

The types of contingencies that occur most frequently typically revolve around lines and generators. These contingencies primarily lead to two types of violations.

A. **Low Voltage Violations:** Bus infractions indicate low or high voltage levels, with the typical operating voltage range between 0.95 and 1.05 per unit (p.u.). Low voltage issues involve reactive power supply, while high voltage issues require buses to absorb reactive power to maintain normal voltage. Reactive power is typically used to increase voltage profiles in low-voltage situations, while in high-voltage cases, buses absorb reactive power to maintain normal voltage [54].

B. **Line MVA Limits Violations**: Power system contingency occurs when a line's MVA rating exceeds its designated rating, often due to increased current amplitude [55-56]. Lines are designed to withstand up to 125% of their MVA rating, but utility procedures trigger alarms when current exceeds 80-90% of this limit [57].

4. Steady-state security assessment

Maintenance of power system security is crucial for proper operation. Security assessments assess system safety and conduct contingency screening to detect key scenarios and implement preventive measures.

Contingency selection involves identifying the worst possible contingency scenarios using ranking or screening techniques. These scenarios include likely outages like transmission line overloads or bus limit violations. Critical contingencies are classified according to severity using ranking procedures and screening methods. These techniques help address potential breaches and ensure timely remedial action [58-59].

Performance indices (PIs) are commonly used in evaluation, but traditional methods like AC load flow analysis and mathematical calculations are unsuitable for online applications. To ensure safe power system operation, quick, reliable, and accurate online security assessment tools are needed [60].

On the other hand, Static security assessment evaluates the power system's ability to return to steady state without violating constraints after disturbance [61-63]. The static security status of the power system is categorized into three security levels based on PIs:

i. Class I (Most critical contingencies): These contingencies are the most severe and require more attention.

ii. Class II (Critical contingencies): These contingencies are less severe than the previous class but still represent great adverse effects on the network operation. In such cases, proper preventive control actions are necessary to alleviate their occurrence consequences.

iii. Class III (non-critical contingencies): These contingencies are always safe and secure under any operating condition. However, normal operation of the electrical power system network requires satisfying some constraints. These constraints are as follows, [39]:

$$\Sigma_i P_{Gi} = P_D + P_L \quad (3)$$

$$\Sigma_i Q_{Gi} = Q_D + Q_L \quad (4)$$

The secure operation of the system requires the imposition of inequality constraints, which ensure that certain conditions are met. These constraints involve various parameters, including P_{Gi} and Q_{Gi} (real and reactive powers of the generator at bus i), P_D and Q_D (total real and reactive load demands), and P_L and Q_L (real and reactive losses in the transmission network) [64]. These inequality constraints play a critical role in maintaining the system's stability and secure operation. The constraints are as follows:

$$V_{min} < V_j < V_{max} \; for \; j = 1 \; to \; N_B \quad (5)$$

$$S_l < S_{lmax} \; for \; l = 1 \; to \; N_L \quad (6)$$

$$P_{Gi,min} < P_{Gi} < P_{Gi,max} \; for \; i = 1 \; to \; N_G \quad (7)$$

$$Q_{Gi,min} < Q_{Gi} < Q_{Gi,max} \; for \; i = 1 \; to \; N_G \quad (8)$$

The variables involved in the equation are as follows: V_j represents the voltage at bus j, S_l represents the apparent power of line l, and N_B, N_L, and N_G represents the number of buses, lines, and generators, respectively.

Conducting contingency analysis is crucial before conducting a security assessment. This analysis determines the limitations imposed by contingencies based on system operator knowledge but does not predict security thresholds [65-66]. Analyzing single outages of lines, generators, or multiple outages is essential before scheduling secured dispatch. When an element reaches its maximum limit, it can cause damage to multiple lines and generators.

To ensure successful power system operation under normal balanced three-phase steady-state conditions, the following requirements must be met [49]:

i. Generation must supply the demand (load) in addition to losses.

ii. Voltage magnitudes on the buses should remain close to their rated values.

iii. Generators should operate within specified limits for real and reactive power.
iv. Transmission lines and transformers should not be overloaded.

The power-flow computer program, also known as load flow, serves as the fundamental tool for examining these requirements [67].

The power-flow computer program calculates voltage magnitude and angle at each bus in a power system under balanced three-phase steady-state conditions [68]. It determines losses and calculates actual and reactive power flows for equipment. The solution evaluates bus voltage, branch current, real power flow, and reactive power flow, assessing bus voltage tolerance and line or transformer loading [69]:

i. Various system loading conditions, such as peak and off-peak periods.
ii. In the event of specific equipment outages.
iii. When new generators are added to the system.
iv. Upon the addition of new transmission lines or cables.
v. When interconnecting with other systems.
vi. During load growth studies.
vii. Evaluating the impact of line loss.

power system security evaluation is crucial to assess network protection against potential incidents. It involves measuring static security status and security margin in the present state or near future. There are two main types: static security studies and dynamic security studies [70-72].

Static security studies examine power system response to contingencies, focusing on overvoltage and undervoltage conditions at buses and line overload status. A network is considered static secure if voltage magnitudes at all buses fall within specified range, and no line is subjected to overload. Insecure networks are not met [73- 75].

Dynamic security assessment examines system variables before, after, and during transient phases, including steady-state conditions [76-77]. It analyzes rotor angle and small-signal security, evaluating power systems' dynamic behavior and stability during contingencies [78].

The evaluation methods for power system security can be categorized into three groups: classifiers, feature selection, and extraction approaches [79-80]. These methods affect speed and accuracy, and static security assessment references can be classified based on power system implementation aspects. The classification considers contingency, random data creation correlation, input data type, measurement method, and security indices to determine comprehensiveness of proposed methods. Figure 1 illustrates this categorization.

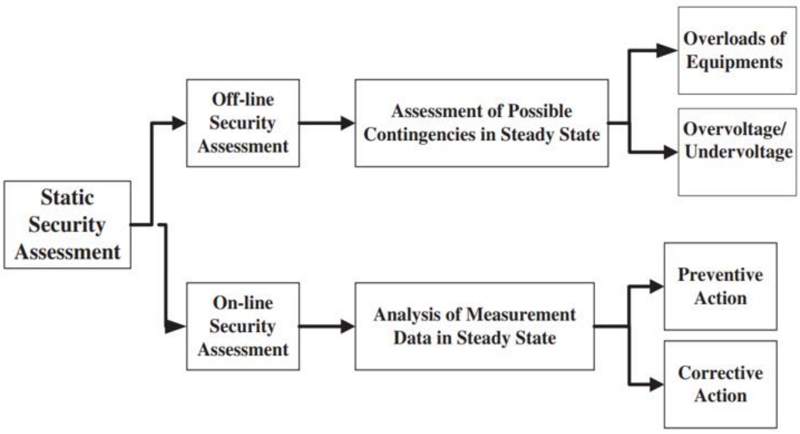

Figure 1. Categorization of security assessment problems [76].

5. Remedial action schemes

Remedial Action Schemes (RAS) are crucial in power system utility planning, addressing unforeseen violations and reducing critical contingencies that could disrupt the system. These plans outline procedures for normal system functioning, also known as System Integration Schemes (SIS) or Special Protection Schemes (SPS).

Remedial action is necessary for single critical outages, multiple critical single contingency outages, and double or multiple contingencies. Different scenarios require varying levels of preparedness and corrective actions. Automatic reclosing during stressed operating conditions can eliminate immediate remedial action, but appropriate action through the RAS may still be required [81].

Remedial Action Schemes (RAS) encompass various types of actions that can be taken to address contingencies and restore the power system to a stable state. Some common types of RAS include [80]:

i. Shunt capacitor switching: This involves switching shunt capacitors in the power system to regulate voltage levels and improve power factor.
ii. Generation Re-dispatch: In this method, the generation resources within the power system are adjusted and redistributed to address imbalances caused by contingencies and maintain system stability.
iii. Load shedding refers to the controlled and temporary reduction of power demand by selectively disconnecting certain loads from the system. This helps to alleviate overloading and prevent system collapse during contingencies.
iv. Under load tap changing (ULTC) Transformer: ULTC transformers are equipped with tap changers that adjust the voltage ratio and regulate the voltage level during contingencies. It can help in maintaining voltage stability within acceptable limits.
v. Distributed Generation: Integrating distributed generation, such as renewable energy sources or microgrids, can provide localized generation capacity and enhance system resilience during contingencies.
vi. Islanding refers to the intentional separation of a portion of the power system into an isolated microgrid during contingencies or when the main grid is disrupted. It allows for continued power supply to critical loads and improves system reliability.

These RAS actions, among others, are designed to mitigate the impact of contingencies, maintain system stability, and ensure the reliable operation of the power system. The specific choice and implementation of RAS depend on the nature and severity of the contingencies encountered.

6. Applications of artificial Intelligence in contingency analysis and steady-state security.

Transmission line overloads in steady-state power systems can cause disruptions, potentially leading to partial or complete blackouts. Contingency Analysis (CA) is used in network design, maintenance, and identifying prone zones for addressing this vulnerability. The significant impacts of the system with the integration of the intelligent controls are Automatic and fast response control, decrease occurrence of power losses, smooth and continuous decongestion of power lines, Improve the overall effectiveness of grid operation, improve the stability of power grids, and economic impact (The implementation of the intelligent control algorithm will result in millions of dollars in savings).

In a study conducted in [81], the CA approach was applied using the Newton Raphson Load Flow (NRLF) method within the DIGSILENT Power Factory software. This study aimed to analyze the impact of each outage on the operational limitations of the system. By employing this method, comprehensive reports can be generated, detailing all critical scenarios and the associated violations that occur during contingencies. AC load flow algorithms capture the impact of an outage online flows and system voltages better than the DC load flow [82]. The novelty of this algorithm is to perform the power system security under N-1 and N-1-1 contingency conditions. Figure 2 shows the flow chart of contingency based power system security problem solution algorithm.

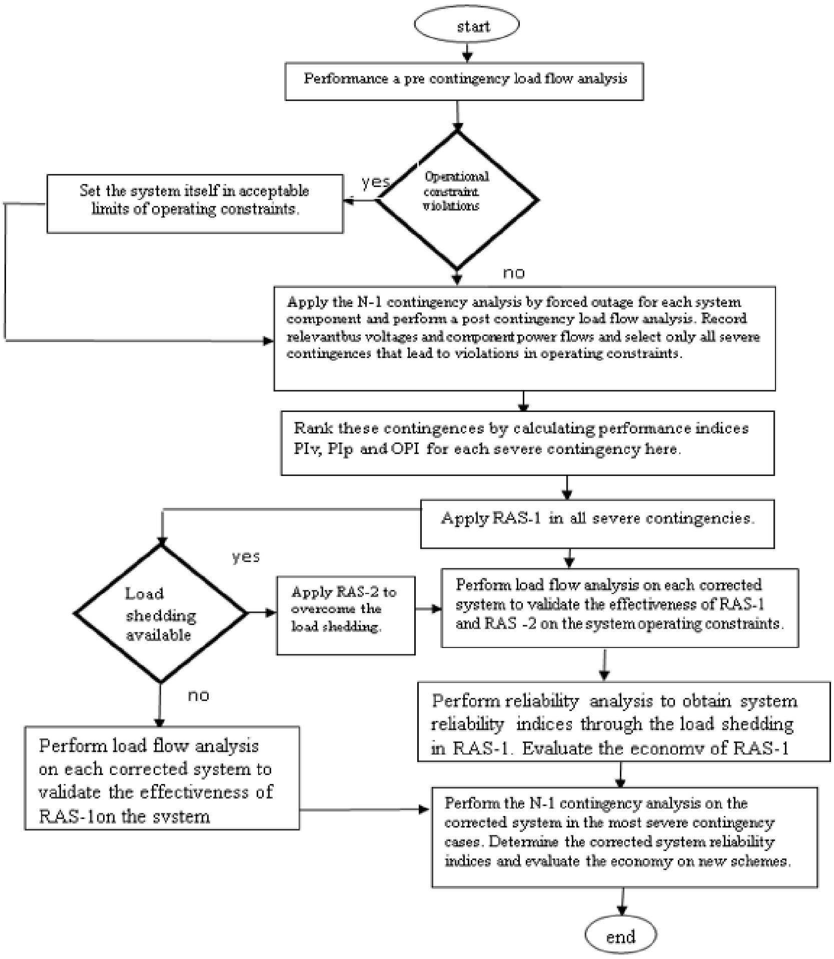

Figure 2. Flow chart of problem solution algorithm [81].

Violations statistic of N-1 CA shown in Table 1 is specified according to the system operating constraints. The minimum and maximum limits of allowed voltages were taken by 0.95 p.u and 1.05 p.u. The maximum thermal loading of elements is taken by 80 % and 100 % under normal and contingency conditions respectively. The performance indices and contingency ranking using NRLF are shown in Table 2. In this table, the performance indices and contingency ranking using Back Propagation Artificial Neural Network (BP-ANN) are obtained to clearly demonstrate the readability of work. The latest tendencies using ANN have brought lot of development inside the speed of contingency screening. Contingency ranking using BP-ANN is performed in MATLAB environment [81].

Table 1. Violations statistic of N-1 contingency [81].

Severe contingencies	Violations	Lower Voltage Limit
L1	1	0.839
L2	1	0.938
L6	1	0.942

Table 2. Violations statistic of N-1 contingency [81].

NRLF Algorithm					BP-ANN Algorithm			
Severe Contingencies	**PIV**	**PIp**	**OPI**	**Rank**	**PIv**	**pIp**	**OPI**	**Rank**
L1	5.737	0.0455	5.782	1	5.659	0.0452	5.754	1
L2	1.027	0.0539	1.081	2	1.025	0.0521	1.062	2
L6	0.992	0.0288	1.020	3	0.991	0.0267	1.016	3

In [39], A contingency analysis of the IEEE 14 bus system uses soft computing technologies for security assessment and contingency planning. A supervised learning approach using a Feed-Forward Artificial Neural Network (FFNN) and feature selection based on correlation coefficient ensures higher precision.

In [15], The paper discusses violations of PIDFs and LODFs, highlighting remedial actions and contingency plans. The proposed scheme accurately demonstrates higher-order contingencies and introduces remedial control actions.

In [14], The paper examines a six-bus power system, focusing on violations and corrective measures, and aims to enhance utilities' understanding of fast and intelligent computing techniques. In [4], The paper discusses classical research and modern contingency analysis trends, including hybrid artificial intelligence methods. It focuses on steady-state stability assessment in power systems to evaluate system resilience and propose corrective measures. It also offers guidance on using technical intelligent gateways for real-time contingency scenarios, incorporating contributions from multiple researchers, making it a valuable resource for further studies and development.

In [29], A study presents an online model for predicting voltage collapse using machine learning and the new line stability index (NLSI_1). The approach uses a multilayer feed-forward neural network and was tested on the IEEE 14-bus system and Nigeria 330-kV, 28-bus National Grid (NNG).

AI is a promising field for security analysis and contingency planning, with advancements in artificial neural networks accelerating the process. These techniques classify real-time data online and learn from offline training data, providing a faster alternative to analytical solutions. The accuracy of neural networks depends on factors like hidden layers and neurons selection.

In [83], a radial basis function neural network (RBFNN) improves online ranking of contingencies causing bus voltage and power flow violations, offering simplicity and accuracy in classification. Multiple severity indices are proposed in [84] for online contingency screening in dynamic security analysis (DSA). Fast contingency screening is a

crucial component of any realistic online DSA. Dynamic security contingency screening and ranking have been successfully achieved using multi-layer perceptron neural networks in [85-86]. These trained neural networks perform contingency screening and ranking based on the current operating conditions.
A backpropagation-trained multi-perceptron is used for power system contingency screening and static security evaluation [87-88]. A secure system maintains operational points within acceptable ranges despite disturbances. Operators predict potential contingencies and implement preventive control actions to maintain system integrity and supply continuity.

In [89], The authors developed three artificial neural network models: FFNN, layer recurrent, and RBF, to approximate fast voltage stability index (FVSI) under load scenarios. The study compared their accuracy in predicting critical lines and buses in test systems. RBF had better prediction accuracy, while FFNN showed better generalization with a maximum error of 0.03.

In [90], an RBF neural network approximates voltage security in a power system using L-index but requires more hidden neurons to achieve the same training error as a backpropagation trained FFNN.

For voltage stability analysis, a risk-based evaluation method utilizing the L-index was employed in [91]. The study utilized two ANN models, the generalized regression neural network (GRNN), and the multilayer perceptron neural network (MLFFN), to create the index. The results showed that the MLFFN provided a more accurate approximation than the GRNN, with a mean square error (MSE) of 7.107 * 10^ (-7). In [92], A FFNN and line stability index were combined to forecast voltage stability in IEEE 14 and IEEE 30 bus systems. The network achieved convergence with an MSE of 4.085 * 10^ (-4) and 7.132 * 10^ (-5), confirming its effectiveness.
In [34], utilized an ANN-based technique with the L-index as a stability indicator to evaluate voltage stability in the IEEE 14-bus system. According to the authors, this strategy yielded more accurate results, with an MSE of 0.0077424 and an R-value of 0.85998.

Lastly, [93] the main contribution of this work is to provide a scheme for the power systems to learn how to adjust the output power of the generators for different transmission line contingencies to prevent cascading failure and blackout which occurs due to transmission line overloaded sequential tripping of the lines. This article proposes a novel RL control approach based on the Q-learning algorithm for adaptive adjustment of the generated power from different generators to prevent cascading transmission line outages and blackout after N-1 and N-1-1 contingency conditions without using any load shedding.

This article presents an experimental implementation of the proposed approach on a hardware of the high-voltage (HV) side of the IEEE 30-bus system as shown in figure3. The applicability of the proposed RL method for the large-scale IEEE 118-bus power system is verified by simulation studies as well.

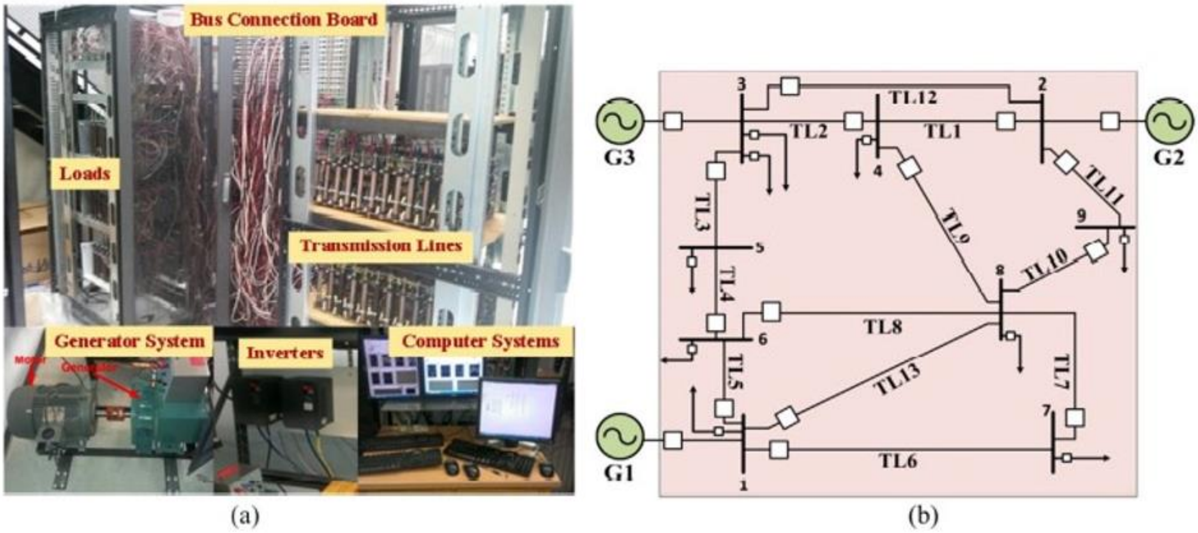

Figure 3. (a) Experimental setup in the lab (b) nine-bus power system (single line diagram.

N-1 contingency results without control (blackout)as shown in figure 4**.**

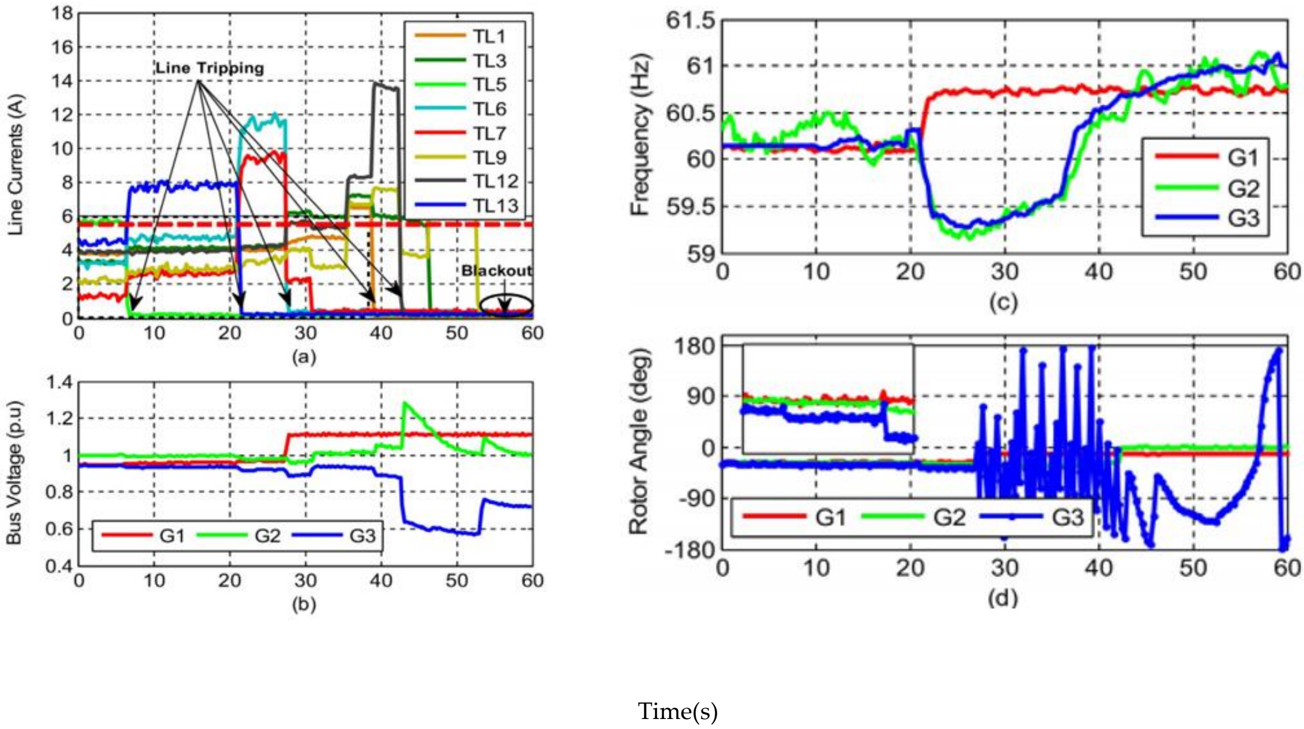

Figure 4. N-1 contingencies without control (blackout) [93].

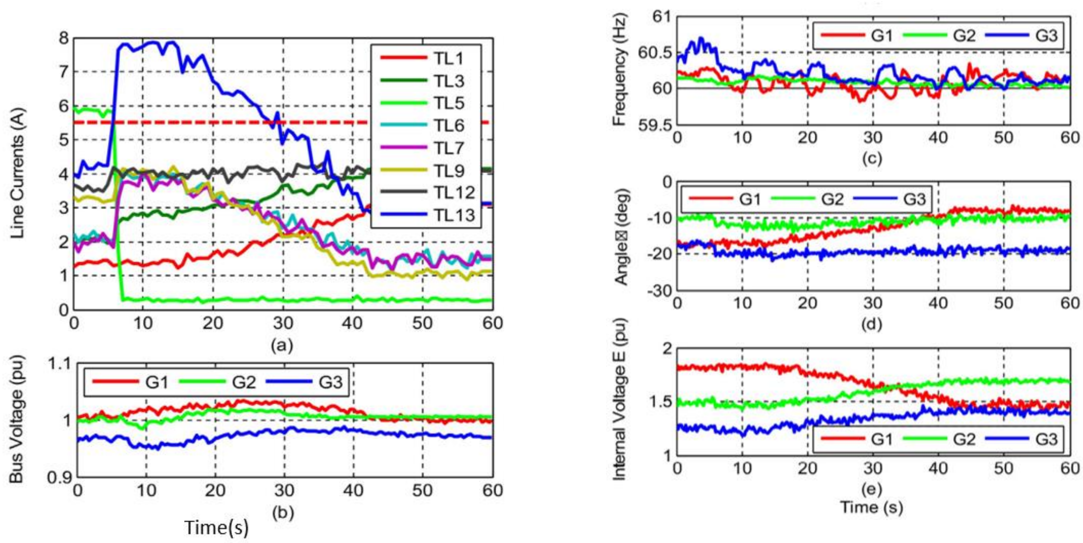

Figure 5. N-1 contingency with control RL control [93].

N-1 contingency results with Q-learning control algorithm in this scenario, the proposed Q-learning control algorithm was implemented on the system for the best action selection of output power adjustment to prevent cascading failure from propagating. Based on the obtained optimal action(s) with the highest Q-values from the training results. The best action signal(s) was (were) applied by the generator agents to change the power flowing through the transmission lines. The results after N-1 contingency as shown in figure 5.

7. Conclusion

In this review paper, we have explored the topic of power system security analysis and contingency planning, focusing on the application of artificial intelligence (AI) techniques. One area of particular importance that emerged from our discussions is the significance of remedial action schemes (RAS) in ensuring power systems' reliable and secure operation. RAS, also known as Special Protection Schemes (SPS) or System Integration Schemes (SIS), play a vital role in addressing violations and mitigating the impact of contingencies. These schemes consist of a set of steps and corrective measures that need to be implemented to restore the system to its regular operation and prevent further disruptions. Various types of RAS were identified, including shunt capacitor switching, generation re-dispatch, load shedding, under-load tap changing (ULTC) transformer, distributed generation, and islanding. Each type of RAS is designed to address specific contingencies and ensure the system remains within acceptable operating limits.

Furthermore, we emphasized the importance of different types of security assessments in power system analysis. Static security assessment (SSA) focuses on examining the steady-state response of the power system to contingencies, evaluating overvoltage/Undervoltage conditions, and assessing line and transformer overloads. Dynamic security assessment (DSA) investigates system variables before and after contingencies, analyzing the transient behavior and evaluating the stability of the system.

AI techniques, especially artificial neural networks (ANNs), have proven to be effective in both RAS implementation and security assessment. ANN-based models, such as feed-forward neural networks (FFNNs), recurrent neural networks (RNNs), and radial basis function (RBF) neural networks, have demonstrated their ability to classify contingencies, predict critical conditions, and suggest appropriate remedial actions.

The integration of AI into power system security analysis offers utilities advanced tools to enhance the speed, accuracy, and efficiency of security assessments. These techniques enable operators to make informed decisions, take preventive control actions, and maintain the integrity and continuity of the power supply.

As the field of AI continues to evolve, further research and development efforts are necessary to improve the robustness and applicability of these techniques. Future studies should focus on refining RAS strategies, developing advanced ANN models, and exploring hybrid AI approaches to address the dynamic and complex nature of power systems.

Overall, this review paper emphasizes the pivotal role of remedial action schemes and different types of security assessment in power system security. By leveraging AI techniques, utilities can enhance the resilience and reliability of power systems, ensuring the delivery of uninterrupted and high-quality electricity to consumers.

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