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An Overview of Contingency Analysis Regarding Steady State of Power System

Ghada Wahby [1,*], **Ahmed A.M. El-Gaafary** [2] , **Adel A. Elbaset** [2]

[1] *Electrical and Communication Engineering Department, Modern Academy for Engineering and Technology, Cairo, Egypt.*
[2] *Electrical Engineering Department, Faculty of Engineering, Minia University, El-Minia, Egypt.*

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ABSTRACT

Consistent security is a concept that pertains to the resilience of power systems in the face of predictable power grid emergencies, as assessed using a steady state model. This paper offers a comprehensive examination of strategies for assessing the steady-state security of power systems in the event of contingencies. Conventional techniques for evaluating steady-state security in power systems include full AC power flow analysis, simplified methods, and ranking contingencies. Research is conducted to optimize the full AC power flow algorithm and enhance the accuracy of approximate techniques. Furthermore, the criteria used for ranking contingencies, such as the performance index and the voltage stability margin, are explored in detail.

1. Introduction

Every industrialized nation's economy relies heavily on electricity. A constant and steady supply of electricity is essential in today's world, which heavily relies on it for various purposes such as powering electronic devices, supporting industrial production, and facilitating daily activities. Even a brief blackout or failure of all electricity can cause major disruptions to the region's essential infrastructure, including transportation, hospitals, water supplies, and even emergency services like fire, ambulance, and police. On the other hand, the odds of the transmission lines failing are growing because of increased overload.

Recently, blackouts have increased in frequency across the globe. Therefore, establishing an efficient system for managing contingencies is the main challenge in the world today.

The primary objective of this paper is to conduct a contingency analysis specifically within the context of the steady state security category. The following sections provide an extensive review of the literature on contingency analysis, covering a range of methods and techniques that are of significant interest to engineers. The remainder of the paper is structured as follows. In

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*** Corresponding author**

E-mail address: *eng_ghadawahby@hotmail.com*

Section II, a comprehensive presentation of the definition and research history of contingency analysis is provided. Section III reviews specialized approaches for contingency analysis during the security planning phase. Traditional approaches to contingency analysis for ensuring the steady-state security of power systems are discussed in Section IV. Section V shows conclusions and discusses future research needs.

2. Analyzing Contingencies

An operational outage in one or more equipment, like transformers, generators, and transmission lines, is referred to as a contingency. The practice of predicting potential outcomes for a power system in the event of unforeseen component breakdowns or topological changes is known as contingency analysis.

Because of high precision, Newton Raphson’s load flow approach is adopted. The following are the equations for real power, reactive power, and voltage magnitude:

$$Pi = \sum_{j=1}^{n} |V i||V j || Yij| \cos(\theta i j - \delta i + \delta j) \tag{1}$$

$$Qi = -\sum_{j=1}^{n} |V i||V j|Yij|\sin(\theta i j - \delta i + \delta j) \tag{2}$$

$$|Vi| = \frac{(Pi - j\, Qi)}{\sum_{j=1}^{n} |V i||V j|| Yij| \cos(\theta i j - \delta i + \delta j) + \sum_{j=1}^{n} |V i||V j|Yij|\sin(\theta i j - \delta i + \delta j)} \tag{3}$$

$$VSI = \frac{V_i}{\Delta V_i} \tag{4}$$

where n represent the total number of buses; |Vi| is the voltage magnitude at ith bus; |Vj| is the voltage magnitude at j bus; |Pi| is the real power; |Qi| is the reactive power; |Yij| and θij are bus admittance voltage and the angle at bus i and j respectively, VSI is voltage stability index and δi and δj are voltage angles at bus i and j respectively [20-21].

- **Steady estimator (N)**

  The steady estimator (N) aims to ensure sufficient facilities are available for the benefit of transmission customers and to provide a basis for safe, reliable, and affordable growth of the transmission system [1].

  When the system is stable and its equipment functions well within authorized ratings, this is the normal operation condition (N condition).

- **Contingency**

  Contingency analysis in its most basic form involves conducting a comprehensive AC power flow calculation for every potential interruption that is being examined. The process of calculating the MW flows, MVA flows, and bus voltage magnitudes of a power system following outages can be time-consuming due to the necessity to consider hundreds of branches, even in the case of a small power grid. Contingency analysis should ideally be conducted in real-time to ensure prompt implementation of corrective control measures following a contingency event [2]. If the strain is not alleviated, it may result in additional branch outages and prompt protective measures (such as load shedding and generator tripping) to be taken. In the most severe scenario, these chain reactions could culminate in catastrophic cascading failures, as depicted in Figure 1.[14] This section intends to define the issue of pinpointing these catastrophic cascading failures in power grids. Initially, a comprehensive mathematical model is proposed to represent the practical cascading failure of power grids under a variety of disruptive situations. So, there are two types of contingencies:

- **Single Contingency (N-1)**

  A single contingency N-1 of the system is the loss of a single system component. The system impacts at the contingency condition must keep the normal operation limits as voltage limitations and emergency loads supply. Thus, the N-1 condition means that the system can continue to operate within normal condition limits even if a single element fails.

- **Double Contingency(N-2)**

  Double contingency involves the loss of double system elements. This is frequently known as a (N-2) occurrence. The allowable system effect for an N-2 event is the same as for an N-1, In the event of loss of loads, as much as possible, we reduce the loss and consider this in the necessary loads permitted in an outage situation.

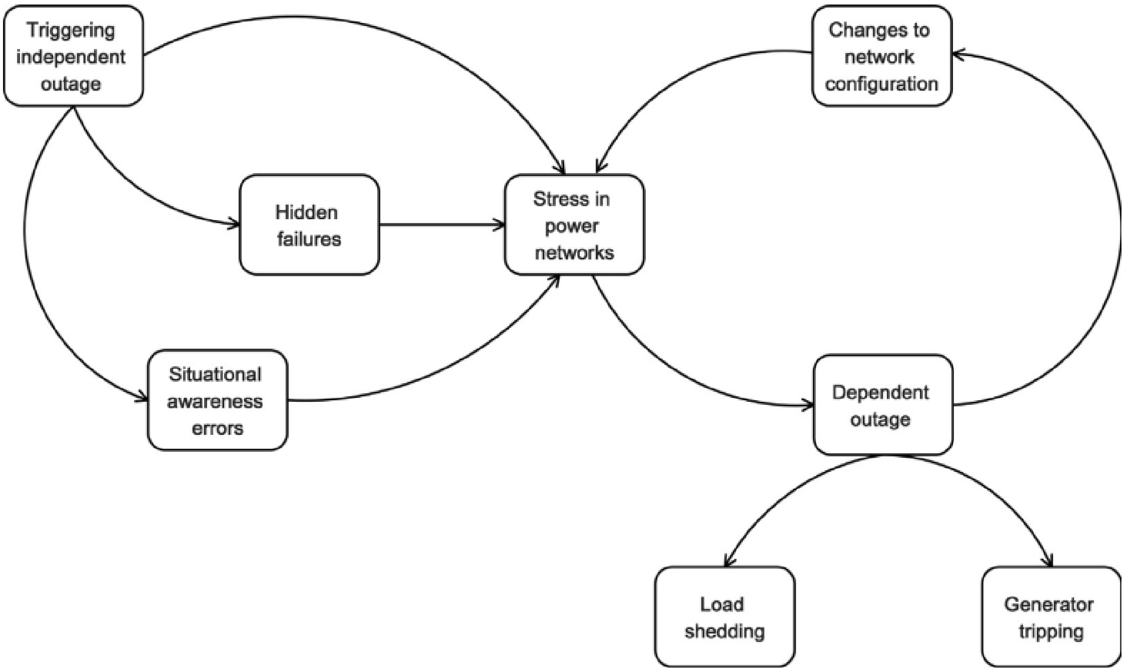

Fig.1. Failure process of power grids

3. Contingency study during the formulation level

Contingency analysis is crucial during the planning stage to ensure the steady-state security of a power system, which is vital in both the planning and operational phases. The planning stage encompasses both construction and operational planning. Widely utilized in these stages, contingency analysis helps maintain power system security. During the construction planning phase, the power grid is engineered to endure contingencies through an appropriate grid structure. For the operational planning phase, it's essential to choose contingency lists beforehand to prepare operators for potential scenarios following predictable power grid failures**.** For contingency, algorithms are shown in Figures 2 and 3 [20].

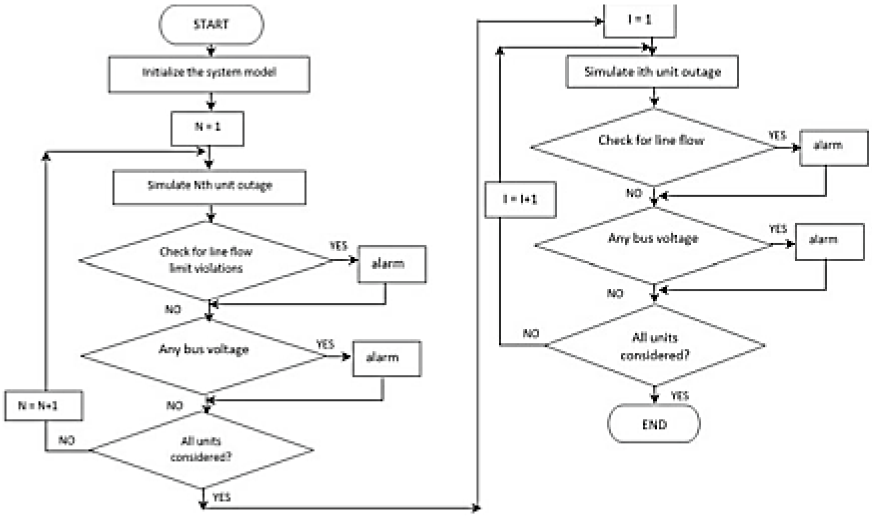

Fig. 2. Contingency analysis using simple method

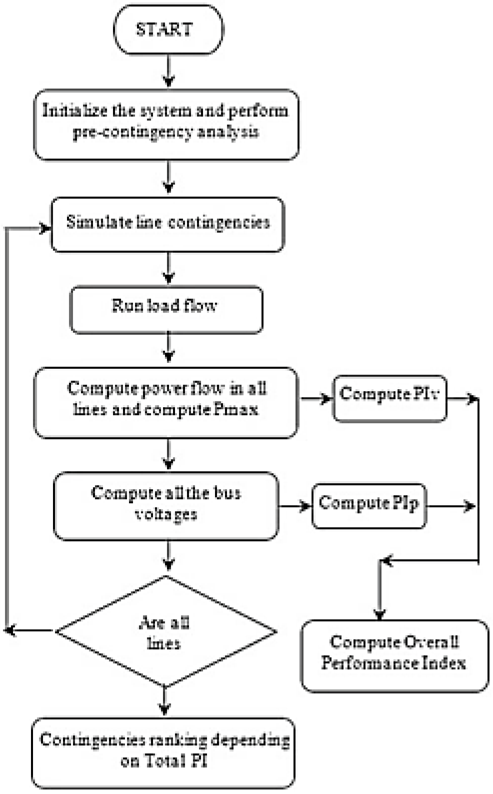

Fig. 3. Contingency analysis using Newton Raphson method

It proposes a strategy for placing Interline Power Flow Controllers (IPFC) based on a Composite Severity Index (CSI) to measure stress in power lines in terms of mega-watt overloading and voltage instability. The IPFC placement strategy is optimized using Differential Evolution (DE) and compared with Genetic Algorithm (GA), showing DE to be more effective. The Real Power Performance Index is used to determine the severity of loading on the system under normal and contingency conditions. The paper demonstrates that tuning the IPFC using DE significantly reduces the CSI, leading to improvements in system parameters such as active power loss, reactive power loss, and voltage deviation even under increased loading conditions. Weighting factors are introduced to reflect the relative importance of different indices in the system, with equal weightage given to all indices in this study. Overall, the study showcases the effectiveness of IPFC placement and tuning in enhancing power system performance and reducing the impact of contingencies [3].

Also, this research paper focuses on the optimal placement and sizing of Interline Power Flow Controllers (IPFC) for congestion and contingency management in power systems. It proposes a method for placing IPFC based on the probability of severity, utilizing the Composite Severity Index for contingency ranking of lines. The study uses the IEEE 14 bus system data to apply the proposed methodology, where IPFC placement is optimized using the cuckoo search algorithm. Results from the application of the methodology on the IEEE 14 bus system show a reduction in the system's overall Composite Severity Index, active power, and reactive power, indicating improved system performance. The paper also discusses the formulation of a multi-objective function to determine the optimal size of IPFC, considering objectives such as minimizing active power loss, total voltage deviations, security margin, and the usage of the minimum installed IPFC value. The study gives equal preference to all the objective functions in the multi-objective function formulation, with weighing factors used to reflect the relative importance of each objective [4].

Another method introduces a new method for determining the best location for Static VAR Compensators (SVC) in power systems, focusing on optimizing reactive power flows through transmission line switching to improve system performance and stability. By calculating a contingency index, the methodology identifies the most critical contingency affecting voltage levels in the system. It utilizes optimal AC power flows to minimize operational costs while considering various constraints like line switching, charge ability, and voltage limits. Testing on IEEE test systems of different sizes confirmed the methodology's effectiveness in selecting the optimal node for SVC placement and determining the required compensation value. The stability of the Electrical Power System (EPS) was also assessed to validate the approach. The study was supported by Universidad Politecnica Salesiana and GIREI - Smart Grid Research Group, aiming to optimize operational costs by balancing active and reactive power generation, demand, and flow through transmission lines [5].

Dynamic voltage-reactive compensators (DVCs) are essential for optimizing power systems by effectively managing reactive power through transmission lines. With their rapid response time, DVCs can quickly adjust reactive power injection, which helps improve system performance and stability during voltage fluctuations. By mitigating fast voltage variations and reducing excessive voltage regulator operations caused by factors like photovoltaic (PV) systems, DVCs contribute to enhancing system stability and reliability. DVCs offer the advantage of independently adjusting voltage-reactive injection on each phase, ensuring precise control over reactive power flow to maintain stable voltage levels across the distribution system. The incorporation of DVCs in power systems helps reduce power losses, mitigate voltage flicker, and minimize voltage imbalances, resulting in improved overall system efficiency and performance. DVCs provide continuous and fast control of reactive current, making them a valuable addition to existing voltage control devices such as capacitor banks and tap-changing regulators, as demonstrated in [22].

The swift advancement and widespread availability of phasor measurement units (PMUs) have led to the extensive application of measurement-based voltage stability assessment (VSA) in recent years. A hybrid VSA approach, integrating modelling and measurement, has been introduced for N-1 contingency analysis. Initially, a piecewise linear sensitivity method, which accounts for Q limit violations, is utilized to forecast post-contingency conditions using PMU data. Subsequently, these anticipated post-contingency states are employed to determine voltage stability indices through the Thevenin equivalent model. This hybrid technique is notably precise in estimating the voltage stability of the system during N-1 contingencies. A key benefit of this method is its ability to process all N-1 contingencies concurrently, thereby calculating the voltage stability index efficiently, making it highly suitable for real-time applications [6].

Transmission cables face significant challenges in the current market due to increased demand and the need to operate profitably. The reliability of the cables depends heavily on different outage situations, which are graded according to their severity using the Performance Index. Which, the performance index of the mathematical model is characterized by the ability to reduce power losses, optimize power flow distribution, and enhance system reliance against extreme events, as demonstrated through simulations analysis.

The design of power systems makes them particularly prone to malfunction, and although it is challenging to forecast an unplanned power outage, it is essential to analyse potential failures and foresee their effects on the electrical system's security. To assess the security of the electrical system, contingency analysis is used, and to forecast the characteristics of the power system after any number of outages, single or multiple models are employed. The primary objective of this study is to identify critical double-line failures that would lead to line flow violations in the power system. N2 contingency analysis is used to describe this. It takes a very long time to complete a thorough analysis of all conceivable N2 outcomes. An AC or DC power flow can be used to find significant double-line outages without evaluating all N2 possibilities. These results are contrasted with the entire AC power flow statistics, and these methods can identify many double-line outages that lead to line flow violations [15].

The study proposes a method for evaluating system severity by employing the Overall Performance Index (OPI) and the Newton-Raphson load flow technique to classify static security into five levels: secure, critically secure, insecure, highly insecure, and most insecure. This classification is enhanced by using the K nearest neighbour CCOPF (KNN) machine learning strategy, resulting in more accurate assessments [16].

The performance of machine learning classifiers trained on the IEEE 30 bus system is evaluated on the IEEE 14, IEEE 57, and IEEE 118 bus systems, demonstrating improved categorization of power system security assessment. Furthermore, a fuzzy logic approach is investigated for forecasting the five security classifications on the IEEE 14 bus test system, providing valuable insights for real-time security assessment applications.

4. Contingency Analysis on Steady-State Security

Some researchers focus exclusively on evaluating specific types of outages, such as branch outages. Others concentrate solely on assessing post-contingency voltage without interest in creating a ranking list. Many publications are dedicated to contingency ranking yet omit the evaluation aspect. Conversely, some studies integrate all these aspects into a single process. Across all these scenarios, the practice of contingency selection is greatly preferred by both researchers and practicing engineers.

This paper [7] describes a Safety Level Classification (SLC) method to quantitatively and qualitatively evaluate the safety level of power systems. The method ranks security levels based on the Comprehensive Security Index (CSI), which integrates the System Margin Index (SMI) and entropy load. The SMI takes into account the operating load and total supply capacity (TSC) under the N-1 emergency, while the load entropy reflects the heterogeneity of the load distribution calculated from entropy theory. To calculate the TSC under N-1 emergency accurately and efficiently, it is transformed into the Extended Cone Quadratic Programming (ECQP) model. In addition, a Load Limit Vector (LBV) model was created to determine the maximum capacity of each load bus, and to identify potential risks in power systems. The feasibility of the SLC method was verified by studying two practical modified power systems and an IEEE 118-bus test system.

Paper [1] shows how to enhance the security assessment of energy systems by providing a comprehensive approach that takes into account various factors to accurately and efficiently determine the security level. This is by focusing on the operations and oversight objectives of the Southern Operating Area (SOA) Section to ensure the safe, secure and economical operation of the system during the peak summer of CY2016. It discusses identifying operating conditions, system bottlenecks, and control procedures necessary to maintain system stability and equipment safety under various emergency scenarios. Power flow studies have been performed to evaluate the security of large grids and clusters under various outage scenarios, including single transmission facilities and limited dual emergencies. The study also addressed thermal overloads, voltage violations, and the need for additional generating or support equipment to maintain system voltage within specified limits. The paper highlights the importance of system planning criteria, performance evaluations, and the use of the Power System Simulation for Engineering (PSS/E) computer package in analyzing current power flow in SOA.

Contingency Optimal Power Flow (CCOPF) is a power system optimization problem that ensures generation dispatch remains within limits during contingencies [8]. introduces a Quadratically Constrained Quadratic Programming (QCQP) formulation for preventive CCOPF, minimizing changes in power dispatch post-contingency. An extended OPF model is proposed for corrective CCOPF, maintaining node voltage equality pre- and post-contingency with different power dispatch scenarios. The QCQP strategy requires a conversion function to transform the system into a QCQP problem, while the extended OPF approach does not need additional solvers but requires a new constraint for node voltage equality post-contingency The OPF formulation involves decomposing variables into real and imaginary parts, organizing constraints matrices for each node, and considering constant terms for equality and inequality constraints. The research paper proposes a preventive augmented power dispatch model to enhance power system resilience against extreme events by considering a new N-1-1 security criterion and an iterative contingency assessment process based on the line outage distribution factor.

The model is designed to minimize the risk of overload outages by optimizing the power flow across transmission lines and integrating controllable series compensation devices to enhance the distribution of power flow. Case studies on systems indicate that the proposed model can avert branches from bearing excessively heavy loads, particularly during extreme events, resulting in a 40% decrease in average power losses when compared to traditional economic dispatch models as detailed in [9].

The research [10] presents a framework for power system contingency analysis using hierarchical clustering and principal component analysis (PCA). The study focuses on assessing the impact of losing elements in power systems to ensure network integrity and security. The proposed framework utilizes the IEEE 24-bus test system to evaluate the performance of the hierarchical clustering algorithm under different scenarios, such as single-generation unit outages and multiple transmission line failures. Different similarity measures for agglomerative hierarchical clustering are explored, including single linkage, complete linkage, ward, and average methods, with the ward method showing the best results for further investigation. The framework involves generating contingencies using MATLAB, applying fast decoupled power flow algorithms, and using insecurity indices to quantify the severity of each contingency.

The research aims to optimize power systems' resilience through a heuristic approach that integrates DCOPF, OTS, and contingency analysis, ultimately improving system response and reliability under disturbances. [11] The research focuses on enhancing the resilience of electrical power systems post a contingency by strategically switching transmission lines using a heuristic approach that combines optimal dc power flows (DCOPF), optimal transmission switching (OTS), and contingencies analysis. The methodology involves determining the order of reconnection for elements that go out of operation after a contingency, utilizing DCOPF to establish operating conditions and OTS to identify the maximum number of lines that can be disconnected with minimal impact on the contingency index. By analysing different line-switching scenarios and selecting the one with the lowest J value for reconnection, the system's resilience is maximized, ensuring stable and reliable operation within set parameters.

In this [12] study emphasizes the importance of considering uncertainties from renewable resources and probabilistic contingencies in the stochastic co-optimization of energy and reserves, providing valuable insights into enhancing power system performance and avoiding failures during contingency situations. It introduces the stochastic security-constrained economic dispatch (SSCED) model to optimize economic dispatch decisions during uncertainty, focusing on the complexities arising from the stochastic nature of renewables and contingency occurrences. The proposed SSCED model co-optimizes frequency control reserves with energy dispatch to handle uncertainties from renewable energy availability and probabilistic contingency conditions, showcasing technical and financial benefits through case studies on a grid-connected microgrid system.

The authors [13] propose a mathematical approach using the Jacobian-Free Newton-Krylov method to pinpoint these initial contingencies accurately without relying on the Jacobian matrix, making the computations more manageable and efficient. A numerical algorithm is developed in the study to effectively search for these disruptive events that can lead to cascading failures in power systems. The algorithm showcases guaranteed convergence accuracy theoretically. The efficacy of the proposed identification approach is demonstrated through case studies conducted on IEEE test systems utilizing various cascade models. This helps showcase the practical application and success of the developed method.

The authors introduce a novel analytical method for calculating the "N-1" transmission line outage post-contingency states of the power system in a swift manner, without the need for repetitive calculations. This technique is optimal for online vulnerability assessments involving large-scale transmission networks and wind power resources. The proposed methodology is based on the concept of a pretending line outage principle and a pre-contingency Taylor Series Approximation. Additionally, an adaptive approach is suggested for selecting the critical lines. The method's effectiveness in addressing the uncertainty of operating conditions, brought on by wind power resources and load demand forecast errors, is studied in the IEEE 118-bus and IEEE 300-bus test systems. Lastly, the simulation results demonstrate the proposed approach's efficiency and accuracy, making it a suitable choice for online operational vulnerability assessments.[14]

The authors in [17] show that transient load fluctuations exacerbate challenges for generators, transmission lines, and distribution networks. To determine the system's characteristics, it is crucial to examine the most appropriate load modelling techniques. In this study, a ZIP load model is utilized because it generates precise and long-lasting representations of loads when combined with contingency criteria, constant impedance, constant-current, and constant-power loads. The goal of this research is to devise a method that uses machine learning to determine the contingency ranking in the event of a single transmission line outage, ensuring the system's behaviour. The proposed mathematical model, which incorporates a Particle Swarm Optimization algorithm, is used to conduct stability analysis both with and without considering STATCOM and Unified Power Flow Controller, as well as cost analysis. The power system faces numerous unforeseeable conditions or contingency scenarios, such as single and double transmission line outages, generator outages, and load variations. This paper primarily focuses on obtaining the contingency ranking for single transmission line outages and generator outages. The recommended stability analysis is valuable in establishing a dependable transmission power system.

Contingency analysis is a mathematical approach for predicting the failure of specific equipment or a system and taking corrective action before it reaches an unstable state. One contingency could be the insertion or removal of one or more components in an electrical network. By making these adjustments, the power system may no longer function within safe operating limits. Immediate corrective action is necessary to prevent the system from entering an unstable state. Contingency ranking selection is a useful method for evaluating the safety of a power system. This article outlines the research conducted on contingency analysis, including the identification of performance indicators and their classification based on severity. A small system consisting of 14 buses was tested for various emergencies, and it was found that the number of violations decreased, and the majority of the parameters fell within safe operating limits.[18]

5. Conclusion

This paper reviews several prominent methodologies for contingency analysis in power system steady-state security, as discussed in the current literature. Traditionally, contingency analysis relies on established methods. Yet, full power flow methods are hindered by their computational intensity, and approximate methods do not provide sufficient accuracy. Contingency ranking methods seek a balance between computational efficiency and accuracy. Recent advancements in artificial intelligence and parallel computing seem promising in addressing the technical limitations highlighted in this document. Moreover, trends indicate that online security analysis will become a key research focus in this field.

Contingency analysis is a vital aspect of ensuring the steady-state security of power systems. There are several traditional methodologies used for this purpose, including:

1. Full AC Power Flow Analysis: This method involves solving the complete set of nonlinear AC power flow equations for the entire network. Although it provides accurate results, it can be computationally intensive, especially for large-scale systems.
2. Approximate Methods: These techniques simplify the power flow equations to reduce computational complexity. Examples include the DC power flow model, which neglects reactive power, and the decoupled load flow method, which separates real and reactive power calculations.
3. Contingency Ranking: Contingency ranking assesses the impact of specific contingencies, such as line outages or equipment failures, on system security. It identifies critical contingencies based on severity indices, allowing operators to prioritize corrective actions.
4. Stability Margin Index: This index quantifies the margin between the operating point and stability limits. By evaluating stability margins for different contingencies, operators can assess system robustness.

ORCID iDs

Adel A. Elbaset https://orcid.org/0000-0002-0762-5180

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