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Research Article

$N-1$ Security Criteria Based Integrated Deterministic and Probabilistic Framework for Composite Power System Reliability

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Unpredictable variations in load demand and unanticipated component failures are progressively impacting the operation of modern power systems, making system evaluation more stochastic in nature. Although deterministic approaches were formerly the norm for determining system status, probabilistic approaches have greatly improved the capacity to capture the stochastic behavior characteristic of power system operations. The presented work in the paper recommends the use of probabilistic modelling approaches with deterministic approaches, highlighting their crucial function in augmenting the reliability and security of contemporary power systems to unanticipated failures. In this paper, $N-1$ security criteria based reliability of the composite power system (CPS) is proposed using an integrated deterministic and probabilistic framework (D-P) considering outage of the transmission line. For the deterministic approach (DA), line overloading on available lines is determined using the static security index (SSI). For the probabilistic approach (PA), reliability indices such as expected loss of power (ELOP), expected frequency of contingency (EFOC), expected loss of load (ELOL), probability of load curtailment (PLC), and expected duration of load curtailments (EDLC) are calculated. Further, for each contingency, a performance index is determined using both approaches to assess the severity of the contingency that occurred on the power system. Based on the $N-1$ security criteria based reliability analysis using an integrated D-P framework, a credible critical set of transmission lines is obtained, which can serve as important information to system operators. The proposed techniques have been tested on IEEE 24 bus reliability test system (RTS).

1. Introduction

1.1. Background. Composite power systems (CPSs) involve the integration of various power sources, transmission lines, and components, presenting different challenges in the evaluation of security and reliability. The complexity of CPS comprises various interactions between components and uncertain operating conditions; thus, contingency analysis is a significant part of power system security and reliability. For a secure power system, reliability evaluation becomes important for power system transmission design and operations. Examining the performance of a power system and the requirement for new transmission expansion due to load growth or generation expansion is an important aspect of power system planning and reliability. In an unforeseen event, security assessment informs system operators about the secure and insecure nature of operating states, allowing suitable control/corrective action to be initiated within the safe time limit. In the planning and operation of CPS, many electric power companies conventionally use deterministic methodologies [1–4]. The deterministic approach (DA), in the context of $N-1$ security criterion, evaluates the system's ability to withstand the loss or outage of any single critical component without resulting in a system failure. This approach provides an appropriate and deterministic framework for security evaluation, assuring that the power system remains secure even when subjected to insecure/outage scenario. By assessing various operating conditions,

including outage scenarios such as line outages, contingency analysis provides critical insights into the reliability and security status of CPS [4, 5].

Most utilities use conventional DAs considering the limitations on operational parameters (e.g., generation, MW flow, and voltage) for evaluating power system reliability and security. DA has significant drawbacks when used for evaluating power system reliability. It is based on simplified assumptions and static models that assume fixed operating conditions and constant parameters, resulting in an inaccurate representation of uncertain nature of the practical power system. Also, these approaches do not incorporate the probability of occurrence of the contingencies [6]. DA fails to incorporate stochastic behavior of CPS; therefore, probabilistic approaches (PAs) are introduced to simulate the randomness of contingencies. The inherent uncertainties and variability in power system components and operating conditions are recognized and incorporated in CPS by PA. The approach calculates the likelihood of system failure under various scenarios, providing a more comprehensive understanding of the system's response to uncertainties and contributing to a precise evaluation of security and reliability. These approaches generate quantitative indices that may be used to determine whether the system performance is satisfactory or changes are required [4–6]. PAs incorporate the reliability aspect into the system for evaluation of system security. The occurrence of contingencies, particularly line outages, is stochastic and can impact the system heavily. To broadly classify risk due to component failure, PAs can be applied with DAs to evaluate system security to quantify the impact on the system and to develop a critical contingency set of components. The combined use of DA and PA is a novel concept that emphasizes on the benefits of both methodologies. This integration is especially important for assessing the security and reliability of power systems using the $N-1$ criterion [5, 7, 8]. The integration of DA and PA in current research scenarios improves reliability analysis by providing a thorough understanding of CPS behavior. Since DA ensures a rigorous evaluation under certain conditions, PA adds a probabilistic dimension to account for the uncertainties inherent in real-world power systems. This integrated methodology enables a more nuanced assessment of the system's security and reliability, particularly under diverse and changing operational conditions like component outage. The integrated approach assists operational personnel in implementing an appropriate control action plan to mitigate the impact of component outages on the system [8, 9].

1.2. Literature Review. A lot of research has been carried out in the area of security evaluation of power systems using deterministic and probabilistic approaches. In [4], emphasis has been made on the impact of single contingencies using the probabilistic technique by calculating expected energy not supplied (EENS) on composite power systems. In [10], a deterministic and probabilistic reliability criteria approach is proposed for bulk power system expansion planning considering uncertainties in network components based on the cost of construction. In [6], a combined adequacy and security framework is proposed considering generation and transmission deficient environment on the system using $N-1$ probabilistic reliability criteria. In [11], a comparative analysis of deterministic and risk-based security assessments is proposed considering the level of risk due to different weather conditions on the system by simulating the outage of components ($N-1$ criteria). In [5, 7, 12, 13], a detailed overview of security evaluation of power systems using deterministic and probabilistic methods is proposed, including the severity of components as a function of peak load, contingency analysis, and multiarea reliability assessment for transmission planning and system analysis. Ranking of severity of transmission lines using a probabilistic performance index for contingency analysis is proposed in [14, 15]. In [16], a probabilistic voltage security assessment is presented to enhance situational awareness in power systems considering different risk levels of voltage violations. In [17–19], contingency ranking by evaluating risk on power system using various strategies such as classification of reliability criteria from $N-1$ deterministic to probabilistic approach based on expected total cost and service reliability levels, a bilevel optimization model for evaluation of *N-k* contingency, and artificial neural network for static security assessment. In [20, 21], a short-term reliability evaluation highlighting various reliability criteria is proposed considering TSOs' (transmission system operators) short-term decision-making by socioeconomic and reliability indicators using the probabilistic approach over the $N-1$ deterministic approach. A short-term reliability management approach and criteria are proposed using a probabilistic approach in terms of energy not supplied, and the fairness aspect is perceived. In [22–24], composite power system security evaluation, which includes transmission planning, is highlighted by considering deterministic criteria and probabilistic reliability criteria by assessing component failures on the system. Furthermore, a delivery marginal rate (DMR) for deterministic reliability is proposed with expansion planning by evaluating the minimization of total cost considering N-k contingencies. In [25], a risk-based ranking approach is proposed which incorporates voltage violations and line thermal limits with consideration of failure rates. In [9], a probabilistic approach is proposed to evaluate system reliability and flexibility associated with generating units by considering various uncertain factors such as component outages and load forecasting errors.

On the basis of literature review, the advantages and disadvantages can be elucidated within the current research scenario emphasizing on evaluation of security and reliability of power systems.

1.2.1. Advantages

(i) DA provides a fundamental and vital assessment of power system security under prescribed conditions for measuring the impact of a single component outage ($N-1$ criteria). DAs are computationally efficient and effective which is beneficial for scenarios involving a quick and interpretable

evaluation. The familiarity and historical use of DA provides a baseline for evaluating changes and improvements in power system reliability strategies [10, 11, 19, 25].

(ii) PA considers fluctuations in load demand, generator output, and component reliability to determine the possibility of system failure under various scenarios using risk-based computational models emphasizing on limit violations, energy not supplied, and other uncertain factors resulting in a comprehensive risk assessment [4, 7, 9, 12, 14, 15, 22–24].

1.2.2. Disadvantages

(i) The major drawback of existing literature on implementing DA is its ineffectiveness to meet the complexities and uncertainties involved with changing power systems with dynamic demand patterns. The probabilistic aspect of certain events, particularly those with a stochastic or random component, is not taken into account by DA. This shortcoming can be challenging for system operators for assessing reliability indicators in scenarios with varying and unpredictable conditions [10, 11, 19, 25].

(ii) PAs employed in existing literature are computationally demanding especially in real-time applications and for systems with a significant scale. Further, PA heavily relies on accurate data for load profiles, generator characteristics, and equipment reliability. Hence, deterministic statistical handling of data in PA for measuring risk and reliability indices is crucial for enhancing decision-making for system operators [4, 7, 9, 12, 14, 15, 22–24].

In the current research environment, the shortcomings of a purely deterministic approach to solving the problems presented by contemporary power systems are becoming increasingly apparent. To improve the CPS reliability evaluation, there is a growing need to integrate them with probabilistic methods. With this integration, uncertainties, variances, and unforeseen events may be taken into account more realistically, leading to a thorough understanding of system behavior.

1.3. Novelty and Contributions. The extensive literature review emphasizes the crucial role of security assessment in composite power systems (CPS) and its important ramifications for system operators' ability to make well-informed decisions. Notably, the research emphasizes the necessity of a comprehensive investigation and the importance of the deterministic approach. However, an important paradigm shift towards a more comprehensive probabilistic framework, particularly with regard to improving system reliability, is necessary. This shift in perspective is considered crucial in order to enable system operators to acquire a complete set of contingency strategies that account for line interruptions and stress the importance of adhering to the $N-1$ security criterion. Thus, the integrated deterministic-probabilistic approach becomes an essential tool for handling the intricate problems in CPS, providing operators with useful information to strengthen system resilience and ensure a constant, reliable power supply for end users.

This paper aims to evaluate the reliability of CPS, considering the deterministic and probabilistic approach incorporating $N-1$ security criteria. Single-line outage contingency is applied on the test system, and various indices have been calculated. The proposed approach is investigated on IEEE 24 reliability test system (RTS). The major contributions of the paper are as follows:

(i) System security is evaluated using the deterministic approach (DA) by analyzing the line overloading due to line outage on other available lines with the static security index (SSI) and performance of the contingent line is assessed by calculating the line performance index (PI).

(ii) To incorporate the stochastic nature of the power system in the security evaluation, the reliability aspect is considered by evaluating using the probabilistic approach (PA). In this approach, different reliability indices have been calculated, including expected loss of power (ELOP) and expected frequency of contingency (EFOC). Load curtailment indices have been calculated where the loss of load scenario occurred due to a single line outage on the system. These indices include expected loss of load (ELOL), probability of load curtailment (PLC), and expected duration of load curtailment (EDLC).

(iii) Further, a comparative analysis has been carried out from both approaches. For proper engineering judgement, the system operator can obtain maximum benefit by combining information obtained from both approaches. Therefore, in this paper, an integrated deterministic-probabilistic (D-P) framework is proposed which gives a credible contingency set of critical transmission lines for comprehensive security and reliability analysis considering the system's stochastic behavior.

The integrated deterministic-probabilistic (D-P) framework presented in this study offers a robust framework for conducting security evaluations in composite power systems (CPS) when confronted with line outage contingencies. Table 1 presents an extensive review of relevant literature that highlights the relative benefits of the proposed methodology in comparison to studies that apply either the probabilistic approach (PA), deterministic approach (DA), or both for CPS security or reliability evaluations. Notably, the proposed approach may be used to a variety of system types, facilitating an exhaustive evaluation that complies with the $N-1$ security requirements and incorporates a wide range of reliability indices, all performed within a substantially shorter computation time.

Table 1: Comparison of the proposed approach with other studies.

Comparison parameters	Al-Shaalan [15]	Heylen et al. [17]	Kumar and Mathew [19]	Nguyen and Negnevitsky [22]	Tan and Shaaban [25]	Billinton and Mo [4]	Proposed approach
Applicability	Only for small systems	Only for small systems	For both small and large systems	Only for small systems	For both small and large systems	For both small and large systems	For both small and large systems
Evaluation of system security (DA, PA, or D-P)	PA	PA	DA	PA	DA	D-P	D-P
Reliability indices	None	ETC, RLC	None	None	None	EENS	ELOP, EFOC, ELOL, PLC, EDLC
Computation time	Low	Low	Low	High	High	High	Low

1.4. Paper Organization. The paper has been categorized as follows: in Section 2, the $N-1$ deterministic approach has been explained to evaluate system security; in Section 3, the $N-1$ probabilistic approach has been highlighted considering the reliability perspective; Section 4 discusses the proposed integrated D-P framework considering $N-1$ security criteria; Section 5 depicts the results on IEEE 24 RTS using both the methods and the proposed framework, and the conclusion of the paper is highlighted in Section 6. Limitations and future scope are discussed in Section 7.

2. $N-1$ Security Criteria Based Deterministic Approach (DA)

Security evaluation in composite power systems has been a concern for many years in power system planning. Component failures that cause network violations may lead to catastrophic effects on the system [4]. Over the years, deterministic approaches have been considered for the security evaluation of the system. Here, $N-1$ contingency analysis has been considered to determine the impact of outage of only one component on the system. Deterministic approaches are convenient to power system planners as they are less complex and can be easily applied. The objective behind these approaches is to analyze the system for most likely outages which may result in line overloads or voltage violations [5, 11]. In this paper, the static security index (SSI) is considered for deterministic analysis of composite power system security.

2.1. Static Security Index (SSI). The line overloading problem is quite common in power systems when transmission line outage takes place. The severity of line outage on other transmission lines is one of the essential aspects when security evaluation of CPS is carried out. This severity of the contingency is expressed by security indices which measure the stress on the system in terms of line overloading [19]. The impact of a single line outage on other transmission lines is greatly influenced by loading conditions as it affects the power flow of other lines. This impact can be measured using an index called the overloading index (OI) given as

$$\mathrm{OI}_k^i = \frac{S_{k,i}^{\mathrm{post}}}{S_k^{\max}} \approx \left\{ \begin{array}{ll} \mathrm{OI}_k^i \geq 1, & \text{line is overloaded} \\ 1 < \mathrm{OI}_k^i \geq 0.5, & \text{line is operating in insecure state} \\ \mathrm{OI}_k^i < 0.5, & \text{line is operating normally} \end{array} \right\}. \tag{1}$$

Monitoring OI_k^i ensures that transmission lines operate within their thermal limits. Based on the assessment of the overloading index using equation (1), a categorization is formulated and it is shown as follows:

(1) For $\mathrm{OI}_k^i < 0.5$, when OI_k^i for line k falls below 0.5 as a result of line i outage, it implies a nominal impact on available line k. In simple terms, this means that despite the outage of line i, line k is operating normally.

(2) For $1 < \mathrm{OI}_k^i \geq 0.5$, when OI_k^i falls between 0.5 and 1 following the outage of line i, it indicates that line k is in an insecure state. According to this, line k is operating at a higher risk of overloading and might potentially have a severe impact system security.

(3) For $\mathrm{OI}_k^i \geq 1$, when OI_k^i for line k is more than 1 as a result of a line i outage, it indicates that line k is overloaded. This represents a critical state in which line k capacity has been exceeded, providing an impending risk of equipment stress and potential breakdowns. It also emphasises the importance of intervening and taking corrective measures to relieve the load on line k and prevent cascading effects that could jeopardise the overall security of CPS.

Based on OI_k^i of transmission lines, static security evaluation is carried out. This evaluation accounts for whether, after a disturbance, a steady state operating condition is reached without violation of network constraints. For this, the power flow solution is obtained during normal operation while satisfying the following network constraints [18, 19, 26]:

(i) Power balance constraints are as follows:

$$\begin{aligned} \sum_{g=1}^{N_G} P_g - P_D &= \sum_{m=1}^{N_{\mathrm{bus}}} |V_d||V_m||Y_{dm}| \operatorname{Cos}(\theta_d - \theta_m - \delta_{dm}), \\ \sum_{g=1}^{N_G} Q_g - Q_D &= \sum_{m=1}^{N_{\mathrm{bus}}} |V_d||V_m||Y_{dm}| \operatorname{Sin}(\theta_d - \theta_m - \delta_{dm}). \end{aligned} \tag{2}$$

(ii) Generation constraints are as follows:

$$\begin{aligned} P_{g_{\min}} \leq P_g \leq P_{g_{\max}}, \\ Q_{g_{\min}} \leq Q_g \leq Q_{g_{\max}}. \end{aligned} \tag{3}$$

(iii) Bus voltage limits are as follows:

$$V_{d_{\min}} \le V_d \le V_{d_{\max}}. \quad (4)$$

(iv) Line MVA limit is as follows:

$$|S_{dm}| \le |S_{dm}^{\max}|. \quad (5)$$

The static security index (SSI) is proposed to determine whether the line outage contingency on the system is critical or not. SSI evaluates the static security of the system when line outage contingency takes place accounting for all overloading on all the lines. SSI can be expressed for the contingent line or outage of transmission line i as [26]

$$\mathrm{SSI}_i = \sum_{k=1}^{Na} \mathrm{OI}_k^i. \quad (6)$$

The three categories for the contingent transmission line based on SSI are given in Table 2.

The contingent line is noncritical (NC) if SSI is within acceptable limits and the system is also secure. If the obtained SSI values fall under the other two categories of most critical (MC) or critical (C) category, then it may force the system towards the insecure condition. Also, those contingent transmission lines are placed in the most critical category where the power flow failed to converge.

2.2. Line Performance Index (PI). The extent of SSI assessed for each transmission line can be quantified by evaluating the performance of transmission lines on outage, considering overloading lines due to its outage. This formulation can be accomplished using an index called the line performance index (PI) [14, 15]. The line performance index is an extended analytical index that accounts for the overloading of lines in the system due to the outage of a transmission line. PI of line i on outage can be expressed as

$$PI_i = \sum_{k=1}^{N_{ol}} \frac{wt}{X} \left(\frac{S_{k,i}^{\mathrm{post}}}{S_k^{\max}} \right)^X, \quad (7)$$

where wt is the positive weighting factor considered equal to 1 and X is the order of the function considered as $2n$. For this analysis, the value of n is considered as 1. The number of insecure or overloaded lines for PI calculation is selected on the basis of the formulation of SSI.

Data preprocessing is essential in calculating indices which ensures overall robustness and interpretability of the approach. For this, the data are normalized to minimize redundancy and improve data integrity. The indices calculated for each transmission line in DA are normalized between 0 and 1, and criticality is analyzed. For each value of x (input or output), it can be normalized as x_{norm} as follows:

$$x_{\mathrm{norm}} = \frac{x - x_{\min}}{x_{\max} - x_{\min}}, \quad (8)$$

where $x_{\max}$ and $x_{\min}$ are maximum and minimum values of parameter x.

Table 2: Categorization of contingent transmission lines based on SSI.

Range	Category
$\mathrm{SSI} \ge 0.8$	Most critical (MC)
$0.3 \le \mathrm{SSI} < 0.8$	Critical (C)
$\mathrm{SSI} < 0.3$	Not critical (NC)

Deterministic approaches are generally applied for the $N-1$ criterion where outage of one component can be analyzed. The important limitation of this approach is the failure to incorporate the random or stochastic nature of the power system. This random nature usually occurs when any component failure takes place or unexpected load demand arises. Predetermined constraints on operating parameters such as MW flow and generation voltages are considered when failure of the component takes place. Contingencies occurring are stochastic, and considering the limits of constraints as a function of probability is difficult. So, deterministic approaches incline the system towards costly operating conditions where the level of risk is low. To consider the stochastic nature of power system operation, probabilistic methods are considered for security evaluation which incorporates the probability of occurrence of line outage contingency and its impact on the system.

3. $N-1$ Security Criteria Based Probabilistic Approach (PA)

Probabilistic approaches for security evaluation consider the probability of outage occurring on the system. These approaches consider the impact of contingency on system adequacy and security. These two aspects are related to the reliability of composite power systems. The main advantage of incorporating the probabilistic approach is that they can be applied with deterministic approaches to quantify the risk on the system to a more considerable extent [4, 5]. In this study, to analyze single-line outage conditions, reliability indices are calculated, and deterministic PI calculated in Section 2.2 is made probabilistic to assess the criticality of contingency on the system.

3.1. Reliability Indices. Reliability evaluation in CPS is assessed through a set of indices known as reliability indices. These indices are estimated through the past performance of components (generator or transmission line). The past performance data are generated through various techniques, which include both conventional and hybrid approaches such as Monte Carlo simulation (MCS) [2, 27], MCS-ANN-based methods [28–31], and cross entropy-based techniques [32, 33]. To evaluate reliability considering $N-1$ security criteria, the probability of each line outage contingency is estimated using the availability and unavailability (forced outage rate (FOR)) of each transmission line. Mean time to failure (MTTF) and mean time to repair (MTTR) are calculated based on recorded statistical and historical events of

the transmission line in terms of failure rate and repair rate. Availability and unavailability of a transmission line are formulated as follows [2]:

$$A(T_k) = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}}, \tag{9}$$

$$U(T_i) = \frac{\text{MTTR}}{\text{MTTF} + \text{MTTR}}, \quad i, k \in Nl. \tag{10}$$

The probability p of contingent line i is evaluated as [15]

$$p_i = \prod_{k=1}^{\text{Na}} A(T_k) \prod_{i=1}^{\text{No}} U(T_i), \tag{11}$$

where $A(T_k)$ is the availability of transmission line k, No is number of lines on outage and $U(T_i)$ is the unavailability of transmission line i (contingent line).

The contingency departure rate (Dr) of each contingency is modelled as summation of repair rate of failed components plus summation of the failure rate of available components [15]. It is expressed as

$$\text{Dr}_i = \sum_{k=1}^{\text{Na}} \lambda_k + \sum_{i=1}^{\text{No}} \mu_i \ \frac{\text{outages}}{\text{yr}}. \tag{12}$$

The following indices are estimated in this paper to evaluate the security of composite power systems:

(i) ELOP: expected loss of power is expressed in MW which deals with the probability of loss of power due to component failure (transmission line) [1, 2]. It can be formulated for contingent line i as

$$\text{ELOP}_i = \sum_{i \epsilon Nl} p_i . P_{\text{FL}}^i \ \text{MW}. \tag{13}$$

(ii) EFOC: expected frequency of contingency is expressed in occ/yr, illustrating the contingency occurrence, including component failure in a year. It is formulated by multiplying the probability of each contingency with its respective contingency departure rate [1, 2, 30]. For contingent line i, EFOC is framed as

$$\text{EFOC}_i = p_i . \text{Dr}_i \ \frac{\text{occ}}{\text{yr}}. \tag{14}$$

(iii) ELOL: expected loss of load is expressed in MW which measures the probability of loss of load due to component failure where system adequacy is hampered [2]. For a contingent line i which leads to loss of load, ELOL can be formulated as

$$\text{ELOL}_i = \sum_{i \epsilon S_l} p_i . P_L^i \quad \text{MW}. \tag{15}$$

(iv) PLC: probability of load curtailment measures the probability of the system's state where load curtailment or loss of load takes place due to component failure [1, 2, 5]. It can be formulated for transmission line i, which leads to load curtailment as

$$\text{PLC}_i = \sum_{i \epsilon S_l} p_i. \tag{16}$$

(v) EDLC: expected duration of load curtailment expressed in hr/yr accounts for the duration of load curtailment over a year [1, 2, 5]. It is formulated for contingent line i on the basis of PLC_i, which leads to load curtailment (loss of load) as

$$\text{EDLC}_i = \text{PLC}_i \times 8760 \ \frac{hr}{yr}. \tag{17}$$

3.2. Expected Performance Index (EPI). The line performance index for each transmission line outage outlined the severity of the line and the extent of the impact on the system. Line outages occurring in the system are stochastic, and accounting for the probability of occurrence of line outage contingencies using deterministic approaches is difficult. To incorporate the stochastic or random nature of contingencies in the composite power system, deterministic PI is expressed into probabilistic one and is called the expected performance index (EPI) [15]. This index signifies system's nature a more realistic view and gives system operators a broader insight on the performance of each transmission line outage that may occur on the system. The formulation of EPI is an extended version of deterministic PI, which incorporates component probability into it. It can be formulated for a contingent line i as

$$\text{EPI}_i = p_i \times \text{PI}_i. \tag{18}$$

The criticality of transmission line on the basis of EPI can be categorized as shown in Table 3.

4. $N-1$ Security Criteria Based Integrated D-P Framework

Emergence of probabilistic approaches in CPS to account the stochastic nature in tandem with deterministic approaches to evaluate system security gives a realistic picture of the system when any disturbance occurs on the system to the system operators. The proposed integrated D-P framework can help the system operator decide between preventive and corrective actions to be taken for a given operating condition [4, 5, 17]. The integrated framework allows for a more comprehensive assessment of system reliability. The probabilistic approach (PA) takes uncertainties into consideration, whereas the deterministic approach (DA) concentrates on system performance under known conditions. Integrating the two approaches allows for the consideration of a larger range of scenarios, encompassing both anticipated and unforeseen events, and results in a deeper comprehension of reliability. In isolation, PA estimates the likelihood of system failures but does not provide an

Table 3: Criticality of transmission lines based on EPI.

Range	Category
$\mathrm{EPI} \geq 0.8$	Most critical (MC)
$0.3 \leq \mathrm{EPI} < 0.8$	Critical (C)
$\mathrm{EPI} < 0.3$	Not critical (NC)

unambiguous plan for risk management. By identifying the most crucial components and scenarios where reliability improvement efforts are most effective, integrating DA offers a more systematic approach to risk mitigation. Integrating DA and PA improves the efficacy of risk-mitigation techniques. It detects potential failure events and their likelihood, allowing operators to prioritize and implement risk-mitigation strategies.

4.1. Problem Formulation. The integrated D-P framework combines wide range of quantitative indices which offer a comprehensive view of system security and reliability. Indices offer perceptions into the system's operation in various scenarios, enabling operators to modify strategies as necessary to maintain security and reliability [6, 7]. The integrated D-P framework provides a more comprehensive understanding of system behavior, facilitates effective risk management, and enhances system operator's decision-making to improve power system reliability. The proposed framework is very useful in dealing with the increasing complexities and uncertainties in modern power systems. A generalized schematic of the proposed D-P framework is shown in Figure 1 highlighting the use of DA and PA by considering $N-1$ criteria in order to develop a credible contingency set of components (transmission line).

The mathematical formulation of development of the credible contingency set of transmission lines in the integrated D-P approach is based on the set of critical lines developed using deterministic and probabilistic approaches. The set of critical transmission lines based on $\mathrm{SSI}_i/\mathrm{PI}_i$ using deterministic approach is formulated as

$$S_A = \begin{cases} 0.3 \leq \mathrm{SSI}_i < 0.8, & \text{critical lines,} \\ \mathrm{SSI}_i \geq 0.8, & \text{most critical lines.} \end{cases} \tag{19}$$

Line interruptions in the system are stochastic, and incorporating the probability of occurrence of line outage contingencies using DA presents various challenges. The deterministic PI is expressed using the probabilistic approach known as EPI to address this. This improvement permits the random nature of contingencies to be incorporated into the CPS. The set of critical lines formulated based on EPI_i is

$$S_B = \begin{cases} 0.3 \leq \mathrm{EPI}_i < 0.8, & \text{critical lines,} \\ \mathrm{EPI}_i \geq 0.8, & \text{most critical lines.} \end{cases} \tag{20}$$

Further, the reliability of CPS is calculated using ELOP and EFOC using PA highlights the stochastic nature of line outages on the system. The probability of occurrence of contingency is expressed using (11) formulates the reliability indices using (13) and (14). The calculated indices are ranked based on their criticality. The set of critical lines developed using $ELOP_i$ and $EFOC_i$ based on their ranking and expressed as follows:

$$S_C = \{\mathrm{ELOP}_i\,(\text{Rank 1}), \ldots \ \ldots \ \ldots, \mathrm{ELOP}_i\,(\text{Rank 5})\}, \tag{21}$$

$$S_D = \{\mathrm{EFOC}_i\,(\text{Rank 1}), \ldots \ \ldots \ \ldots, \mathrm{EFOC}_i\,(\text{Rank 5})\}, \tag{22}$$

where $i \in$ contingent lines.

Certain line outages contribute towards loss of load events. To evaluate the criticality of loss of load events, reliability indices are calculated using (17)–(19). The set of critical lines formulated based on loss of load events are expressed based on ELOL_i, PLC_i, and EDLC_i and shown as

$$S_{\mathrm{loss}} = \left\{ \begin{matrix} \mathrm{ELOL}_i \\ \mathrm{PLC}_i \\ \mathrm{EDLC}_i \end{matrix} \right\} \approx \text{loss of load events for} \quad i \in \text{contingent lines.} \tag{23}$$

The set of critical lines formulated based on both DA and PA can be combined together to illustrate the cumulative effect on CPS, and it can be mathematically expressed as

$$S_{\mathrm{cumulative}} = S_A \cup S_B \cup S_C \cup S_D. \tag{24}$$

The development of the credible contingency set considering the integrated D-P framework is crucial for system operators to enhance their decision-making for implementing timely corrective measures. S_{credible} is formulated based on criticality of line outage expressed from both DA and PA and also highlighting effect of loss of load events. S_{credible} using the integrated D-P framework is expressed as

$$S_{\mathrm{credible}} = S_{\mathrm{cumulative}} \cap S_{\mathrm{loss}}. \tag{25}$$

The development of a credible contingency set using (25) for the test system provides system operators to conduct security and reliability studies and enhances their decision-making for rapid deployment of corrective control

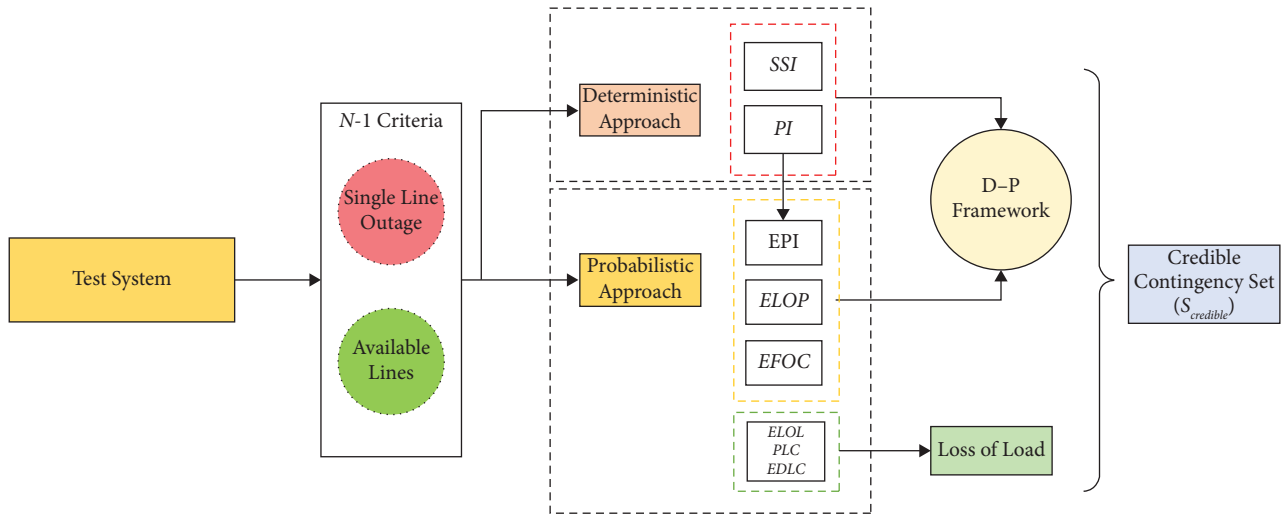

Figure 1: Schematic of the proposed integrated D-P framework.

measures. The pseudocode and flow chart of the proposed methodology illustrating the integrated D-P framework is presented in Section 4.2.

4.2. Proposed Methodology. The integrated framework provides an exhaustive assessment of system security and reliability for the $N-1$ criteria by considering both the deterministic and probabilistic approaches. This comprehensive approach provides an improved representation of the behavior of the power system under various scenarios. The pseudocode of the proposed integrated D-P framework for the formulation of credible contingency set is illustrated as Algorithm 1 and is shown as follows:

The flowchart of the proposed integrated D-P framework is presented in Figure 2. Algorithm steps of the integrated D-P framework for $N-1$ security criteria considering single line outage on the system are as follows:

(i) System is configured at base case load and optimal power flow is solved when the system is operating in normal condition.

(ii) Availability and unavailability data are generated using (9) and (10) from different techniques on the basis of past performance of each transmission line.

(iii) Single line outages at the desired load level are simulated by ACOPF and violations of operating limits are checked.

(iv) For each contingent line i simulated, state probability is calculated using (11).

(v) At each line outage condition, power flow (P_F) in available lines Na is solved using AC power flow.

(vi) Contingency departure rate (Dr) of contingent line i is calculated using (12).

(vii) Considering a line outage condition i, OI of available lines Na is calculated using (1). On the basis of OI_k^i, each available line k is categorized as normal, insecure, or overloaded as mentioned in Section 2.1.

(viii) SSI of each contingent line i is evaluated using (6). The obtained values of SSI of all transmission lines are normalized between 0 and 1 using (8).

(ix) Ranking of SSI of all transmission lines is done and categorized based on Table 2.

(x) Reliability indices such as ELOP and EFOC of each contingent line i is calculated using (13) and (14). Rank each transmission line on basis of reliability indices.

(xi) At certain states where loss of load (LOL) occurs on the system due to single-line outage condition, load curtailment indices such as ELOL, PLC, and EDLC are calculated using (17)–(19), respectively. These states fall in the category of MC.

(xii) On the basis of the overloading index where $\mathrm{OI}_k^i \geq 0.5$ (operating insecurely or overloaded), the line performance index (PI) is calculated for each contingent line i using (7).

(xiii) The PI obtained is extended to probabilistic one and EPI is calculated using (18) for each contingent transmission line i. Rank criticality of each transmission line on the basis of EPI and similarly a categorization based on Table 3.

(xiv) Criticality of each transmission line is assessed based on $\mathrm{SSI}_i/\mathrm{PI}_i$, and S_A is computed using (19).

(xv) Similarly, considering the PA, criticality is assessed based on EPI_i and reliability indices, and further, S_B, S_C, S_D are computed using (20)–(22).

(xvi) Loss of load is a crucial event in the power system. Line outages leading to LOL are the most critical, and based on reliability indices calculated for such events, S_{loss} is computed using (23).

(xvii) Considering the outcomes from both the approaches, $S_{\mathrm{cumulative}}$ is evaluated using (24).

```
procedure Integrated D-P framework
load test system load data P_D, Q_D
perform Load Variation
Normal PDF for P_D, Q_D at ±5%
perform AC-OPF at base case load
while temp = 0
  perform Deterministic Approach
    for each contingent line i
      perform AC-OPF
      Calculate OI_k^i = S_{k,i}^post / S_k^max
        if OI_k^i < 0.5
            Line is operating normally
        else if 1 < OI_k^i ≥ 0.5
          Line is in insecure state
        else
          Line is overloaded
      Calculate SSI_i = Σ_{k=1}^{Na} OI_k^i
        if SSI_i < 0.3
          Line is Not Critical (NC)
        else if 0.8 < SSI_i ≥ 0.3
          Line is Critical (C)
        else
          Line is Most Critical (MC)
      for OI_k^i ≥ 0.5
        Calculate PI_i = Σ_{k=1}^{N_ol} wt/X (S_{k,i}^post / S_k^max)^X
      end for
    end for
  perform Probabilistic Approach
    for Available line k || Unavailable line i (Contingent Line)
      Calculate A(T_k) || U(T_i)
      Calculate Outage probability (p_i) using (11)
      Calculate Dr_i using (12)
      perform AC-OPF for each outage condition
        Check OPF convergence
          if OPF converged for each outage condition
            Calculate Reliability Indices—ELOP_i, EFOC_i
          else
            Calculate Reliability Indices—ELOL_i, PLC_i, EDLC_i (Loss of Load)
      Calculate EPI_i = p_i × PI_i
        if EPI_i < 0.3
          Line is Not Critical (NC)
        elseif 0.8 < EPI_i ≥ 0.3
          Line is Critical (C)
        else
          Line is Most Critical (MC)
    end for
end while
Compute S_A, S_B, S_C, S_D using (19)–(22)
Compute S_loss using (23)
Compute S_cumulative using (24)
Compute S_credible using (25)
end procedure
```

Algorithm 1: Development of $\mathbf{S_{credible}}$ using integrated D-P framework.

(xviii) At last, a credible contingency set (S_{credible}) is developed using (25) at each operating point considering system state, criticality at each line outage contingency, and LOL events on the basis of security and reliability perspective.

Reliability evaluation considering $N-1$ security criteria (single line outage) using both the approaches and proposed integrated D-P framework is applied on IEEE 24 RTS, and it is discussed in Section 5.

5. Case Study and Results

In this paper, a single-line outage scenario is developed on IEEE 24 RTS [2], and deterministic and probabilistic approaches have been incorporated. The annual peak load of the test system is 2850 MW, and the total generation capacity is 3405 MW. The system includes 38 transmission lines (which include 30 single-circuit lines and 4 double-circuit lines), 24 buses, and 32 generating units [1, 2]. Using the random normal distribution, the system load is randomly varied at each bus to account for the uncertain nature of load at the ±5% level of the base case data (2850 MW). The impact of each transmission line outage on the system is analyzed using both approaches, and a critical contingency set is developed using an integrated D-P framework.

5.1. Results Obtained Using Deterministic Approach (DA). Considering each line outage with network constraints, AC power flow is performed. The severity of line outage condition on the system can be analyzed by considering its impact on other transmission lines. This impact on other lines is greatly influenced by loading conditions, and further, it impacts the power flow of other lines. To analyze this impact, OI_k^i is calculated using (1), which illustrates the overloading on other lines due to line outage, and further, SSI is computed using (6) of the contingent line. Table 4 depicts the SSI of each transmission line (normalized using (8)) when their outage is considered one by one ($N-1$ criterion) on the test system considered for analysis and the severity rank of the transmission lines.

Formulation of OI for each available line is crucial to depict the criticality of contingent line using DA (SSI) approach. Sample results of OI are shown in Figures 3–5 for MC, C, and NC categories, respectively. Figures 3 and 4 show the results for sample line outages of line 14–16, 3–24, and 15–24 (MC lines) and 6–10, 12–23, and 10–12 (C lines) which have a major impact on the system resulting in operation of maximum number of lines in insecure or overloaded state. Severity of outage of line 2–4, 9–12, 2–6 (NC lines) have very less impact on the system as only a few number of lines are operating in insecure state or overloaded. Table 5 depicts the number of lines which are operating insecurely or overloaded due to MC, C, and NC lines.

Line 15–24 results in cascading outage on the system as power flow on line 3–24 becomes approximately zero. Also, a similar impact is seen when lines 6–10 and 2–6 are on outage as they result in complete violation of line MVA limit of lines 2–6 and 6–10, respectively.

From the SSI analysis, it has been inferred that power flow was not converged when an outage of line 7-8 (line 11) has occurred. It is because outage of line 11 leads to LOL, so the convergence of power flow was not possible.

Further, the performance of each transmission line can be analyzed on the basis of SSI calculated. SSI highlights the overloading on other lines due to line outage, and this impact was analyzed by calculating OI_k^i for each transmission line. This performance is illustrated by calculating PI of transmission line using (7). Table 6 shows the PIs of each transmission line of the test system.

As seen from Table 6, the PI values obtained from DA for the test system are unable to clearly indicate the critical nature of the transmission lines and their overloading subjected to single-line outage. In order to make the PI from DA more informative for the system operator, probabilistic nature is incorporated to determine EPI. This helps in proper identification of the critical nature of the transmission lines in terms of their severity.

5.2. Results Obtained Using Probabilistic Approach (PA). System component (transmission line) failure is stochastic; therefore, reliability evaluation considering $N-1$ security criteria using the probabilistic approach is carried out. Reliability study considered on the test system includes calculation of ELOP and EFOC when line outage takes place. The probability of each transmission line outage highlights the stochastic nature of line outages, and it is calculated using (11). AC power flow is performed to calculate the line flow in each transmission line. The mentioned reliability indices are calculated using (13) and (14) and are shown in Table 7, including ranking based on indices calculated.

ELOP and EFOC highlight the loss of power in the system and occurrence of contingency when any line outage occurs in the system. These indices are crucial as with the help of ELOP and EFOC, operators and planners may prioritize maintenance and investment decisions by identifying susceptible regions within the power system and receiving a comprehensive evaluation of the possible risk associated with line interruptions.

From the DA, line 11 was critical as its outage led to LOL, and power flow was not converged. Reliability analysis is carried out using (16)–(18) and (17) of line 11 and is shown in Table 8.

PI calculated accounts for the deterministic nature of the system, and to underline the stochastic nature of the power system and transmission line criticality, EPI is computed using (18), and it is shown in Table 9.

5.3. Results Obtained Using the Integrated D-P Framework. Security evaluation in composite power systems is vital for power system design and planning. Here, DA and PA have been applied, considering a single-line outage to analyze the $N-1$ criteria. In DA, transmission line failure is entirely determined by SSI calculated, and to account for the randomness of the line failures, a PA is applied by calculating reliability indices. Deterministic PI is approximated into a probabilistic one (EPI). Graphical representation of

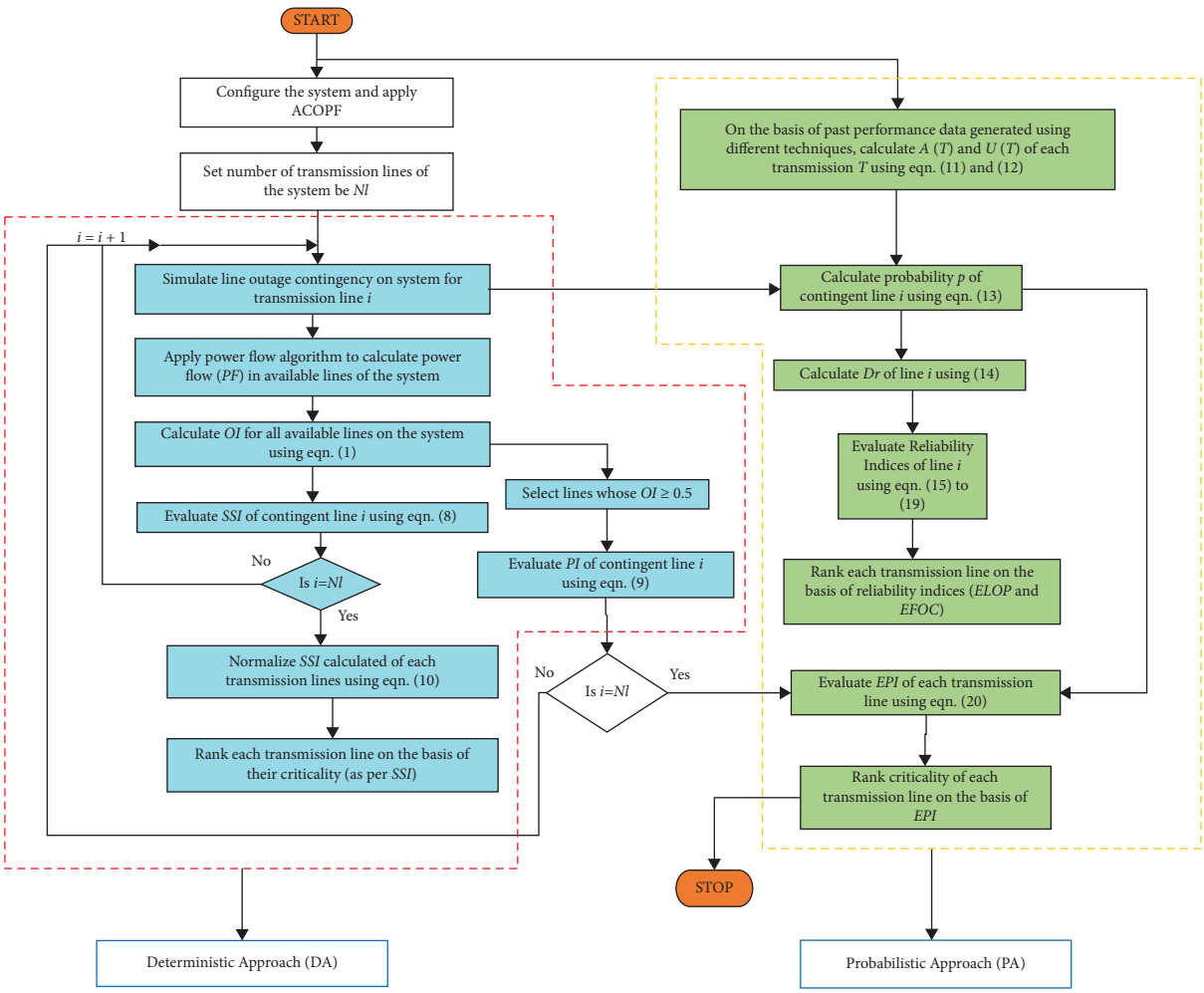

Figure 2: Flowchart of the proposed integrated D-P framework.

Table 4: Static security index (SSI) calculated of each transmission line outage.

Line number	From bus	To bus	SSI	Severity rank	Criticality
1	1	2	0.1531	31	NC
2	1	3	0.1978	27	NC
3	1	5	0.3778	12	C
4	2	4	0.2836	15	NC
5	2	6	0.2561	18	NC
6	3	9	0.2033	26	NC
7	3	24	0.9937	2	MC
8	4	9	0.2546	19	NC
9	5	10	0.2057	24	NC
10	6	10	0.6993	4	C
12	8	9	0.2244	22	NC
13	8	10	0.2357	21	NC
14	9	11	0.2398	20	NC
15	9	12	0.2830	16	NC
16	10	11	0.3977	10	C
17	10	12	0.4712	6	C
18	11	13	0.2146	23	NC
19	11	14	0.3029	14	C
20	12	13	0.1850	29	NC
21	12	23	0.5389	5	C
22	13	23	0.4043	9	C
23	14	16	1.0000	1	MC

Table 4: Continued.

Line number	From bus	To bus	SSI	Severity rank	Criticality
24	15	16	0.3234	13	C
25	15	21	0.2591	17	NC
26	15	24	0.9834	3	MC
27	16	17	0.4665	7	C
28	16	19	0.3954	11	C
29	17	18	0.1162	32	NC
30	17	22	0.4281	8	C
31	18	21	0.2041	25	NC
32	19	20	0.1868	28	NC
33	20	23	0.1840	30	NC
34	21	22	0.0000	33	NC

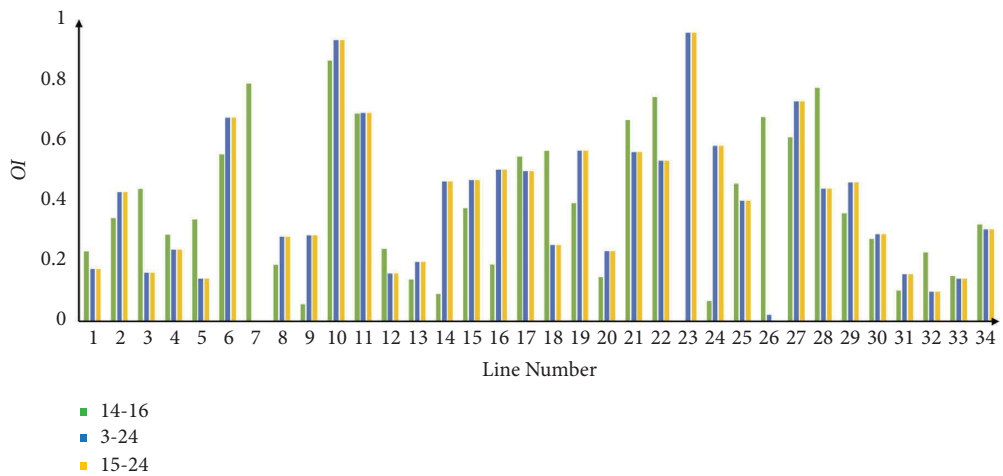

Figure 3: Results of OI for sample lines of MC category.

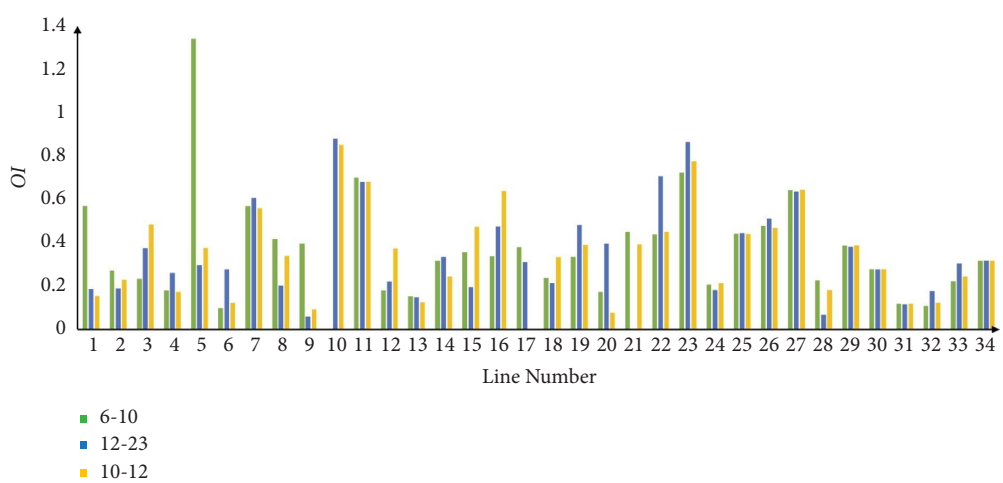

Figure 4: Results of OI for sample lines of C category.

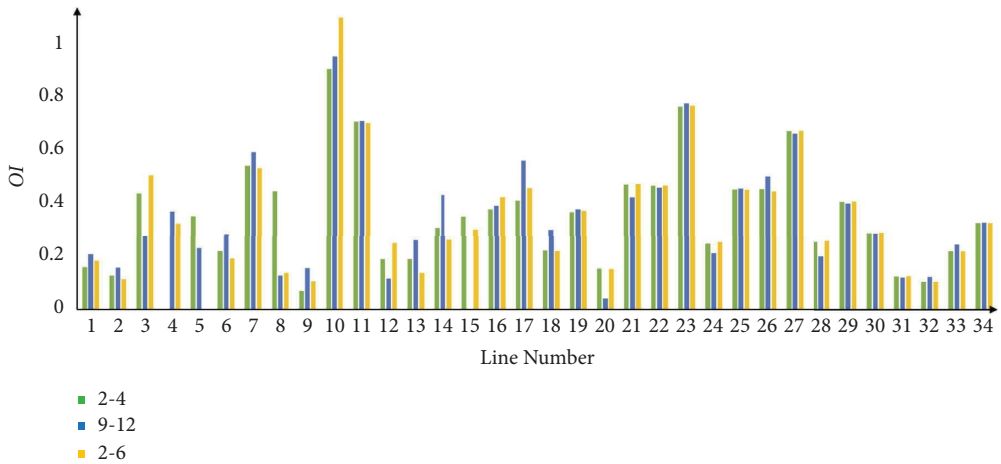

Figure 5: Results of OI for sample lines of NC category.

Table 5: Number of lines operating insecurely or overloaded in each category.

Most critical (MC) lines			Critical (C) lines			Not critical (NC) lines		
14–16	3–24	15–24	6–10	12–23	10–12	2–4	9–12	2–6
11	10	10	6	6	6	5	6	5

Table 6: Line performance index (PI) for each transmission line outage.

Line number	From bus	To bus	PI
1	1	2	1.2544
2	1	3	1.2544
3	1	5	1.2544
4	2	4	1.2544
5	2	6	1.2544
6	3	9	1.1148
7	3	24	1.4999
8	4	9	1.2544
9	5	10	1.2544
10	6	10	0.9016
12	8	9	1.2544
13	8	10	1.2544
14	9	11	1.2544
15	9	12	1.3429
16	10	11	1.3429
17	10	12	1.3298
18	11	13	1.2544
19	11	14	1.2860
20	12	13	1.3581
21	12	23	1.4536
22	13	23	1.4218
23	14	16	1.4390
24	15	16	1.3311
25	15	21	1.4270
26	15	24	1.4999
27	16	17	1.2630
28	16	19	1.4156
29	17	18	1.2356
30	17	22	1.3311
31	18	21	1.2544
32	19	20	1.2544
33	20	23	1.2544
34	21	22	1.2931

Table 7: Reliability indices of each transmission line.

Line numbers	From bus	To bus	ELOP (MW)	EFOC (occ/yr)	Rank (ELOP)	Rank (EFOC)
1	1	2	1.219	57.235	31	26
2	1	3	1.194	133.213	32	2
3	1	5	2.851	42.205	27	28
4	2	4	3.032	70.091	26	21
5	2	6	5.317	97.403	23	5
6	3	9	1.692	65.659	30	23
7	3	24	67.775	7.799	1	33
8	4	9	3.035	74.620	25	14
9	5	10	1.073	81.454	33	11
10	6	10	24.567	72.899	11	15
12	8	9	3.684	88.668	24	8
13	8	10	2.115	88.668	29	8
14	9	11	35.405	8.124	6	29
15	9	12	40.268	8.124	4	29
16	10	11	50.534	8.124	3	29
17	10	12	55.736	8.124	2	29
18	11	13	8.597	80.724	20	12
19	11	14	19.359	91.166	12	6
20	12	13	6.039	80.724	22	12
21	12	23	37.135	131.898	5	3
22	13	23	17.230	61.855	15	24
23	14	16	30.998	68.221	8	22
24	15	16	10.027	72.230	18	17
25	15	21	18.726	70.478	14	20
26	15	24	18.780	70.478	13	19
27	16	17	32.736	82.068	7	10
28	16	19	10.265	72.155	17	18
29	17	18	12.482	54.015	16	27
30	17	22	27.038	157.216	9	1
31	18	21	6.690	89.775	21	7
32	19	20	2.401	58.563	28	25
33	20	23	8.734	72.630	19	16
34	21	22	25.488	131.761	10	4

Table 8: Reliability indices due to outage at line 11.

Line	From bus	To bus	PLC	EDLC	ELOL	EFOC
11	7	8	0.0432	379.0571	5.4089	38.4510

Table 9: Expected performance index (EPI) of transmission lines.

Line numbers	From bus	To bus	EPI	Criticality
1	1	2	0.128167	NC
2	1	3	0.188092	NC
3	1	5	0.05958	NC
4	2	4	0.098954	NC
5	2	6	0.137526	NC
6	3	9	0.082385	NC
7	3	24	0.481341	C
8	4	9	0.105343	NC
9	5	10	0.114989	NC
10	6	10	0.250035	NC
12	8	9	0.125187	NC
13	8	10	0.125187	NC
14	9	11	0.419315	C
15	9	12	0.448918	C
16	10	11	0.448918	C
17	10	12	0.444545	C

Table 9: Continued.

Line numbers	From bus	To bus	EPI	Criticality
18	11	13	0.125187	NC
19	11	14	0.144946	NC
20	12	13	0.135543	NC
21	12	23	0.237065	NC
22	13	23	0.10874	NC
23	14	16	0.121366	NC
24	15	16	0.118859	NC
25	15	21	0.124345	NC
26	15	24	0.130698	NC
27	16	17	0.128137	NC
28	16	19	0.126276	NC
29	17	18	0.082507	NC
30	17	22	0.258777	NC
31	18	21	0.139213	NC
32	19	20	0.090817	NC
33	20	23	0.112625	NC
34	21	22	0.210656	NC

security evaluation using both the approaches highlighting SSI, PI, and EPI of each transmission line is shown in Figures 6–8.

From Figures 6–8, the following observations are made:

(i) As per SSI and PI, lines (14–16), (3–24), (15–24), (6–10), (12–23), (16–19), (13–23), and (15–21) are the most critical lines for the test system considered. This set of critical lines is formulated using (19).

(ii) As per EPI, lines (3–24), (9–12), (10-11), (10–12), and (11–13) are the most critical lines for the system, and this set of critical lines is shown by S_B and calculated using (20).

(iii) It has been noted from the above analysis that determination of SSI, PI, and EPI of line 11 is not possible as its outage leads to LOL, and power flow was not converged.

Similarly, graphical representations of reliability indices calculated for each transmission line are shown in Figures 9 and 10.

From Figures 9 and 10, the following observations have been drawn:

(i) As per ELOP, lines (3–24), (10–12), (10-11), (9–12), and (12–23) are the most critical lines, and this set of lines is formulated using (21).

(ii) As per EFOC, lines (17–22), (1–3), (12–23), (21-22), and (2–6) are the most critical lines where line failures' occurrence is highest among all the transmission lines and this set is formulated using (22).

From the above observations, the following conclusions are drawn:

(i) From the deterministic approach,

$$S_A = \left\{ \begin{array}{c} (14-16), (3-24), (15-24), (6-10), (12-23), (16-19), \\ (13-23), (15-21) \end{array} \right\}. \tag{26}$$

(ii) From the probabilistic approach,

$$\begin{aligned} S_B &= \{(3-24), (9-12), (10-11), (10-12), (11-13)\}, \\ S_C &= \{(3-24), (10-12), (10-11), (9-12), (12-23)\}, \\ S_D &= \{(17-22), (1-3), (12-23), (21-22), (2-6)\}. \end{aligned} \tag{27}$$

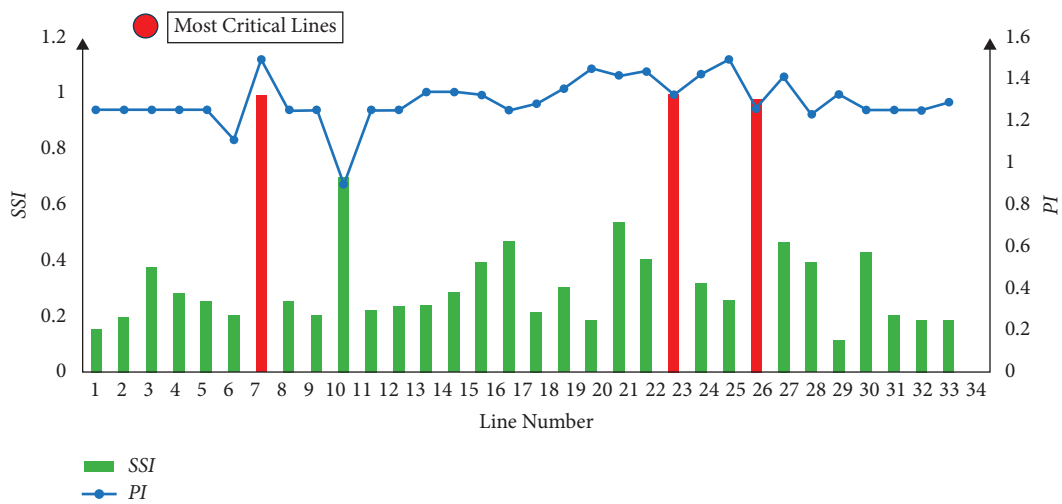

Figure 6: SSI and PI of each transmission line with DA.

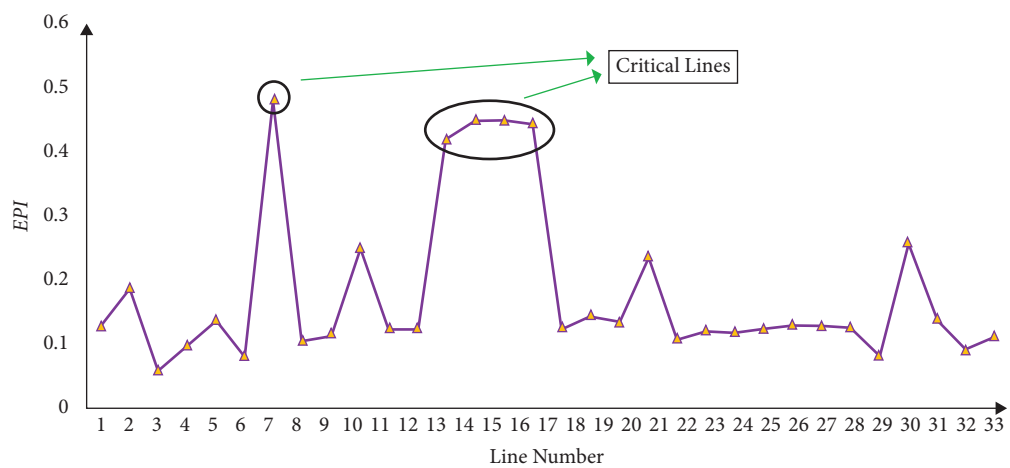

Figure 7: EPI of each transmission line with PA.

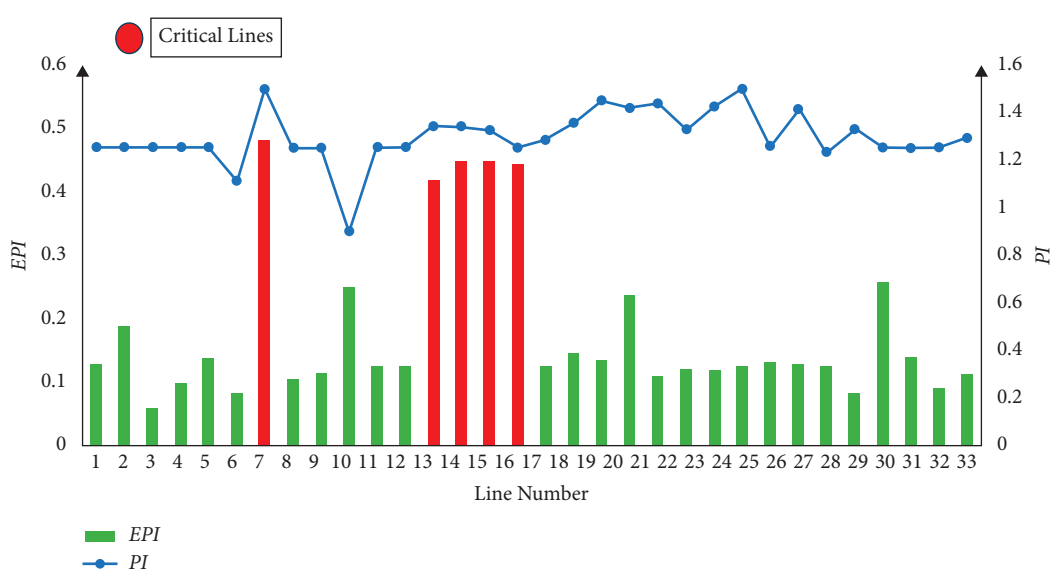

Figure 8: Comparison drawn from PI and EPI.

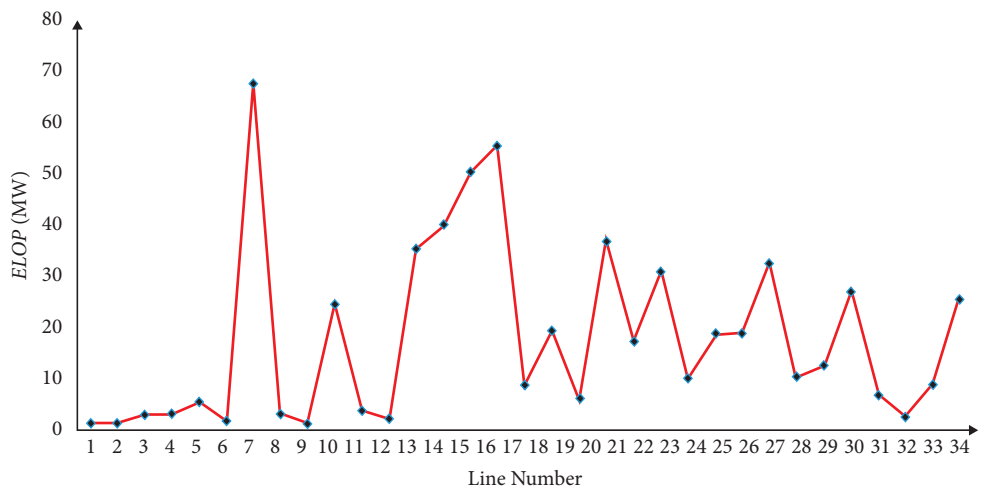

Figure 9: ELOP vs. transmission line.

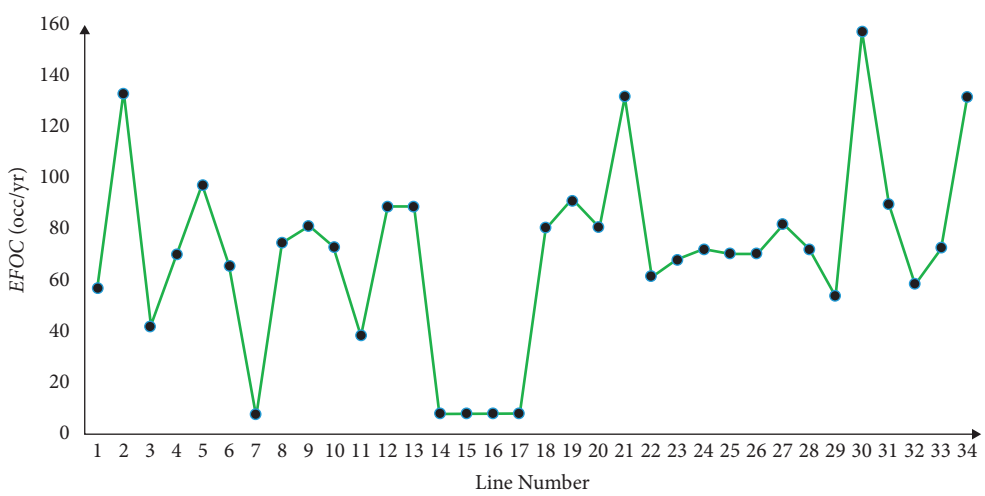

Figure 10: EFOC vs. transmission line.

(iii) The cumulative set, $S_{\text{cumulative}}$, of critical transmission lines from both approaches is formulated based on sets S_A, S_B, S_C, and S_D using (24) as

$$S_{\text{cumulative}} = \left\{ \begin{array}{c} (14-16), (3-24), (15-24), (6-10), (12-23), (16-19), \\ (13-23), (15-21), (9-12), (10-11), \\ (10-12), (11-13), (17-22), (1-3), (21-22), (2-6) \end{array} \right\}. \tag{28}$$

(iv) Lines 7-8 (line 11) lead to loss of load at bus 7, so from a reliability perspective, resource adequacy of the system becomes poor as load curtailment takes place. Indices are calculated and are shown in Table 8. So, from this analysis, it can be concluded that line 11 is one of the most critical lines for the system, and on the basis of it, S_{loss} is expressed using (23) and shown as

$$S_{\text{loss}} = \{(7-8)\}. \tag{29}$$

(v) Credible contingency set, S_{credible}, of transmission lines for the test system is developed as shown in Figure 2 based on the integrated D-P framework and loss of load events considering security and reliability perspective using (25) is

$$S_{\text{credible}} = \left\{ \begin{array}{c} (3-24), (7-8), (9-12), (10-11), (10-12), \\ (14-16), (17-22), (12-23) \end{array} \right\}. \tag{30}$$

The credible contingency set obtained based on security and reliability point of view highlights the critical transmission lines, which stresses the system heavily. The contingency set developed from the integrated D-P framework can provide crucial information to system operators with a shorter computation time and assist them in decision-making for timely implementing suitable corrective action plans.

6. Conclusions

Security evaluation of power systems is crucial for planning and design purposes. In this paper, $N-1$ security criteria are highlighted considering single-line outage contingency to evaluate the system security of CPS using the integrated deterministic and probabilistic framework. The proposed approach is tested on IEEE 24 RTS. Through the application of deterministic methodology, security evaluation in power systems entails the calculation of critical parameters such as SSI and PI, which account for possible overloading on available transmission lines. However, this paper proposes a radical shift towards a comprehensive probabilistic framework for evaluating system security, stressing the critical need to include reliability considerations in modern power system analyses, given the intrinsically stochastic nature of power systems and their potential susceptibility to random line failures. Various reliability indices are calculated where the loss of load state is also considered. The index, EPI, calculated from PA uses the information from DA to show the stochastic nature of the power system. Further, a comparative analysis is carried out for both approaches, and a credible contingency set of transmission lines is developed based on the severity rank using the integrated D-P framework.

The establishment of a credible contingency set for the test system presents a valuable opportunity to conduct robust security and reliability studies. This, in turn, equips system operators with essential insights for informed decision-making, facilitating the timely implementation of tailored corrective control measures. As a result, system operators are better equipped to make informed decisions, allowing for the prompt deployment of specific corrective control measures. The proposed approach's adaptability broadens its applicability to larger systems, supporting multiple contingencies and diverse operating situations, highlighting its potential to greatly advance contemporary power system assessments.

7. Limitations and Future Scope

Establishing integrated D-P models frequently entails managing complex interactions between numerous deterministic and probabilistic variables, which can complicate interpretation and increase the processing burden. Obtaining and maintaining the vast amounts of data required for probabilistic and deterministic studies can be difficult and resource-intensive, especially for systems with limited accessibility to data. The underlying assumptions made in the models can have an impact on the reliability outcomes of the integrated D-P framework, indicating the necessity for a detailed investigation of these assumptions and their potential consequences.

The efficiency and scalability of integrated D-P models can be greatly increased by further developments in computational methods and high-performance computing, which can speed up and improve the accuracy of larger and more complicated CPS analyses. By incorporating data analytics and machine learning techniques into the integrated D-P framework, system operators may make more informed decisions and anticipate complex system responses with more accuracy. The overall reliability and security of modern power systems can be improved by integrating the D-P framework with real-time monitoring and control systems, which can enable dynamic adjustments and preventive measures in response to changing system conditions, such as rapid changes in load demand, cascading outages, and uncertainty related to intensive utilization of renewable energy sources (RES).

Nomenclature

Abbreviations

CPS: Composite power system
DA: Deterministic approach
PA: Probabilistic approach
SSI: Static security index
ELOP: Expected loss of power
EFOC: Expected frequency of contingency
ELOL: Expected loss of load
PLC: Probability of load curtailment
EDLC: Expected duration of load curtailments
LOL: Loss of load
MTTR: Mean time to repair
MTTF: Mean time to failure

Sets

N_G: Number of generators
N_{bus}: Number of buses
Nl: Number of transmission lines of the test system
Na: Number of nonoutage or available transmission lines
N_{ol}: Number of insecure or overloaded lines
No: Number of lines on outage
S_l: Set of all system states associated with load curtailment (loss of load)
S_A: Set of critical lines developed based on DA
S_B: Set of critical lines developed based on EPI using PA

S_C, S_D: Set of critical lines developed based on ELOP and EFOC using PA
S_{loss}: Set of critical lines developed based on ELOL, PLC, and EDLC using PA
$S_{\text{cumulative}}$: Set of critical lines based on both DA and PA
S_{credible}: Credible contingency set of transmission lines

Parameters and Variables

OI_k^i: Overloading index for line k due to outage of line i
$S_{k,i}^{\text{post}}$: MVA power flow of line k after line outage of line i
$S_k^{\max}$: MVA rating of line k
P_g, Q_g: Active and reactive generation of generator g
P_D, Q_D: Active and reactive load demand
V_d, V_m: Voltage magnitude at bus d and bus m $d, m \in N_{\text{bus}}$
θ_d, θ_m: Voltage angle for bus d and bus m
Y_{dm}: Admittance between bus d and bus m
δ_{dm}: Admittance angle between bus d and bus m
$P_{g_{\min}}$, $P_{g_{\max}}$: Minimum and maximum active power generation at generator g
$Q_{g_{\min}}$, $Q_{g_{\max}}$: Minimum and maximum reactive power generation at generator g
$V_{d_{\min}}, V_{d_{\max}}$: Minimum and maximum bus voltage at bus d
S_{dm}: Power flow in line connecting bus d to bus m
$S_{dm}^{\max}$: MVA limit of line connecting bus d to bus m
SSI_i: Static security index for contingent line i
PI_i: Line performance index of line i
$A(T_k)$: Availability of transmission line k
$U(T_i)$: Unavailability of transmission line i (contingent line)
p_i: Probability of contingent line i
Dr_i: Contingency departure rate of contingent line i
λ_k: Failure rate of line k
μ_i: Repair rate of line k
P_{FL}^i: Loss of power due to outage in transmission line i
P_L^i: Load loss due to outage of transmission line i
EPI_i: Expected performance index of line i.

Data Availability

The data will be available on reasonable request.

Disclosure

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] R. Billinton and R. N. Allan, *Reliability Evaluation of Power Systems*, Plenum Publishing, New York, NY, USA, 1984.
[2] R. Billinton and W. Li, *Reliability Assessment of Electric Power Systems Using Monte Carlo Methods*, Plenum Press, New York, NY, USA, 1994.
[3] R. N. Allan, R. Billinton, A. M. Breipohl, and C. H. Grigg, "Bibliography on the application of probability methods in power system reliability evaluation," *IEEE Transactions on Power Systems*, vol. 14, no. 1, pp. 51–57, 1999.
[4] R. Billinton and R. Mo, "Deterministic/probabilistic contingency evaluation in composite generation and transmission systems," *IEEE Power Engineering Society General Meeting*, vol. 2, pp. 2232–2237, 2004.
[5] R. Billinton, H. Bao, and R. Karki, "A joint deterministic probabilistic approach to bulk system reliability assessment," in *Proceedings of the 10th International Conference on Probablistic Methods Applied to Power Systems*, pp. 1–8, Rincon, PR, USA, May 2008.
[6] R. Billinton and W. Wangdee, "A combined bulk electric system reliability framework using adequacy and static security indices," *Journal of Electrical Engineering and Technology*, vol. 1, no. 4, pp. 414–422, 2006.
[7] U. Shahzad, "Probabilistic security assessment in power transmission systems: a review," *Journal of Electrical Engineering, Electronics, Control and Computer Science*, vol. 7, no. 4, pp. 25–32, 2021.
[8] M. Ebeed and S. H. A. Aleem, "Overview of uncertainties in modern power systems: uncertainty models and methods," in *Uncertainties in Modern Power Systems*, pp. 1–34, Academic Press, Cambridge, MA, USA, 2021.
[9] J. Ma, Y. Liu, S. Zhang, L. Wu, and Z. Yang, "Comprehensive probabilistic assessment on capacity adequacy and flexibility of generation resources," *International Journal of Electrical Power & Energy Systems*, vol. 145, Article ID 108677, 2023.
[10] J. Choi, T. Tran, A. El-Keib, T. H. Oh, and R. Billinton, "A method for composite power system expansion planning considering probabilistic reliability criteria," *IEEE Power Engineering Society General Meeting*, vol. 2, pp. 1270–1276, 2005.
[11] D. S. Kirschen and D. Jayaweera, "Comparison of risk-based and deterministic security assessments," *IET Generation, Transmission & Distribution*, vol. 1, no. 4, pp. 527–533, 2007.
[12] X. Xu and M. J. S. Edmonds, "Probabilistic reliability methods and tools for transmission planning and system analysis," in *Proceedings of the 2006 International Conference on Probabilistic Methods Applied to Power Systems*, pp. 1–6, Stockholm, Sweden, June 2009.
[13] P. Pourbeik, B. Chakrabarti, T. George, J. Haddow, H. Illian, and R. Nighot, *Review of the Current Status of Tools and Techniques for Risk-Based and Probabilistic Planning in Power Systems*, CIGRE, Paris, France, 2010.
[14] S. Y. Musa, M. A. Madaki, and J. Haruna, "Development and application of probabilistic performance index for ranking N-1 contingencies," *European Journal of Engineering and Technology Research*, vol. 6, no. 5, pp. 63–69, 2021.
[15] A. M. Al-Shaalan, "Contingency selection and ranking for composite power system reliability evaluation," *Journal of*

King Saud University-Engineering Sciences, vol. 32, no. 2, pp. 141–147, 2020.

[16] N. A. Netto and C. L. Borges, "Enhancing the situational awareness of voltage security region via probabilistic reliability evaluation," *International Transactions on Electrical Energy Systems*, vol. 30, no. 1, Article ID e12150, 2020.

[17] E. Heylen, M. Ovaere, S. Proost, G. Deconinck, and D. Van Hertem, "A multi-dimensional analysis of reliability criteria: from deterministic N− 1 to a probabilistic approach," *Electric Power Systems Research*, vol. 167, pp. 290–300, 2019.

[18] T. Ding, C. Li, C. Yan, F. Li, and Z. Bie, "A bilevel optimization model for risk assessment and contingency ranking in transmission system reliability evaluation," *IEEE Transactions on Power Systems*, vol. 32, no. 5, pp. 3803–3813, 2017.

[19] S. K. Kumar and A. T. Mathew, "Online static security assessment module using artificial neural networks," *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 4328–4335, 2013.

[20] E. Heylen, M. Ovaere, G. Deconinck, and D. Van Hertem, "Fair reliability management: comparing deterministic and probabilistic short-term reliability management," in *Proceedings of the 2018 IEEE Power & Energy Society General Meeting (PESGM)*, pp. 1–5, Portland, OR, USA, August 2018.

[21] E. Heylen, W. Labeeuw, G. Deconinck, and D. Van Hertem, "Framework for evaluating and comparing performance of power system reliability criteria," *IEEE Transactions on Power Systems*, vol. 31, no. 6, pp. 5153–5162, 2016.

[22] D. H. Nguyen and M. Negnevitsky, "A probabilistic approach for power system security assessment," in *Proceedings of the 2012 22nd Australasian Universities Power Engineering Conference (AUPEC)*, pp. 1–6, Bali, Indonesia, September 2012.

[23] J. Cha, J. Park, J. Choi, Y. Jung, and Y. Yun, "Determination of a deterministic reliability criterion for composite power system expansion planning," in *Proceedings of the 2009 IEEE Power & Energy Society General Meeting*, pp. 1–6, Calgary, Canada, July 2009.

[24] T. M. Choi and R. Thomas, "Transmission system expansion plans in view point of deterministic, probabilistic and security reliability criteria," in *Proceedings of the Second International Conference on Innovative Computing, Informatio and Control (ICICIC 2007)*, Kumamoto, Japan, September 2007.

[25] W. Tan and M. Shaaban, "Ranking of power system contingencies based on a risk quantification criterion," in *Proceedings of the 2015 IEEE Student Conference on Research and Development (SCOReD)*, pp. 356–361, Kuala Lumpur, Malaysia, December 2015.

[26] K. Verma and K. R. Niazi, "Supervised learning approach to online contingency screening and ranking in power systems," *International Journal of Electrical Power & Energy Systems*, vol. 38, no. 1, pp. 97–104, 2012.

[27] Y. Hou, X. Wang, and J. Guo, "Quasi Monte Carlo method for reliability evaluation of power system based on Dimension Importance Sorting," *International Transactions on Electrical Energy Systems*, vol. 27, no. 3, p. e2264, 2017.

[28] A. M. Leite da Silva, L. C. de Resende, L. A. da Fonseca Manso, and V. Miranda, "Composite reliability assessment based on Monte Carlo simulation and artificial neural networks," *IEEE Transactions on Power Systems*, vol. 22, no. 3, pp. 1202–1209, 2007.

[29] D. Urgun and C. Singh, "Composite power system reliability evaluation using importance sampling and convolutional neural networks," in *Proceedings of the 2019 20th International Conference on Intelligent System Application to Power Systems (ISAP)*, pp. 1–6, New Delhi, India, December 2019.

[30] D. Urgun and C. Singh, "A hybrid Monte Carlo simulation and multi label classification method for composite system reliability evaluation," *IEEE Transactions on Power Systems*, vol. 34, no. 2, pp. 908–917, 2019.

[31] M. Kamruzzaman, N. Bhusal, and M. Benidris, "A convolutional neural network-based approach to composite power system reliability evaluation," *International Journal of Electrical Power & Energy Systems*, vol. 135, Article ID 107468, 2022.

[32] R. A. González-Fernández, A. M. Leite da Silva, L. C. Resende, and M. T. Schilling, "Composite systems reliability evaluation based on Monte Carlo simulation and cross-entropy methods," *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 4598–4606, 2013.

[33] Y. Wang, V. Vittal, M. Abdi-Khorsand, and C. Singh, "Probabilistic reliability evaluation including adequacy and dynamic security assessment," *IEEE Transactions on Power Systems*, vol. 35, no. 1, pp. 551–559, 2020.