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Probabilistic Security Assessment in Power Transmission Systems: A Review

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***Abstract*–Power system security is an essential component of power transmission system planning and operation. Conventionally, it has been evaluated using deterministic approach, such as *(N-1)* criterion, under worst-case severe system loading levels. Though, such worst-case deterministic approach does not deliver a clear evaluation of the probability of component failure of the system, and the probability of the outages is dealt in the same manner. The key disadvantage of the *(N-1)* security criterion is that it does not provide any information regarding failure probability. With the dawn of various renewable energy sources, and the rising complexity of power systems, the amount of uncertainty in power networks has considerably increased. These energy sources, in addition to the traditional uncertainty sources (load, generation availability, transmission assets, etc.) present the drawbacks of the traditional deterministic security assessment. Moreover, the occurrence of contingencies in power systems and their effects are non-deterministic, justifying the requirement to incorporate probabilistic approaches for power system security assessment. Considering its importance in power system planning and operation, this paper attempts to review some major works on probabilistic security assessment (PSA). Consequently, some significant research gaps are identified. It is believed this paper will be very beneficial for the power system research community, particularly, for students and researchers in the domain of power system security and risk assessment.**

Keywords- Planning; renewable; risk; security; transmission

I. INTRODUCTION

Renewable energy sources have added supplementary uncertainty to power systems. These sources, further add to the conventional sources of uncertainty due to probabilistic nature of the load, the availability of generation resources, and transmission assets, and thereby, adds to the drawbacks of the conventional deterministic power security assessment in power system analysis applications. To manage uncertainties, probabilistic approaches can provide a valued input [1].

Composite power system reliability evaluation is usually grouped into two groups: adequacy and security [2-3]. Adequacy involves the assessment that there are sufficient generation facilities in the network to meet the customer load demands, considering scheduled and rationally anticipated unscheduled outages of system components [4]. Adequacy is a steady-state issue and deals with both generation and transmssion capacity. Security deals with the response of the network to sudden disturbances, such as line outages or faults. Security is further divided ino two categories: static and dynamic. Static security deals with steady-state analysis of post-disturbance system conditions to authenticate that there is no line overload or bus voltage violations. Dynamic security assessment (DSA) is the analysis needed to find out whether a power system can meet stated reliability criteria in transient time frames for all credible disturbances. The classification of power system security is elaborated in Figure 1. Moreover, various kinds of security states are displayed in Figure 2.

The power system is normally designed to sustain some disturbances, nominated based on substantial probability of occurrence. They are typically defined by the loss of a single component, either spontaneously or preceded by a short circuit fault. This approach is commonly known as the *(N-1)* criterion as it scrutinizes the performance of an *N*-element system, after the loss of any one of its elements [5]. In recent years, there has been a sharp upsurge in integrating stochastic renewable energy sources with the power systems. The security assessment of these renewable-integrated power systems using traditional deterministic approaches is swiftly becoming inappropriate and therefore, novel probabilistic assessment methods are required [6]. Transient stability evaluation is an integral component of security assessment. It deals with evaluating the stability of the system, after a fault occurrence. If, for a given fault, the conventional synchronous generators can maintain synchronism, system is said to be transiently stable for that fault.

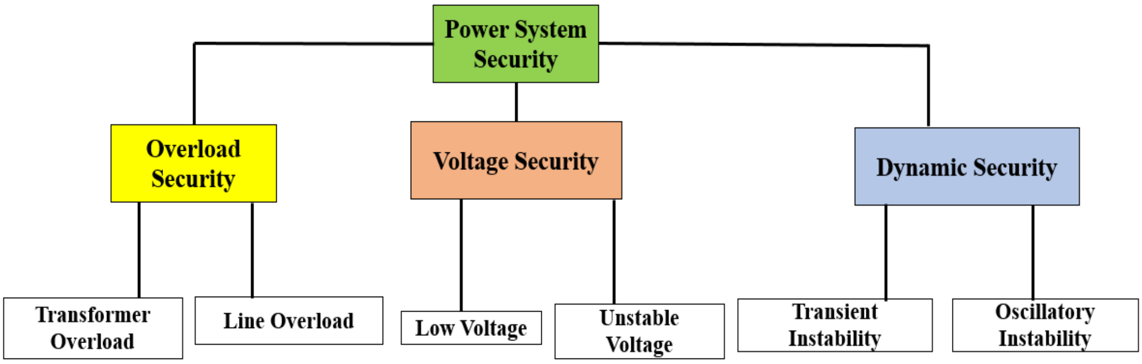

Figure 1. Types of power system security

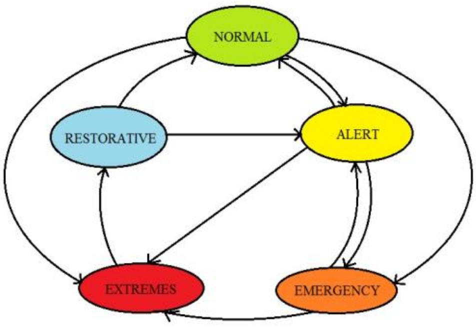

Figure 2. States of power system security

Deterministic security evaluation methods have been extensively used for system planning studies, and generally they lead to highly secured, and robust power systems [7]. The deterministic approach does not consider the probability of operating conditions. Therefore, apart from the high cost due to conservative designs, the chief disadvantage with the deterministic assessment techniques is that they treat all security problems to have equal risk [8]. The product of the probability of an unforeseen event and its impact is commonly known as risk [2]. The risk is an integral part of network security. The higher the risk, the lower the security and vice-versa. The risk-based probabilistic approach can be used to improve the security-economy decision-making [9]. A comprehensive contrast between the deterministic and the probabilistic approach is given in [10]and [11]. Blackout that took placed in North America power system in August 2003 suggested to not underestimate the facts about power system security. Also, the consequences of other historic major blackouts, such as 2015 Pakistan blackout, 2012 India blackout, 2005 Indonesia blackout, 2003 Italy blackout, and as recent as 2021 Queensland (Australia) blackout, indicate that the significance of power system security and stability must not be neglected. Moreover, uncertainties in power system and the popularity of deregulated electricity market has paved the way for probabilistic assessment in security analysis. The main kinds of uncertainty in a typical power system are shown in Figure 3. Thus, the main aim of this paper is to review some work pertinent to probabilistic security assessment (PSA) in power transmission systems.

The rest of the paper is organized as follows. Section II describes deterministic and PSA procedures in power system. Section III provides a review of major works in the domain of PSA in transmission systems. Section IV indicates the potential research gaps. Finally, Section V concludes the paper with suggested directions for future research.

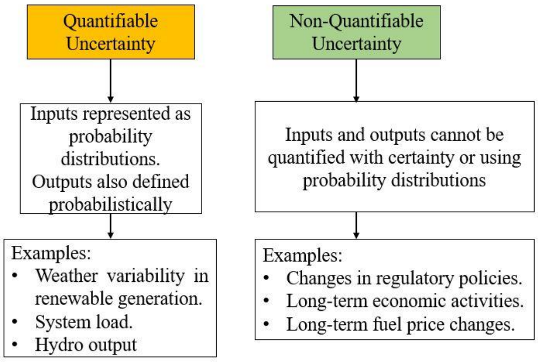

Figure 3. Main types of power system uncertainty

II. Deterministic and Probabilistic Security Assessment

Traditionally, deterministic criterion has been used for security evaluation for power system planning and operation [12-13]. This method is generally considered for a single operating condition, commonly known as the worst-case scenario. In most cases, the *(N-1)* contingency principle is used, i.e., individual system components are removed one at a time for the assessment. While this worst-case approach is well established in the power industry; however, in a competitive environment, the utilities require to know the risk levels such that they can adjust their service quality based on consumer's expectation [14]. The conventional security assessment follows a step-by-step procedure in which the factors such as the load, fault types, fault locations, etc., are selected in advance, usually in accordance with the worst-case philosophy [14]. Furthermore, to guarantee that the most severe disturbance is selected, the contingency types and locations are normally provided in advance.

The deterministic approach has at least the following three drawbacks [15-16]: "(1) Only consequences of contingencies are evaluated, but probabilities of occurrence of contingencies are ignored. Even if the consequence of a selected contingency is not very severe, system risk could still be high, if its probability is relatively large. Conversely, if the probability of an outage event is extremely small, the contingency analysis of such an event may result in an uneconomic operational decision; (2) all uncertain factors that exist in real life (such as uncertainty of load variations, variability of renewable generation, random failures of system components, fuzzy factors in parameters or input data, errors in real-time information, volatility of power demand on the market, etc.) are ignored in the deterministic analysis. This can lead to results, biased from the reality; (3) the deterministic approach is based on pre-selected worst cases. In implementation, however, the actual worst case may be missed [16]."

Moreover, as the result of deterministic security analysis is binary (secure or insecure), therefore, the risk could not be quantified. The matter of fact is that the electric power sectors need to know the risk level to take actions to upsurge the system security. Therefore, examining the system security by applying risk assessment has become a crucial research technique [17]. A pictorial representation of a typical framework for deterministic security assessment is shown in Figure 4.

The probabilistic studies consider the probabilistic nature of the real power system. They consider the probability distribution of one or more uncertain parameters, and hence, reflect the actual system in a better manner. Although, it has been long established that deterministic studies may not sufficiently characterize the entire extent of system dynamic behavior, the probabilistic approach has not been extensively used in the past in power system studies, mainly due to lack of data, limitation of computational resources, and mixed response from power utilities and planners [13, 15-16, 18]. Probabilistic approaches are mainly appropriate, for the examination of a system, with randomness and uncertainty, which are obviously the main features of future power networks.

In the past several years, there has been a considerable increase in connections of intermittent and stochastic, power electronics interfaced renewable energy generation sources. These uncertainties are becoming one of the crucial characteristics of modern power systems. The security assessment of such systems using traditional deterministic methodology is swiftly becoming inappropriate and thus, novel probabilistic evaluation methods are desirable, and are being established [19-20]. These rising power system uncertainties has motivated the application of probabilistic methodologies, for transient stability assessment. It is, thus, of great significance to propose a risk-based approach, for overcoming the shortcomings of the deterministic approach. The probabilistic analysis can provide a more inclusive, coherent, and realistic measure of the system stability level. A pictorial representation of a typical framework for PSA study is shown in Figure 5.

III. Literature Review

In [21], a risk-based security assessment procedure was proposed, which allowed the evaluation of operational security of a power network's future state under uncertainty originating from different topologies and forecast errors. The practice modeled input uncertainty with a copula function-based Monte Carlo framework. In [22], a novel scheme for PSA was presented. The method can tackle different kinds of probability distributions modeling power injections and can explicitly represent the effects on system security of correlation among nodal power injections.

Reference [23] presented a technique for assessing line overload risk of wind-integrated power systems with the deliberation of wind and load-power generation correlation. The proposed risk assessment model fully considered the probability and the consequence of wind uncertainties and line flow fluctuations. The point estimate method was used to deal with the probability of line overload and the severity function was applied to quantify line flow fluctuations. Reference [24] presented a process for probabilistic assessment of the grid security based on the power system stress level, i.e., the proximity of violating the technical restrictions. The technique quantified the network security using risk indices. In [25], a probabilistic methodology to evaluate the security of electrical power systems was applied. The distributions of security indices such as Expected Demand Not Served are derived by performing non-sequential Monte Carlo simulations and by considering remedial actions (load shedding and line tripping). To account for the uncertainty in the knowledge of their values, various failure probabilities for the individual elements of the power system were considered. Results were discussed in terms of evaluating both the method applied and the resulting security of the examined networks.

Reference [26] proposed a probabilistic method in power system security assessment with momentous wind power penetration within operational context considering the uncertainty of wind. The results showed that the probabilistic method delivers an improved perspective on the system security resulting in efficient operational decision-making. A probabilistic static voltage security evaluation model was proposed in [27]. By analysis of probability index, contingencies making the most contribution to the system static voltage insecurity probability were obtained. Reference [28] suggested various probabilistic analytical methods and tools such as contingency enumeration, multi-area reliability assessment, and Monte Carlo simulation that can be used for transmission planning, generation expansion and system reliability assessment. It also included some case study results of applying these probabilistic methods and tools to real system planning and analysis. One study quantified network probabilistic reliability measures with respect to numerous system problems, including branch overloads, loss of loads, voltage limit violations, and voltage collapse conditions as recognized in contingency assessment for an extra high voltage electric grid. The probabilistic measures complemented the deterministic contingency results.

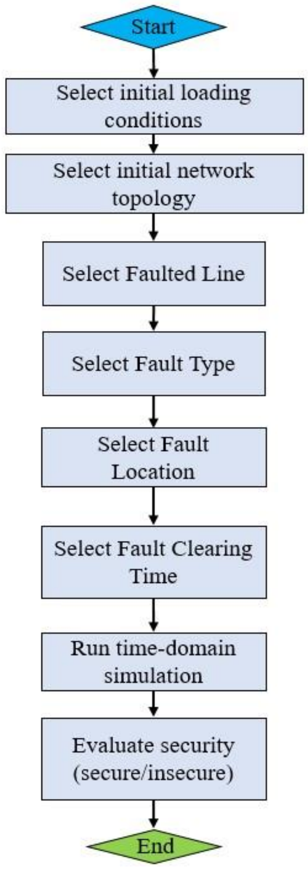

Figure 4. Framework for deterministic security assessment

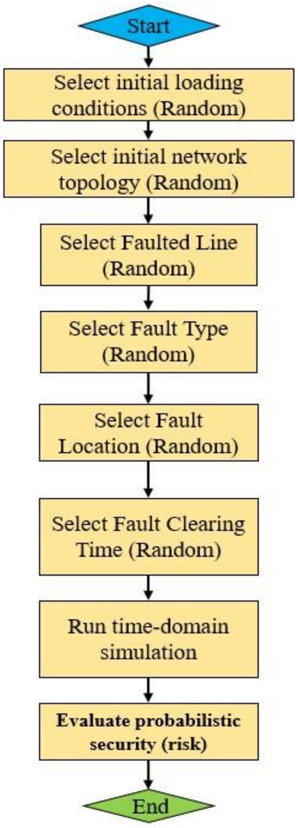

Figure 5. Framework for probabilistic security assessment

The work discussed in [29] was inspired by an apparent upsurge in the frequency at which power system operators are confronting high stress in transmission networks and the corresponding necessity to advance security monitoring of these networks. Online risk-based security assessment provided rapid online quantification of a security level associated with an existing or forecasted operating condition. In [30], a cumulant-based probabilistic power flow method was proposed to analyze power system security assessment under uncertainty.

Reference [31] suggested a security region based probabilistic steady-state and DSA framework. In the proposed approach, constraints of transient stability, static voltage stability, node voltages and line currents were incorporated. In [32], an online risk-based security assessment system was established and applied at China Southern Power Grid. The approach calculated the likelihood of each undesirable event in the transmission network and evaluated the conforming severity using a well-defined risk index.

Reference [33] presented a risk-based security assessment practice, based on an extended definition of risk and envisioned to forecast the riskiest contingencies which will affect the power system, based on the *k*-hour ahead forecasts of the weather proceedings. Reference [34] discussed a probabilistic *(N-1)* security assessment approach that incorporated dynamic thermal line rating. To model the probability distributions of specific meteorological values, a copula approach was adopted. Reference [35] proposed a probabilistic risk assessment practice which can provide useful information to help operators recognize emerging risk of cascading.

An analytical method to probabilistic DSA of power systems incorporating wind farms was presented in [36]. Reference [37] suggested a risk evaluation system for HVDC planned maintenance using probabilistic method. Two main indices i.e., loss of load probability and security index, were formulated. Reference [38] summarized the state of the art on dynamic probabilistic risk assessment of cascading outages and consequently, presented numerous methods to solve the existing challenges. Reference [39] proposed a technique to analyze the operational risk in power networks considering different aspects (loss of load, high currents and low voltages) and signifying preventive control actions to decrease the risk.

IV. RESEARCH GAPS

Review of various research papers mentioned above indicates that PSA is a promising area and further work needs to be conducted in this domain. Probabilistic methods can prove to be very beneficial for reliability and security assessment. There is a dire need to develop unique mathematical methods additional analysis. In real-time (online) security assessment, the computing speed is vital. Research on certain soft computing approaches must be conducted to determine the optimum method, in terms of computational resources and desired accuracy [16].

Moreover, there is a need to establish multiple scenarios to consider long-term uncertainties that impact transmission security process. The chief uncertainties that can impact transmission security processes are – federal, state, and local regulations related to environmental restrictions and economic growth. Presently, planners simulate the deterministic scenario without any clear treatment of uncertainties. This may no longer be adequate to address intermittence of renewable generation, and spikes in extreme weather. Probabilistic methods can provide a very useful alternative to fulfil this important objective. Risk-based probabilistic security analysis requires active research and industry participation for its wider acceptance. Governments and local utilities can promote research efforts and collaborate with research organizations and universities [40].

There is a need for extensive data manipulation, processing, analyzing, and complex operation which are beyond what is desirable in the deterministic methods. Complexity of dependent and independent variables, and their correlation is also a significant research gap. With the power system incorporating numerous independent and dependent events, variables, conditions, parameters, the computation becomes very burdensome. There is also a strong lack of risk-based indices and criteria for security assessment [41].

It is also important to determine what kind of studies are impacted most by inherent and external uncertainties. The major hurdles in transition from the conservative deterministic to novel probabilistic need to be assessed and consequently, the required knowledge must be gained by planners and utilities for this transition. Also, upgradation of existing industry standards (e.g., NERC TPL) is required to incorporate risk-based probabilistic approaches. Various recent research [42-54] indicates that PSA is an upcoming area, and further research is required to fully comprehend this domain. These works also signify that incorporating uncertainties, including intermittence of renewable generation, in PSA is inevitable and highly desirable for correct decision-making. Also, probabilistic approaches must be incorporated for operational and planning procedures in the power system.

V. Conclusion and Future Work

PSA is a critical component of power system planning and operation. Not following standard procedures for PSA can result in ineffective decision making. Therefore, this paper reviewed some major works in this domain, and provided some useful and prominent research gaps. Although, numerous transmission planners and utilities agree that the shifting nature of power systems call for using risk-based approaches, there are others who are cynical regarding the timeliness and significance of these methods. However, it is hoped that this review paper will help the industry and utilities to have a good comprehension regarding risk-based approaches for security assessment. The two most important aspects of PSA are: (1) quantifying major uncertainties that impact the PSA procedure, and (2) the transition from conservative security methods to risk-based based approaches.

As a future work, research on PSA of integrated power and natural gas systems can be conducted for large-scale systems. Moreover, soft computing approaches, such as machine learning, fuzzy logic, genetic algorithms, and deep learning, for improving computation time are another open area of research. A new power system model, incorporating network topology changes and *(N-2)* contingency criterion, is a good starting point for PSA, of future power systems.

Unquestionably, additional research is essential to further refine the methods and tools associated with PSA. However, findings of this paper can be used as a basis to promote awareness on a broader adoption of probabilistic risk and security assessment approaches among federal policy regulators, research organizations, researchers, students, and utilities.

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