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A Comprehensive Review on Power System Risk-Based Transient Stability

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***Abstract*–Power systems are getting more complex than ever and are consequently operating close to their limit of stability. Moreover, with the increasing demand of renewable wind generation, and the requirement to maintain a secure power system, the importance of transient stability cannot be overestimated. Considering its significance in power system security, it is important to suggest a different methodology for enhancing the transient stability, considering uncertainties. Current deterministic industry practices of transient stability assessment ignore the probabilistic nature of variables (fault type, fault location, fault clearing time, etc.). These approaches typically provide a cautious principle and can result in high-priced expansion projects or operational limits. With the increasing system uncertainties and widespread electricity market deregulation, there is a strong inevitability to incorporate risk in the traditional transient stability analysis. Accurate assessment of transient stability in a modern power network is becoming a strict requirement both in planning and in real-time operation, due to the increasingly intricate dynamics of a power system. Further, increasing sources of uncertainty in forecast state and in the reaction to faults highly implies the implementation of risk-based approach in assessing transient stability. Thus, this paper aims to provide a comprehensive review of risk-based transient stability in power networks and the accompanying research. It is believed that this review can be an inception for investigators in the field of power system planning and security.**

Keywords-Risk; security; stability; uncertainty; wind

I. INTRODUCTION

Driven by various techno-economic and environmental factors, the electric energy industry is anticipated to undergo a paradigm shift, with a significantly augmented level of renewables, especially, wind and solar power sources, gradually replacing conventional power production sources (coal, diesel, natural gas, etc.) [1-2]. This increasing demand of large-scale wind integration in the conventional power system, along with the inherent and external uncertainties of the system, brings a lot of challenges [3-4]. Power systems are regularly exposed to unanticipated faults. Such faults can cause transient instability and can consequently lead to prevalent outages [5]. With the implementation of a deterministic criterion for system stability, power systems generally operate with a large stability margin. "Usually, these deterministic criteria provide safe, but conservative limits for system operating conditions. The most critical security criterion is the (*N*-1) security criterion that guarantees safe operation of the power system, after the failure of a single element of the system, where *N* is the total number of system components [5]."

In recent times, various sources of probabilistic renewable energy generation are on the rise. These uncertainties, coupled with load uncertainties, are becoming the key features of contemporary power networks [6]. The current industry practices use the deterministic approach for Transient Stability Assessment (TSA) [7-8]. Although, the deterministic approaches result in highly stable power systems, but they fail to incorporate the probability of various system components and conditions. In addition to the great expense due to conventional models, the key drawback with the deterministic strategies is that they consider all stability problems to have equal risk [9]. Various papers [8-14] mention that probabilistic risk-based transient stability (RBTS), and incorporating risk in power planning procedures, is a future research area, and consequently, work needs to be done in this domain. Moreover, planning manuals of various utilities [15-18] recommend using risk-based probabilistic approaches in the near future. Moreover, the integration of renewable generation, presents more stochasticity in the system, making the application of probabilistic practices essential in the TSA process.

The rest of the paper is organized as follows. Section II discussed the background of deterministic and probabilistic transient stability (PTS). Section III presents literature review regarding RBTS. Section IV discusses the research gaps and recommendations for future work. Finally, Section V concludes the paper.

II. DETERMINISTIC AND PROBABILISTIC TRANSIENT STABILITY

"Conventionally, deterministic criterion has been used for transient stability evaluation for power system planning and operation" [19-20]. Although this worst-case approach has served the industry well; however, in a deregulated environment, the utilities require to know the risk value [21-23]. The consequence of deterministic stability analysis is binary; hence, the transient instability risk cannot be quantified. Therefore, computing the system transient stability by using risk assessment has become a critical research strategy [24]. A graphical description of a standard framework for deterministic TSA is shown in Fig. 1.

As the uncertainty and renewable generation is increasing, a probabilistic assessment approach becomes tremendously beneficial [25]. "The probabilistic studies consider the stochastic and probabilistic nature of the real power system. It considers the probability distribution of one or more uncertain parameters, and hence, reflects the actual system in a better manner. Although, it has been long established that deterministic studies may not sufficiently characterize the full 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 [20, 22-23, 26]. 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."

Although, the deterministic approaches result in very secure power systems, but they blatantly ignore the stochastic characteristics of a real power network. Also, with the introduction and acceptance of competitive electricity markets and intricacy in solving practical problems of power system planning, the deterministic methods are insufficient and obsolete [27]. This, along with the emerging power system, uncertainties have greatly driven the application of probabilistic approaches, for TSA. A pictorial representation of a standard framework for probabilistic TSA is shown in Fig. 2.

To the best of author's knowledge, there exists no work which comprehensively reviews RBTS of power systems. Thus, the main objective and contribution of the current paper is to review work related to RBTS and provide research gaps and recommendations for future work.

III. LITERATURE REVIEW: RISK-BASED TRANSIENT STABILITY

The product of probability of an unforeseen event and its impact is commonly known as risk, which is generally mathematically defined as (1) [28-32].

$$Risk = \sum_i Pr(Ei) \times Sev(Ei) \qquad (1)$$

where Ei is the i^{th} event (contingency) and $Pr(Ei)$ is its probability. $Sev(Ei)$ quantifies the impact of Ei.

The risk is the system's exposure to failure and is generally determined by considering both the probability of occurrence of an event and the impact of the event [29]. A simple example can be used to outline the significance of using risk in power systems.

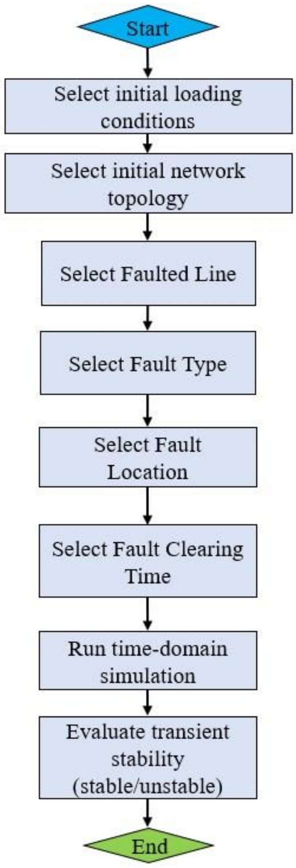

Fig.1. Framework for deterministic TSA

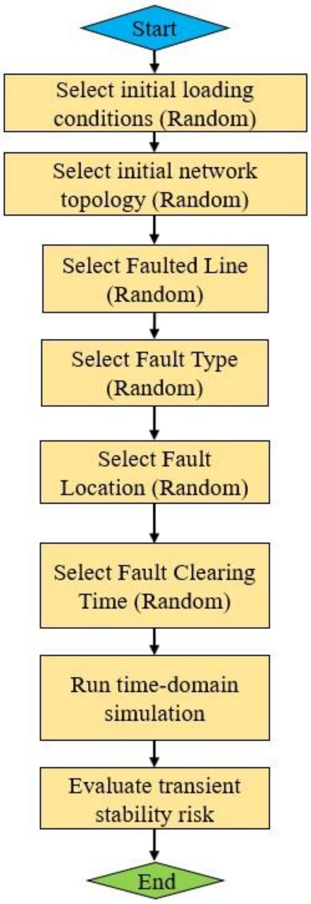

Fig. 2. Framework for probabilistic TSA

Consider two contingencies (*C1* and *C2*), along with their probability of occurrence and the corresponding severity (impact), as outlined in Table I. If decision-making is assumed to be based on deterministic criteria, *C2* is found to be more severe as its impact is greater than *C1*; however, if risk-based (considers both probability and impact) decision-making is used, the converse is true.

TABLE I. RISK VALUES FOR TWO DIFFERENT CONTINGENCIES

Contingency	Probability	Impact	Risk
C1	0.05	20	1
C2	0.02	30	0.6

Risk-based approach describes possibility of contingency by probability, and the corresponding impact (or consequence) by severity function. The product of this probability and associated severity is termed as risk. In risk-based stability assessment, the risk index consists of each possible contingency occurrence probability and the associated impact [33]. The first attempt toward RBTS was proposed in [34] and [35], where the notion of limiting operating point functions was used. These functions return the limiting generation level for any fault type and fault location. Reference [36] used risk-based approach, to analyze the transient stability of power networks, incorporating wind farms. The proposed methodology of transient instability risk assessment is based on the Monte Carlo (MC) method and eventually, an inclusive risk indicator, based on angle and voltage stability, is devised. The work considered only three phase line faults.

Reference [37] presented a distributed computing approach for transient stability analysis, in terms of measuring critical clearing time and the overall risk index, for various uncertainties. The work considered only a three phase to ground fault. [38] presented a method to determine the risk of transient stability. It described the application of Rotor Trajectory Index (RTI), to assess the severity of power systems, when it was subjected to a three-phase fault. Reference [39] focused on risk of transient instability. A procedure was suggested to evaluate the potential loss of synchronism of a generator, in terms of probability and consequences. A transient risk assessment method, based on trajectory sensitivity, was presented in [40].

In [41], the transient stability risk assessment framework incorporating circuit breaker failure and severe weather was presented. All related random variables, such as load demand, fault type, fault location, and Fault Clearing Time (FCT) were considered using appropriate probability density functions (PDFs). Reference [42] proposed a two-stage power system TSA method based on snapshot ensemble Long Short-Term Memory (LSTM) network to quantify the risk of transient stability. The two stages consisted of dynamic hierarchical assessment and application of regression to screen credible samples and predict their transient stability margin, respectively.

Reference [43] provided an algorithm for the rapid on-line transient instability risk assessment related with existing or forecasted operation conditions, using IEEE 39-bus system. The transient instability risk was defined in terms of the probability of transient instability and its cost. [44] used Radial Basis Function Neural Network (RBFNN) to compute transient stability risk in a cyber physical power system. It used a synchro phasor data analytics based predictive algorithm for detecting vulnerable generating units contravening the stability boundaries for proactive control actions. A summary of these research papers is shown in Table II. Some other research work associated with RBTS can be found in [45-47].

IV. RESEARCH GAPS AND FUTURE RECOMMENDATIONS

From the broad literature review of key works in RBTS, numerous gaps were identified. The major research gap in these works include not considering all the fault events (faulted line, fault type, fault location, FCT) randomly, i.e., only some of the events are considered random variables, while others are considered as deterministic. To fully encapsulate the concept of risk, it is important to consider all parameters. Moreover, there is a string need to establish a standard risk metric for transient stability. Majority of research takes a very simplistic approach to treat the randomness of associated variables (load, renewable generation, component availability, fault type, generator fuel price, etc.).

Also, there is a need to extensively include renewable generation and external weather events while assessing this risk. There is a need to establish advanced software and tools which can deal with probabilistic analysis of large-scale power systems to ensure accurate RBTS assessment. It is important to consider more than single contingency as ignoring the higher order contingences will result in a very conservative analysis of transient stability. Big data analytics must be researched further to delve into the various possibilities of data regarding random input and output variables of power system, and to comprehend unknown patterns, correlations, market developments and customer preferences. Given the exceptional changes in the electric power industry, and the stringent requirements to maintain system reliability at a minimum cost, RBTS planning is becoming intricate than ever. In this regard, some significant recommendations in this are outlined below [13]. All the existing North American Electric Reliability Corporation (NERC) transmission planning standards are deterministic. Though, recently NERC has shown significance in incorporating probabilistic approaches in transmission planning by organizing multiple workshops in Eastern Interconnection and Western Electricity Coordinating Council (WECC).

This study provided a review of key research works in RBTS. This can be an offset for researchers in the domain of power system stability. Contemporary research [48-65] reveals that there is a lot of work which needs to be done in the domain of RBTS.

TABLE II. SUMMARY OF VARIOUS PAPERS ON RBTS

Reference Number	Research Objective	Proposed Solution	Advantages	Disadvantages	Results
[34]	To develop a risk-based security assessment method in an operating environment considering any kind of security violation.	Characterize the operating point using pre-contingency controllable parameters.	Accounts for fully reliable conventional protection equipment and for main breakers passive and active failures.	The effect of special protection scheme reliability on risk of transient instability was ignored.	Probability of instability was computed.
[35]	To present a new risk-based security index which accounts for probability and impact of instability.	Use the concept of composite risk for evaluating security index.	Accounts for variation in fault types and location instead of assuming a worst-case disturbance scenario.	Several other methods of identifying a specific risk-based limit were neglected.	Security assessment index for stability-limited electric power systems was evaluated.
[36]	To research the transient stability of power systems incorporating wind farms by utilizing risk assessment methods.	Use the concept of risk to assess the transient stability of power networks.	Wind penetration variation and multiple stochastic factors of power systems were considered.	Various kinds of wind generators were not considered in the analysis.	System comprehensive risk indicator was computed.
[37]	To propose a new method for risk assessment of power system due to transient instability using distributed computing approach.	Use distributed computing approach in terms of measuring critical clearing time and the overall risk index for various uncertainties.	Various practical sources of uncertainty were considered.	Wind generation was not included in the analysis.	The risk index of the system was computed using probabilistic modelling of load and fault locations.
[38]	To use rotor trajectory index to assess the severity of power systems.	Use the machines' rotor angles obtained at each step of a time domain simulation to compute trajectory index.	Approach was tested on a well-known and established test system for stability study.	Double line contingencies were ignored.	Degree of stability of the system was calculated.
[39]	To compute the probability of transient instability.	Use transient stability index to quantify probability of instability.	Uncertainty of fault location, fault type, load level and clearing time were considered.	Wind generation was not included in the analysis.	Degree of stability of the system was calculated, considering uncertainty.
[40]	To compute transient risk assessment considering uncertainty.	Use trajectory sensitivity to compute transient risk assessment.	Contingency cost was considered as minimum control cost to move the system from instability to stability.	Renewable generation was not included in the analysis. Other kinds of stability issues were ignored.	Risk indices based on load curtailment and control cost were evaluated.
[41]	To incorporate the impact of circuit breaker failure and severe weather in the transient stability risk assessment procedure.	Use transient stability risk assessment framework.	Impact of severe weather and breaker failure were considered for risk assessment.	Double line contingencies were ignored.	Transient stability risk index was computed incorporating circuit breaker failure and severe weather.
[42]	To propose a two-stage transient stability evaluation method based on snapshot ensemble long short-term memory network.	Use dynamic hierarchical assessment through the classifier.	Real-time disturbed trajectory measurements were incorporated.	Partial measurement data missing caused by PMU failure was ignored.	Binary information representing transient stability status of samples was computed.

V. CONCLUSION AND FUTURE WORK

Power system transient stability is an integral part of power system planning and operation. Traditionally, it has been assessed using deterministic approach. Also, current NERC reliability standards are deterministic and do not include any probabilistic methods. With the increasing system uncertainties, environmental pressures of incorporating green energy, and widespread electricity market liberalization (deregulation), there is a strong need to incorporate risk in conventional transient stability analysis in transient stability evaluation. RBTS can entirely consider both the probability and impact of the unexpected event (fault), and thus, can quantify the indicator of risk. This method has a greater logic compared to conventional methods as uncertainty, renewable generation, and deregulation are characteristics of modern power system.

This paper provided the groundwork for complete research for RBTS assessment. It is considered that this review would provide a good offset for any future research in the realm of power system risk-based stochastic stability. A novel and unique new power system model, integrating system topology modifications will provide an excellent practical kick-off for RBTS of modern power systems.

Nomenclature

Notation	Meaning
i	Sample number for the MC simulation
Ei	i^{th} contingency (event)
$Pr(Ei)$	Probability of i^{th} contingency (event)
$Sev(Ei)$	Severity (impact) of E_i
$C1$, $C2$	Contingency

List of Abbreviations

Abbreviation	Meaning
FCT	Fault Clearing Time
LSTM	Long Short-Term Memory
MC	Monte Carlo
NERC	North American Electric Reliability Corporation
PTS	Probabilistic Transient Stability
RBFNN	Radial Basis Function Neural Network
RBTS	Risk-Based Transient Stability
RTI	Rotor Trajectory Index
TSA	Transient Stability Assessment
WECC	Western Electricity Coordinating Council

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