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Calculating probability density function of critical clearing time: Novel Formulation, implementation and application in probabilistic transient stability assessment

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ABSTRACT

Due to increasing of uncertainty in nowaday power systems, probabilistic security assessment has become one of the challenging issues in power systems. This paper, proposes a new real-time approach for calculating probabilistic critical clearing time (CCT) which is applicable to probabilistic transient stability assessment. The proposed method aims to provide a low computational burden and high-accuracy to calculate the probabilistic density function (PDF) of CCT in two stages. In the first stage, proposed method presents a novel sensitivity based approach, which calculates CCT in the first step of the simulation. Determination of CCT by taking structure preserving into account, guarantees the accuracy of the proposed method. In the second stage, by applying Quasi Monte Carlo (QMC) simulation, the PDF of CCT is obtained. Several different parameters that affect uncertainty of CCT such as load and generation and also fault location are considered in order to obtain the PDF of CCT. Several case studies have been conducted on IEEE 9 bus and 68 bus test systems to show the efficiency of the proposed method. Simulation results indicate that the proposed method has notable accuracy along with substantial speed in performing the required calculations.

1. Introduction

Providing a more effective and realistic assessment of stability based on probabilistic analysis which comprehensively evaluates the stability level of the system, causes profound intuition into power system stability compared with deterministic methods [1]. Among the different security issues of power systems, transient stability (TS) has become one of the most challengeable problems for decades [2]. By turning traditional power grid into smart one, the TS problem experiences more challenges due to extra uncertainty. Also, from the type of assessment point of view, the online probabilistic assessment of TS causes quick measuring of stability level related to given operating conditions. This paper aims to propose an online method for finding the PDF of CCT which is applicable to the probabilistic transient stability assessment (PTSA).

A review of the literature in this area shows that the proposed method must be investigated from two aspects: first, deterministic calculation of CCT and its circumstances and related issues, second, finding PDF of CCT.

Studying the previous published papers for finding CCT, it can be seen that the previous deterministic TS assessment methods have the following objects: First, Structure preserving; which focuses on considering the details in modeling the present components in the power system. It must be mentioned that the most of the stress of structure preserving issue is on the generators modeling. To be more specific, the order of the generators differential equations increases by modeling automatic voltage regulator (AVR) and governor. The second object is considering the fault-on trajectory, which focuses on considering the impact of the fault location on the calculation of transient stability index (such as critical clearing time(CCT), unstable equilibrium point (UEP) and etc.). Finally, independency from post-fault data, which focuses on ensuring the real-time and online assessment of transient stability during fault condition.

From these points of view, the methods in finding CCT are categorized in four groups: First, the approaches that belong to group 1 (G#1) [3] which are based on time domain simulation (TDS) and consider all details into account. Despite simplicity in implementation, these approaches are unable to calculate CCT in real time since they are time-consuming. Second, the approaches in group 2 (G#2) which are based on transient energy function (TEF) [4–11] and difficult to be implemented especially due to many potential terms in the general function. Also, these approaches need post-fault data for finding

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Nomenclature

Abbreviation	Definition
CCT	Critical clearing time
PDF	Probabilistic density function
CDF	Cumulative distribution function
QMC	Quasi Monte Carlo simulation
TS	Transient stability
PTSA	Probabilistic transient stability assessment
TDS	Time domain simulation
TEF	Transient energy function
UEPs	Unstable equilibrium points
AI	Artificial intelligent
ML	Machine learning
MCS	Monte Carlo Simulation
LCS	Large change-sensitivity
MEAC	Modified equal area criterion
KE	Kinetic energy
CKE	Corrected kinetic energy
CCKE	Critical corrected kinetic energy
PoS	Probability of stability
SI	Stability Index

unstable equilibrium points (UEPs) and as a result, they are not suitable for CCT calculation. Third, the proposed approaches stated in group 3 (G#3) [12–15] which are usually implemented by utilizing artificial intelligent (AI) and machine learning (ML) algorithms and are based on historical data. This means that these approaches are trained for many scenarios; while occurrence of contingencies and the involved parameters such as location have probabilistic nature. Therefore, the set of training data may have lack of comprehensiveness in considering all scenarios. These methods have fast response and are suitable for real-time applications. Eventually, the fourth group (G#4) so-called Hybrid approaches [16–18], attempt to calculate CCT with combination of some modification in equal area criteria, TEF, and statistics calculations. These methods have supremacy in reducing computational burden and simultaneously improving the accuracy.it is worth noting that afore-mentioned methods focus on the conventional synchronous generator units. However, the TSA of power system comprising with different wind turbine generators and also combined ac-dc networks have been addressed in [19–24]. In addition, calculation and estimation of CCT utilizing model reduction of induction machine based wind turbine has been investigated in [23].

In [25], the importance of PTSA has been properly addressed. The Analytical methods utilize conditional probability theory to analytically assess the probability of stability [1,26–28]. These methods consider the impacts of fault type, fault location, and fault duration into PTSA. Moreover, these approaches utilize some approximation in order to calculate probability of system stability as a function of CCT. Only in [1,29], authors have suggested an online method based on corrected transient energy margin for PTSA. However, it is unclear that how the method utilizes potential terms in TEF and simultaneously it is online. In contrast with the analytical approaches, the Monte Carlo Simulation (MCS) based approaches are utilized to estimate the probability of stability by calculating PDF of CCT [30–33]. These approaches have capability to deal with highly large and complicated networks without sacrificing any detail. However, due to large computational burden, they are not suitable for real-time applications.

It must be mentioned that the main focuses of this paper is on finding a deterministic and online solution similar to G#4 for calculating CCT and eventually estimating a PDF for CCT of each generator that is able to anticipate the probability of stability of each generator during severe disturbances.

This paper presents an innovative approach for calculating the PDF of CCT based on TEF. The intention of the proposed approach is determining a fast solution for calculating PDF of CCT with two essential objects: consideration of maximum network details and simultaneously minimization of dependency to post-fault data which results in high-precision real-time CCT calculation. To such aim, the paper contains some novel contributions which are listed as follows:

- Unlike to the previous-published methods in G#2 to G#4, which need an initial point even for offline calculation of potential terms, the proposed method (PM) does not need a two stage solution for finding critical kinetic energy. The proposed method utilizes the solution of the TEF function of the generator for worst case scenario (e.g. three phase fault at terminal of generators).

For more transparency, the previous-published methods in G#2–G#4, need an initial point even for offline calculation of potential terms (G#2 and G#3) or to calculate the initial kinetic energy (G#4). Conventionally, the methods in (G#2 and G#3) have chosen as initial point where is operating point of the generator before fault occurrence.

- To take into account the effects of AVR and governor, it is vital to have a framework that considers the structure preserving. To deal with this issue, the proposed algorithm solves the TEF function of the synchronous generator for worst case scenario (e.g. three phase fault at terminal of generators). This stage which is performed in offline, results in having critical kinetic energy and corresponding critical rotor speed for worst case scenario.

For more transparency, it was mentioned that the lack of consideration of structure preserving in G#2 and G#3 influences accuracy of TS assessment. While the existent methods in G#4 deal with structure preserving with some approximation of the critical kinetic energy, it must be mentioned critical kinetic energy in this stage is more accurate because it is obtained by solving both potential and kinetic equations and the framework has no approximation.

- TS assessment approaches in G#2 and G#3 groups have a mutual problem in taking fault-on trajectory into consideration. This becomes very important especially in real-time assessment of TS. To deal with this problem, as will be discussed in the implementation section, the new LCS based sensitivity formulas is also proposed to correct critical kinetic energy for a given fault-on trajectory. In this calculation which is done for online stage, the critical kinetic energy will be corrected based on the sensitivity of the kinetic energy to the maximum power of generator. The new formula, corrects the effects of AVR and governor obtained in worst case scenario for a given fault. The online stage of the proposed method is implemented based on non-complex formulation and the CCT will be calculated with minimum computational burden during fault. As a result, the new proposed sensitivity based formulas can analytically and effectively consider the dependency on fault trajectory as well which causes low computational burden and post fault independency.
- In the calculation of the PDF of CCT, a simple but effective criteria based on the impedance distance is utilized that helps to select and allocate appropriate value of critical kinetic energy of worst case scenario in online calculation. Also, to calculate and estimate the PDF of CCT, proposed method employs QMC estimation. It has been proven that computational burden will substantially decrease compared with the conventional MCS [34].

The organization of this paper is as follows: Section 2 provides general platform and philosophy of the proposed method along with its mathematical description. Section 3 describes the circumstance about