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A sensitivity approach for computation of the probability density function of critical clearing time and probability of stability in power system transient stability analysis

Saffet Ayasun [a,*], Yiqiao Liang [b], Chika O. Nwankpa [c]

[a] *Department of Electrical and Electronics Engineering, Nigde University, 51200 Nigde, Turkey*
[b] *ALSTOM Drives & Controls, Pittsburgh, PA 15238, USA*
[c] *Department of Electrical and Computer Engineering, Drexel University, Philadelphia, PA 1904, USA*

Abstract

This paper presents a linear approximation method to determine the probability density function (PDF) of the critical clearing time (CCT) and probability of stability for a given disturbance in power system transient stability analysis. The CCT is the maximum time interval by which the fault must be cleared in order to preserve the system stability. The CCT depends on the system load level and thus, is modeled as a random variable due to the probabilistic nature of system load demand. The proposed method first determines the sensitivity of the CCT with respect to the system load, and using these sensitivities it computes the PDF of the CCT based on the PDF of the system load. The probability of system being transiently stable for a particular disturbance and for a given fault clearing time is calculated using the PDF of CCT. This approach is verified to be accurate under the condition of small load deviation by Monte Carlo simulations method. Moreover, the proposed method reduces the computational effort significantly in Monte Carlo simulations indicating that it could be used in real-time on-line applications.

Keywords: Electric power system; Transient stability; Critical clearing time; Linearization; Probability density function; Probability of stability

1. Introduction

Transient stability assessment is a major requirement for safe operation of power systems. The transient stability is analyzed considering the effect on the system of large disturbances such as faults, loss of loads or generators, line switching, etc. A power system is *transiently stable* for a particular steady-state operating condition and for a particular large disturbance if, following that disturbance; it reaches an acceptable

* Corresponding author.
E-mail addresses: saffet@nwankpa.ece.drexel.edu, sayasun@nigde.edu.tr (S. Ayasun), liang@gegelec.com (Y. Liang), chika@nwankpa.ece.drexel.edu (C.O. Nwankpa).

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steady-state operating condition [1]. The time domain simulations and direct methods are the two methods commonly used in transient stability studies. The time domain simulation method solves the differential-algebraic equations that describe the power system dynamics under different faulted conditions in order to find out if the system will preserve its stability. The method suffers in its slow speed and inability to provide an index that enables to measure the degree of stability of the system quantitatively.

Direct methods, on the other hand, employing energy functions provide a stability index that gives stability margin of an operating point in terms of energy stored in the system [2–4]. There are several variants of the direct method such as potential energy boundary surface (PEBS) method [5]; boundary of stability region based controlling unstable equilibrium point (BCU) method [6] and equal area criterion (EAC) [7–9]. The main objective of the various direct methods is to determine the critical fault clearing time and the corresponding critical energy value without solving the system differential equations in order to assess the transient stability of the system. The critical clearing time (CCT) is the maximum time interval by which the fault must be cleared in order to preserve the system stability. In direct stability assessment methods, the CCT is calculated and compared with the actual fault clearing time. If the former is greater than the latter the system is determined to be transiently stable. The difference between these two values can be used as an index to quantify the degree of system stability. A higher value of this index indicates a more stable system. The difference between the critical energy value and the energy at the fault clearing time is sometimes employed as an index as well. Even though the direct methods have drastically improved the program speed, the size of electrical power systems and the complexity of the transient stability problem still involve prohibitive calculations. With the advent of more advanced algorithms and faster computers, transient stability study has been implemented in Energy Management System (EMS) for real-time on-line operation. Like many other application programs in the EMS system [10], the transient stability program (TSP) is continually executed in a certain interval of time. Depending on the computing power of the EMS system, this interval can range from tens of minutes to an hour. The execution flow of this program is illustrated in Fig. 1.

At time t_k TSP is started and it gets a snapshot of system data such as load level and equipment parameters at this instant of time and performs necessary calculations to determine the CCT. After Δt amount of time, the program terminates and conclusions regarding the system transient stability are obtained. At time t_{k+1} the above procedure will be repeated. The system data captured at time t_k or t_{k+1} reflects the steady-state operating condition of the system and parameters. Among those, the load level is one of the parameters that heavily affects the stability. In other words, the stability of the system or equivalently, the critical clearing time (CCT) is a function of the system load level. Thus, the conclusions drawn based on the system load at time t_k will not always hold true from $t_k + \Delta t$ to t_{k+1} due to the fact that the system load keeps changing in actual operation. Therefore, the CCT should be modeled as a random variable in order to take into account the random nature of the system load. Based on the arguments above, a system being transiently stable under a particular contingency is also a random event. The information on the probability of this random event is crucial for power system planning studies and safe operation. Under the assumption that the probability density function (PDF) of the CCT is known, the probability of the system being transiently stable can be calculated by

$$P\{\text{system being stable}\} = P\{t_c < t_{cc}\}, \tag{1}$$

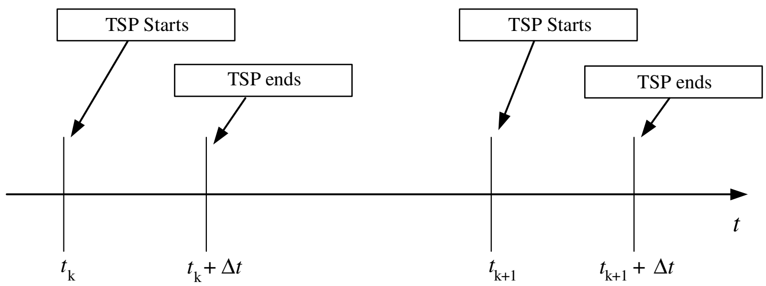

Fig. 1. TSP execution flow in the EMS system.