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A novel recursive approach for real-time transient stability assessment based on corrected kinetic energy

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ABSTRACT

Real-time assessment of transient stability is one of the main issues of power system operators in online applications. This paper proposes a novel recursive approach based on corrected kinetic energy which has the capability of real-time assessment and real time computation of transient stability margin in the power system. This approach considers all details of power system by using network preserving model to simulate transient stability. This paper uses a hybrid method based on the new concept of equal area criterion to estimate initial value of critical point of the system and corrected Kinetic Energy Function to estimate high precision value of the critical point. Also, this paper proposes a recursive method which uses large change sensitively (LCS) analysis to correct initial condition point of the system when the topology of system is changed by a disturbance. In order to validate the proposed method, comprehensive case studies have been conducted on IEEE39-bus test system. Comprehensiveness in considering the details, simplicity in implementation and low computational cost are the outstanding features of the proposed approach. Also, simulation results approve that the proposed approach can be used in real-time application without loss of any detail in the transient stability assessment.

1. Introduction

During the last two decades, the main research studies directions in the large scale power system are allocated to the power system transient stability assessment [1]. Also, real-time stability assessment of transient stability in the system control center is one of the most challenging issues faced by the engineers [2]. An accurate and applicable security assessment tool should be performed for obtaining a desirable amount of stability and security. The evaluation of transient stability is one of the most significant issues in the power system because: first, to assess the system capability to tolerate large disturbances and second, to propose corrective instructions. The nature of this problem is basically non-linear and it should be solved in the large-scale power network [3]. Although, the increase of computing power has resulted in a speed-up of online and real-time simulations, but simultaneously, the amount and complication of simulations has also grown. The enhancement request for more detailed and complex models can simply push any given computer to its limits [4].

The issue of the transient stability assessment has been investigated since 1970s and developed in practicability and application in the last two decades. It should be noted that the transient stability assessment can be classified into two categories: evaluation and prediction [5]. In the first group, the main key to assess the stability of power systems is critical clearing time (CCT) of short circuits [6]. During fault occurrence, the maximum time interspace that a fault may sustain in power systems and the system is retrieved to a new steady-state condition is called CCT [7]. All of the methods in calculating CCT are time-consuming and they need too many simulation data. Therefore, their computational costs are too much and they are not suitable for online and real-time applications. In the prediction transient stability, the aim is monitoring and forecasting the movement of the power system transient after intense contingencies, which causes to anticipate conditions of the system operation [7].

Various methods for transient stability assessment such as time-domain simulation, direct methods (such as Lyapunov), extended equal area criterion (EEAC), pattern recognition or hybrid methods have been proposed in [8–11]. Time domain approach is simple, flexible and accurate which is used for evaluation of transient stability during disturbance and post disturbance periods. However, this approach is not suitable for online simulation and real-time application [12,13].

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Nomenclature

CCT	Critical clearing time
EAC	Equal area criterion
EEAC	Extended equal area criterion
UEP	Unstable equilibrium point
BCU	Based controlling unstable
TEF	Transient energy function
SDG	Severely disturbed group
LDG	Less disturbed group
PM	Proposed method
SM	Simulation method
COI	Center of inertia
DT	Decision tree
δ_i	Rotor angle of i-th generator
$\delta_{i_{crit}}$	Critical rotor angle of i-th generator
ω_i	Rotor speed of i-th generator
ω_0	Reference rotor speed
M_i	Inertia momentum of i-th generator
D_i	Damping constant of i-th generator
P_{mi}	Input mechanical power of i-th generator
P_{ei}	Electrical power of i-th generator
Z_s	Series impedance of a transmission line
Z_L	Shunt admittance as a local load
x'_{di}	Direct axis transient reactance
x'_{qi}	Quadrature axis transient reactance
x_{di}	Direct axis synchronous reactance
x_{qi}	Quadrature axis synchronous reactance
E_i	Constant voltage behind direct axis transient reactance
B_{ij}	Network transfer admittance between bus i and bus j
G_{ij}	Network transfer conductance between bus i and bus j
T_{vi}	Time constant of AVR
μ_i	Feedback gain of AVR
l_i	A constant gain to adjust the location of the desired operating points
T'_{doi}	Direct axis transient open-circuit time constant
T'_{qoi}	Quadrature axis transient open-circuit time constant
E'_{di}	Direct axis internal voltage magnitude at bus i
E'_{qi}	Quadrature axis internal voltage magnitude at bus i
P_k^d	Real power demand at load node k
$Q_k^d(V_k)$	Reactive power demand at load node k
$I_{LK}\angle\phi_k$	Constant current injection at load node k
V_i	External generator voltage magnitude at bus i
θ_i	External generator voltage angle at bus
V_k	Voltage magnitude at load node k
θ_k	Voltage angle at load node k
$I_{Lk}\angle\phi_k$	Constant current injection at load node k
E_{fi}	Excitation voltage magnitude
$1, \ldots., n$	Generator internal buses
$n+1$	Infinite bus
$n+2, \ldots, n+m+1$	Load buses

Several research studies have been conducted to develop monitoring techniques for transient stability assessment by utilizing synchronal phasor data. Basically, monitoring index obtained from PMU-based methods can be classified according to the phase angle differences, voltage magnitudes, frequency or rate of change of frequency [12,13]. Recently, several methods utilizing PMU data to assess the system stability have been proposed in [14–20]. A statistical structure of fast-slow networks and critical slowing down to evaluate the stability reaction of a system under fault condition has been introduced in [19]. Also, a method has been proposed in [20] to monitor rotor angle dynamics by utilizing Lyapunov exponent.

Furthermore, many assessment methods based on pattern recognition approach have been proposed in [21–28]. They use heuristic methods such as artificial neural network which are described in [10,28–31] and fuzzy neural network that is mentioned in [21,24]. Another method known as Support vector machine is used in [25,26]. Also, decision tree (DT) and kernel ridge regression methods are used to transient stability assessment in [2,22], but all of these methods need data training for a certain network and as a result they are not able to provide a comprehensive resolution for evaluating of power systems stability.

Probabilistic assessment of power system transient stability has been proposed in [32]. In this approach, the transient stability probability (TSP) is determined and assessed by including the casual nature of both the system loads and the fault clearing times. However, control parameters of the power system are not observed in transient stability evaluation. In order to assess the dynamic security of the power system for online application, DT algorithm, as a classifier tool, has been used in [3,22,33–35], which is calculated off-line to ascertain basic and vital parameters that specify the system stability. After which, acquired DT is utilized for security evaluation which is applicable only in the pre-trained network. There are other security evaluation algorithms for online application which assess the transient stability by utilizing data provided from the Supervisory Control and Data Acquisition system/Energy Management System with corresponding delay time [36].

According to [37–39] Lyapunov function method is another method for transient stability assessment and estimation of CCT. This method is fast enough for calculating Lyapunov function of the system, however this method does not consider all detail of system and uses the network reduction model for transient stability assessment of power system. This method also needs post fault data to calculate potential energy function and the new updated Lyapunov function when topology of the system is changed during disturbances. Therefore, this methodology is not suitable for real time and online applications [37]. There are three main steps in direct method of Lyapunov which is explained in, first step is finding the post fault steady state dynamic variable and the next step is finding stability boundaries by the system trajectories on energy surface around the post fault equilibrium point and the final step is discrete numerical integration of energy function from the pre disturbance of the system operation condition until stability boundaries of Lyapunov function [39]. According to the previous expression, Lyapunov function needs post fault computations to estimate transient stability of power systems, but these computations are much less than computations of time domain simulations method. However, performance of direct method depends on estimation of the controlling unstable equilibrium point (UEP) [12]. In order to determine the UEP, a practical approach is needed which is called the Based Controlling Unstable (BCU) method. The main concept of BCU method has been mentioned in [13]. The BCU method seems to be a practical method and it has been widely used among the major utilities of the world, however the main problem of this approach is lack of general energy function for multi machine power systems with losses and ignoring the details of power network model [37]. On the other hand, all of previous energy methods need the post fault data to calculate CCT and margin stability; therefore they are not appropriate tools for real time purposes.

As mentioned in the above, parallel aims have been investigated which is categorized in two groups: first, considering all details and nonlinearity in power system such as [8,12,40,41] and second, evaluating transient stability in real-time such as [1,2,7,14].