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A high-precision real-time approach to calculate closest unstable equilibrium points

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ABSTRACT

In this paper, an innovative real-time approach is presented in order to compute the closest unstable equilibrium points of system. The proposed approach estimates unstable equilibrium points of system at the first time step of fault duration and there is no need to post the fault data. To such aim, a new concept of equal area criteria is proposed in this paper which estimates the initial value of critical points of the system. This value is used in order to calculate corrected kinetic energy and as a result the closest unstable equilibrium point by taking into account the fault trajectory. Moreover, the details of power system are considered to calculate unstable equilibrium point by utilizing network preserving model. Finally, several case studies have been conducted on IEEE 9 bus and the New-England 39 bus test systems to illustrate the benefits of the proposed approach. It is worth noting that considering structure preserving in modeling and at the same time simplicity in implementation and low computational burden are the main salient features of the proposed approach. As a result, the proposed method is suitable for real-time applications.

1. Introduction

1.1. Importance

Power system transient stability assessment has become an important issue in the large scale power systems. It's real-time assessment is one of the most challenging problems in the control center systems [1]. Evaluation of transient stability is one of the most significant topics in power systems since its calculation is necessary, first to assess the system capability for tolerating the large disturbance and second to propose the corrective instructions. This is a non-linear problem in nature and it should be solved in a large scale [2].

Although the increase of computing power has resulted in a speed-up of online and real-time simulations, but the amount and complication of simulations have also grown simultaneously. The enhancement request for more detailed and complex models can simply push any given computer to its limits [3].

1.2. Previous work

Direct energy methods were suggested in early 80s [4] and extended to the level of industrial deployments during the last four decades [4]. Transient energy function methods which utilize special form of Lyapanov function are an alternative approach to assess the system transient stability based on the system energy [5,6]. They prepared fast and efficient stability evaluation for diverse disturbances. However, lack of accuracy in the stability assessment as a result of utilizing network reduction model, was a significant disadvantage of the conventional direct energy methods. Also, the methods depend on recognition of unstable equilibrium point (UEP) of energy function that makes the transient stability assessment a very difficult problem. In the last decades, numerous research studies have been carried out on both development of energy function to the different system components [7] and the advancement of methods for identification the UEPs [8]. It is worth mentioning that the concept of controlling UEP [9] results in a feasible and less conventional path to acknowledge stability of the given post fault state based on awareness of the fault trajectory. The significant disadvantage of the controlling UEP algorithm is the intrinsic problem of direct recognition of the controlling UEP [10].

It should be noted that there are only a few works on contingency screening taking no fault-on dynamics simulations into account. Specifically, in [11] the closest UEP method has been extracted and an algebraic formulation for estimating the critical clearing time has been captured based on polynomial expansion of the swing equations. But, considering latter assumption that dynamic related to the rotor angle in the fault duration is a constant positive acceleration, makes this method unrealistic.

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Nomenclature

CCT	critical clearing time
EAC	equal area criterion
$NCEAC$	new concept of 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
TDS	time domain simulation
COI	center of inertia
DT	decision tree
AVR	automatic voltage regulation
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

According to achievement of Lyapanov family function introduced in [6,12] authors in [13] proposed an approach to estimate critical clearing time based on bounding fault-on trajectory and thereby the fault-cleared state.

1.3. Contribution and organization of the paper

As mentioned, parallel goals have been investigated in the previous published papers which is categorized into two groups: first, methods that consider details and nonlinearity in power system such as [4,14–18] and second, methods evaluate transient stability in real-time such as [19–24]. Unfortunately each group has serious drawbacks which are listed as follows:

The approaches suggested in the first group are pursuing transient stability assessment taking details and nonlinearity into account. These approaches are not suitable for real-time or near real-time transient stability assessment application because:

1. These approaches have considerable computational cost.
2. They need to find the potential function of each element may be added into network.
3. They require post-fault data for transient stability assessment.

Since transient stability assessment is interested in large scale power systems, as a result, the approaches in the first group are not reliable for real-time analysis of large scale power networks.

The approaches presented in the second group, first priority is real-time assessing of the power system. Authors of these approaches have applied network reduction model in the problem solving and as a result, the accuracy of the evaluation has been decreased significantly.

In this paper, an innovative hybrid approach to find closest unstable UEP is proposed which simultaneously considers two aforementioned goals of the groups. The proposed approach is based on the corrected kinetic energy and also new concept of equal area. The proposed approach in this paper, calculates UEP which is applied for estimating critical clearing time and as a result assessing power system transient stability. The general novelties are described as follows:

(1) Despite of previous suggested methods in [3,6–9,12], proposed method in this paper estimates initial critical angle that is relatively very close to the exact UEP. To do so, new concept of equal area criteria is proposed. This method is a modification of EAC that determines initial critical angle from generator terminal regardless the effect of AVR and GOVERNOR.

(2) While in [3,5,14,25], authors suggested methods based on network reduction model, proposed methods in [2,4,10,16], have demonstrated that it is vital to consider network preserving structure. In this paper, proposed method utilizes network preserving structure to take specifically the effect of dynamic controllers such as AVR and GOVERNOR into consideration. To do so, an innovative and uncomplicated method based on corrected critical kinetic energy is proposed, that consider the effect of AVR and GOVERNOR without solving any complicated potential equations.

(3) To real-time assessment of transient stability and UEP, it is important to have a method with two salient features: (1) low computational burden and (2) independency form post fault data. We propose a method that has very low computational cost. Also our method is capable of calculating UEP in real-time, after first time step of fault occurrence, without scarifying any details in system modeling and considering fault trajectory into account.

1. Low computation burden: For more clarification, as mentioned before, proposed methods in [4,12,26,27] are basically offline from computational burden point of view.