A BCU-GUIDED TIME-DOMAIN METHOD FOR ENERGY MARGIN CALCULATION OF PRACTICAL POWER SYSTEMS

Hsiao-Dong Chiang, Yan Zheng
School of Electrical Engineering
Cornell University
Ithaca, NY 14853, USA

Yasuyuki Tada, Hiroshi Okamoto
Research and Development Ceneter
Tokyo Electric Power Company
Yokohama, 230-8510, JAPAN

Yicheng Zhou, Kaoru Koyanagi
Applied Technology Systems Dept.
TEPCO System Corporation
Tokyo, 105-0004, JAPAN

Abstract –The task of calculating accurate energy margin for every contingency has long been regarded as a challenge one. The existing direct methods proposed in the literature can not reliably and accurately compute energy margin for every contingency. In this paper, a BCU-guided time-domain method for accurate energy margin calculation of every contingency is developed. The BCU-guided method is highly effective compared with existing time-domain-based methods in terms of accuracy and speed. The BCU-guided time-domain method has been applied to a practical 200-bus power system with very promising results. The proposed method has been incorporated into an integrated package for on-line dynamic security assessment.

Keywords – Dynamic Security, Transient Stability, Energy Function, Energy Margin, Time-Domain Simulation.

1 INTRODUCTION

After decades of research and developments in the direct methods, it has become clear that they can not replace the time-domain approach in stability analysis. Instead, the capabilities of direct methods and that of the time-domain approach complement each other [1,2]. The current direction of development is to combine a direct method and a fast time-domain method into an integrated power system stability program to take advantages of the merits of both methods.

Significant progress has been made recently in the practical application of direct methods. Direct methods not only avoid the time-consuming numerical integration of the (post-fault) power system models but also provide a quantitative measure (e.g. energy margin) of the degree of system stability. Another advantage of direct methods is the ability to provide useful information regarding how to derive preventive control actions based on energy functions and their derivatives.

There are several direct methods proposed in the literature for computing energy margins with various degree of accuracy. From a practical viewpoint, the existing direct methods can not reliably compute accurate energy margin for every contingency. Some direct methods compute energy margin just for some type of contingencies while others compute energy margins just for another type of contingencies. An effective method which can reliably compute accurate energy margins for every contingency is still in demand.

Theoretically speaking, the exact energy margin is the difference between the energy value at the exit point of the original (post-fault) system and the energy value at the fault clearance point. Here, the exit point of the original system is the intersection point between the (sustained) fault-on trajectory and the stability boundary of the (post-fault) power system. It is well known that the task of computing the exit point of the original system is very time-consuming and requires several time-domain simulations. Hence, the task of computing the exact energy margin is challenging. This challenge can be explained as follows.

Given a contingency on a power system, the energy margin, an indicator for system stability and a measure for the degree of stability/instability, for the given contingency is $\Delta V = V_{cr} - V_{cl}$, where ΔV is the energy margin, V_{cr} is the (exact) critical energy with respect to the given fault, V_{cl} is the energy at the fault clearing time. Attempts to develop a method for computing energy margin will encounter the following difficulties

- the (exact) critical energy with respect to the given fault is very difficult to compute
- the (functional) relationship between energy margin and fault clearing time is nonlinear and difficult to derive.

Indeed, the energy function value along a fault-on trajectory is a nonlinear function of the fault clearing time; moreover, this nonlinear functional relationship can be established only from the knowledge of fault-on trajectory.

One basic requirement for developing energy functions is for their functions to reflect the degree of severity of the study contingency, leading the underlying system toward an undesired stage (i.e. an unstable state). It has been shown in [7] that the basic requirements can be met provided the study energy function satisfies the required three conditions. In this paper, we employ such an energy function in computing energy margins.

The present paper describes our development of a BCU-guided time-domain method for accurate energy margin calculation. The proposed BCU-guided method is highly effective compared with existing time-domain-based methods: it is reliable and yet fast for exact stability assessment and energy margin computations. Another important property is that the energy margins computed by the proposed BCU-guided time-domain method is comparable with, and yet less than, exact energy margins which are computed by an exact time-domain stability method. The effectiveness can be attributed to the fact that some pieces of information provided by BCU method such as the exit point, the minimum gradient point are fully integrated into the BCU-guided method to significantly reduce the duration of time interval within which time-domain stability simulations are performed.

2 OVERVIEW OF EXISTING METHODS

We propose that any time-domain based method intended for energy margin calculation must meet the following essential requirements:

(B-1)The critical energy values computed by the method must be accurate and reliable

(B-2)The critical energy values computed by the method must be compatible with the critical energy values computed by the controlling UEP

(B-3)The method is reasonably fast.

Regarding requirement (B-2), it can be shown that the controlling u.e.p. method developed in [7] can accurately assesses stability properties of single-swing as well as multi-swing power system behaviors under the conditions that the study power system model is valid for multi-swing behaviors and an energy function exists for the model.

One criterion to evaluate the accuracy of a computed energy margin is to find the corresponding critical clearing time. Indeed, an accurate and yet conservative energy margin gives an accurate and yet conservative clearing time.

All of the existing time-domain based methods proposed thus far for computing energy margins are composed of the following two steps:

Step 1: (stability assessment) apply the time-domain approach to simulate the system trajectory and then assess its stability based on the simulated post-fault trajectory.

Step 2: (energy margin calculation) the corresponding energy margin is calculated based on either the simulated post-fault trajectory alone (e.g. the equal-area criterion based methods and the hybrid method) or with the inclusion of some other system trajectories (e.g. the improved hybrid method and the second-kick method).

It is obvious that these methods discriminate stable and unstable contingencies very accurately to the model validity. They are however too slow for on-line applications and their accuracy in computing energy margins is not satisfactory. Moreover, these time-domain based methods can not meet the requirements (B-1) through (B-3) stated above, mostly due to the following difficulties:

(D1) The critical energy value (hence the energy margin) can only be obtained after the critical clearing time is first calculated.

(D2) They are lack of theoretical basis

(D3) The relationship between fault clearing time and energy margin is rather complex and may have no functional relationship

(D4) For stable or multi-swing contingencies, the required computational time for time-domain simulation programs may be very long

It can be shown that any time-domain based method proposed for accurate energy margin calculation must be iterative in its computation process. Hence, any non-iterative time-domain based method can not consistently compute accurate energy margins for every contingency.

We next describe a time-domain based method for calculating exact energy margins where the critical clearing time (CCT) is first found and the energy value at the corresponding state is then used as (exact) critical energy values:

Step 1.For the given fault clearing time, perform a time-domain simulation to determine stability property of the post-fault system;

Step 2.If the post-fault system is stable, then incrementally increase the fault clearing time, say by the golden-bisection method, until the system is unstable. Go to Step 4

Step 3.If the post-fault system is unstable, then incrementally decrease the fault clearing time, say by the golden-bisection method, until the system is stable. Go to Step 4

Step 4.The iterative process continues until the differences between fault clearing times for stable and unstable cases are sufficiently small. The final fault clearing time for stable post-fault system is an approximated CCT and the energy value at the corresponding state is then the critical energy.

The above method seems too time-consuming to be practically useful. We will however use it as a ‘benchmark’ method.

Another approach, trajectory sensitivity-based time-domain methods, has been suggested in literature. The basic idea of this approach is to make use of sensitivity information from the last simulated system trajectory to predict the next trajectory within a given error tolerance. The parameter to be altered is the fault clearing time which can be translated into changes of the initial conditions of two post-fault systems. It may appear from the surface that the trajectory sensitivity-based time-domain method might be faster than regular time-domain based methods. However, for a practical power system, the task of calculating trajectory sensitivity with respect to initial conditions always encounters the difficulty of formidable dimensionality explosion. This difficulty arises especially for large power systems and the trajectory sensitivity-based method may not be applicable to practical power systems.

3 OVERVIEW OF BCU METHOD

Recently, a systematic method, called BCU method, to find the controlling unstable equilibrium point was developed [4,5]. In developing a BCU method for a given power system stability model, an associated reduced-state model must be defined first. We consider the general network-preserving transient stability model with losses shown below

$$\begin{aligned} 0 &= -\frac{\partial U}{\partial u}(u, w, x, y) + g_1(u, w, x, y) \\ 0 &= -\frac{\partial U}{\partial w}(u, w, x, y) + g_2(u, w, x, y) \\ T\dot{x} &= -\frac{\partial U}{\partial x}(u, w, x, y) + g_3(u, w, x, y) \\ \dot{y} &= z \\ M\dot{z} &= -Dz - \frac{\partial U}{\partial y}(u, w, x, y) + g_4(u, w, x, y) \end{aligned} \tag{1}$$

where $U(u, w, x, y)$ is a scalar function. Regarding the original model (1), we choose the following differential-algebraic system as the associated reduced-state model

$$\begin{aligned} 0 &= -\frac{\partial U}{\partial u}(u, w, x, y) + g_1(u, w, x, y) \\ 0 &= -\frac{\partial U}{\partial w}(u, w, x, y) + g_2(u, w, x, y) \\ T\dot{x} &= -\frac{\partial U}{\partial x}(u, w, x, y) + g_3(u, w, x, y) \\ \dot{y} &= -\frac{\partial U}{\partial y}(u, w, x, y) + g_4(u, w, x, y) \end{aligned} \tag{2}$$

The fundamental ideas behind the BCU method can be explained in the following. Given a power system stability model (which admits an energy function), the BCU method first explores special properties of the underlying model with the aim to define an artificial, state-reduced model such that certain static as well as dynamic relationships are met. The BCU method then finds the controlling u.e.p. of the state-reduced model by exploring the special structure of the stability boundary and the energy function of the state-reduced model. Third, it relates the controlling u.e.p. of the state-reduced model to the controlling u.e.p. of the original model.

A conceptual BCU method

Step 1.:From the fault-on trajectory (u(t), ω (t), x(t), y(t), z(t)) of the network-preserving model (1), detect the exit point (u^*, w^*, x^*, y^*) at which the projected trajectory (u(t), ω (t), x(t), y(t)) exits the stability boundary of the post-fault reduced-state model (2).

Step 2.Use the exit point (u^*, w^*, x^*, y^*), detected in Step 1, as the initial condition and integrate the post-fault reduced-state model to an equilibrium point. Let the solution be $(u_{co}, w_{co}, x_{co}, y_{co})$.

Step 3.The controlling u.e.p. with respect to the fault-on trajectory of the original network-preserving model (1) is $(u_{co}, w_{co}, x_{co}, y_{co}, 0)$. The energy function at $(u_{co}, w_{co}, x_{co}, y_{co}, 0)$ is the critical energy for the fault-on trajectory (u(t), ω (t), x(t), y(t), z(t)).

Step 1 and Step 2 of the conceptual BCU method compute the controlling u.e.p. of the reduced-state system. Note that the stable manifold of $(u_{co}, w_{co}, x_{co}, y_{co})$ .contains the exit point (u^*, w^*, x^*, y^*) of the projected fault-on trajectory. Step 3 relates the controlling u.e.p. of the reduced-state model to the controlling u.e.p. of the original model. A numerical implementation of the conceptual BCU method for network-preserving power system models is presented below:

A numerical BCU method

Step 1.From the (sustained) fault-on trajectory $(u(t), w(t), x(t), y(t), z(t))$ of the original system, detect the exit point (u^*, w^*, x^*, y^*) at which the projected trajectory $(u(t), w(t), x(t), y(t))$ reaches the first local maximum of the numerical potential energy function $U_{num}(\cdot, \cdot, \cdot, \cdot)$.

Step 2.Use the point (u^*, w^*, x^*, y^*) as the initial condition and integrate the post-fault, reduced-state system (2) to the (first) local minimum of the norm of the post-fault, reduced-state system. Let the local minimum be $\left(u_0^*, w_0^*, x_0^*, y_0^*\right)$.

Step 3.Use the point $\left(u_0^*, w_0^*, x_0^*, y_0^*\right)$ as the initial guess and solve the following set of nonlinear algebraic equations

$$\begin{aligned} &\left\|\frac{\partial U}{\partial u}(u, w, x, y) + g_1(u, w, x, y)\right\| \\ +&\left\|\frac{\partial U}{\partial w}(u, w, x, y) + g_2(u, w, x, y)\right\| \\ +&\left\|\frac{\partial U}{\partial x}(u, w, x, y) + g_3(u, w, x, y)\right\| \\ +&\left\|\frac{\partial U}{\partial y}(u, w, x, y) + g_4(u, w, x, y)\right\| = 0 \end{aligned}$$

Let the solution be $\left(u_{co}^*, w_{co}^*, x_{co}^*, y_{co}^*\right)$.

Step 4.The controlling u.e.p. relative to the fault-on trajectory $(u(t), w(t), x(t), y(t), z(t))$ of the original model is $\left(u_{co}^*, w_{co}^*, x_{co}^*, y_{co}^*, 0\right)$.

Steps 1 to 3 of the above numerical network-preserving BCU method compute the controlling u.e.p. of the reduced-state system (2) and Step 4 relates the controlling u.e.p. of the reduced-state system to the controlling u.e.p. of the original system. In step 3 of the numerical BCU method, the minimum gradient point (MGP) is used as a guide to search for the controlling u.e.p. From a computational viewpoint, the MGP can be used as an initial guess in the Newton method to compute the controlling u.e.p. If the MGP is sufficiently close to the controlling u.e.p., then the sequence generated by the Newton method starting from the MGP will converge to the controlling u.e.p. Otherwise, the sequence may converge to another equilibrium point or diverge. A robust nonlinear algebraic solver should be used in Step 3.

It should be noted that the BCU-guided time-domain method proposed in this paper does not employ the controlling u.e.p. to search for the corresponding critical energy; instead, pieces of information provided by BCU method such as the exit point, the minimum gradient point are fully integrated into the BCU-guided method to significantly reduce the duration of time interval within which time-domain stability simulations are performed

4 THE PROPOSED APPROACH

We believe that the only viable approach to develop a time-domain based method for computing energy margin is the one which satisfies the following guidelines:

(G-1) It is based on the calculation (or approximation) of the critical clearing time,

(G-2) It can effectively reduce the duration of the time interval within which time-domain stability simulations are performed in order to determine the critical clearing time. (Obviously, the shorter the duration of the time interval is, the lesser the number of time-domain stability simulations is required and the faster the method will be.)

We develop a (two-stage) BCU-guided time-domain method, which is a time-domain based, BCU-guided method, for stability assessment and computing critical energy values. The method is reliable in calculating energy margin whose value is compatible with that computed by the controlling UEP method. Hence, the method meets the essential requirements (B1) through (B3).

The BCU-guided time-domain method uses a BCU-guided scheme to specify, within a given time interval, a reduced-duration time interval and employs the golden bisection interpolation algorithm to the specified time interval to reduce the total number of time-domain simulations required for finding the CCT, which is then used to compute critical energy. For an illustrational purpose, let the CCT, say t_{clr}, of a contingency in a time interval, say $[0, T_{max}]$ (see Fig. 1(a)). The first stage of the BCU-guided time-domain method uses a BCU-guided scheme to identify within $[0, T_{max}]$ a sub time-interval $[t_{min}, t_{max}]$, with $t_{min} < t_{clr} < t_{max}$ (see Fig. 1(b)). The second stage of the method employs the golden-bisection algorithm to the interval $[t_{min}, t_{max}]$ and performs several time-domain simulations to pinpoint a sufficiently small interval $[t_{clr}^{min}, t_{clr}^{max}]$ satisfying the following conditions

$$\begin{cases} t_{clr}^{min} < t_{clr} < t_{clr}^{max} \\ \left| t_{clr}^{max} - t_{clr}^{min} \right| < \varepsilon \end{cases}$$

We thus obtain an approximated CCT (see Fig. 1(c)). Note that the second stage of the method is largely involved with a small number of time-domain simulations. We apply the golden bisection algorithm to find the critical clearing time lying in a time interval.

Given a study contingency, suppose that the post-fault SEP exists and that within a certain time interval, say $[t_1, t_2]$, the post-fault system is stable if the fault clearing time is set at t_1 and is unstable if the fault clearing time is set at t_2. The critical clearing time hence lies within the interval $[t_1, t_2]$. We apply the golden bisection algorithm to compute the critical clearing time lying in the time interval $[t_1, t_2]$ with the following steps:

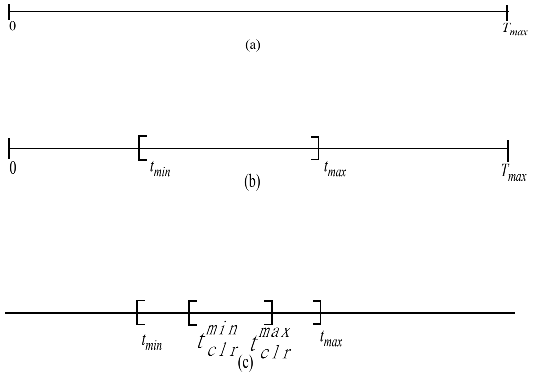

Figure 1: Illustration of the BCU-guided time-domain method in finding CCTs in a given time interval (see (a)). The method first specifies, within a given time interval, a reduced-duration time interval using a BCU-guided scheme (see (b)) and employs the golden bisection interpolation algorithm to the specified time interval to reduce the total number of time-domain simulations required for finding the CCT (see (c)).

Step 1: Using the golden bisection method to calculate two fault clearing time instants from the interval $[t_1, t_2]$

$$\begin{cases} t_0^{(1)} = 0.618\,t_1 + 0.382\,t_2 \\ t_0^{(2)} = 0.618\,t_2 + 0.382\,t_1 \end{cases}$$

Step 2: Perform a time-domain stability analysis for the contingency with the fault clearing time $t_0^{(1)}$. If the post-fault system is unstable, then set $t_2 = t_0^{(1)}$ and go to Step 3; otherwise set $t_1 = t_0^{(1)}$ and perform a time-domain stability analysis for the contingency with the fault clearing time $t_0^{(2)}$. If the post-fault system is stable, set $t_1 = t_0^{(2)}$; otherwise set $t_2 = t_0^{(2)}$.

Step 3: Check convergence: If $\|t_1 - t_2\| \le \varepsilon$, go to Step 4; otherwise go to Step 1.

Step 4: The critical clearing time is set as t_1 and the system energy at this critical clearing time is set as the critical energy.

Prior to applying the golden bisection algorithm to compute the critical energy, one important task is to set both the lower and upper bounds of the initial (fault clearing) time interval for the golden bisection algorithm to perform bisections. In the present paper, a BCU-guided scheme for determining such an initial time interval is developed based on some of the following pieces of information:

- the potential energy V_{ep} at the exit point (EP),
- the potential energy V_{mgp} at the minimum gradient point (MGP),

- some interpolation time-domain simulation results

5 BCU-GUIDED TIME-DOMAIN METHOD

We present a BCU-guided time-domain method for accurate calculation of critical energy. The BCU-guided time-domain method achieves its reliability and accuracy through effective exploration of the merits of both the BCU method, the golden-bisection algorithm and the time-domain simulation method.

The following notations will be used in our presentation of the BCU-guided time-domain method: t_{cl} denotes fault clearing time, t_{mgp} denotes the time at the MGP, t_{ep} denotes the time at the exit point, V^{PE}_{cl} denotes the potential energy at fault clearing time, V^{KE}_{cl} denotes the kinetic energy at the fault clearing time, V_{mgp} denotes the energy at the MGP, V_{ep} denotes the energy at the exit point, V_{uep} denotes the energy at the controlling unstable equilibrium point.

A detailed description of the BCU-guided time-domain method for each contingency is as follows. This description is presented for the situation that the following condition holds.

$$t_{cl} < minimum\{t_{uep}, t_{mgp}, t_{ep}\}$$

The method is easily modified accordingly if the condition is different.

BCU-guided Time-Domain Method

Input: a power system with related data for dynamic security assessment and a contingency

Output: stability assessment and energy margin value for the contingency on the power system

Step 1: Apply the BCU method (to the study power system with the contingency) to compute the exit point (i.e. the PEBS crossing point). If the exit point can be found with a certain period (e.g. within two seconds), then go to Step 2; otherwise, if the energy at the end point is positive, then the post-fault system is declared to be highly stable and the energy margin is assigned as 999 and stop the process; otherwise, the post-fault system is declared to be highly unstable and the energy margin is assigned as -999 and stop the process.

Step 2: If the energy at the exit point is positive, then go to Step 3; otherwise, the post-fault system is declared to be highly unstable and the energy margin is assigned as -999 and stop the process.

Step 3: Continue the BCU method to compute the MGP. If the MGP is found, then go to Step 6; otherwise, go to Step 4.

Step 4: Do the following: (i) (Estimation) Set the critical energy to be the energy value at the exit point, i.e. $V_{cr} = V_{ep}$, and find the corresponding fault-on time (i.e. t_{ep}) from the fault-on trajectory. (ii) (Verification) Perform a time domain simulation with t_{ep} being the fault clearing time. If the post-fault system is stable, then set V_{ep} to be V_{cr} and stop the process; otherwise, go to Step 5.

Step 5: Perform a time-domain simulation of the post-fault system with the state at t_{cl} as the initial condition. If it is stable, then set $t_0 = t_{cl}$ and $t_1 = t_{ep}$; otherwise, set $t_0 = 0$ and $t_1 = t_{cl}$. Go to Step 8.

Step 6: Continue the BCU method to compute the CUEP. If the CUEP is found, then go to Step 9; otherwise, do the following: (i) (Estimation) Set the critical energy to be the energy value at the minimum gradient point, i.e. $V_{cr} = V_{mgp}$, and find the corresponding fault-on time (i.e. t_{mgp}) from the fault-on trajectory. (ii) (Verification) Perform a time domain simulation with t_{mgp} being the fault clearing time. If the post-fault system is stable, then set V_{mgp} as the critical energy and stop the process; otherwise, go to Step 7.

Step 7: Perform a time-domain simulation of the post-fault system with the state at t_{cl} as the initial condition. If it is stable, then set $t_0 = t_{cl}$ and $t_1 = t_{mgp}$; otherwise, set $t_0 = 0$ and $t_1 = t_{cl}$. Go to Step 8.

Step 8: Do the following to determine the critical energy value

(i) (Interpolation) Make an interpolation between (t_0, t_1) using the Golden bisection-based interpolation method to find an instant, denoted as $t^{(0)}$.

(ii) (Verification) Perform a time domain simulation with $t^{(0)}$ being the fault clearing time; if the post-fault system is stable, then treat $t^{(0)}$ as the critical clearing time and the energy value at the corresponding state as the critical energy and stop the process; otherwise set $t_1 = t^{(0)}$ and go to (i) of this Step (i.e. another interpolation is conducted between the interval $\left(t_0, t^{(0)}\right)$).

Step 9: The energy value at the computed CUEP is used as the critical energy value. Stop the process.

From the above computational steps, it can be seen that energy margins computed by the proposed BCU-guided time-domain method are always conservative and numerically compatible with that computed by the controlling UEP method. The most time-consuming step in the BCU-guided method is Step 8. Our numerical experience shows that, on average, between 3 and 5 time-domain simulations are required for the BCU-guided time-domain method to compute an accurate energy margin, compared with the average 6 to 8 time-domain simulations required by the golden bisection-based method.

Step 9 of the BCU-guided time-domain method can be modified so as to improve the conservative nature of the BCU method at the expense of time-domain simulations. For those contingencies which are assessed by the BCU method as stable, then the corresponding energy margins are kept unchanged (i.e. the energy margin is determined based on the BCU method); for those contingencies which are assessed by the BCU method as unstable, then the corresponding energy margins can be modified as follows:

Step 10: If the contingency is assessed by the computed CUEP as stable, then the corresponding energy margin is kept unchanged and stop the process; otherwise, perform a time-domain simulation of the post-fault system with the state at t_{cl} as the initial condition. If it is unstable, then set $t_0 = 0$ and $t_1 = t_{cl}$ and go to Step 8; otherwise, go to Step 11.

Step 11: Perform a time domain simulation with t_{mgp} being the fault clearing time. If the post-fault system is stable, then set V_{mgp} as the critical energy and stop the process; otherwise, set $t_0 = t_{cl}$ and $t_1 = t_{mgp}$ go to Step 8.

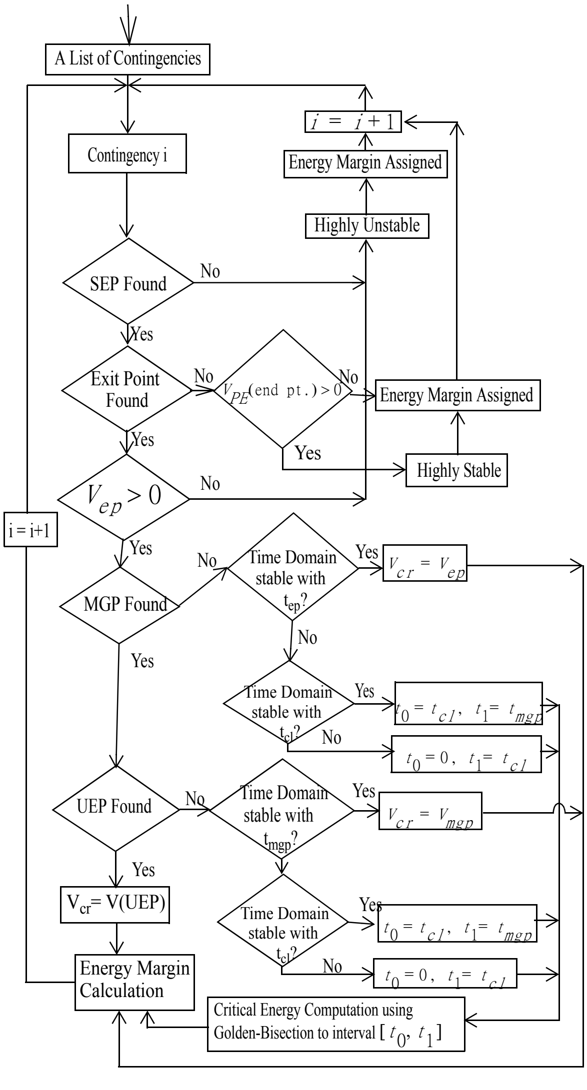

Figure 2: The flow chart of the BCU-guided time-domain method for reliable stability assessment and energy margin calculation.

6 NUMERICAL STUDIES

To illustrate the capability of the proposed BCU-guided time-domain method in meeting the three essential requirements (B1) through (B3), we applied the method to a practical 200-bus power system with a set of contingencies. In addition, a comparison study among the BCU-guided method, the second-kick method and the exact time-domain method in terms of accuracy and computational speed is conducted on the practical power system. These numerical results are summarized in Table 1 for easy comparison. The following observations are derived from this comparison:

- For every contingency, the BCU-guided time-domain method always computes an energy margin which is less than, and yet close to, that computed by the exact time-domain method. This property indicates the conservativeness of the BCU-guided method in computing the energy margin. This property, which lies in the spirit of direct methods, is desirable in practical applications.

- The second-kick method can compute an energy margin for every contingency; however, the computed energy margin is either higher or less than that computed by the exact time-domain method. This property suggests that the second-kick method may be inconsistent in computing energy margins which can lead to both under-estimation or over-estimation in an intended applications.
- A comparison between the computational speed of the BCU-guided time-domain method and that of the exact time-domain method is roughly the ratio of 1 to 2.
- The three methods share one common character: they calculate energy margins for every contingency.
- (accuracy) The energy margins computed by the BCU-guided time-domain method are compatible with those computed by the exact time-domain method
- (speed) Overall, the BCU-guided method has the fastest computational speed among the three methods.

7 CONCLUSIONS

We have shown that any time-domain based method intended for accurate energy margin computation must be iterative in its computing process since the task of finding critical clearing time is an iterative, time-consuming process. The only viable approach to develop a time-domain based method for computing energy margin is the one that can effectively reduce the duration of the time interval within which time-domain simulations are required to determine the critical clearing time. Hence, any non-iterative time-domain based method can not consistently compute accurate energy margins for every contingency.

Table 1. A Comparison of Energy Margins Computed by the Exact Time-Domain Method, the BCU-guided Method and by the Second-Kick Method

Case Number	Stability Assessment	Energy Margin		
		Exact Time Domain Method	BCU-guided Method	Second-Kick Method
1	Stable	0.81	0.797	2.545
2	Stable	0.894	0.88	1.911
3	Stable	1.595	1.55	4.39
4	Stable	3.239	3.199	3.409
5	Stable	2.683	2.674	6.228
6	Stable	3.267	3.232	2.029
7	Stable	7.765	6.857	3.22
8	Stable	7.602	6.833	3.169
9	Stable	4.322	4.219	3.36
10	Stable	8.266	7.005	3.462
11	Stable	0.25	0.226	1.477
12	Stable	1.311	1.259	0.987
13	Stable	7.526	6.806	3.138
14	Stable	8.108	7.126	3.397
15	Stable	2.678	2.387	0.904
16	Stable	2.493	2.483	2.171

We proposed an appropriate criterion to evaluate the accuracy of a computed energy margin is to find the corresponding critical clearing time. Indeed, an accurate and yet conservative energy margin gives an accurate and yet conservative clearing time.

We have developed a two-stage BCU-guided time-domain method for accurate energy margin computation of every study contingency. The BCU-guided time-domain method is exact in stability assessment and is reliable and yet fast for computing energy margins which are comparable with exact energy margins. The effectiveness of the method can be attributed to the fact that some pieces of information provided by BCU method such as the exit point, the minimum gradient point are fully integrated into the BCU-guided method to significantly reduce the duration of time interval within which time-domain stability simulations are performed.

To illustrate the effectiveness of the proposed BCU-guided time-domain method, we have applied the method to a practical 200-bus power system with a set of contingencies. A comparison study among the BCU-guided method, the second-kick method and the exact time-domain method in terms of accuracy and computational speed has been conducted on the practical power system. The comparison study highly favors the proposed BCU-guided time-domain method in terms of computational speed and accuracy of energy margins. The proposed BCU-guided time-domain method is applicable to detailed power system models and can assess both single-swing and multi-swing power system behaviors.

We believe that the energy margin of a study contingency is an ‘intermediate’ result. The energy margin itself is not the final product and its value lies in its practical applications; for example, in determining the operating (load/generation) margin to transient stability limit; or in determining available transfer capability constrained by transient stability limits. Another example of application is the determination of real power re-dispatch (or re-scheduling) to increase operating margin to transient stability limit.

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