CHAPTER 3

REAL-TIME TRANSIENT STABILITY ASSESSMENT

In Chapter 2, the basic multimachine theory and the different dynamic, state and transient energy equations have been presented and the basic criterion for transient stability assessment has been stated. In the Energy Approach, a system's total energy at the clearing time is compared with its potential energy at the Controlling Unstable Equilibrium Point (c.u.e.p.) to determine the system transient stability. If the total energy is larger than the potential energy, the system is considered unstable; otherwise, it is considered stable. As introduced earlier, the geometric characteristic of a system trajectory can be employed to determine a system transient stability by assessing the dominant u.e.p. Following this idea, the algorithm described bellow is based on the prediction of the post-fault trajectory. Using that prediction, the Energy Margin (EM) is quickly evaluated in order to decide whether or not the system will be able to maintain its synchronism. In the first part of this chapter, the different characteristics of the surface on which the post-fault transient trajectory lies, are proposed. In the second part, after stating the different assumptions on which is based the proposed method, a detailed methodology is developed. Meanwhile, few words of caution regarding the Energy Approach are stated. In a third part, different direct methods for transient stability analysis are viewed and compared. Three distinct methodologies are considered and discussed. The first and second methods were developed respectively by Y. Ohura et al. [6] and by Bettiol et al. [12]. The third method is related to an application of decision trees for real-time transient stability prediction [5]. To conclude the third chapter, series of test are conducted on the 10-machine New-England power system.

3.1 Characterization of the region of attraction

The potential energy is often envisioned as a "bowl" in the multi-dimensional space of machine angles in the COA reference frame [2]. The Stable Equilibrium point (s.e.p.) is located at the bottom of the bowl. This region is commonly called the Region of Attraction of the s.e.p. The Unstable Equilibrium Points (u.e.p.'s) surrounding the s.e.p. are located on the "rim" of the bowl, which is called the Potential Energy Boundary Surface (p.e.b.s.). The trajectory of a point representing the evolution of the transient state of the post-fault system in a marginally unstable case passes near a u.e.p., called the controlling u.e.p., as it goes over the rim toward instability.

All those points can be overlooked in Figure 3.1, which represents one configuration of the potential energy surface of the Athay's 3-Machine System.

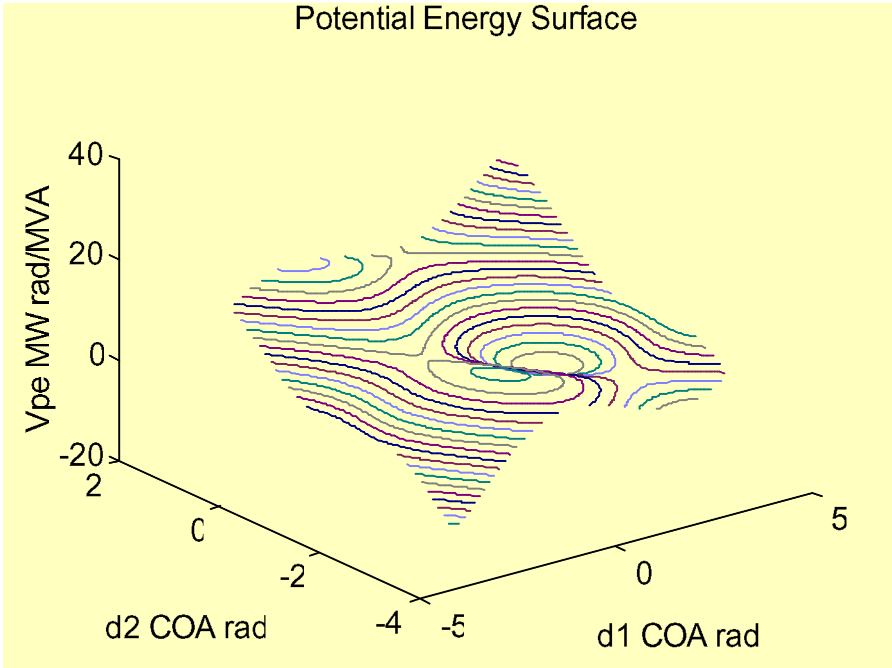

Figure 3.1: 3-Machine Potential Energy Surface

The boundary of the stability region is usually called the stability boundary of the s.e.p. and consists of all the stable manifolds of the unstable equilibrium points located on the boundary [1]. A stable manifold of an equilibrium point is the set of all states such that trajectories starting from those states approach the equilibrium point as time goes to infinity. Similarly, an unstable manifold of an equilibrium point is the set of all points such that trajectories starting from these states approach the equilibrium point as time goes to minus infinity.

The p.e.b.s. is mathematically characterized in two different ways. Traditionally a point on the p.e.b.s. is determined approximately by moving along a ray in the angle space away from the post-fault s.e.p. until a local potential peak is encountered. Different points on the p.e.b.s. are thus obtained by scanning along different rays. However, a peak in potential energy is reached only if the ray intersects orthogonally with the p.e.b.s. As shown in Figure 3.2, which represents a 3-machine system p.e.b.s., a more rigorous characterization is offered by a set of "gradient equations" in the angle space.

Once a point is located on the p.e.b.s., it can be used as the initial condition to solve these differential equations numerically to trace the p.e.b.s. The different procedures are well developed in numerous articles ([1],[3],[11]) and are not reviewed in this thesis. Notice that both definitions match when either the stability boundary of the reduced system is orthogonal to the ray emanating from the s.e.p. or at the different equilibrium points.

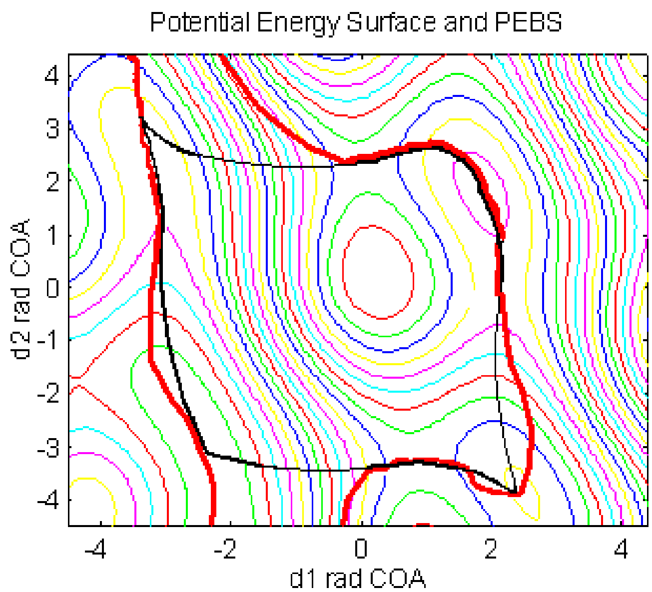

Figure 3.2: Comparing the Gradient and Ray Method for p.e.b.s. detection

3.2 The proposed method : "Curve Fitting"

In the previous part, the Region of Attraction of an s.e.p. and the p.e.b.s. have been defined. A similitude with a ball rolling on the potential energy surface has also been developed. Depending upon the total energy of the ball at the time of fault clearing, the ball can either escape from the bowl over a saddle (i.e., an unstable case) or it can continue to oscillate within the bowl (i.e., a stable case). This constitutes the main idea for using the energy approach in transient stability analysis.

3.2.1 Assumptions

As stated before, the critical step of the stability assessment using the energy approach is to find the Controlling Unstable Equilibrium Point (c.u.e.p.). Therefore, to get an accurate result, it is important to compute the c.u.e.p. with high efficiency. The contribution of this thesis is the development of a new and fast method that finds the post-fault c.u.e.p. Before developing the proposed methodology, it is not worthless to focus on the different assumptions which have been made. First, as our concern is in transient stability, the classical power system model is used. In the classical model, the mechanical power inputs are assumed to be constant, the synchronous machine is modeled as a constant voltage behind the transient reactance, and the loads are represented by constant impedances. The moment of inertia is also assumed to be constant as the variation in angular velocity relative to the synchronous speed of all the machine in the system is not typically large during the transient period. Finally, all over this thesis, the damping coefficient is neglected in the dynamic and state equations.

At this stage, it is important to recall that transfer conductance cannot be ignored since all of the loads are represented as constant impedance. As they are not ignored, the integration of the power system equations does not yield a closed-form (path-independent) expression for the potential energy (2.15). However, a closed-form expression for the path-dependent components of potential energy has already been obtained thanks to a linear path approximation between any two states whose potential energy difference is of interest. This is a mathematical approximation that may or may not be valid in a particular case. As shown in [16], in the case of HVDC lines and phase shifters, the previous assumption is acceptable only if these network elements are electrically far from the system disturbance. Nevertheless, among all the methods proposed in the literature [1], the ray approximation seems to be the most accurate choice.

3.2.2 Methodology

Assuming the availability of synchronized phasor measurements at each generator, the developed methodology for determining the transient stability of a multimachine system is based on the prediction of the post-fault trajectory and on the use of the stability criterion as defined at the end of chapter 2. To simulate those phasor measurements, a step-by-step integration of the state equations (2.13) using a fourth order Runga-Kutta method is performed. It proceeds in the following way. Before the fault, the system is in equilibrium, i.e. the initial angular velocity vector is zero and the initial machine angle vector, which is the s.e.p., is obtained from:

$$E_i \exp\left(j\delta_i\right) = Vt + jX'_d \frac{\left(Pg + jQg\right)^*}{Vt^*}, \qquad (3.1)$$

where:

Pg+jQg is the complex power supplied by machine I, Vt is the Phasor voltage at the terminals of machine i, and X'_d is the transient reactance of machine i.

During the fault, 0<t<tcl, the state equations are integrated numerically. P^f_i (2.10), C^f_{ik} and D^f_{ik} (2.7) are obtained considering the fault. A fault clearance can be realized in two basic ways. In self cleared situations, the electrical power P_{ei} (2.7) for each machine is the same before and after the fault, and then the pre-fault and post-fault s.e.p.'s are at the same location. On the contrary in a line cleared situation, the electric power for each machine P_{ei} is different and the post-fault s.e.p. is different from the fault-on s.e.p. When the fault is self cleared, a way to know with precision the clearing time is to follow the accelerations of each generators (2.13). Following these values, a step change occurs at the clearing time as shown on figure 3.3.

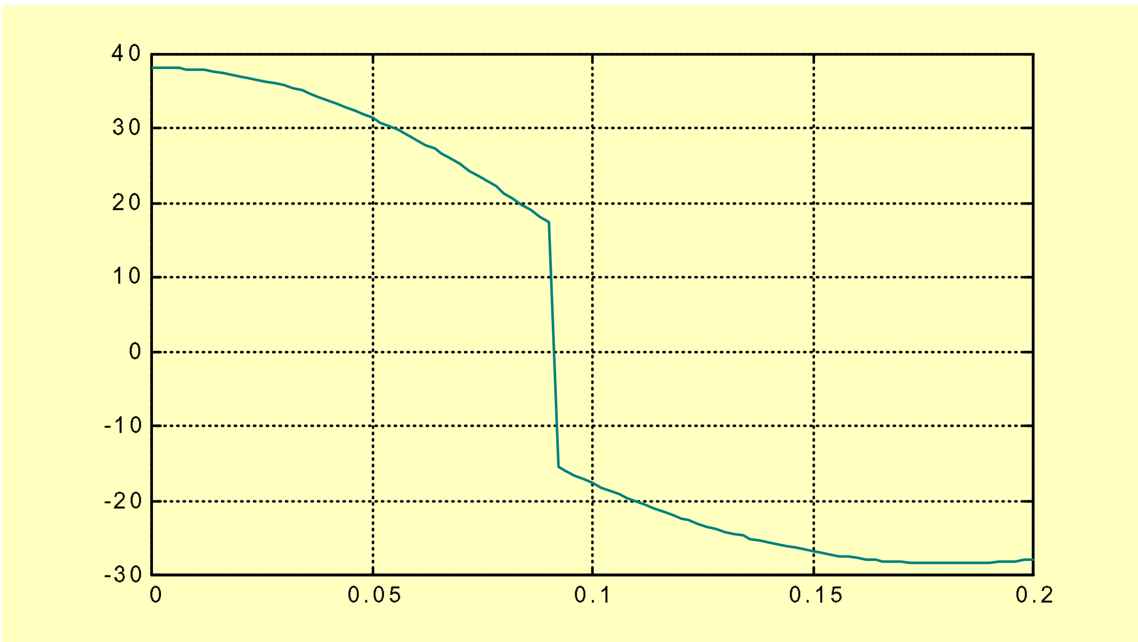

Figure 3.3: Acceleration of generator 1 ($rad.s^{-2}$) versus time: tcl=0.09sec

During the post-fault period, the state equations are again integrated numerically. But the power P_i given by (2.10), the coefficients C_{ik} and D_{ik} given by (2.7) are not the same as those of the fault-on period since generally a line opens in order to clear the fault. Once the machine angle measurements are simulated, a Curve Fitting method can be applied. The post-fault trajectory is predicted from the data given by machine angle measurements in the angle subspace. The different types of estimator and model will be developed in Chapter 4. We can specify that the process can be started again at each new measurement. Also, the method can be extended to the second swing transient stability analysis.

The post-fault trajectory is predicted until it reached the stability boundary. Notice that the purpose of the prediction is to give an accurate idea on the c.u.e.p. The exit point is approximated by the point where the first maximum of the potential energy along the predicted post-fault path is encountered. The detection of a local potential energy peak can be identified by a change in sign from negative to positive in the directional derivative of the potential energy gradient (3.2), which is given by

$$\sum_{i=1}^{n}\left[P_i - P_{ei}\left(\underline{\tilde{d}}\right) - \frac{M_i}{M_t} P_{COA}\left(\underline{\tilde{d}}\right)\right] * \underline{\tilde{w}_i} = 0 \qquad (3.2)$$

However as detailed in [18], this is only acceptable if the system under study is well behaved and exhibits simple plant mode stability phenomenon. In practical multimachine systems, there may exist inter-machine oscillations which produce a few potential energy peaks during the first swing. This is illustrated in Figure 3.4, which shows one possible post-fault trajectory under inter-machine oscillations.

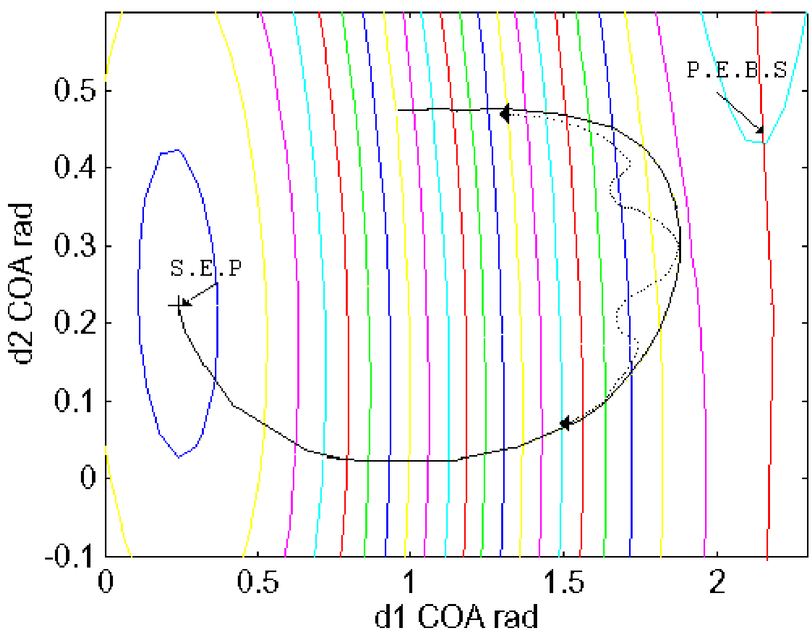

Figure 3.4: Dash: Syst. Traj. with inter-oscillations
& Full: Syst.Traj with no inter-oscillations

It would be natural to conclude that the different potential energy peaks could be reproduced by the predicted post-fault path and could result in the detection of an exit point which is still located in the region of attraction of the post-fault s.e.p. Therefore, the first point at which V_{pe} attains a local maximum on the ray starting at the s.e.p. and in the direction to the last point of the prediction is taken. However, as explained in the beginning of this chapter, a peak in potential energy is reached only if the ray intersects orthogonally with the p.e.b.s. The bottom and top left side of Figure 3.2 can be zones where there is no local maximum detection. Alternatively, the exit point can be detected in those cases thanks to the Ball-Drop method developed in [22]. A state is immediately assessed to being inside or outside the p.e.b.s. by a single, path independent procedure. The details of this method are explained in Chapter 4. It is important to notice that the Ball Drop method is also used for the prediction of the post-fault path as a security. The prediction can be stopped at any time if the Ball Drop method senses that the path is crossing the p.e.b.s.

The main goal of the prediction is to give us an idea on the direction where the controlling unstable equilibrium point may be located. Using the previous exit point as starting point, the minimum gradient point is computed. The predicted controlling unstable equilibrium point is then obtained by solving a set of non-linear algebraic equations with the minimum gradient point as initial guess. The procedure is similar to the B.C.U method. The shadowing method is also used. These different ways to find the c.u.e.p will be explained in Chapter 5. So far, the potential energy of the predicted c.u.e.p. can be compared with the total energy of the system at the clearing time. If the potential energy of the c.u.e.p. is larger than the total energy of the system at the clearing time, the system's trajectory has the possibility to leave the stability region, signifying that the system is unstable.

The contribution of the curve fitting method is a new computationally fast way to detect the c.u.e.p. of the post-fault trajectory and thus open up the possibility to use the energy approach to assess transient stability. Furthermore, the overall procedure can be started again for a multi-swing stability analysis. After a first swing, the trajectory is under the control of a new c.u.e.p. that could lead the system to leave the stability region. In that case, we are in the same situation as before the first swing and the method can again be applied. Examples of single swing and second swing analysis are shown in Figure 3.5 and 3.6.