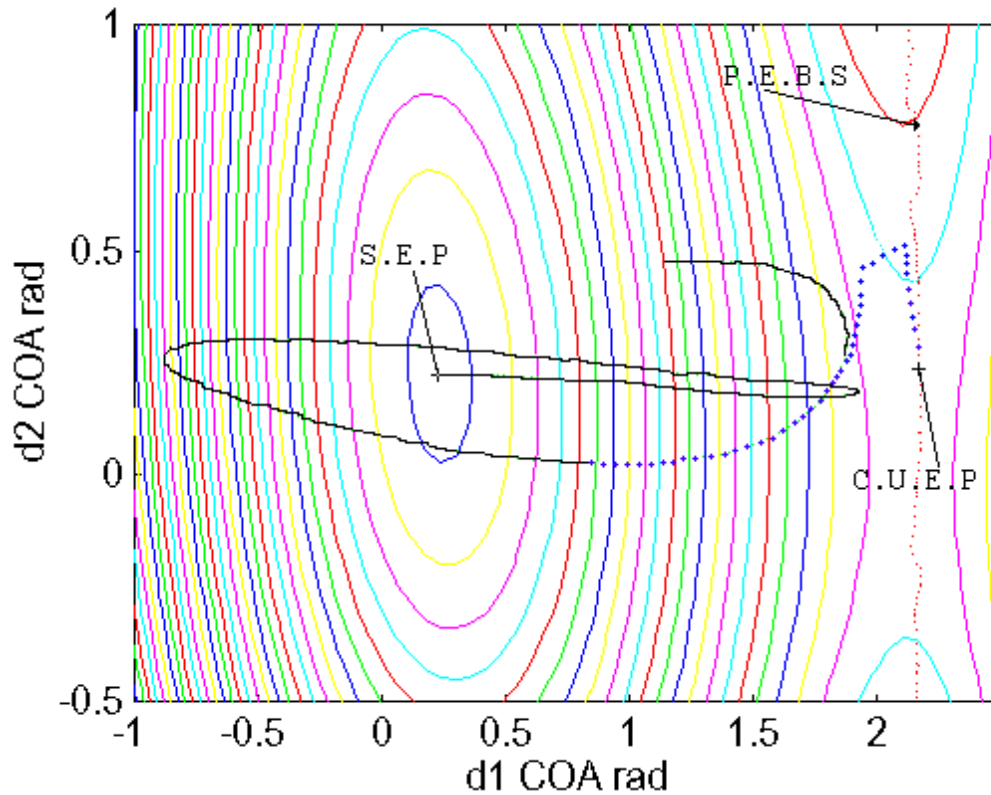(Full: real trajectory & Dash: predicted trajectory)
Figure 3.5: 3-machine system; Tcl=0.20 sec, Zf2=(1+j)*10^(-5)

In Figure 3.5, a simulation has been executed on Athay's 3-machine system. For the simulation case, a self-cleared fault on bus 2 with an impedance of Zf=(1+j)*10^(-5) has also been applied. The fault is assumed to be cleared at 0.20 sec after the fault occurred, which is the critical clearing time. As the simulated disturbance is assumed to include the initiation and clearing of fault on a power system, the critical clearing time is the maximum time between the initiation and the clearing such that the power system is transiently stable [1]. This critical clearing time is obtained thanks to a time domain simulation method.

The step integration for simulation is 5 msec and 75 msec after clearing time are used to estimate the prediction model. The c.u.e.p. that have been found has for coordinate 2.18 rad; 0.26 rad and -0.545 rad. The potential energy at this point is of 7.869 MWrad/MVA and the total energy of the system at clearing time is of 7.5 MWrad/MVA. The first swing is then assessed to be stable following the Energy criterion. To conclude this example, 275 milliseconds after the fault occurred were required to assess the system to be transiently stable. The Curve-Fitting method has demonstrated, in this example, its efficiency to quickly enhance the energy margin of a power system following a disturbance.

(Full: real trajectory & +: Predicted trajectory)
Figure 3.6: Second swing transient stability prediction

In Figure 3.6, a multi-swing transient stability is presented. The considered fault is the same as previously. On the graph, the full path is the real trajectory, which is stable. The dotted line represents the prediction. The stability is predicted at 1.1 sec using 20 pts to estimate the prediction model. With a step integration of 5 milliseconds, the second swing is then assessed to be stable at 1.2 sec after the fault occurred.

The curve fitting method has demonstrated its ability to assess the transient stability for a second swing case. One other relevant point of this method is the fact that it does not need any preliminary studies to reduce the system to a power system model. As it is shown bellow, most of the actual implemented methods require a preliminary work to create a model as close to the reality as possible. Nevertheless, the method is highly linked with the quality of the data brought by phasor measurements. Their sampling rate and the amount of noise will determine the quality of the estimation and, ultimately, its accuracy. Detailed explanations on those points are explained in the next chapter.

3.3 Survey and Comparison

3.3.1 The TEPCO method

The system proposed by Tokyo Electric Power company and Toshiba Corporation ([6], [7]) measures the relative angle between generator that may lose synchronism and the voltage angles of the bus in the main area, predicts loss of synchronism from the change of the relative angle in the future, and determines the number of generators to be shed to restore stability. The phase difference between the generator and the bus in the main area is approximated by:

$$\mathrm{d}(t) = \mathrm{d}_0 + A e^{\mathrm{a} t} \sin(w t + \mathrm{b}) \qquad (3.3)$$

where

d_0 : initial value of phase difference
w : angular frequency of phase difference
a : damping constant
A : amplitude

This equation is used to calculate the predicted value. When the predicted phase difference exceeds the setting value $\mathrm{d}_{\lim it}$, it is decided that the power swing between the two groups is unstable. The threshold value is determined by computer simulation under varying conditions. This procedure has been implemented in and for a large-capacity power station, which is connected to the network via a long transmission line. In fact, this power system model represents the electric power system of the Tokyo Electric Power Company. The majority of electric power is supplied to the main area of consumption via extremely heavy loaded 500 kV-double-circuit lines. The TEPCO method is applied to a reduced power system model that requires a preliminary study to find the generator that may lose synchronism. Second, they calculate phase differences instead of using the transient energy method. Moreover, a nonlinear model is used to predict the power system evolution. This has the disadvantage to be highly dependent on the quality of the starting points of the iterations. If the initial conditions are not close to the solution, the algorithm may diverge. However, an approach to use this model in the first stage of the curve-fitting method is explained in Chapter 4.

3.3.2 Decision trees for transient stability prediction

Decision trees are constructed from a training set of examples. Each example in the training set consists of an input vector along with its correct classification [5]. The tree building process seeks to fit the training set data without over-fitting the data. The resulting tree is tested on an unseen test set where the predicted class is compared with the true class for each example. The classification error rate for the test set measures the method's success. A decision tree

classifies each input vector according to a series of tests. The diagram of a decision tree is a flow-chart in the shape of an upside-down tree as seen in figure 3.7.
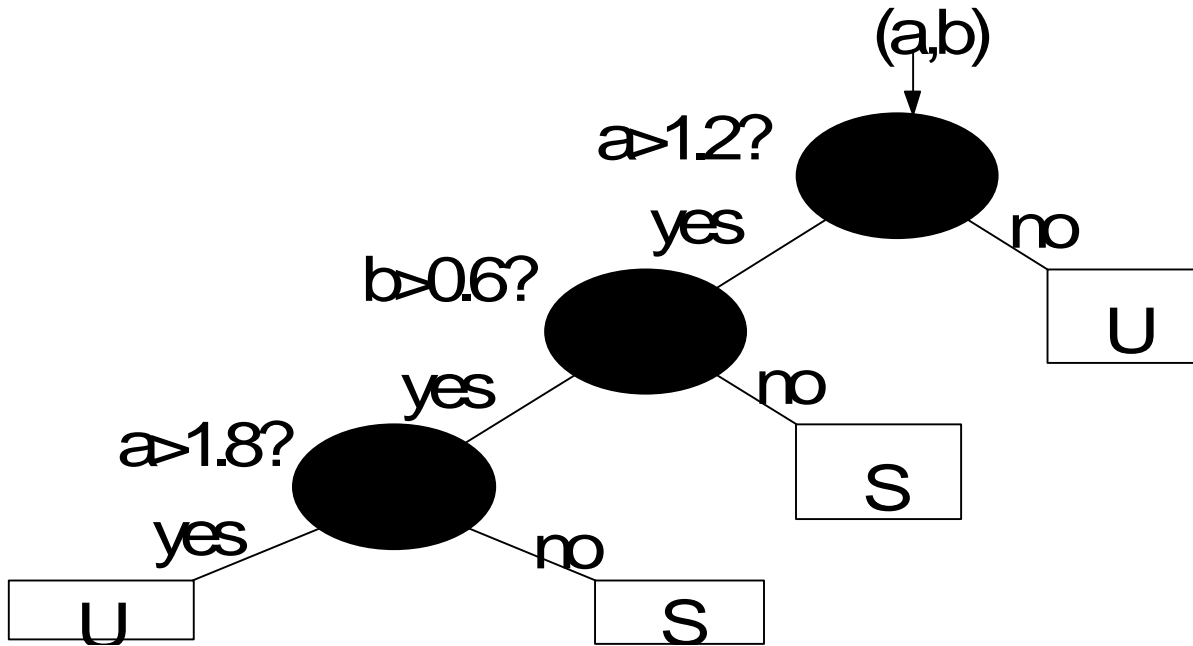
Figure 3.7: A simple decision tree for illustration purpose

Starting at the top node, the flow branches right or left depending on the outcome of the simple test. For numerical data, the test is whether a particular element of the input vector exceeds a threshold. The procedure proceeds down the tree until a terminal node is reached. The input is classified according to the class of the terminal node. First, a decision tree designed to work for arbitrary fault locations should have a sufficiently diverse training set. Faults of various lengths should be simulated to build decision trees. Moreover, each example of a fault should contain the simulated post-fault phasor measurements along with the decision whether the particular fault results in instability. Large numbers of examples are aggregated together into training and test sets, from which trees are constructed. Second, an actual implementation would require simulating a large number of faults for a large number of system configurations. This fact will require the use of a reduced-order model. Potential applications in real-time protection demand high accuracy from the system model. Some models are well known for giving optimistic results, predicting stability in the case of instability, while others give conservative results. The reliability of this method depends on the level of sophistication of the model.

The main idea is to train with a model of sufficient accuracy to predict real-life conditions. The method developed in this section were based on the use of decision trees for real-time transient stability prediction. This method requires numerous experiments in order to set the decision trees and a power system model as close as possible from the reality. On one hand, it is very difficult and expensive to predict all the fault that may occur on a system and on the other hand, it is also very difficult to find a good model that closely represents an actual power system.

3.3.3. Hybrid Method: SIME (Single Machine Equivalent)[12]

SIME is a method proposed by Bettiol et al. [12] for real-time transient stability emergency control. It uses real-time phasor measurements to appraise stability margins and identify relevant machines. These pieces of information are provided by a hybrid method called SIME. The principle of the proposed approach is as follows. In the event of a disturbance inception and after its clearance, the generator data are used and are transmitted in real-time to construct at each time sample an appropriate one machine equivalent system. It predicts the swing to assess the margin and, whenever needed, to decide corrective actions. Basically, SIME relies on a time-domain program that observes in a very specific way the loss of synchronism of a power system originated from the irrevocable separation of its machines into two clusters. It is possible to successively replace these two clusters by a two-machine system, then by a one-machine infinite bus (OMIB) system properly selected ("relevant OMIB"). Finally, SIME calls upon the equal-area criterion to assess the transient stability of the relevant OMIB using its transient stability margin, defined as the excess of its decelerating over its accelerating energy.

From this brief review of the method, three comments can be underlined. First as for the Curve Fitting method, it has been assumed that the individual power plant variables may be obtained by synchronized phasor measurement devices placed in each power plant together with some local processing power to determine generator angles, speeds, accelerations and powers from terminal voltages and currents. Second, the above method suggests that relevant OMIBs are defined on unstable cases only; indeed, they rely on the irrevocable separation of the machines into two groups. Third, the relevant OMIB depends strongly on the stability case considered, i.e. on the operating conditions, the applied contingency and its clearing scenario; a change of either of these conditions may yield a different relevant OMIB.