Chapter 5

Integration of Dynamic Security Assessment and Stability Controls

Dynamic security assessment (DSA) or transient security assessment (TSA) determines a system's ability to survive contingencies with a safety factor (margin). To ensure that a system remains dynamically secure, preventive or corrective remedial actions are designed. Preventive actions are applied in the pre-contingency system so that after any credible contingency the system remains secure. Examples include restrictions on interface flows, angle differences across a particular interface, and total generation out of a plant. Corrective remedial actions (stability controls) are those taken following a contingency. Examples include generator or load tripping, and capacitor bank or reactor switching.

Traditionally, preventive and corrective dynamic security measures have been developed from numerous off-line simulations. Transfer limits are determined by selecting extreme system conditions and simulating critical contingencies. The limits derived are conservative, since they are based on extreme system conditions.

Recently, on-line dynamic security assessment tools have been developed [5-1–7,5-19,5-21] a few of which have found their way to real system implementation [5-1–3,5-6,5-7]. These tools differ in the methodology but they share the same concepts and fundamental blocks. This chapter describes on-line dynamic security assessment methods as part of the remedial stability control determination, and describes in detail its different components. Transient security assessment for arming of generation tripping stability control is described. Stability control is made adaptive based on the on-line security assessment.

5.1 On-Line Transient Stability Assessment Design

An on-line DSA tool should meet the following requirements:

- *Reliability.* Both the hardware and software of on-line DSA should perform reliably under all feasible system operating conditions.
- *Accuracy.* The accuracy of DSA is of ultimate importance to ensure the dynamic security of a power system. In particular, it should accommodate detailed models for system components, as well as for disturbances that may include autoreclosures and other complex switching actions. The general trend is that on-line DSA should give comparable results with the best off-line study tools for a given system model.
- *Performance.* The processing speed of DSA is often critical in meeting the requirements for on-line real-time or near real-time operations. In order to achieve the best computation speed, advanced techniques in software and hardware design must be used. Other performance requirements for DSA include flexibility in data input/output and good user interface.

As described in the following subsections, on-line dynamic security assessment consists of the following four elements:

- preprocessing

- security assessment
- post-processing
- process control and integration

5.1.1 Preprocessing

The task of preprocessing includes static state estimation, housekeeping for base case development, and contingency screening and ranking.

A major impediment to DSA for *interarea* stability problems in large interconnections is the difficulty of state estimation to obtain the on-line power flow base case. For a particular control center, the main difficulty is with the external network model. Considerable inter-utility data exchange is required. There are other difficulties associated with measurement accuracy, unbalance operation, network parameter uncertainty, etc. [5-24].

State estimation can be improved by high quality digital measurements from throughout the interconnection. Synchronized positive sequence phasor measurements are valuable [5-22,5-25, 5-26]. Conceptually, with high quality bus voltage magnitude and angle measurements, bus power flow states are known.

External network models for on-line DSA is obtained by selecting from a number of previously stored dynamically reduced system models [5-1,5-2]. Alternatively dynamic reduction techniques can be used in real-time to develop the external model. This will facilitate base case initialization and helps maintain the base case within certain size limit so that the computation speed requirements can be met.

In addition to power flow data, other data required for DSA may also need to be updated for a new system snapshot. For instance, the settings of a PSS for a pumped storage generation unit may need adjustment for the different modes of operation of the unit. The contingencies may also need update when the network topology or system operation condition changes.

It's impossible to assess all the credible contingencies within the confines of available computational resources and required response times. Therefore, the list of credible contingencies has to be reduced to make it manageable by the security assessment module.

The contingency screening and ranking method could be based on transient energy functions [5-10–17], expert systems [5-2,5-8,5-30], neural networks [5-8,5-9], extended equal area criteria [5-17–20], or indices derived from energy properties or fast time domain simulations using simplified models [5-6,5-7,5-10]. The common requirements of candidate contingency screening and ranking methods are high speed and accuracy of the final results. While all these methods can be used for contingency screening and ranking, the final limit computations should be done using more accurate methods.

The performance of a contingency screening and ranking method can be evaluated in terms of its misclassification. Misclassification consists of two components of False Alarm and False Dismissal as described below.

- *False alarm:* a stable contingency that is identified as an unstable one (critical one)

- *False Dismissal:* an unstable contingency that is identified as a stable one (non-critical one)

An acceptable contingency screening and ranking method should have zero false dismissals and a very low number of false alarms.

5.1.2 Security assessment

Detailed time domain simulation is the most reliable security assessment approach [5-1–7,5-19, 5-21]. Commercial-grade software is available that can normally be customized for a utility's required modeling and disturbances. This allows on-line security assessment with unlimited modeling capabilities capable of handling a full-scaled power system.

Normally, DSA assesses transient stability of a power system, or the ability of the system to maintain synchronism after a credible contingency. As power systems operate in more and more stressed conditions, another form of angle stability, i.e., small-signal stability in the form of sustained or growing oscillations in part or all of the system, may become critically restricting to the system operating limits. This has already happened in some parts of the North American interconnected power systems. The requirement to address this type of stability problem calls for an efficient and reliable method to compute the critical mode of the system. This is still an area with room for research. One approach based on the time domain simulation technique is to obtain an estimate of the critical mode by post-processing simulation results. This is further described in the following section.

5.1.3 Post-processing

Online implementation of time simulation requires a built-in intelligence for the following:

- Assessing the system dynamic performance (stable, unstable).
- Determining the degree of stability or instability (margin).
- Determining the sensitivity of the margin to key variables (transfer limit and generation tripping).
- Determining the transfer limit or preplanned stability control actions (e.g., arming of generator tripping).

In the following, several methods that have been used in the post-processing stage are described.

Second-kick method [5-2, 5-4]. The second kick method was based on energy concepts for determining stability margin and other useful information from the simulations. It was inspired by the hybrid method [5-3]. Although there are different implementation methods available for this algorithm [5-5,5-29], the original concept [5-2] is described below.

Detailed time domain simulation is performed with calculation of potential energy, kinetic energy and corrected kinetic energy. No modeling assumptions are made and no analytical equation is used to calculate potential energy. The minimum of the corrected kinetic energy, Kemin1 is identified, after the contingency. If the minimum is greater than zero (system unstable), the margin is calculated from the value of the corrected kinetic energy at this point. If the system is stable (corrected Kemin = 0), at Tkemin1, a second fault (second kick) which is long enough to make the system unstable, is applied and simulation is continued until the second minimum of kinetic energy, Kemin2, is obtained. This point also reflects the crossing of the potential energy boundary surface (PEBS), as shown in Figure 5-1. The transient energy margin is then calculated using the values of the corrected kinetic energy at the second minimum of kinetic energy (Kemin2) and the value after the second fault recovery (Kerec2) taking into account adjustments due to potential energy change during the second kick. Figure 5-1 shows the system trajectory on the potential energy surface.

The basic idea here is that the kinetic energy injected into the system by the second kick minus the value of the kinetic energy left in the system at the crest of potential energy hill, (PEBS crossing) should give the transient energy margin. This value should be adjusted for the potential energy change during the second kick. The transient energy margin, therefore is calculated by:

TEM = Kerec2- Kemin2 + Dpe

where Dpe is the change in potential energy during the second kick.

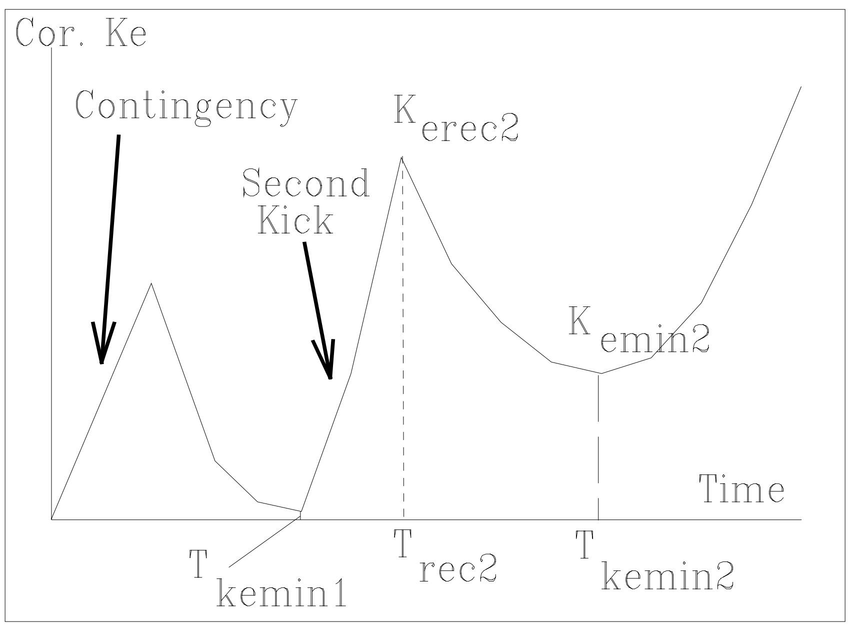

Fig. 5-1. Corrected kinetic variations.

Extended equal area criterion (EEAC) [5-17, 5-18]. The EEAC was developed based on the fact that the loss of synchronism in a power system is always initiated from the splitting of the system into the following two parts:

- Critical cluster of generators (CCG)
- Rest of the system

These methods have evolved in their developments through three major stages, each of which is characterized by a special version of the method:

- Static method

- Dynamic method
- Integrated method

The SIngle Machine Equivalent (SIME) method belongs to the last type [5-21].

The basic difference among these versions is the number of Critical Cluster Center of Inertia (CCCOI) transformations that are performed to obtain the parametric One-Machine Infinite Bus (OMIB) system. The static method does only one static transformation and therefore its accuracy is usually not satisfactory. The dynamic method improves the accuracy by using several transformations. This is achieved by simplifying power system modeling, and by using the Taylor-series expansion technique to obtain the approximate trajectory of the system. In the integrated method, the transformation is integrated with the detailed time-domain simulations. Thus, no modeling compromise is required and the stability index so computed is very accurate.

Figure 5-2 shows the principle of the integrated EEAC. System snapshots are taken from the conventional time-domain simulation results (Figure 5-2 (a)) and for each snapshot a CCCOI transformation is performed to obtain the parametric OMIB system trajectory (Figure 5-2 (b)). The stability index η of the system can then be defined as

$$\eta = \begin{cases} 100 \times \dfrac{A_{dec} - A_{inc}}{A_{dec}} \text{ If the system is stable } (A_{dec} > A_{inc}) \\ 100 \times \dfrac{A_{dec} - A_{inc}}{A_{inc}} \text{ If the system is unstable } (A_{inc} > A_{dec}) \end{cases}$$

Thus, $-100 \le \eta \le 100$, and

$\eta \le 0$ if the system is unstable

$\eta > 0$ if the system is stable

The computation of this index requires a straightforward implementation of the integrated method on top of the time-domain simulation engine. As described earlier, such an index is not subject to any modeling restrictions and it is also able to identify multi-swing stability problem.

In systems for which angle stability is the only concern to the dynamic security, the integrated method implementation can be made to check the system status during the simulation. If the system is found to be definitely stable or unstable prior to the end of the simulation, the simulation is terminated. For all other cases a complete simulation is required. This is an area for which more research is needed to equip this class of methods with more sophisticated early termination techniques.

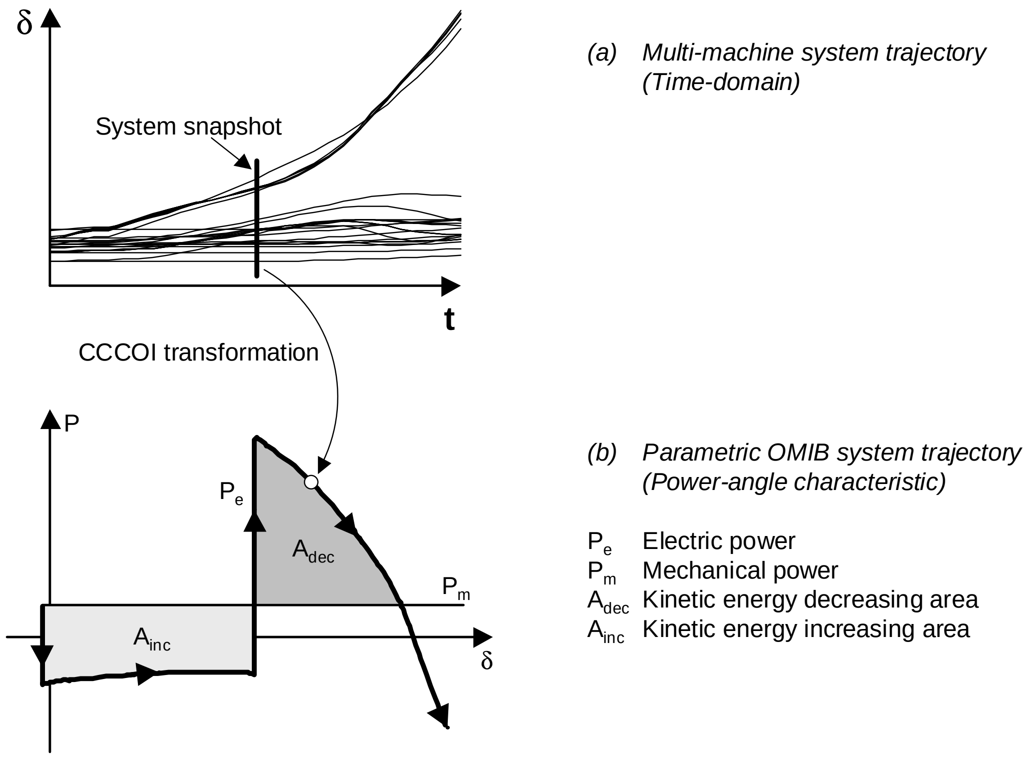

Fig. 5-2. Integrated EEAC.

Other methods to determine stability margin. Reference 5-6 defines a stability index using dot products of generator rotor angles, speeds, and accelerating powers obtained from time-domain simulations. The idea is based on the path of the post-fault system trajectory: the system is stable if its trajectory "swings back" before reaching PEBS or unstable if its trajectory "exits" the PEBS. A DSA system using this index has been developed and is now operational on-line.

Reference 5-7 describes an approach for establishing the required generator tripping. It uses one time domain simulation and with the help of the generator's angular swing and kinetic energy estimates the required tripping. Using a conservative threshold, the authors have verified the performance of the method on a developed prototype. The "Transient Stability Control" system has been in service since June 1995, and has since been extended.

Reference 5-31 uses the signal energy obtained from time-domain simulations to define a stability index. The authors successfully applied this index to determine the transient stability transfer limit for the Hydro Quebec system.

Stability Limit Calculation: The final outcome of TSA are guidelines for system operation in the form of pre-contingency transfer limits and generation tripping remedial action immediately following a fault.

Several approaches have proposed to determine the power transfer limits, all of which make use of the stability margin or index as a measure of system stability:

- Sensitivity-based method [5-5,5-20].
- Curve fitting method [5-6].
- Binary and accelerated binary search method [5-31].

Figure 5-3 shows the application of the sensitivity-based method (in this case, the stability margin obtain by the second kick approach is used). To find the power transfer limit and the required generation tripping, sensitivity values are calculated for stability margin with respect to generation tripping, or generation change in the case of power transfer limit calculations. These analytical equations can only be used in the first step to calculate the conditions for the next one and be abandoned afterwards. After the second run linear interpolation is used to obtain the sensitivity values from the two previous stability margin calculations.

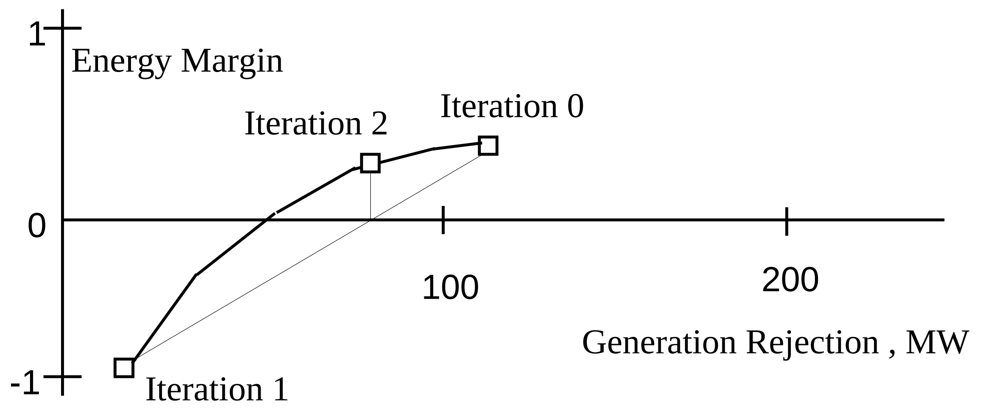

Fig. 5-3. Limit calculation using sensitivity factors.

Historically, utilities have established remedial action controls, e.g. units for generation shedding, based on design limitations and experience. There seems to be a need for rigorous methods which can establish the most effective remedial actions in real-time. Reference 5-28 has moved in that direction by establishing the corrective actions necessary to stabilize all dangerous contingencies simultaneously, while ensuring the maximum allowable transfer between areas.

Critical damping estimate: As mentioned earlier, an increasing concern on the angle stability of power systems is the oscillation problems, and DSA needs to handle these problems. Reference 5-32 presents a method of estimating the damping of the critical mode (i.e., the least stable mode) in a system by using the multi-channel Prony analysis. The advantage of this approach is that it makes use of the time-domain simulation results with very small computational overhead. The multi-channel Prony algorithm helps improve drastically the accuracy of the results as compared with the commonly used single-channel analysis.

This method is illustrated in the following, using a system model consisting of 6139 buses and 798 generators. Figure 5-4 shows the simulation results for selected generator rotor angles for a typical contingency. It can be seen that, although the system is transiently stable, sustained oscillations exist. It’s therefore important to identify the critical mode in order to assess the security of the system.

Table 5-1 contains the critical mode identified using a four-channel Prony analysis algorithm. For comparison, the results from the full eigen-value analysis and the conventional Prony analysis on each individual channel are also shown in the table. The eigen-value analysis clearly shows the critical mode at 0.79 Hz with almost zero damping; so does the four-channel Prony algorithm. However, the results from individual generator rotor angles are apparently not reliable.

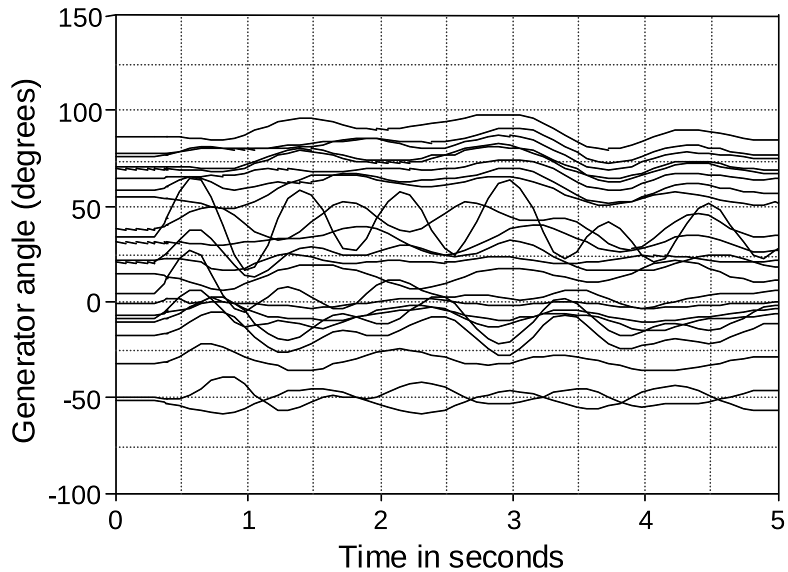

Fig. 5-4. Simulation results for the sample system.

Table 5-1: Critical mode comparison from different methods

Computation Method	**Freq. (Hz)**	**Damping (%)**
Prony on rotor angle of generator ‘A’	0.71	2.57
Prony on rotor angle of generator ‘B’	0.80	-3.20
Prony on rotor angle of generator ‘C’	0.62	-3.75
Prony on rotor angle of generator ‘D’	0.79	-3.11
Four-channel Prony on rotor angles of ‘A’, ‘B’, ‘C’, ‘D’	0.75	-0.58
Full eigen-value analysis	0.79	0.03

5.1.4 DSA performance enhancements

As an on-line application, the computation speed of DSA has been of critical importance to the end users. As typical requirements, an on-line DSA system should be able to process hundreds of contingencies for dozens of transactions within a 10 to 20 minutes cycle. Further complicating the matter is the tendency that utilities are using larger and larger base case models in their EMS. It is inevitable that on-line DSA systems have to work with EMS models of 5,000 to 10,000 buses and up to 1,000 generators. Thus, techniques that speed up DSA performance need to be developed and deployed in order to meet the requirements.

Among the techniques that aim at improving DSA performances, the following are noteworthy:

- *Development of better contingency screening method.* Any fast contingency screening method that can reduce the false alarm rate while maintaining zero false dismissals can drastically reduce the computation time needed for detailed analysis of the critical contingencies.
- *Enhancement of Early termination techniques.* When using time-domain simulations for detailed analysis of the critical contingencies, it's desirable to terminate the simulation as soon as the stability of the system can be identified using a stability index.
- *Parallel or distributed computations.* This is the classical method of improving the speed of simulations. Since DSA involves multi-transaction, multi-contingency simulations, parallel or distributed simulations for transactions or contingencies can be easily achieved.

5.2 Other Integration of DSA and Stability Controls

The previous section described DSA methods where the output is used for stability control adaptation—namely, arming of the correct number of generating units for tripping. This can be thought of as very slow, outer-loop adaptive supervisory control.

Another potential use of DSA in advanced stability control is pattern recognition based control where DSA provides the database. This is described in Chapter 4.

Other synergism is possible between DSA and stability controls. High quality digital measurements can both improve state estimation as described above, and be used for direct monitoring and stability control. Synchronized positive sequence phasor measurements are one type of digital measurements. Phasor measurements may be sufficiently related to dynamic states such as rotor angles and speeds to be useful for stability control; see discussion in §4.3. In addition, fast digital measurements support stability control development, commissioning, and monitoring as discussed in Chapter 2.

Another application of DSA for stability controls using measurements is found in reference [5-27]. In this work, the real-time transient stability emergency controls are derived by feeding the Single-Machine Equivalent method [SIME] with real-time measurements taken at the power plants to control the system transient stability in real-time and in a closed-loop fashion. The main steps of this approach are the prediction (say, 150 to 200 ms ahead) of the transient stability status of a system after a fault occurrence and its clearance by protective relays and its degree of instability if instability is detected. In the latter case, the amount of generation tripping required to compensate for this margin is assessed and the system status after the corrective action has been triggered is monitored to establish whether this action is sufficient or additional remedial action is required.

Complementing the computer-based contingency analysis described in the previous section, monitor-based DSA is valuable for both system operators, and for stability control analysts and developers [5-23].

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