Chapter 5

ON-GOING RESEARCH AND DEVELOPMENT

5.1 Introduction

Chapter 3 presented a general set of requirements for on-line DSA systems. Some of these requirements have clearly been achieved as indicated in the state-of-the-art implementations described in Chapter 4. However, on-line DSA remains an emerging technology and the potential capabilities, and need for such capabilities, is enormous. Aside from the ever increasing power of computers, a number of developmental areas include,

- improved system architectures and computing methods
- use of intelligent systems
- new analytical tools and techniques
- use of new technologies such as PMUs or real-time damping measurement devices
- improvement in state estimation and modeling
- application of DSA results to protection and control

This Chapter outlines some of the on-going research and development underway in various parts of the world.

5.2 On-going R&D in Canada - Hydro Quebec

Off-line studies, based on stability robustness and respect of different criteria and constraints, try to find the best optimal limits applicable for a large range of operation. These limits are stored in the LIMSEL system as previously described. For some real-time power network conditions, these limits sometimes computed more than one year before, are still conservative and could be improved.

Since 1994, Hydro-Québec has stored all historical snapshot data in every 5 minutes coming from the state estimator with the corresponding dynamic models. These data can be accessed by an in-house developed software called CILEX and have already been used for stability studies on real cases or for post-mortem analysis and also for giving feedback to off-line studies.

Hydro-Québec’s specificities in term of security and organization require, due to its challenging power network dynamic characteristic, strong and strict interrelation, continuity and coherency between operation planning and operational environments. An on-line DSA system, if just indicating the real operational state is secure or not, is not sufficient because we already have this information in LIMSEL system. An on-line DSA system computing real-time transfer limits provide limited economic gains because these limits are not available for planned transactions. However, economic analysis has shown that the best gains happen for specific constraint situations in operation planning.

Currently, an on-going DSA research project at Hydro-Quebec takes knowledge from expertise and develops a systematic approach to determine off-line, optimized transfer limits for the Hydro-Quebec transmission system for a specific network configuration corresponding to a constrained planning operation or operation situation or to a network event (see Figure 5-1). The transfer limit determination process has to be revised and optimized to allow a global response time of only a couple of days for a constrained situation foreseen by example one week in advance. Presently, this process as described before takes several months for a complete study on a main corridor. Limits are stored in LIMSEL system and correspond to off-line study done often on a worse case scenario. The new approach has the potential for a specific configuration to raise the transfer limits by taking into account a better knowledge of the real state of the network (CILEX can be used) and the uncertainties associated with certain variables. The new limits will replace, just for a short period of time corresponding to the constrained forecasted situation, the limits already stored in the control center LIMSEL system covering this specific configuration.

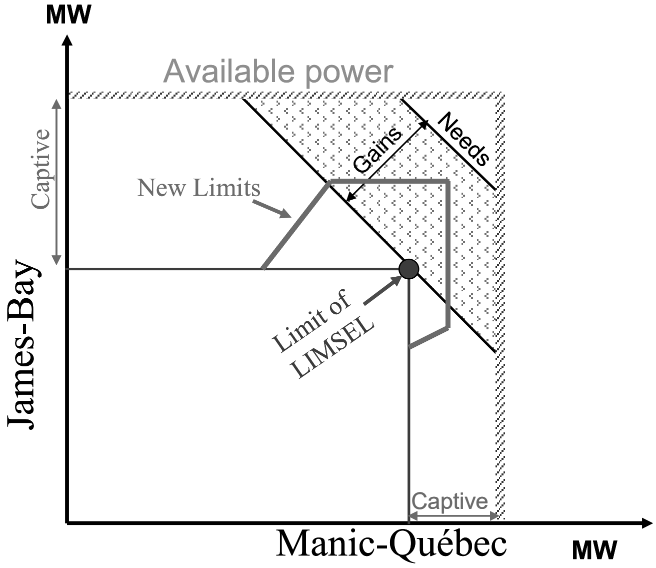

Figure 5-1 - Transfer limits optimized by the new approach

The new approach will provide operation planning engineers a fast and systematic process to establish in advance secure transfer limits and also to optimize the daily operation scheduling over a horizon of up to a few weeks. This process is expected to reduce the study time from several days to a few hours eventually. It will also be used for off-line studies and give operation planning engineers opportunities to explore more network configurations which can not be covered before.

The challenge of this research project is to generate, for a constrained situation and in a time frame compatible with the operation planning (ideally a few hours), a systematic way to output limits which will be valid for a specific period of time. The way to determine the limits has to be built in continuity with the current process. In the first step (short term horizon), the limits will be computed in a more systematic way with the help of the operation planning engineers supported with data processing and decision making tools. This process can last a few days. In the second step (mid term horizon), the engineers will only supervise the process execution and validate the results before entering them in the LIMSEL system at the control center.

Another challenge of this research project is the performance of the contingency analysis which is crucial for the success of the second step of the project. With the complex and detailed modeling required for a good simulation of the power system behavior and with the use of specific voltage and frequency criteria by operation planning engineers, it is difficult if not impossible with current contingency analysis methods to provide 100% reliability with a good efficiency.

5.3 On-going R&D in China - CEPRI

CEPRI is developing a number of projects related to DSA, including,:

(1) Improved dynamic security assessment.

Based on the results of the parallel computation, the DSA system will carry out fast stability sensitivity analysis, which gives the pre-decision to improve the stability level of the power system, even give the real-time control. The sensitivity analysis includes transient stability assessment, small signal stability assessment and voltage stability assessment.

The national dispatch center of China is now establishing the dynamic stability monitoring and control system, which is based on the DSA and other advanced technology.

(2) Dynamic security area visualization research.

The function is based on parallel computation, using the stability maximum of the transmission power of the important power system interfaces and uses 2D and 3D visualization software to draw the current operation point and the security area. Thus the operator of the dispatch center can quickly understand the stability level of the power grid at any point in time.

5.4 On-going R&D in Europe

5.4.1 Transient stability assessment and control

Current and further research activities in the field of SIME-based TSA and control are/will be focused around testing and possible refinements of E-SIME (most notably extension to the use of phasor measurements) and Open Loop Emergency Control (OLEC), development of SIME-based adaptive emergency control, application of OLEC technique in liberalized electricity markets as well as design of system protection schemes (more specifically through so called contracts for system protection schemes).

E-SIME

Following a disturbance inception and its clearance, the E-SIME aims at predicting the system transient stability behaviour and, if necessary, at deciding and triggering control actions early enough to prevent loss of synchronism. Further, it aims at continuing monitoring the system, in order to assess whether the control action has been sufficient or should be reinforced. The method relies on real-time measurements, informing about machines parameters.

Predictive transient stability assessment

The prediction relies on real-time measurements, acquired at regular time steps, t_i **’s,** and refreshed at the rate Δt_i , in post-fault stage. The procedure consists of the following steps.

(i) Predicting the OMIB structure: use a Taylor series expansion to predict (say, 100 ms ahead), the

individual machines' rotor angles; rank the machines according to their angles, identify the largest angular distance between two successive machines and declare those above this distance to be the "candidate critical machines", the remaining ones being the "candidate non-critical machines". The suitable aggregation of these machines provides the "candidate OMIB".

(ii) Predicting the $P_a - \delta$ curve: compute the parameters of this "candidate OMIB", and in particular its accelerating power and rotor angle, P_a and δ, for three successive data sets acquired at $t_i - 2\Delta t_i$, $t_i - \Delta t_i$, t_i. Write the equation

$$P_a(\delta) = a\delta^2 + b\delta + c \tag{1}$$

for the three different times and solve for a, b, c. Subsequently, using newly acquired sets of measurements and processing a least squares technique, which shows to be particularly robust, refine the estimated curve. A further improvement consists of using a weighted least-squares (WLS) technique, by giving more important weights to the last sets of measurements.

(iii) Predicting instability: search for the solution of

$$P_a(\delta_u) = a\delta_u{}^2 + b\delta_u + c = 0 \tag{2}$$

to determine whether the OMIB reaches the unstable conditions

$$P_a(\delta_u), \quad \dot{P}_a(\delta_u) > 0 .$$

If not, repeat steps (i) to (iii) using new measurements sets.
If yes, the candidate OMIB is the critical one, for which
the method computes successively [1] , [2], [3],
– the unstable angle δ_u
– the unstable margin

$$\eta = -\int_{\delta i}^{\delta u} P_a d\delta - \frac{1}{2} M\omega_i^2 \tag{3}$$

– the time to instability

$$t_u = t_i + \int_{\delta i}^{\delta u} \frac{d\delta}{\sqrt{(2/M)\int_{\delta i}^{\delta} -P_a d\delta + \omega_i^2}} \tag{4}$$

where δ_i stands for $\delta(t_i)$ and ω_i for $\omega(t_i)$.

(iv) Validity test. The validity test relies on the observation that under given operating and contingency conditions, the value of the (negative) margin should be constant, whatever the time step. Hence, the above computations should be repeated at successive Δt_i's until getting a (almost) constant margin value.

Salient features

- The method uses real-time measurements acquired at regular time intervals and aims at controlling the system in less than, say, 500 ms after the contingency inception and its clearance.
- The prediction phase starts after detecting an anomaly (contingency occurrence) and its clearance by means of protective relays. Note that this prediction does not imply identification of the contingency (location, type, etc.).
- The prediction is possible thanks to the use of the OMIB transformation; predicting the behavior (accelerating power) of all of the system machines would have led to totally unreliable results.
- There may be a tradeoff between the above mentioned validation test and time to instability: the shorter this time, the earlier the corrective action should be taken, possibly before complete convergence of the validation test.

Above descriptions aim at giving a mere flavor of the method. Detailed developments may be found in [1], [2], [3], [4].

Emergency control

On the basis of real-time measurements taken at the power plants, the method pursues the following main objectives:

- to assess *whether* the system is stable or it is driven to instability; in the latter case
- to assess "*how much"* unstable the system is going to be; accordingly,
- to assess *"where"* and *"how much corrective action"* to take (pre-assigned type of corrective action);
- to continue assessing whether the executed corrective action has been sufficient or whether to proceed further.

Block 2 of Figure 5-2 covers the two first steps: prediction of instability, and appraisal of the size of instability, in terms of margins and critical machines. Block 3 takes care of the design of control actions. For example, when generation shedding is of concern, the action consists of determining the number of generators to shed.

Further, the method sends the order of triggering the action, while continuing to monitor and control the system in closed-loop fashion, until getting power system stabilization.

Observations:

- The prediction of the time to (reach) instability may influence the control decision (size of control; time to trigger it; etc).
- The hardware requirements of the emergency control scheme are phasor measurement devices placed at the main power plant stations and communication systems to transmit (centralize-decentralize) this information. These requirements seem to be within reach of today's technology [5].
- The emergency control relies on purely real-time measurements (actually a relatively small number of measurements). This frees the control from uncertainties about power system modeling, parameter values, operating condition, type and location of the contingency.

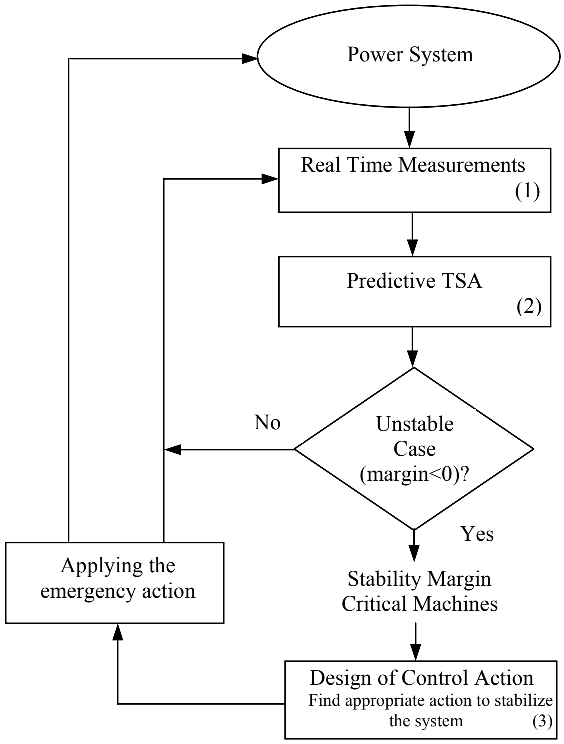

Figure 5-2 General framework for closed-loop transient stability emergency control (E-SIME)

Using phasor measurements

Measurements acquired by Phasor Measurement Units (PMU) such as voltage and current magnitudes, and voltage and current phase angles, are not directly usable by E-SIME and have to be pre-processed. Current research efforts are focused around the use of Artificial Neural Networks (ANN) to estimate (and predict) internal machine angles, rotor speeds and accelerations from the measurements acquired by PMU located at extra-high voltage side of the substation of a power plant. The important engineering observations about PMU measurements with respect to their use in transient stability assessment and control are:

- The rotor angles and speeds of the synchronous generators are the most important quantities in power system transient stability assessment and control.
- PMU measured quantities are electrical variables that may experience fast changes unlike rotor angle which is a mechanical variable. PMU measured quantities can experience discontinuity under switching in the electrical network.
- Wrong or noisy rotor angles and speeds may result in wrong transient stability prediction and wrong determination of control actions.

The rotor angle is a nonlinear function of the machine terminal variables and the main idea is to employ a pattern recognition scheme to map the patterns of inputs (variables measured by a PMU) to the required rotor angle (and speed, two schemes are currently under investigation [6], [7], estimation and prediction of rotor angles, and rotor angles and speeds). This mapping can be represented by

$$f : \{u_k\} \in R^n \rightarrow \{\delta_k\} \in R^1 \qquad (5)$$

where $\{u_k\} = [V_k(t), I_k(t), V_k(t-1), I_k(t-1), \theta_{vk}(t)...]^T$ at any instant k, and n depends on the number of input variables as well as number of previous measurements used.

To realize the mapping of the machine terminal variables measured by a PMU to the rotor angle we use the multi-layer feed-forward ANN. Multi-layer feed-forward ANNs with back propagation supervised learning have several advantages over conventional computing methods. Those advantages are robustness to input and system noise, learning from examples, ability to memorize, handling situations of incomplete information and corrupted data, and performing in real-time. The results of our initial and current research efforts in solving this problem can be found in [8] and [9].

Further refinements

Current E-SIME technique has some limitations that have to be tackled in near future research activities. These limitations are as follows:

- Though E-SIME prediction scheme has been validated on various realistic power systems other power systems may bring some new phenomena and prediction scheme should be adjusted accordingly. It is expected that prediction scheme will be system dependent.
- Methodology relies on the proper contingency occurrence and its clearance identification. Both problems may be solved by using consecutive phasor measurements (this problem is to be investigated in terms of proper fault clearance detection procedure). This requests for additional processing power and will tight requirements on time delays.
- Appraising various types of control actions such as load shedding, fast excitation control, fast valving, dynamic breaking, mechanical power modulation, etc., should be examined (in the available version, E-SIME deals only with the generation tripping). The emergency control scheme will be strongly system dependent and appraising different types of control action will make algorithm much more flexible. Even existing generation tripping scheme should be modified to meet different requirements that different systems can impose (generation pattern in the system, giving slight priority to hydro plants, taking into account benefits and impacts of generator tripping, etc.). The generators could be ranked (prioritized) according to some specific criteria that are to be investigated.

E-SIME deals with global rather than local control. In emergency one should rely on local control actions that are fast enough and less demanding in terms of information needed and corresponding communication requirements.

For the time being, E-SIME assumes that the rotor angles, speeds and acceleration are known for all system machines. It would be interesting to explore how to reduce the number to a small subset (of course, w. r. t. a given “fragilized” area of the power system).

It could happen that the system problem cannot be solved by generation tripping at one power plant only and coordinated control should be examined. The E-SIME provides the amount of generation to be tripped. There are two possible approaches. The first is to trip at once all the estimated generation to be tripped, as soon as the first unstable margin appears, by tripping the most advanced machines that comprise the estimated generation to be tripped (this is the case when estimated time to instability is tight with respect to the delays in control action application). The second approach is to trip machines one by one, by tripping the most advanced machine first, then monitor system state, if the computed stability margin is still negative and time to instability is large enough trip again the most advanced machine and continue until the margin becomes positive, but if after tripping the first machine the time to instability is tight with respect to the delays, trip all the remaining generation (estimated to be tripped) at once.

Because of short time frame (system emergency states) delays in data collecting, processing and delays in determined control actions application can considerably influence whole system. The delays due to data acquisition and processing in the PMU are:

$$T_{acq} = T_c + T_p \leq T_{rate}$$

where:

T_c – sampling period of instantaneous quantities measured at PMU site

T_p – adjourning period of processing by PMU

T_{rate} – sampling rate (e.g., every cycle of fundamental frequency)

The whole cycle (data acquisition and processing - prediction, assessment, decision on control action - control action application) can be expressed as:

$$T = T_{rate} + T_s + T_e + T_{sime} + T_s + T_{sw} \leq T_u$$

where,

T_s – delay in communication system (it is assumed that delay in receiving measurements are approximately the same as the delay in sending control signal to the system, in reality the delays are slightly different),

T_e – identification of the fault clearing.

T_{sime} – time occupied by E-SIME to properly predict instability and to decide on appropriate control action.

T_{sw} – delay in switchgear operation ($T_s + T_{sw}$ – delay in application of the control action).

T_u – the time to instability.

The longer the delays in communication system the shorter the time to E-SIME to predict instability (appearance of the first unstable margin). All this can result in a 'too late' control action application, for some particular situations.

Current E-SIME algorithm is intended to first-swing instability control and has to be disarmed as soon as the system goes into back-swing. Further development is needed to assess its applicability in back-swing and multi-swing modes.

OLEC

The leading idea is to mitigate preventive actions (generation shifting) by complementing them with emergency actions (generation tripping) that would automatically be triggered only if the postulated contingency actually occurs. The procedure realizing this idea is summarized in the following steps [8].

1. For an initially unstable scenario (operating condition subject to a pre-defined harmful contingency and its clearing scheme), compute the corresponding (negative) margin and determine the corresponding critical machines.
2. Assuming that (some of) these machines belong to a power plant equipped with a generation tripping scheme, select the number of units to trip in the emergency mode.
3. Starting with the initial scenario, perform SIME's simulations up to reaching the assumed delay of generation tripping; at this time, shed the machines selected in step 2, and pursue the simulation until reaching instability or stability conditions. If stability is met, stop; otherwise, determine the new stability margin and corresponding critical machines (to check whether they are the same or not with the previous simulation).
4. Run the transient stability control program to increase to zero this new (negative) margin. To this end, perform generation shifting in the usual way, from the remaining critical machines to non-critical machines.
5. The new, secure operating state results from the combination of the above generation rescheduling taken preventively, and the consideration of the critical machines, previously chosen to trip correctively.
6. Repeat the above steps 1 to 5 with each one of all possible patterns of critical machines to trip, until getting an operating condition, which realizes a good compromise between security and economics.

7. After the "optimal" number of machines to trip is determined, the settings of the special protection activating the generation tripping scheme in the plant is adapted so as to automatically disconnect these machines in the event of the contingency occurrence.

Application of OLEC technique to liberalized electricity markets

In the restructured electric industries, the operating condition of the system is set up in several cascading markets, which can be purely financial futures markets, used for expanding the system, or short-term markets for the physical delivery of electric energy. Generators scheduling is performed by bilateral contracts and auction markets that run one-day up to 1 hour ahead of real time operation. After this new "unit commitment" process, the system operator conducts real-time markets in order to balance system generation and load and solve transmission constraints or "congestions". The specific rules of these real-time markets vary from one system to another, but they share a common feature: generators submit their prices for being re-dispatched up or down (if necessary) and the operator performs this security rescheduling with the economic objective of minimizing its total cost.

Most of the current markets take into account thermal constraints only. The near-optimal preventive control techniques proposed in [9] provide valuable tools for including transient stability limits in the auction mechanism of the balancing market. Note that these techniques may call upon an OPF software, as advocated in [9], or be adapted to any auction market software currently in use.

In the context of optional balancing markets, an additional advantage of the near-optimal preventive control techniques is that they can perform transient stability control using only a sub-set of the critical machines [9]. This allows meeting requirements regarding transparency of operator's decisions and non-discriminatory access of all transactions to the transmission system.

Nevertheless, the examples described in the present paper show that, in some cases, the sole re-dispatch mechanism of the balancing market becomes very expensive. In such cases, the OLEC technique provides interesting alternatives, allowing considerable reduction of the power to re-dispatch preventively and hence of its cost.

Another interesting aspect of OLEC is that it can enhance significantly the security of the system by making economically possible its protection against the whole set of harmful contingencies, considered simultaneously.

OLEC is also helpful in adapting on-line the optimal number of generators to trip to the current system operating conditions, so as to minimize the imbalance between generation and load. Note that, depending on the amount of disconnected generation, this imbalance is generally compensated either by bringing on-line spinning reserve (in less severe cases), and/or by shedding load (in the most constraining cases). Hence, whenever necessary, i.e., if generation tripping is too important or generation rescheduling too difficult to realize, the amount of load to automatically shed in the emergency state should be assessed preventively by OLEC.

A final notice: other congestion management methods, like counter trading, can also be adapted to include transient stability constraints, using SIME-based information about critical machines' identification and corresponding amount of power shifting.

Contracts for system protection schemes

Installing system protection schemes is significantly easier in vertical utilities than in liberalized electric industries where, however, such schemes could be fully justified. Indeed, experience has always shown that system protection devices have a positive impact on the overall financial account of the electric utilities, besides improving power system dynamic performance. They allow operating the system under conditions very close to those established by economic considerations (minimum cost in traditional utilities, equilibrium of the auction market in restructured electric industries) while ensuring system stability, thus achieving a good compromise between economics and security.

In order to apply OLEC, the system operator can sign contracts with the companies owning the generating plants in which system protection schemes are installed. This type of contracts, which have already been implemented in some electricity markets [10], can also be used in other transient stability-constrained systems.

An advantage of using contracts for emergency control is that it allows mitigating considerably the preventive countermeasures and hence keeping almost unchanged the power system operating conditions established by the market; generally, the emergency control scheme remains inactive, since the triggering event does not occur often.

SIME-based adaptive emergency control

Converting a remedial scheme in an adaptive system protection is a very hard task, because their action should consider the **overall system dynamic behavior**. One of the solutions to this problem consists in using pre-calculated arming tables (computed off-line in the operation planning context) for updating the settings of the generation tripping device. Solutions to compute **on-line** the settings of the remedial scheme can be classified into the following two main approaches:

- System protection scheme (SPS) becomes response-based, and use (almost) instantaneous real measurements to assess system stability and adapt their control action depending on the current dynamics, after the contingency has actually occurred [11]
- System protection scheme remains as an event-based device, automatically triggered by system protections when a pre-selected contingency takes place, but their settings (like the amount of generators to shed and the time to perform the control), are updated by simulations performed on-line at the EMS (or other location) under changing system operating conditions, on a periodical basis [11]

SIME-based control is now able to perform, and combine, both types of system protection schemes against transient instabilities:

- E-SIME as a response-based system protection scheme.
- OLEC as the event-based system protection scheme.

This combination is described below.

Coupling E-SIME with OLEC

Generally speaking, closed-loop and open-loop controls have more or less complementary features and assets [12], [13]. Hence the idea of combining closed-loop with open-loop emergency control techniques. The idea is even more appealing when the two techniques rely on the same basic method.

Indeed, despite important assets, E-SIME needs some delay (say, 450 ms from the disturbance inception) before triggering the control action, and the larger this delay, the larger the generation shedding needed. This delay can even become fatal to the system integrity, if the contingency is very severe.

On the other hand, OLEC is likely to act much faster (say, 150 ms after the disturbance inception) since the automatic protection activating the generation tripping scheme uses only local measurements to detect the fault and act, in contrast to E-SIME, which- at least in principle- needs all machines' rotor angles and powers. But the suggested action may be incorrect, at least partly, given the uncertainties about the anticipated operating conditions.

Coupling the above two techniques may combine their advantages while avoiding part of their weaknesses, at least from a theoretical viewpoint. In short, this combination yields the following scenario of events.

• **At t_0**: disturbance inception.
• **At t_1 = 150 ms**: triggering the generation shedding pre-defined by OLEC.
• **At t_2 = 180 ms:** based on sets of real-time measurements (supposed to arrive every 20 ms): E-SIME predicts instability size (margin); time to instability (when the system will lose synchronism irrevocably in the absence of control action); CMs) and decides about control action (number of CMs to shed).
Further, E-SIME compares the above control action based on the measurements with the one decided by OLEC and already triggered 30 ms earlier, and:

- if E-SIME assesses the latter to be sufficient, it does not take any additional action but simply continuous monitoring the system, based on incoming sets of measurements;
- if, on the contrary, it deems the OLEC action insufficient, it predicts the system new transient stability status (new instability size and time to instability), given the action already triggered.

Note that the new time to instability is larger than the one assessed under the assumption of no OLEC action; hence, there is more time left to refine its assessment, if necessary, and/or to make the delay of 300 ms sufficient for preserving the system integrity.

Figure 5-3 sketches the main steps of the above procedure.

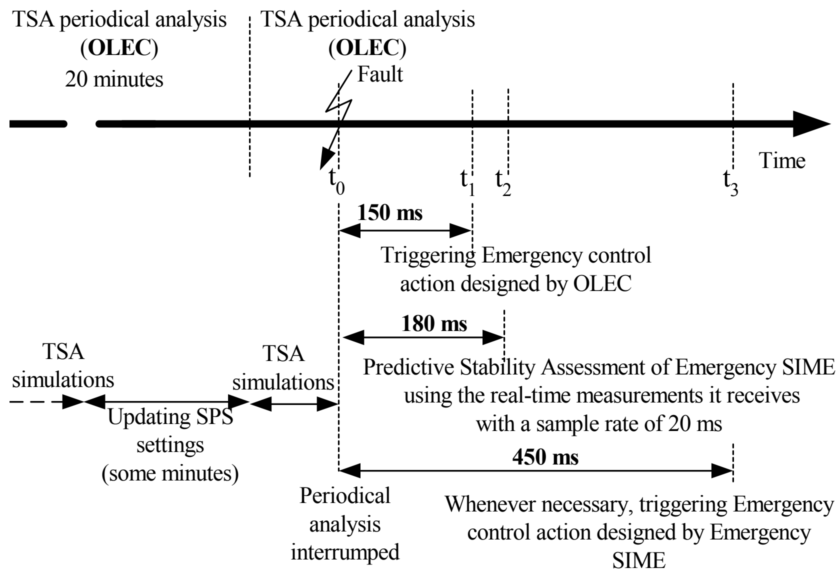

Figure 5-3 SIME-based emergency control actions against transient stability (Adapted from [13].)

5.4.2 Voltage stability assessment and control

PREVENTIVE CONTROL

Sensitivity analysis

Sensitivities computed from the Jacobian matrix of the load flow or long-term equilibrium equations have been used for a long time. Within the VSA context, sensitivities have been proposed as voltage stability indicators, although in practice the latter are not likely to be as meaningful as the power margins provided by ATCs.

A central contribution to sensitivity analysis has been provided by [14], where a general formula is obtained for the sensitivity of a loadability margin to parameters. It involves the left eigenvector relative to the zero eigenvalue of the Jacobian matrix computed at a saddle-node bifurcation point.

This formula was derived within the context of loadability limit computation. An extension to the analysis of post-contingency unstable scenarios was proposed in [15], which involves the computation of sensitivities along the system trajectory and eigenvector at the so-called *critical point*.

Another early approach to the diagnosis of voltage instability relies on the modal analysis of the reduced Jacobian of reactive power with respect to voltages [16]. Information is retrieved from eigenvectors or participation factors relative to real dominant eigenvalues. This approach can suggest instability modes at normal operating points. However, owing to nonlinearities, the analysis has to be performed at the saddle-node bifurcation or at the critical point [17], where the Jacobian has an (almost) zero eigenvalue. The corresponding eigenvector is included in the eigenvector of the unreduced Jacobian, which is preferred in order to exploit matrix sparsity.

The above two approaches identify the best remedial actions from the eigenvector of an (almost) zero eigenvalue. This, however, may suffer from two drawbacks. First, dominant eigenvalue computation methods may experience problems when the initial estimate of the dominant eigenvalue is not accurate enough. This is especially true when the loadability limit corresponds to a *switching point,* where a generator field current limit is imposed, in which case the real dominant eigenvalue jumps from a negative to a large positive value [18]. Second, in practice, voltages are often requested to stay above some thresholds (corresponding for instance to under-voltage tripping of equipments). In some cases, these minimum voltage limits can be more constraining than voltage stability limits. If so, the system response will be already unacceptable before the loadability limit is reached. At the last acceptable operating point, voltages are low but stable and the Jacobian eigenvalues are still on the stable side; hence, the eigenvector computation does not apply.

A unified approach that encompasses the low voltage, the zero eigenvalue and the switching loadability limits described above has been proposed in [19], where it is proposed to replace the eigenvector computation by a simple sensitivity calculation which provides very close results, but is non iterative and can still be computed when the system reaches low but stable voltages. This method is combined to time simulation and consists of:

- identifying bus ℓ that experiences the largest voltage drop (due to the load increase when computing loadability limits, or the contingency when performing contingency analysis);
- computing the sensitivities of the V_ℓ voltage at that bus with respect to the candidate controls $\mathbf{p}$ (which are most often bus power injections):

$$\frac{\partial V_\ell}{\partial \mathbf{p}} = \begin{bmatrix} \frac{\partial V_\ell}{\partial p_1} & \cdots & \frac{\partial V_\ell}{\partial p_n} \end{bmatrix}^T \tag{6}$$

- evaluating these sensitivities:
  - in voltage unstable situations: at the point of the trajectory where a Jacobian eigenvalue passes through zero (this is easily detected through sensitivities changing sign through infinity);
  - in low voltage situations: at the final point of the system evolution.

It can be shown that in voltage unstable cases, the proposed sensitivities computed near the loadability limit or the critical point, yield practically the same control ranking as the eigenvector-based formula [14] and can be substituted to the eigenvector to compute the sensitivity of the power margin to $\mathbf{p}$. In low but stable voltage cases, the information carried by sensitivities is also meaningful. Last but not least, the method is simple and reliable, since it is non-iterative and requires solving a single sparse linear system only.

Security constraints

An Optimal Power Flow can be used to optimally modify the controls $\mathbf{p}$ so as to restore power margins to a desired value M_d. Denoting by $M(\mathbf{p}^o)$ the margin corresponding to the current value

$\mathbf{p}^o$ of $\mathbf{p}$, the following inequality constraint can be embedded in an OPF:

$$\sum_{j=1}^{n} S_j \, \Delta p_j \quad \geq \quad M_d - M(\mathbf{p}^o)$$

where the sensitivities S_j are computed as outlined in the previous section and $\Delta p_j = p_j - p_j^o$ is the change in the j-th control variable. A constraint (13) is considered for each contingency with a margin below of somewhat above the threshold M_d. Further details and examples can be found in [19]. A similar formulation has been applied for the optimization of network autotransformer taps in order to maximize loadability margins in the presence of switching loadability limits [H].

Multiple (simultaneous) limits

Switching loadability limits occur when a sudden event, such as the activation of the over-excitation limiter of a generator, causes an immediate instability that prohibiting a further increase in system loading. Such limits can occur simultaneously which results in non-smooth loadability conditions, for which sensitivity formulas and other linearized indices cannot be used without further analysis. [20].

5.4.3 Improved Load Modeling

Loads play an important role in Voltage Stability. Many efforts have been devoted to collecting information about load behaviors and setting up appropriate models. However, work remains to be done in several directions

The effect of induction machine load (and generation in some special cases where simple squirrel cage machines are used for wind power generation) is causing significant concern for VSA analysis. QSS simulation can easily incorporate induction machines by adding a single torque equilibrium equation for each motor. Alternatively, aggregate load models can be used that incorporate motor and static loads in a parametric representation.

Motor stalling can be identified as a loss of short-term equilibrium and this can be further analyzed using the method outlined in Section 3.3 below.

Finally, better models are needed for representing both short and long-term behaviors of load aggregates fed through sub-transmission networks (i.e. the loads seen from the bulk transmission system). The idea of parametric model can be re-used while properly accounting for the losses in the sub-transmission network as well as for the load power restoration by the multiple load tap changers controlling distribution voltages.

A different, although somewhat related, issue is the representation of large wind parks in voltage security assessment. Studies are on the way to set up a model offering a good compromise between simplicity and accuracy.

Incorporation of Induction machine models in VSA

The effect of induction machine load (and generation in some special cases where simple squirrel cage machines are used for wind power generation) is causing significant concern for VSA analysis. On-line VSA can easily incorporate induction machines using equilibrium conditions as part of the QSS simulation. Possible short-term voltage instability in this case is identified as a loss of short-term equilibrium and this can be further analyzed using eigenvalue/vector techniques.

Alternatively aggregate load models can be used that incorporate motor and static loads in a parametric representation.

QSS SIMULATION IMPROVEMENTS AND EXTENSIONS

Coupling between QSS and detailed simulations

The QSS approximation is very appropriate for checking voltage security with respect to "normal" (typically N-1) contingencies [21]. When dealing with severe disturbances, expectedly the QSS model meets some limitations.

The first limitation lies in the implicit assumption that the neglected short-term dynamics are stable. After a large disturbance, the system may lose stability in the short-term time frame (within - say - the first 10 seconds after the disturbance) and hence never enter the long-term phase simulated under the QSS approximation.

The second limitation is linked to the discrete events. A large disturbance may trigger controls with great impact on the system long-term evolution (e.g. shunt compensation switching, under-frequency or under-voltage load shedding, etc.). Since the sequence of controls depend on the continuous dynamics, it might not be correctly identified from the simplified QSS model.

To deal with the above situations, a coupling between detailed and QSS simulation has been proposed in [22]. Detailed time simulation is used to analyze the short-term period following the simulated disturbance, detect possible instability and identify the discrete controls triggered. Next, QSS simulation is used to simulate the same time interval with the discrete controls imposed as external events before letting the system evolve as usual in the long term. Successful results have been obtained on the Hydro-Québec system, where it is going to be used in combination with the PSS/E software.

Extension to frequency dynamics

QSS simulation belongs to the family of long-term dynamic simulation methods. The QSS model extensively used in long-term voltage stability studies can be extended to incorporate the frequency dynamics that takes place over the same time scale. This extended QSS model relies on a common-frequency assumption. Its advantages, limitations and possible improvements are discussed in [23] where simulation results are provided on the Hydro-Québec system, in particular a comparison with full time scale simulation. Disturbances with an impact on either frequency or voltages are considered and the coupling between these two aspects of long-term dynamics is briefly discussed.

Diagnosis of QSS singularities

When the QSS equations stop having a solution, the simulation undergoes a singularity. Reference [24] proposes a method to identify which component(s) are responsible for the loss of equilibrium. The corresponding equations are identified using the Newton method with optimal multiplier. The method has been validated with respect to full time simulation, in cases where long-term voltage instability triggers loss of synchronism. The proposed method enhances the QSS time simulation at very low computational cost and can also help correcting model and/or operating point errors.

5.4.4 References

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