Preventive vs. Emergency Control of Power Systems

Louis Wehenkel and Mania Pavella

***Abstract–* A general approach to real-time transient stability control is described, yielding various complementary techniques: pure preventive, open loop emergency, and closed loop emergency controls. The organization of the resulting control schemes is then revisited in order to make it able to cover static and voltage security, in addition to transient stability. Distinct approaches for preventive and emergency operating conditions are advocated.**

***Index Terms–* Transient stability, preventive control, emergency control, OPF, integrated security control.**

1 Introduction

Power system security is more and more in conflict with economic and environmental requirements. Security control aims at making decisions in different time horizons so as to prevent the system from undesired situations, and in particular to avoid large catastrophic outages. Traditionally, security control has been divided in two main categories: preventive and emergency control.

In preventive security control, the objective is to prepare the system when it is still in normal operation, so as to make it able to face future (uncertain) events in a satisfactory way. In emergency control, the disturbing events have already occurred, and thus the objective becomes to control the dynamics of the system in such a way that consequences are minimized.

Preventive and emergency controls differ in many respects, among which we list the following [1]:

Types of control actions: generation rescheduling, network switching reactive compensation, sometimes load curtailment for preventive control; direct or indirect load shedding, generation shedding, shunt capacitor or reactor switching, network splitting for emergency control.

Uncertainty: in preventive control, the state of the system is well known but disturbances are uncertain; in emergency control, the disturbance is certain, but the state of the system is often only partially known; in both cases, dynamic behavior is uncertain.

Open versus closed loop: preventive control is generally of the open loop feed-forward type; emergency control may be closed loop, and hence more robust with respect to uncertainties.

In the past, many utilities have relied on preventive control in order to maintain system security at an acceptable level. In other words, while there are many emergency control schemes installed in reality, the objective has been to prevent these schemes as much as possible from operating, by imposing rather high objectives to preventive security control. As to any rule, there are exceptions: for example controlled generation shedding has been used extensively in North America to handle transient stability problems; in the same way, corrective control has been used in many systems as an alternative to preventive control in the context of thermal overload mitigation.

Nowadays, where the pressure is to increase trading and competition in the power system field, preventive security control is being considered as an impediment to competition; in turn, this breeds strong incentives to resort less on preventive control and more often on emergency control.

The objective of this paper is essentially twofold: first, to concentrate on transient stability control, both preventive and emergency, and describe a general methodology able to realize convenient tradeoffs between these two aspects; second, to suggest means of integrated security control, coordinating various types of security (static security, voltage and transient stability).

2 Emerging transient stability control techniques

Various generation rescheduling control techniques have recently been proposed, based on the general transient stability method called SIME [2]. This section describes three such techniques dealing respectively with preventive control, closed-loop emergency control, and open loop emergency control; this latter technique aims at mitigating control actions taken preventively with emergency actions triggered only after the threatening event has actually occurred.

In what follows, we briefly describe the basic SIME method, and then concentrate on the advocated control techniques.

2.1 SIME in Brief

2.1.1 Description

SIME (for SIngle-Machine Equivalent), is a hybrid direct–temporal method.

Basically, SIME replaces the dynamics of the multi-machine power system by that of a suitable One-Machine Infinite Bus

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(OMIB) system. By refreshing continuously the OMIB parameters and by assessing the OMIB stability via the equal-area criterion, SIME provides an as accurate transient stability assessment as the one provided by the multi-machine temporal information and, in addition, stability margins and critical machines. In other words, SIME preserves the features of the temporal description (flexibility with respect to power system modeling, accuracy of transient stability assessment, handling of any type of instability- first- or multi-swing, plant or inter-area mode), and, in addition, complements them with functionalities of paramount importance. One of them is the generation rescheduling based on the knowledge of stability margins and critical machines. Indeed, the amount of generation to shift depends on the size of the stability margin, and the generators from which to shift it are the so-called critical machines.

Depending upon whether the temporal information is provided by a Time-Domain (T-D) simulation program or by real-time measurements, the above methodology yields the "preventive" or the "emergency" SIME.

2.1.2 Preventive SIME

In short, the "preventive" SIME analyzes an unstable case by driving a T-D program as soon as the system enters its post-fault configuration. At each step of the T-D simulation, SIME transforms the multi-machine system furnished by this program into a suitable One-Machine Infinite Bus (OMIB) equivalent, defined by its angle δ, speed ω, mechanical power P_m, electrical power P_e and inertia coefficient M. (All OMIB parameters are derived from multi-machine system parameters and are therefore time-varying.) Further, SIME explores the OMIB dynamics by using the Equal-Area Criterion (EAC). The procedure stops as soon as the OMIB reaches the EAC ***instability conditions*** assessed by the closed-form expressions

$$P_a(t_u) = 0 \quad ; \quad \dot{P}_a(t_u) > 0 \qquad (1)$$

where, P_a is the OMIB accelerating power, difference between P_m and P_e, and t_u is the ***time to instability***: at this time the OMIB system loses synchronism, and the system machines split irrevocably into two groups: the group of "advanced machines" that are henceforth referred to as the "***critical machines***" (CMs), and the remaining ones, called the "***non-critical machines",*** (NMs)[1]. Thus, at t_u SIME determines:

the CMs, responsible of the system loss of synchronism, and the stability margin:

$$\eta_u = A_{dec} - A_{acc} = -\frac{1}{2} M \omega_u^2 \quad . \qquad (2)$$

Similar expressions are derived also for stable cases.

2.1.3 Emergency SIME (E-SIME)

Following a disturbance inception and its clearance, E-SIME aims at predicting the system transient stability behavior 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, rather than information provided by time-domain simulation. This is discussed below, in §2.4.

2.2 Principle of SIME-based transient stability control

To stabilize an unstable case, SIME uses the **size of instability (margin)**, **the critical machines,** and **suggestions for stabilization**. These suggestions are obtained by the interplay between OMIB–EAC (Equal-Area Criterion) and time-domain multi-machine representations, according to the following reasoning: stabilizing an unstable case consists of modifying the pre-or post-contingency conditions until the stability margin becomes zero. According to EAC, this implies increasing the decelerating area and/or decreasing the accelerating area of the OMIB δ-P representation. In turn, this may be achieved by decreasing the OMIB equivalent generation power. The amount of the OMIB generation decrease, ΔP_{OMIB}, is directly related to the margin η [2], [3]:

$$\eta = f(\Delta P_{OMIB.}). \qquad (3)$$

2.3 Preventive Control

2.3.1 Iterative stabilization procedure

It is shown that to keep the total consumption constant, the following multi-machine condition must be satisfied, when neglecting loses:

$$\Delta P_{OMIB} = \Delta P_C = \sum_{i \in CMs} \Delta P_{C_i} = -\Delta P_N = -\sum_{j \in NMs} \Delta P_{N_j} \qquad (4)$$

where ΔP_C and ΔP_N are the changes in the total power of the group of critical and non-critical machines, respectively.

Application of eqs (3) and (4) provides a first approximate value of ΔP_C that may be refined via a stabilization procedure, which is iterative since the margin variation with stability conditions is not perfectly linear. Nevertheless, in practice, the number of required iterations (margins) seldom exceeds 3 [3], [4].

2.3.2 Generation rescheduling patterns

Expression (4) suggests that there exist numerous patterns for distributing the total power change ΔP_N among non-critical machines, and whenever there are many critical machines, numerous patterns for distributing the total ΔP_C as well. The choice among various patterns may be dictated by various objectives, related to market or technical considerations.

In the absence of particular constraints or objectives, the total generation power could be distributed proportionally to the inertias of the machines. A more interesting solution consists of using an optimal power flow (OPF) program, as discussed below.

Finally, the above procedure may readily be adjusted for stabilizing many harmful contingencies simultaneously.

[1] The "advanced machines" are the CMs for up-swing instability phenomena, while for back-swing phenomena they become NMs.

2.3.3 Transient stability-constrained OPF

The Optimal Power Flow (OPF) uses control variables like active and reactive generation powers to achieve a good tradeoff between security and economics. More specifically, this program optimizes the power system operating condition with respect to a pre-specified objective (minimum operating cost, maximum power flow), while respecting generator limits and static security constraints (line power flows and bus voltage limits).

Several attempts have been made to imbed transient stability constraints within the OPF. According to the way of handling these constraints, they yielded two different approaches that below we call “global” and “sequential”.

Global approach. A time-domain (T-D) simulation is run. The power system transient stability model is converted into an algebraic set of equations for each time step of this simulation. The set of non-linear algebraic equations resulting from the whole T-D simulation is then included in the OPF as a stability constraint, forming a (generally huge) single non-linear programming problem (e.g., see [5], [6]).

Sequential approach. A T-D simulation is run. The transient stability constraints are directly converted into conventional constraints of a standard OPF program, e.g., active generation power. Hence, they do not affect the size of the power system model and the complexity of the OPF solution method. They can use any conventional OPF program.

Conceptually, the global approach is more appealing: it is supposed to handle the problem as a whole and, hence, to provide an optimal solution, which would be accepted as the reference by the system operator and the electric market participants. However, its practical feasibility has not yet been proven and it also raises a few objections: it lacks transparency about the salient parameters responsible for the system loss of synchronism, and the reasons underlying the advocated solution; it does not propose alternative solutions; it requires heavy computations due to the huge programming model; it generally uses simplified power system modeling in order to make the whole procedure compatible with acceptable computing requirements. Further, in very stressed systems where modeling details are necessary for assessing correctly power system limits, convergence problems can also arise because the additional constraints, modeled as a large set of algebraic equations, may be ill conditioned. Finally, increasing the number of constraints treated by the global function might result in overly conservative stability assessment.

As concerning the sequential approach, the main objection is that it cannot guarantee optimality.

In principle, the SIME-based transient stability-constrained techniques may comply with either of the above approaches. Figure 1 illustrates the use of the sequential approach, which, besides the above-mentioned advantages, may easily comply with market requirements thanks to the flexibility of choice among CMs and NMs on which generation can be re-dispatched.

2.4 Closed-loop emergency control

Closed-loop emergency control relies on the “Emergency SIME”, which was shortly mentioned in § 2.1.3.

The principle of the control technique remains the same with the preventive SIME, but its application has the following important differences ([2], [7], [8], [9]).

• The information about the multi-machine system is provided by real-time measurements rather than T-D simulations.

• The generation shift from critical machines is made here by shedding generation that is not compensated by a generation increase on non-critical machines (at least at the very first instants following the control action).

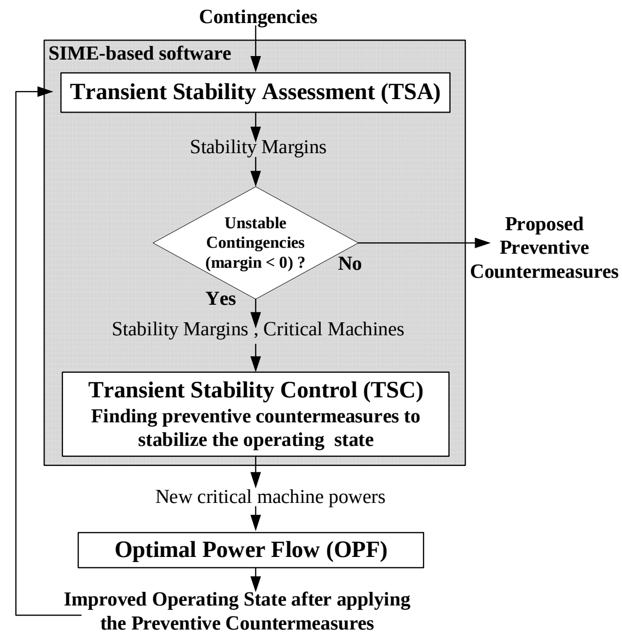

Fig. 1. Transient stability-constrained OPF (sequential approach)

• The system status (unstable margin and critical machines) is *predicted rather than assessed* along the system transient trajectory.

The resulting practical procedure is summarized below.

2.4.1 Predictive transient stability assessment

The prediction relies on real-time phasor measurements, acquired at regular time steps, t_i **’s,** and refreshed at the rate Δt_i . 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, using three successive data sets acquired for the three different times.

(iii) *Predicting instability:* to determine whether the OMIB reaches the unstable conditions (1).

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 the unstable angle δ_u, the corresponding time to instability, t_u , and the unstable margin expressed by (2).

(iv) *Validity test.* Observing that under given stability conditions, the value of the (negative) margin should be constant, whatever the time step, provides a handy validity test: it consists of pursuing the above computations until reaching an (almost) constant margin value.

2.4.2 Salient features

The method 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 or phasor measurements. 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 leads to 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.

2.4.3 Structure of the emergency control scheme

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 Fig. 2 covers the two first steps: prediction of instability, and of its size and critical machines. Block 3 takes care of the control actions i.e., of determining the number of generators to shed. Note that when the order of triggering the action has been sent, the method continues monitoring and controlling the system in a closed-loop fashion, until getting stabilization.

2.4.4 Discussion

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 [10].

The control is free from uncertainties about power system modeling, parameter values, operating condition, type and location of the contingency, since it relies on a (relatively small number of) purely real-time measurements.

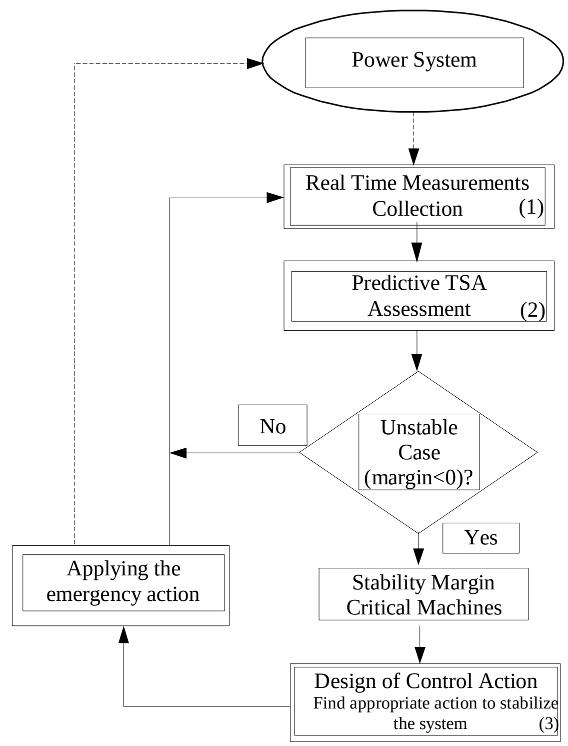

Fig. 2. Closed-loop transient stability emergency control: general framework

2.5 Open loop emergency control (OLEC)

This technique is a mixture of the preceding two techniques: from a methodological viewpoint, it is event driven and relies on transient stability simulations, like the preventive control technique, described in § 2.3; but its application uses generation tripping, like the emergency control technique.

The leading idea is to mitigate preventive actions (generation shifting) by complementing them with emergency actions (generation shedding) that would automatically be triggered only if the postulated contingency actually occurs. The technique relies on the assumption that (some of) the critical machines belong to a power plant equipped with a generation tripping scheme; therefore a certain number of units could be tripped in the emergency mode.

A detailed description of the technique and its variants may be found in [3], [4]. In short, it uses the preventive simulation procedure of §2.3, where, however, a variety of generation tripping patterns (including the delay of generation tripping and the number of critical machines to trip) are successively simulated, in order to get an operating condition that realizes a good compromise between security and economics. 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.

3. DISCUSSION

3.1 A pragmatic approach to integrated security control

3.1.1 Preventive mode security control

The main objective is to incorporate into a single decision support tool for on-line operation security criteria that ensure at the same time static and dynamic security with respect to a list of potentially harmful contingencies identified during the analysis stage. We propose to use the optimal power flow formulation as a generic approach to handle this problem.

More specifically, let CL-SS be a list of potentially harmful contingencies from the viewpoint of static security, CL-TS a list of such contingencies from the viewpoint of transient stability and CL-VS a list of potentially harmful contingencies from the viewpoint of voltage stability. Then, we can formulate an optimization problem incorporating the following constraints:

1. normal mode (i.e. preventive mode) power flow equations, equality and inequality constraints (voltage magnitudes in normal range and branch flows below permanent limit)
2. for each element in CL-SS a set of post-contingency power flow equations, equality and inequality constraints (voltage magnitudes in emergency range and branch flows below emergency state limit)
3. for each element in CL-TS a constraint on the total normal mode generation of the corresponding set of critical generators (e.g. derived by the preventive SIME method)
4. for each element in CL-VS one (or several) constraints on the normal mode active and reactive power injections sufficiently strong to ensure voltage stability with respect to that contingency (e.g. see [11] and [12] for such an approach).

For a given objective function (e.g. minimal deviation, minimal cost of reschedule), the resolution of such an optimal power flow problem can be handled by a conventional security constrained OPF. As long as the number of elements of CL-SS remains small, the CPU time required by a single run of such a tool is normally compatible with on-line requirements. Nevertheless, there is (obviously) no guarantee that the resulting rescheduled operating point exists (feasibility) and is simultaneously secure with respect to all three phenomena. Thus, in principle, it would be necessary to iterate the above resolution scheme according to the same principle as the one given in Figure 1, when handling security constraints only related to transient stability. And (obviously) there is also no guarantee that such an iterative process would eventually converge (in a reasonable number of iterations), and if yes, that the resulting new operating point would indeed be optimal.

We notice that the approach proposed relies on the availability of DSA tools able to express approximations to dynamic security regions in terms of pre-contingency parameters. The more accurate these approximations the better the resulting optimization. In particular, we believe that the proposed scheme is reasonable when combined with methods such as SIME and an appropriate VSA method.

3.1.2 Emergency mode security control

While in preventive mode it is necessary to combine into a single coherent decision making strategy the handling of all security constraints (because they may be conflicting), in emergency mode security control one can generally take advantage of the temporal decoupling of the different phenomena, since thermal problems are typically significantly slower than voltage collapses which in turn are typically much slower than loss of synchronism. Hence, the different emergency control schemes can operate independently from each other.

3.2 Limitations and further research needs

3.2.1 Arbitration between preventive and emergency control

A first limitation of the preceding approach is that it is not able to arbitrate between preventive and emergency control. More precisely the approach supposes that the contingencies and phenomena that must be treated in a preventive way are given a priori. However, from a rational point of view the fact that a certain security problem (or constraint) should be treated in preventive or in emergency mode actually depends on operating conditions (both electrical, economic, and meteorological). For example, if a certain harmful contingency becomes very likely (e.g. because of changing weather conditions), or if the cost of treating in preventive mode is negligible (e.g. because there is cheap load curtailment), then it makes probably more sense to handle it in preventive mode than in emergency mode. Thus, in principle the arbitration between preventive and emergency mode security control should be an output of (and not an input to) the security control decision support tools. However, there are intrinsic difficulties in achieving this objective mainly because of lack of data on probabilities of contingencies (as a function of on-line conditions) and difficulties to model the costs of interruptions, both of which would be required to allow for the simultaneous treatment of preventive and emergency mode security [1][13].

3.2.2 New control devices

New control devices such as variable series compensation, as well as more systematic use of interruptible load, can potentially make it easier to handle security in on-line operation. However, the analytical methods developed today, like SIME, VSA etc, do not take into account these possibilities. Thus, further research is needed in order to develop tools able to suggest how to use such devices.

3.2.3 Uncertainties

A major problem in large-scale systems is that of real-time information concerning the status of neighbor systems and the incorporation of this information into appropriate dynamic equivalents needed to carry out meaningful simulations and DSA computations in real-time. The unavailability of this information translates into modeling uncertainties, which should be taken into account in a conservative way. Here also, research and developments are necessary in order to reduce the amount of arbitrariness of security control [14].

4 Conclusion

This paper has pursued a twofold objective.

On the one hand, it has addressed the issue of real-time transient stability control, which has long been considered to be extremely problematic if at all feasible. Three different schemes have been advocated, able to encounter a variety of specific needs, depending on power systems specifics. It was shown that preventive control and its variant, the open loop emergency control, are mature enough and ready for implementation. Closed loop emergency control, on the other hand, is very much dependent on today's high tech; its implementation might therefore require further adjustments and strong incentives.

The second objective was an attempt towards integrated security control techniques, able to cover dynamic and static security aspects. It appeared that the software tools available today are able to achieve such integrated approaches.

Nevertheless, while from a theoretical viewpoint the above-advocated approaches are within reach, their realization depends on information about the system configuration, including generation status that the liberalized electricity markets seem reluctant to provide. And although such issues have not been addressed in this paper, these authors feel that blackouts will continue threatening the power systems, unless such information is made available, under the pressure of regulatory bodies in the States, Europe, and other continents.

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