REAL-TIME TRANSIENT STABILITY EMERGENCY CONTROL OF THE SOUTH-SOUTHEAST BRAZILIAN SYSTEM

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Abstract : A method is proposed for *during transients* emergency control which *predicts* the evolution of a system undergoing a major disturbance and, if loss of synchronism is anticipated decides control actions able to contain it. The method emanates from SIME, a hybrid time-domain – direct method originally designed for real-time preventive transient stability assessment and control. The devised "emergency SIME" has similar interesting features, namely, robustness, accuracy, speed - and also predictive capabilities. Besides, the emergency approach has some intrinsic advantages over the "preventive" approach, namely, it is free from modelling and/or parameter uncertainties (since it relies on real-time measurements rather than time-domain simulations), and it encounters the real stability problem (operating point and contingency scenario rather than base case solutions and list of plausible contingencies). The method is general with respect to power system configurations, types of generation and of controls. In this paper a generation shedding scheme is worked out and applied to the real-time monitoring of the Itaipu-Foz do Iguaçu corridor. It is shown that it can advantageously complement the existing automatic emergency control scheme.

Keywords : Emergency control; transient stability; SIME; generation shedding; real-time transient stability emergency control.

1 INTRODUCTION

Dynamic security assessment (DSA) has long been recognized to be an issue of great practical concern [Dy Liacco, 1979]. The recent deregulated practices make the need for effective DSA methods more urgent than ever.

What holds true for predictive DSA which deals with "what if" questions holds even more true for emergency DSA : today, emergency DSA becomes a necessity, given the trend to operate the systems increasingly closer to their limits, and given the difficulties in predicting the operating conditions and the troublesome contingencies likely to occur. But at the same time, emergency DSA is even more challenging than preventive one, particularly for transient stability, where the phenomena develop within few hundreds of milliseconds.

This paper deals with "during transients" emergency TSA and control (TSAC), i.e. with situations where the power system is actually undergoing a major disturbance. The purpose is to *predict during the transients the evolution of the system* and if necessary *to appraise and trigger control actions* so as to prevent its serious degradation; more specifically, the concern is to predict the system behaviour following a (major) disturbance by processing real-time measurements taken on the power system, and if instability is anticipated, to assess its degree of instability and decide proper control actions in time so as to prevent loss of synchronism.

Such a stringent objective raises hardware and software problems (e.g., see Centeno et al., 1993; Chang et al., 1993; Fouad et al., 1986; Prasetijo et al., 1996; Rovnyak et al., 1995; Takahashi et al., 1988; Kojima et al., 1997.)

This paper addresses the software problem. The derived method emanates from the "preventive SIME" initially developed in the context of preventive TSAC [Zhang et al.,1997a; Bettiol et al., 1998]. This "emergency SIME" was proposed quite recently [Zhang et al., 1997b]. It is revisited in this paper and further illustrated on a real-world problem namely, the transient stability monitoring of the Itaipu-Foz do Iguaçu corridor.

The paper is organized as follows. Section 2 outlines the emergency SIME. Section 3 describes the derived practical procedure in the particular case of a generation shedding scheme. Section 4 simulates the real-world example

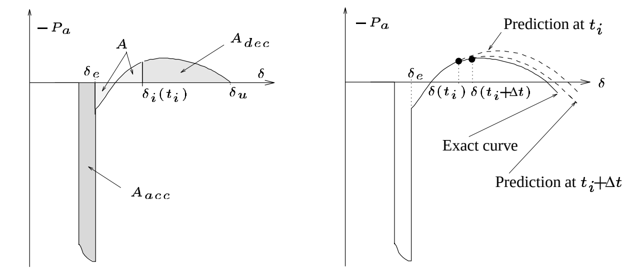


Figure 1 - OMIB P_a curves (Prediction technique)

of Itaipu's emergency control. Section 5 identifies three main classes of emergency control schemes. Section 6 draws conclusions. Appendix A describes SIME's essentials and formulation; the reader who is not familiar with SIME is kindly advised to start with this Appendix.

2 FOUNDATIONS OF THE EMERGENCY SIME

2.1 Problem statement

The "during-transients" emergency approach[1] rely on *real-time measurements* that it processes so as to provide a stability diagnostic *early enough before the system loses synchronism* (e.g. 250 ms ahead). To this end, it transforms the incoming multimachine power system measurements into those of an equivalent one-machine-infinite bus (OMIB) system, and calls upon the equal-area criterion to assess stability.

More precisely, the method aims to predict the stability of the system entering its post-fault configuration, i.e. *after* the disturbance inception and its clearance, using the multimachine data available at successive time samples Δt's (e.g., 1 sample per cycle). Thus, at each time sample, an OMIB analysis is performed to see whether the system keeps stable or it is driven to instability. The main tool for this analysis is the prediction of the OMIB $P_a - \delta$ curve, and hence the prediction of the unstable angle, δ_u, and corresponding stability margin (see the Appendix). This analysis is elaborated below.

2.2 Strategy for real-time stability assessment

The following two questions must be addressed : 1.- which are the most disturbed machines ? 2.- is the system driven to (in)stability and to what extent ? (i.e. what is the sign and size of the stability margin ?). The answers to these questions rely on the following steps, illustrated in Figs 1.

(i) At a time t_i short after the disturbance clearance, $(t_i \geq t_e + 2\Delta t)$ consider the incoming measurements at times $t_i - 2\Delta t$, $t_i - \Delta t$, and use Taylor series to predict the individual machine angles at some time ahead (e.g. 100 ms). Sort the machines in decreasing order of these angles and consider as candidate critical machines those advanced machines which are above the largest gap.

(ii) Construct the corresponding OMIB, determine its parameters $(\delta, \omega, \gamma, P_a)$ [2] from the corresponding parameters of the individual power plants at times $t_i - 2\Delta t$, $t_i - \Delta t$, t_i , and approximate the $P_a - \delta$ curve by solving the expression :

$$P_a(\delta) \;\approx\; a\delta^2 + b\delta + c \qquad (1)$$

for a, b, c at these times.

(iii) Solve eq. (1) to find $\delta_u > \delta(t_i)$ such that

$$P_a(\delta_u) \;=\; 0 \;\;,\;\; \dot{P}_a(\delta_u) > 0 \;\;. \qquad (2)$$

(iv) Compute the decelerating area, A_{dec2} , sketched in Fig. 2 :

$$A_{dec2} \;=\; -\int_{\delta(t_i)}^{\delta_u} P_a d\delta \qquad (3)$$

and, hence the stability margin, η , according to eqs (A.5)-(A.7); it comes :

$$\begin{aligned} \eta \;&=\; A_{dec} - A_{acc} \;=\; A_{dec2} - (A_{acc} - A) \\ &=\; A_{dec2} - \frac{1}{2} M\omega^2(t_i) \;. \end{aligned} \qquad (4)$$

(v) If η is found to be negative or close to zero, declare the system to be unstable and determine control actions (see §§ 2.3, 2.4).

(vi) Compute the *time to instability*, t_u , i.e. the time for the OMIB to reach its unstable angle, δ_u , i.e. to go unstable. This may be computed, for example, by using a Taylor series expansion of $\delta(t)$ about $\delta(t_i)$:

$$\delta_u \;=\; \delta(t_i) + \omega(t_i)\, t_u + \frac{1}{2}\gamma(t_i)\, t_u^2 \qquad (5)$$

and solving for t_u .

(vii) Acquire a new set of measurements and continue monitoring the system.

Remark

Obviously, the above predictive stability assessment relies on two main approximations.

- First, the OMIB used here might not necessarily be the critical OMIB which would be identified at t_u , i.e. when the OMIB actually reaches its unstable angle, δ_u ; however, it is likely to contain part of the most disturbed machines and certainly machines on which corrective action will effectively contribute to stabilize the system.
- Second, the $P_a - \delta$ curve relies on a measurement-based prediction – rather than accurate computation. Various extrapolation techniques may be used, different from the one described above. The least squares technique used in this paper shows to be particularly robust.

Further comments

[1] Here, the type of control provided by the emergency SIME is also called "during-transients" to emphasize that the method is activated *after* a disturbance inception and its clearance, and that the remedial actions are appraised and devised on-line. Therefore, in order to be effective, the method must be ahead of real-time.

[2] Actually, eq. (A.4) shows that when the OMIB inertia coefficient is known (i.e. when the machines inertia coefficients are stored), P_a may be deduced from γ .

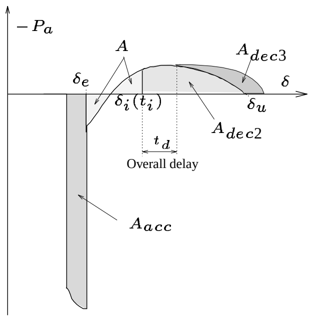


Figure 2 - Principle of emergency control

1.- Computationally, the above strategy is extraordinarily unexpensive and fast; indeed, at each time sample, it merely requires (a) the solution of the individual Taylor series and OMIB identification; (b) computation of the OMIB parameters (see eqs (A.1) to (A.3), and of the P_a curve (1)); (c) its solution (2); (d) computation of the margin (4). Obviously, all these computations require only fractions of ms.

2.- It may happen that the largest gap does not appear clearly enough at the beginning of the post-fault transients, thus leading to an unclear diagnostic. However, in such a case instability is likely to develop rather slowly; hence, time will be available to continue monitoring until the phenomena become clearer.

3.- According to our experience (see also the example in Section 2), a case which from the very first time instants $(t_i - 2\Delta t$ to $t_i)$ yields a stable margin may actually be unstable. It is therefore advisable to continue monitoring the system for $t_i + \Delta t, \ldots,$ for about one second before declaring it definitely stable.

4.- With reference to eq. (4), observe that for given clearing time t_e the margin η should be constant whatever the time t_i. Therefore the margin at successive t_i's should converge to an (almost) constant value; this may be used to assess the accuracy of the $P_a - \delta$ curve computation.

5. The above developments assume that the individual power plant variables may be obtained by synchronized phasor measurement devices placed at each power plant together with some local processing power to determine generator angles, speeds and accelerations.

2.3 Devising emergency control actions

For negative margins, the question of concern is : which corrective actions should be taken to satisfactorily stabilize the system ?

To answer this question, first notice that a negative margin means that the integral term in eq. (3) (area denoted A_{dec2} in Fig. 2) is not large enough : according to eq. (4) and Fig. 2, a straightforward suggestion for stabilizing the system is to increase this area by increasing the decelerating power so as to get

$$A_{dec3} + A_{dec2} = \frac{1}{2} M\omega_i^2 \quad . \qquad (6)$$

Actually, for obvious security reasons it is advisable to design A_{dec3} larger than suggested by eq. (6) :

$$A_{dec3} > \frac{1}{2} M\omega_i^2 - A_{dec2} \quad . \qquad (7)$$

Further, observe that, as sketched in Fig. 2, there is always an additional time delay t_d before the corrective action is triggered; it corresponds to the sum of three terms, viz. the time needed to receive the real-time measurements[3], the time to transmit the order to the power plant and the time to apply the corrective action. Observe that the longer the time delay, the larger the size of the corrective action (e.g., amount of mechanical power to be shed). Figure 2 suggests that the size of the corrective action needed increases more than linearly with the delay time : the decreasing slope of the $(-P_a)$ curve explains this non-linearity.

Existence of this delay makes also more difficult the handling of real-time measurements when designing control actions. Indeed, just after the corrective action has been taken, the incoming measurements refer to the uncontrolled system, while what actually matters is the behaviour of the controlled system. This issue is addressed below.

2.4 Generation shedding assessment

The general procedure of § 2.3 is applied here to the particular case of generation shedding. The generators to be shed are chosen among those belonging to the critical cluster, as identified in § 2.2. Hence, the concern is to appraise the amount of generation to be shed so as to stabilize the system by increasing the decelerating area according to the general eq. (6) and Fig. 2. Subsequently, i.e. after the corresponding control order has been sent to the generator plant, it is important to continue refining the assessment of area A_{dec3} using new real-time measurements. The purpose is to assess whether the generation shedding already determined is indeed sufficient or, otherwise, how much additional generation should be shed. Obviously, because of the transmission delays, one should anticipate the changes introduced by the control, based on information gathered prior to this control. As will be seen, this prediction is possible with good accuracy and straightforward computations.

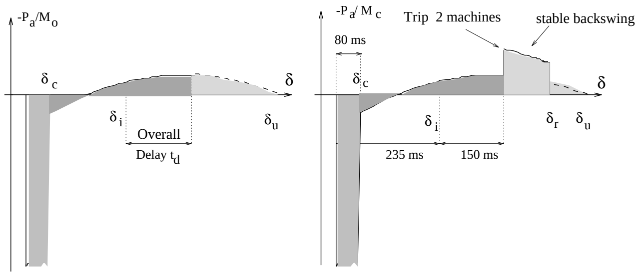
To determine how many generators to shed, we will set up an approximation of the margin in terms of the number of generators shed and solve for the latter so as to yield a positive margin. Figures 3 schematically illustrate the $P_a - \delta$ curves of the original (or) and controlled (c) system; they correspond to the real-world example presented in Section 4.

Let us denote by $M_{or} = \frac{M_{C_{or}} M_{B_{or}}}{M_{C_{or}} + M_{B_{or}}}$ the equivalent OMIB inertia in the original system (to distinguish it from the system after generation shedding) and η_{or} its margin computed at time t according to eqs. (3) and (4), which may also be rewritten as follows

$$\eta_{\rm or} = -\frac{1}{2}\mathrm{M_{or}}\omega_{\rm or}^2 - \mathrm{M_{or}}\int_{\delta_{\rm or}}^{\delta_{\rm uor}} \left[\frac{\mathrm{P_{mC_{or}}} - \mathrm{P_{eC_{or}}}}{\mathrm{M_{C_{or}}}} - \frac{\mathrm{P_{mB_{or}}} - \mathrm{P_{eB_{or}}}}{\mathrm{M_{B_{or}}}}\right] d\delta. \qquad (8)$$

Note that the term $\frac{1}{2}M_{or}\omega_{or}^2$ denotes the kinetic energy that the system will have at time t, when the generation

[3]since measurements concerning the system at time t_i are received with some delay



(a) Original system (8 mach. at Itaipu) (b) Controlled system (6 mach. at Itaipu)

Figure 3 - Generation shedding emergency control

shedding operation is supposed to take place. It may be computed according to the formula (A.7) and yields :

$$\frac{1}{2}\,M\,[\omega_{or}(t)]^2 \;=\; -\,\frac{1}{2}\,M\,[\omega(t_i)]^2 + \int_{\delta_c}^{\delta(t)} P_a d\delta \quad (9)$$

where P_a is computed via the prediction formula (1).

Angle δ at this time instant is also predicted from the last measurements by a Taylor series expansion of the OMIB trajectory.

Denoting by

$$M_c = \frac{M_{C_c} M_{B_c}}{M_{C_c} + M_{B_c}}$$

the equivalent OMIB inertia of the controlled system after shedding of some machines, a similar equation holds for its margin η_c, supposing that generation shedding will take place at time t :

$$\eta_c \;=\; -\frac{1}{2}M_c\omega_c^2 - M_c\int_{\delta_c}^{\delta_{u_c}} \left[\frac{P_{mC_c}-P_{eC_c}}{M_{C_c}} - \frac{P_{mB_c}-P_{eB_c}}{M_{B_c}}\right] d\delta \quad (10)$$

Since the strategy consists of shedding some of the relevant machines,

$$M_{C_c} = X M_{C_{or}} \text{ and } M_{B_c} = M_{B_{or}}\;, \qquad (11)$$

where $X < 1$ denotes the proportion of relevant machines remaining in operation.

Thus, the generation shedding technique amounts to determining the value of X which cancels out η_c . Now, note that in order to predict the value of η_c for a given number of machines shed, we make the following assumptions :

$$P_{mC_c} \;=\; X P_{mC_{or}} \;;\; P_{mB_c} \;=\; P_{mB_{or}} \qquad (12)$$
$$P_{eC_c} \;=\; P_{eC_{or}} \;;\; P_{eB_c} \;=\; P_{eB_{or}} \qquad (13)$$

Eqs (12) merely assume that the mechanical powers of the individual machines are not affected by the generation shedding, during the short time frame considered. Eqs (13) assume that the remaining machines will take over the electrical power initially generated, which amounts to neglecting the increase in the equivalent transient and transformer reactances, thus leading to optimistic errors; if the number of generators shed is small with respect to the total number in operation and if the transmission lines are long, this approximation error will however be negligible.

Thus the procedure to determine the number of generators to shed consists of computing η_c (eq. (10) to (13)) for decreasing numbers of generators in the controlled system.

Another possibility is provided by the direct computation described below.

2.5 Direct computation of the number of machines to shed

The following assumptions allow deriving a formula of the controlled system margin η_c as an analytical expression of X :

$$\omega_c \;=\; \omega_{or} \;;\; \delta_c \;=\; \delta_{or} \qquad (14)$$
$$\delta_{u_c} \;=\; \delta_{u_{or}}\;. \qquad (15)$$

Indeed, with assumptions (11)-(15), eq. (10) may be rewritten as

$$\eta_c \;=\; \frac{M_c}{M_{or}}\eta_{or} + M_c\int_{\delta}^{\delta_{u_{or}}} \frac{1-X}{X}\frac{P_{eC_{or}}}{M_{C_{or}}} d\delta\;. \quad (16)$$

Solving X in the latter equation for $\eta_c \geq 0$ yields

$$X \;\leq\; \frac{\int_{\delta}^{\delta_{u_{or}}} \frac{P_{eC_{or}}}{M_{C_{or}}} d\delta}{\int_{\delta}^{\delta_{u_{or}}} \frac{P_{eC_{or}}}{M_{C_{or}}} d\delta - \frac{\eta_{or}}{M_{or}}}. \qquad (17)$$

Of course in practice only an integer number of generators may be shed.

Notice that assumptions (14) imply that the critical generators are coherent which is generally valid. Assumption (15), on the other hand, is more questionable, since eqs (12-13) imply that $\delta_{u_c} > \delta_{u_{or}}$ (see Fig. 3). Thus eq. (16) essentially underestimates the benefit of shedding. Similarly, eqs (14) lead to underestimating the benefit of control actions.

Comment

While the stability prediction step of the original system requires only information about machine inertias, angles, speeds and accelerations, the generation shedding application requires additional information concerning the electrical and mechanical powers of the machines.

3 PRACTICAL PROCEDURE AND RELATED CONCERNS

This section gives a detailed description of the practical procedure resulting from the previous developments. Its purpose is to clarify and make easier the understanding of the method's application to the real-world example described in next section.

3.1 Notation related to various times

t_e	:	fault clearing time, i.e. time when the system enters its post-fault configuration. In case the contingency comprises successive actions, t_e denotes the end of the last action.
t_i	:	time instant where the system stability is predicted; for example, where it is found to be unstable, i.e. where conditions (2) are reached (cfr to §§ 2.2 and 3.3 below)
t_d	:	time delay between t_i and the moment the corrective action is triggered :
t_d	=	$t_{d_1} + t_{d_2} + t_{d_3}$ where
t_{d_1}	:	time needed to receive the real-time measurements [4]
t_{d_2}	:	time needed to transmit the order to the substation [5]
t_{d_3}	:	time needed to apply the corrective action (e.g., 50 ms)
t	=	$t_i + t_d$
Δt	:	observation rate, i.e. rate at which the measurements are collected (e.g., $\Delta t = 1$ cycle $\approx$ 17 ms).
δ_e	=	$\delta(t_e)$
δ_i	=	$\delta(t_i)$

3.2 General notation

Parameters δ , ω , γ , P_a , P_e , P_m , M denote respectively OMIB rotor angle, speed, acceleration, accelerating power, electrical power, mechanical power and inertia coefficient.

Suffix C (resp. B) refers to the mode of machines' separation into the critical (resp. backward) cluster and the corresponding relevant (resp. backward) machines.

Suffix i denotes parameter values (δ_i , ω_i , etc) at $t = t_i$.

Suffix u stands for "unstable" : unstable angle, δ_u , time to instability, t_u , reached when conditions (2) are met.

Suffices or and c refer to parameter values at $t = t_i + t_d$ where the corrective action is triggered :
or stands for "original" and refers to parameter values before control
c stands for "controlled" and refers to parameter values after control

Suffix uor (uc) refers to the unstable value of angle or speed of the original (controlled) OMIB.

3.3 General procedure

The main steps of the emergency SIME can be summarized as follows.

1. OMIB identification :

   Prediction of the individual machines at some time (e.g. 100 ms) ahead, using Taylor series and multimachine measurements collected at times t'_e , $t'_e + \Delta t$, $t'_e + 2\Delta t$ (where $t'_e = t_e + \epsilon$ denotes a time slightly larger than the clearing time). Continue as in (i) of § 2.2 to identify the mode of machines' separation and hence the corresponding OMIB structure.

2. Prediction of the P_a vs δ curve :

   proceed according to (ii) of § 2.2.

3. Computation of δ_u :

   proceed according to (iii) of § 2.2.

4. Computation of η :

   proceed according to (iv) of § 2.2.

5. Assessment of the number of generators to shed :

   apply eq. (17) to compute X ; consider only integer numbers of generators. In this expression :

   δ , i.e. $\delta(t_i + t_d)$ is obtained by a first order Taylor series expansion about $\delta(t_i)$

   η_{or} is computed via eq. (8) where $M_{or}\omega_{or}^2 = M_{or}[\omega_{or}(t)]^2$ is computed according to eq. (9), given the prediction formula (1)

   P_{eCor} is computed via a prediction formula similar to (1)

6. Checking the accuracy of η :

   repeat above steps (1) to (4) for successive t_i's to check whether the successive η values converge to a constant, as they should (see Comment # 4 of § 2.2), or to continue further.

7. Checking the effectiveness of the corrective action : similarly, repeat step 5 with refreshed parameter values to assess whether the corrective action (generation shedding) has indeed stabilized enough the power system or whether to shed more generators.

4 REAL-WORLD EXAMPLE

4.1 Power system description

The generation shedding scheme proposed in the previous section is illustrated on the South-Southeast Brazilian system. This system comprises 63 machines, 1,180 busses and 1,962 lines; it is modelled in its usual detailed way. The generation shedding scheme is applied to the Itaipu transmission system (there are 8 machines of 700 MW, at the 60 Hz side of Itaipu), whose prefault topology is portrayed in Fig. 4.

This system is equipped with automatic control devices. Their objective is to avoid overloads larger than 50 % on line(s)/transformer(s) resulting from the loss (opening) of other line(s)/transformer(s) following an important disturbance. The order for corrective action is sent by carrier, and consists of disconnecting "n" machines at the 60 Hz power plant of Itaipu. (n should not exceed 5 so as to ensure a minimum of 3 machines in service). The order is triggered 150 ms after the fault initiation, i.e. 70 ms after the fault clearance (20 ms for the order to reach Itaipu and 50 ms for the control action).

[4]since measurements concerning the system at time t_i are received with some delay (e.g., 50 ms).

[5]This delay vanishes when the measurements are collected at (or very close to) the substitution of concern.

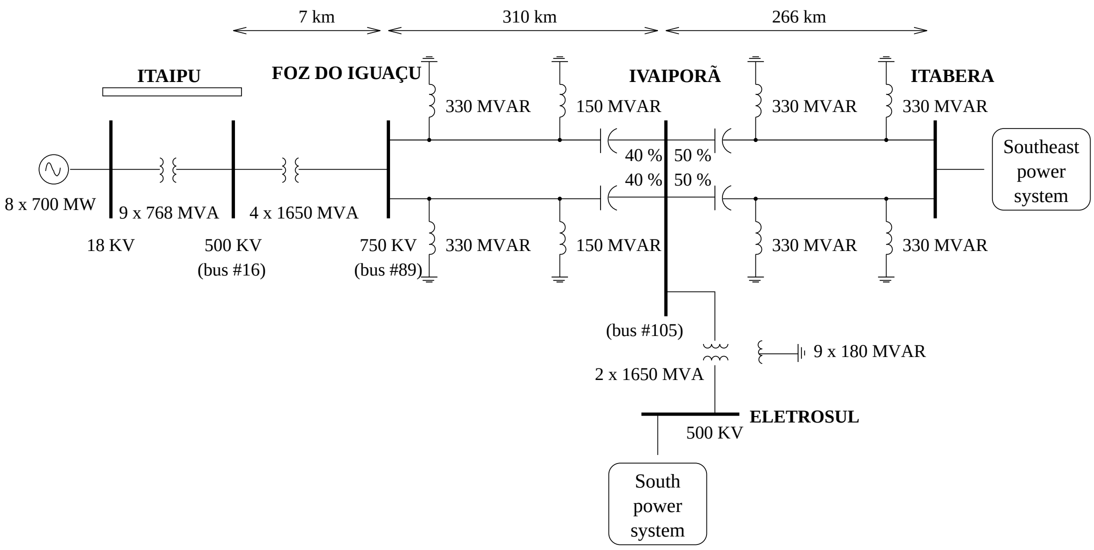


Figure 4 - Topology of the Itaipu's transmission system (60 Hz)

4.2 Simulations description

For want of real-world measurements, the emergency SIME is illustrated on the basis of time-domain simulations using the ST-600 program of Hydro-Québec [Valette et al., 1987]. Real-time measurements are thus "artificially" created. To ease the description, the acquisition of these measurements is supposed to have an observation rate of 20 ms, which is larger than one sample per cycle mentioned earlier in the paper.

The considered contingency consists of a three-phase short-circuit (3ΦSC), applied either at bus # 16 or at bus # 89.

4.3 Simulation results

Two cases are simulated and reported below. The first refers to the application of the "pure" emergency SIME scheme applied to a 3ΦSC at bus # 16; the second to a "hybrid" emergency scheme applied to a 3ΦSC at bus # 89.

4.3.1 3ΦSC at bus # 16

This 3ΦSC is supposed to be cleared at $t_e = 80$ ms by opening of one line connecting buses 16-89.

The first set of measurements is supposed to be acquired at 95 ms, followed by sets acquired every 20 ms : 115, 135, 155.

1.- A second order Taylor series expansion of the multi-machine swing curves about 155 ms gives a first a critical cluster of 62 machines; but the following expansions about 175, 195 , etc. identify the critical cluster to be composed of the 8 machines at Itaipu.

2.- Using the measurement sets acquired every 20 ms and the resulting OMIB at $t_i = 155, 175, \ldots$, the $P_a(\delta)$ curve is predicted and therefrom the parameters δ_u , t_u , η according to the procedure of § 2.2, summarized in § 3.3.

Table 1 gathers the results obtained from $t_i = 155$ ms up to 435 ms. It conveys the following information.

(i) At $t_i = 235$ ms , the η value shows to have been stabilized and therefore the $P_a(\delta)$ prediction to be reliable. Hence, it is decided to shed generation at Itapu in order to cancel the negative margin. This generation is found to amount to "1.4" machines. Hence, it is decided to shed 2 machines. The control decided at 235 ms is supposed to be triggered at 150 ms later, i.e. at 385 ms ($t_d = 150$ ms , with $t_{d1} = t_{d2} = t_{d3} = 50$ ms) .

(ii) Hence, from $t_i = 255$ ms on, column 6 provides the predicted value of the margin obtained after shedding 2 out of the 8 machines at Itaipu, i.e., describes the actual method's monitoring. On the other hand, information of columns 2 to 5 is still reported, essentially for illustration.

(iii) To summarize, the emergency SIME was able to stabilize the (otherwise unstable) stability case by shedding 2 out of the 8 machines of Itapu. The control action was taken at 385 ms after the contingency inception, i.e. 305 ms after its clearance. Note that this time is smaller than the time to instability, which amounts to about 580 ms. Note also that the whole procedure would have been slightly faster if the measurements sampling was of 1 cycle (≈ 17 ms).

Finally we mention that the CCT of this contingency is found to be of 72 ms (i.e. slightly smaller than the as-

Table 1 - Transient stability assessment and control by SIME

1	2	3	4	5	6
t_i (ms)	δ_u (rad.)	t_u (ms)	η/M (rad/sec)^2	CMs Nr	η/M after shedding
155	/	/	> 0	62	/
175	2.08	743	−0.54	8	/
195	2.07	727	−0.58	8	/
215	1.96	596	−1.21	8	/
235	1.96	591	−1.23	8	/
255	1.95	585	−1.28	8	1.82
275	1.93	576	−1.34	8	1.79
295	1.93	575	−1.34	8	1.73
315	1.93	571	−1.35	8	1.74
335	1.93	572	−1.41	8	1.78
355	1.93	572	−1.41	8	1.72
375	1.94	579	−1.35	8	1.78

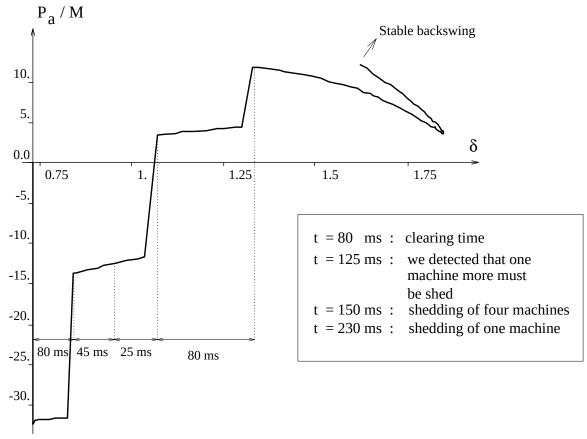


Figure 5 - Chronology of successive control actions

sumed clearing time of 80 ms.)

4.3.2 3ΦSC at bus # 89

This contingency is supposed to be cleared at $t_e = 80$ ms by opening line 89-105. Note that the minimum clearing time that actually could be realized is about 42 ms (2.5 cycles).

The generation shedding device actually implemented at Itaipu to face this contingency consists of shedding 5 machines; the action is taken 70 ms after the line opening (20 ms are needed for data transmission and 50 ms to trigger the action). This important amount of generation shedding is justified by the extreme severity of this contingency.

Obviously, the "pure" emergency SIME scheme could not stabilize such a violent instability, since its action could not be triggered fast enough. Therefore the purpose here was to find the minimum number of machines to shed at $t = 80 + 70 = 150$ ms . The following simulation results are obtained with three different (intervals of) clearing times and different number of machines (n) shed.

- $t_e = 80$ ms
  - $n = 3$ shed at $80 + 70 = 150$ ms : the emergency SIME shows that 3 more machines should be shed subsequendtly, which is not an acceptable solution
  - $n = 4$ shed at 150 ms : the emergency SIME shows that shedding 1 more generator later on may stabilize the system, provided that t_d decreases to 125 ms, which would imply a decentralized control scheme (i.e. a local control at Itaipu). Figure 5 describes the sequence of events. Note that M denotes the OMIB inertia coefficient; its value changes every time the number of the machines of the remaining critical cluster changes.
- $t_e \in [55, 80[$ ms : shedding 4 machines after 150 ms plus one more later on may stabilize the system.
- $t_e \in [0, 55[$ ms : stabilization becomes possible by shedding 4 generators at 150 ms after the disturbance.

In summary, this series of simulations shows that if the contingency can be cleared as early as 54 ms after its inception, the system stabilization may be realized by shedding 4 (instead of 5) generators. The "economy" of 1 generator with respect to the actual automatic shedding procedure is made possible thanks to the emergency SIME and its guarantee to monitor the system in a closed loop fashion.

5 On types of emergency control schemes

Various emergency schemes may be thought of, depending in particular upon the very type of corrective action, the type of instability detection, and the type of decision making/taking. Observe, however, that emergency control is generally a last resort action aiming to protect particularly important parts of a power system (e.g., large hydro-electric generation stations, corridors transferring important amounts of power, etc.). Hence, it is likely that the very type of corrective actions is predetermined and pre-installed. Thus, generally, what has to be assessed is whether and how much of this action to take.

With this observation in mind, one may distinguish the following three broad types of emergency control schemes.

First, the "pure" emergency scheme, where the instability detection, the decision for control and the corrective action triggering are all decided in the during-transients period, after a disturbance has actually occurred and (hopefully) cleared. This scheme relies on real-time measurements only.

Second, the "hybrid" emergency scheme where the detection is done in the during-transients period on the basis of real-time measurements, but the size of the corrective action is pre-decided on the basis of simulations performed in the preventive mode [Kundur, 1997].

Finally, the "off-line emergency scheme" which is designed and taken prior to the actual disturbance inception, on the basis of preventive transient stability assessment and control.

The "pure" during-transients scheme is probably the most economic; but it is also the most difficult to design and less fast to execute. The pure off-line emergency scheme has opposite features.

The emergency SIME described in this paper succeeds in designing a "pure", during-transients transient stability assessment and control scheme : it relies on real-time measurements only; it is contingency independent, in that the contingency influence (occurrence and nature) is implicitly included in the real-time measurements; it provides a closed-loop control. These are assets of paramount importance. As a counterpart, to be effective, the method implies stringent hardware requirements; however, it is anticipated that such hardware concerns can be tackled by existing facilities, or at least by facilities feasible with today's technology; as it often happens, they may become available provided that the method showns to be convincingly interesting, i.e. able to encounter important practical needs.

Admittedly, the method is still in its infance and many aspects should be further investigated and alternatives assessed, in particular the local vs global alternative. The latter scheme relies on the complete set of measurements, collected from all power stations, as is considered in this paper. This scheme is likely to be more accurate than local schemes but also more demanding in hardware facilities and slower to apply (because of the increased delays in collecting measurements); hence it is more expensive, since being activated later it requires more drastic corrective actions. It could even be uneffective in very severe instability cases (see, for example § 4.3.2). On the other hand, local schemes might be more attractive from a pragmatic engineering point of view; but they have still to be devised. In particular, the "area of concern" for a given type of local emergency control should be properly predefined, and substitutes for the information concerning the "outside area" should be designed. These and many other issues are certainly worth to explore. It is anticipated that SIME, thanks to its one-machine representation is likely to overcome the difficulties encountered during this exploration.

6 CONCLUSION

The emergency SIME scheme was investigated and its performances were checked in the particular case of the Itaipu-Foz-do-Iguaçu corridor.

This emergency SIME scheme was shown to have specific, intrinsic features; in particular, it relies on real-time measurements only which free it from system modelling and parameters uncertainties, and from the necessity to identify the type, location and clearing scenario of the contingency; it is extraordinarily fast which is a necessary condition for stabilizing the system in fractions of a second; it has robust predictive capabilities, both for predicting early enough the system loss of synchronism and for monitoring the controlled system relying on measurements acquired before the actual triggering of this control. It is therefore robust enough to self-controlling possible inaccuracies, in a closed-loop fashion.

The application of the emergency SIME to the Itaipu site was shown to provide effective control when used alone as well as in combination with a pre-designed control scheme.

This first application was concerned with generation shedding schemes. The obtained results are quite promising and encourage further research effort to refine developments and extend the method to other types of control.

APPENDIX : SIME's FUNDAMENTALS AND FORMULATION[6]

A.1 Principle

SIME relies on the conjecture that however complex, the loss of synchronism of a power system originates from the irrevocable separation of its machines into two groups. Accordingly, it replaces these groups by successively a two-machine then a one-machine infinite bus (OMIB) system properly identified. The trajectory of this latter is computed from the multimachine trajectories. Its stability is assessed using the equal-area criterion and the derived stability margin, defined as the excess of the decelerating over the accelerating area (see below, § A.4).

[6]The method is extensively described in [Zhang et al., 1997a, 1998].

A.2 Critical machines and resulting OMIB

On an unstable multimachinetrajectory, the identification of the machines' mode of separation uses the following pattern : (i) at each time step, consider the post-fault time evolution of the system machines; (ii) sort these machines in decreasing order of their rotor angles, identify the largest angular deviation (largest "gap") between any two adjacent machines thus sorted, and consider the *candidate* critical machines to be those which are "above this largest gap"; (iii) compute the corresponding candidate critical OMIB's parameters as explained in § A.3; (iv) stop the procedure as soon as the candidate OMIB reaches its unstable angle δ_u (defined in § A.4 and Fig. A.1) and declare it to be the actual "critical OMIB". Figure A.1 (a) describes this procedure.

A.3 OMIB parameters

Let C denote the group of critical machines and B that of the remaining (or backward) machines. The corresponding OMIB parameters are readily computed as follows.

(i) Transform the two clusters into two equivalent machines, using their corresponding partial center of angle. E.g., for cluster C this results in

$$\delta_C(t) \stackrel{\triangle}{=} M_C^{-1} \sum_{k\in C} M_k \delta_k(t) \ \text{ with } \ M_C = \sum_{k\in C} M_k \quad (A.1)$$

where M_k denotes the inertia coefficient of machine k. Similar expressions hold for cluster B and angle δ_B.

(ii) Reduce this two-machine system into an equivalent OMIB system whose rotor angle is defined by

$$\delta(t) \stackrel{\triangle}{=} \delta_C(t) - \delta_B(t) \quad (A.2)$$

and whose rotor speed, ω, and acceleration, γ, are defined in a similar way.

(iii) Define the equivalent OMIB mechanical power by

$$P_m(t) = M\left(M_C^{-1} P_{mC}(t) - M_B^{-1} P_{mB}(t)\right) \quad (A.3)$$

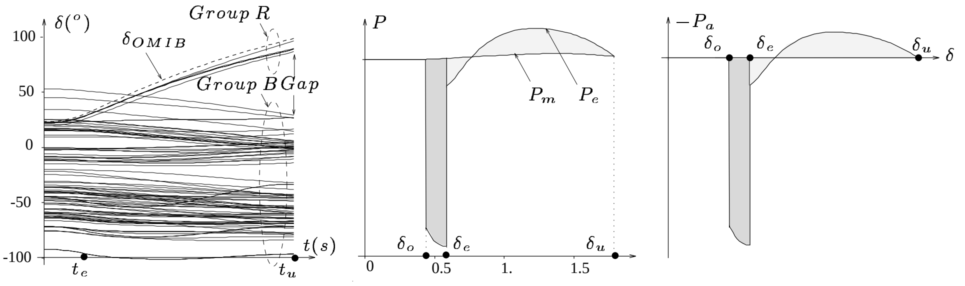
where $M = M_C M_B / (M_C + M_B)$ is the equivalent OMIB inertia coefficient and $P_{mC}(t)$ (resp. $P_{mB}(t)$) stands for $\sum_{k\in C} P_{mk}(t)$ (resp. $\sum_{k\in B} P_{mk}(t)$). The OMIB electrical power P_e takes on a similar expression. Note that all individual machines mechanical (P_{mk}'s) and electrical (P_{ek}'s) powers are considered to be free from any simplifying assumption (they are provided at each time, and so are the derived OMIB powers $P_m(t)$, $P_e(t)$.

A.4 Calculation of stability margins

Denoting by P_a the OMIB accelerating power, the OMIB equation of motion

$$M\ddot{\delta} = M\dot{\omega} = M\gamma = P_m - P_e = P_a \quad (A.4)$$

expresses the OMIB power-angle dynamics. Figure A.1 (b) portrays a typical OMIB power-angle variation, while Fig. A.1 (c) portrays the same variation of the decelerating power $(-P_a(\delta))$.



(a) Swing curves (b) OMIB equal area criterion (EAC) (c) OMIB EAC in terms of P_a vs δ

$R\ (B)$: relevant (backward) group

P_e : electrical power
P_m : mechanical power
$P_a = P_m - P_e$: accelerating power
$-P_a$: decelerating power

δ_o : initial angle
$\delta_e\ (t_e)$: clearing angle (time)
$\delta_u\ (t_u)$: unstable angle (time)
defined by $P_a = 0$ and $\dot{P}_a > 0$

(d) Notation

Figure A.1 -

The well-known equal-area criterion provides a synthetic transient stability assessment via the stability margin :

$$\eta = A_{dec} - A_{acc} \tag{A.5}$$

and states that : *for a given stability scenario , i.e. clearing time* t_e *and corresponding clearing angle* δ_e *, the OMIB system is unstable (resp. stable) if* $\eta < 0$ *(resp.* $\eta > 0$ *). The borderline case,* $\eta = 0$ *, provides the limit (in)stability condition, in terms of critical clearing time or maximum power.* For example, Fig. 1b corresponds to an unstable case.

With the notation of Fig. A.1 (c), we find (Zhang *et al.*, 1997b)

$$\eta = -\int_{\delta_o}^{\delta_u} P_a d\delta \ . \tag{A.6}$$

Equations (A.4)-(A.6) readily yield the following (Zhang *et al.*, 1997a) :

- general expression, for $\delta = \delta(t)$, $t_e \le t \le t_u$:

$$\frac{1}{2} M\omega^2 = \int_{\delta_0}^{\delta_e} P_a d\delta + \int_{\delta_e}^{\delta} P_a d\delta \tag{A.7}$$

- particular expression, if δ reaches δ_u , $t = t_u$ (i.e. unstable case) :

$$\eta = -\frac{1}{2} M\omega_u^2 \ . \tag{A.8}$$

The emergency SIME makes use of these expressions.

Finally, notice that in the emergency SIME context, the area of concern is comprised between $\delta_i(t_i)$ and δ_u (t_i being the time at which SIME starts predicting the system transient behaviour (see Section 2 and Fig. 1). It is thus interesting to modify expression (A.6) as follows (see the notation of Fig. A.1) :

$$\eta = A_{dec} - A_{acc} = A_{dec2} - (A_{acc} - A) \tag{A.9}$$

$$= A_{dec2} - \frac{1}{2} M\omega_i^2 \tag{A.10}$$

$$= -\int_{\delta_i}^{\delta_u} P_a d\delta - \frac{1}{2} M\omega_i^2 \tag{A.11}$$

where $\omega_i = \omega(t_i)$.

Obviously, if $\eta < 0$, i.e. if

$$\frac{1}{2} M\omega_i^2 > -\int_{\delta_i}^{\delta_u} P_a d\delta \tag{A.12}$$

the system will be anticipated to go unstable.

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