SIME : A Comprehensive Approach to Fast Transient Stability Assessment

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Abstract

The Single Machine Equivalent (SIME) is a hybrid method resulting from the coupling of a time-domain transient stability program with the equal-area criterion. Its aim is to set up a software as general as the time-domain program with which it is coupled but much more powerful and faster than it. The paper shows how the method reaches the threefold objective : to properly and readily assess transient stability limits (such as critical clearing times and power limits) under any power system modelling and stability scenario, to identify the relevant system machines and to appraise stability margins. In turn, these latter pieces of information open possibilities towards handy sensitivity analysis and transient stability monitoring. In short, they pave the way for real-time transient stability preventive monitoring and control. A variety of sample simulations highlight the method and its specifics.

Key words : Transient stability; direct methods; relevant cluster identification; stability limits; stability margins; real-time transient stability preventive control.

1 Introduction

Power system transient stability assessment is part of planning and operation planning studies. It concerns the system ability to withstand severe disturbances while ensuring continuity of service.

The conventional, world-wide accepted approach relies on time-domain numerical integration. The main appeal of time-domain programs lies in their ability to handle any power system modelling and to provide detailed description of the phenomena's evolution with time. Their main weakness is that they behave in a "black-box" fashion; in particular, they are unable to identify the parameters driving transient stability and to appraise the degree of system (in)stability – and hence of proximity to instability. Further, time-domain methods remain computationally demanding, despite the dramatic progress of computers in recent years.

To alleviate the above weaknesses, direct Lyapunov-like methods started being developed since the early sixties. (For a survey, see for example [1]). A class of direct methods which now prevail combine the transient energy function with the exit point or BCU method [2,3]. Yet another direct method was proposed around the mid eighties, based on the equal-area criterion [4 to 6]. The Single Machine Equivalent (SIME) is a hybrid direct method : hybrid, as Lyapunov-like hybrid methods [7]; direct, as the extended equal-area criterion from which it originates [6,8,9].

In short, SIME replaces a multimachine power system by a one-machine infinite bus equivalent, and assesses transient stability of the former based on the latter. More specifically, SIME relies on : (i) successive time-domain simulations run for the multimachine system and for short integration periods suggested by the equal-area criterion; (ii) computation via the equal-area criterion of the corresponding stability margins; (iii) appraisal of the stability limit (critical clearing time or power limit) by cancelling out the stability margin. In other words, with respect to power system modelling, contingency scenarios and types of instability, SIME is as general as the transient stability program with which it is coupled. But it is much faster than this latter, since it reduces the number and duration of time-domain simulations. Further, SIME appraises margins, thus providing adequate contingency filtering tools and opening possibilities towards sensitivity analysis [10]. Finally, SIME identifies the relevant machines of the system, thus paving the way for real-time transient stability preventive and emergency control [11].

By construction, SIME is a unified and fully robust method : unified, since it follows the same pattern, whatever the type of transient stability mode (first- or multi-swing; plant or interarea) and assessment (power limits or critical clearing times); fully robust, thanks to its ability to consistently and efficiently converge to the solution sought, no matter how far the initial conditions may be. In this paper, these advantages are further enhanced via recent improvements concerning easy definition of relevant

clusters, analytical expression of margins and systematic handling of all particular cases which may arise.

Section 2 lays the foundations of SIME, while Section 3 focuses on its design. Throughout, real world examples illustrate the developments and allow scrutinizing main features. Synthetic performances are appraised in Section 4 via simulations carried out on the IEEE 50-machine test system.

2 Essentials of SIME

2.1 Foundation

SIME relies on the following two propositions.¹

PROPOSITION 1. *However complex, the loss of synchronism of a multimachine power system originates from the irrevocable separation of its machines into two clusters. Hence, the mechanism of the system transient stability may be inferred from that of a one-machine infinite bus (OMIB) equivalent properly selected.*

PROPOSITION 2. *By virtue of the equal-area criterion [12], the transient stability of a relevant OMIB may be assessed in terms of its margin, η , defined as the excess of its decelerating over its accelerating energy.*

Below, we first deal with the OMIB derivation from a multimachine power system and, assuming it to be the relevant OMIB of concern, we devise OMIB stability rules and measures (§§ 2.2, 2.3). Further, we focus on the definition and selection of relevant OMIBs (§ 2.4). Finally, we gather the pieces of information thus obtained to devise SIME (Section 3).

2.2 OMIB derivation

2.2.1 OMIB structure. It is obtained by : (i) decomposing the system machines into two clusters, the relevant (R) and the "backward" (B) ones; (ii) aggregating the machines of each cluster into an equivalent one; (iii) replacing the latter two machines by a one-machine infinite bus equivalent.

2.2.2 OMIB parameters. With the usual notation, the i -th machine's parameters of an n -machine system are denoted by :

$\delta_i(\omega_i)$	rotor angle (speed)
$P_{mi}(P_{ei})$	mechanical input (electrical output) power
P_{ai}	accelerating power
M_i	inertia coefficient.

To get an OMIB, we decompose the machines into clusters R and B , and proceed as follows.²

¹These propositions are also on the basis of the Extended Equal-Area Criterion (EEAC) method [9]. An essential difference between this latter and SIME is that EEAC assumes simplified classical model, while SIME considers the time variations of the machine parameters (rotor angles, speeds, powers, etc) as they are provided by the time-domain program; this allows SIME to be as general and accurate as the time-domain program with which it is coupled.

²Let us recall that here we focus on the construction of an OMIB and the derivation of related stability information, given a decomposition scheme of the

Fig. 1 : Power-angle representation of a real OMIB
Resulting equal-area criterion.

$P - \delta$ curves in the during-fault (D) and post-fault (P) configurations.

δ_o : original (steady-state) OMIB rotor angle

δ_u : post-fault unstable OMIB angle

δ_e : fault clearing angle delimiting A_{dec} and A_{acc}

δ_c : critical clearing angle = 1.56 rad

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

$$\delta_R \triangleq M_R^{-1} \sum_{k \in R} M_k \delta_k \text{ with } M_R = \sum_{k \in R} M_k \quad (1)$$

Similar expressions hold for cluster B , and yield the angle δ_B .

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

$$\delta(t) \triangleq \delta_R(t) - \delta_B(t) \quad (2)$$

and whose rotor speed, ω , is defined in a similar way.

(iii) Define the equivalent OMIB mechanical power by

$$P_m(t) = M \left(M_R^{-1} \sum_{k \in R} P_{mk}(t) - M_B^{-1} \sum_{j \in B} P_{mj}(t) \right) \quad (3)$$

where $M = M_R M_B / (M_R + M_B)$ is the equivalent OMIB inertia coefficient, and the OMIB electrical power P_e by a similar expression. Note that P_{mi} 's, P_{ei} 's are considered to be free from any simplifying assumption, and so are the derived OMIB powers P_m , P_e .

2.2.3 OMIB dynamics. The equivalent OMIB power-angle dynamics is expressed by

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

Figures 1 portray the actual OMIB power-angle variations, calculated in a real stability case of the IEEE 50-machine system with detailed generator modelling (and constant mechanical power) as described in Section 4; we only mention here that the OMIB used to draw these figures results from cluster R composed of 2 machines and cluster B composed of the remaining 48 system machines.

The notation of Fig. 1 and its caption will be used throughout the paper.

2.3 OMIB stability

2.3.1 Power-angle stability assessment. The well-known equal-area criterion [12] applied to eq. (4) provides a synthetic transient stability assessment via the stability margin :

$$\eta = A_{dec} - A_{acc} \quad (5)$$

and states that : for a given stability scenario the OMIB system is unstable (resp. stable) if $\eta < 0$ (resp. $\eta > 0$). The borderline

system machines into groups R and B . The definition of the proper groups R and B and hence of the OMIB of concern will be addressed in § 2.4.

Critical clearing time = 125 ms

Fig. 2 : Time-domain OMIB trajectories
corresponding to $P - \delta$ representation

case, $\eta = 0$, provides the limit (in)stability condition, in terms of critical clearing time or maximum power. For example, Fig. 1a corresponds to an unstable case, Fig. 1b to a stable case.

With the notation of Fig. 1, the accelerating and decelerating areas corresponding to the fault clearing angle δ_e are expressed as :

$$A_{acc} = \int_{\delta_o}^{\delta_e} (P_{mD} - P_{eD}) d\delta = \int_{\delta_o}^{\delta_e} P_a d\delta \quad (6)$$

$$A_{dec} = - \int_{\delta_e}^{\delta_u} (P_{mP} - P_{eP}) d\delta = - \int_{\delta_e}^{\delta_u} P_a d\delta \quad (7)$$

Hence,

$$\eta = - \int_{\delta_o}^{\delta_u} P_a d\delta \quad (8)$$

Recall that P_{mD} (resp. P_{mP}) stands for the current value of the mechanical input power of the system in its during- (resp. post-) fault configuration. Recall also that, unlike the particular case of a single-machine system with simplified model, in general P_{mD} and P_{mP} vary with time, and hence with δ ; similarly, P_{eD} and P_{eP} vary with δ in a non-sinusoidal fashion.

2.3.2 Stability criteria for time-domain OMIB trajectories.

The above power-angle instability-stability rules may readily be translated in terms of the OMIB trajectory characteristics (rotor angle, speed, accelerating power).

Figures 2 show the correspondence of the power-angle and time-domain OMIB behavior³; they suggest the following simple criteria which allow one to identify unstable and stable OMIB trajectories.

Unstable trajectory : an OMIB trajectory which reaches an angle δ_u at time t_u where

$$P_a(t_u) = 0 ; \quad \left. \frac{dP_a}{dt} \right|_{t=t_u} > 0, \quad (9)$$

with $\omega(t_u) > 0$ is an unstable OMIB trajectory.

Stable trajectory : an OMIB trajectory which reaches a return angle δ_r ($\delta_r < \delta_u$) at time t_r where

$$\omega(t_r) = 0 ; \quad P_a(t_r) \equiv P_{ar} < 0 \quad (10)$$

is a stable trajectory.

³These curves are drawn for the real example already used in Figs. 1. Actually, Fig. 1a (resp. 1b) and Fig. 2a (resp. 2b) are drawn under identical stability conditions. Note that in Fig. 2b the $P_a - \delta$ curve drawn in between δ_r and δ_u is predicted according to the procedure described below in § 2.3.3.

Limit (un)stable trajectory : an OMIB trajectory which reaches the return angle δ_r with $P_a(t_r) = 0$ is a critically (un)stable OMIB trajectory; stated otherwise, the critically (un)stable OMIB trajectory reaches the unstable angle δ_u with $\omega(t_u) = 0$, or simply, it has a return angle δ_r equal to δ_u .

2.3.3 Analytical expression of an unstable OMIB margin. From the dynamic equation (4), we get :

$$M\ddot{\delta} = P_a\dot{\delta} \quad (11)$$

or

$$\frac{1}{2}M\omega^2 = \int_{\delta_0}^{\delta} P_a d\delta = \int_{\delta_0}^{\delta_r} P_a d\delta + \int_{\delta_r}^{\delta} P_a d\delta. \quad (12)$$

Setting in eq. (12) $\delta = \delta_u$ and comparing this with eq. (8) yields the unstable margin as

$$\eta_U = -\frac{1}{2}M\omega_u^2 \quad (13)$$

where subscript “U” holds for “unstable” trajectory and $\omega_u = \omega|_{t=t_u}$.

2.3.4 Analytical expression of a stable margin. Setting in eq.(12) $\delta = \delta_r$ and observing that for $\delta = \delta_r$ ω_r is zero, we get

$$\int_{\delta_0}^{\delta_r} (P_{eD} - P_{mD})d\delta + \int_{\delta_r}^{\delta_u} (P_{eP} - P_{mP})d\delta = 0. \quad (14)$$

Accordingly, eq. (8) yields the corresponding stable margin as

$$\eta_{St} = -\int_{\delta_r}^{\delta_u} (P_{mP} - P_{eP})d\delta = -\int_{\delta_r}^{\delta_u} P_a d\delta = \int_{\delta_r}^{\delta_u} |P_a| d\delta \quad (15)$$

where subscript “St” stands for “stable” trajectory.

Unlike eq. (13) which provides the exact unstable margin, expression (15) must be approximated. Indeed, neither δ_u nor $P_a(\delta)$ ($\delta_u > \delta > \delta_r$) are known, since the OMIB trajectory “returns back” at $\delta = \delta_r$ (see Fig. 2b).

An efficient approximation was recently proposed in the context of the “emergency SIME” [11]. It consists of extrapolating the P_a curve from δ_r to δ_u by writing

$$P_a(\delta) = a\delta^2 + b\delta + c \quad (16)$$

and solving for a, b, c based on P_a values taken at three successive times corresponding to angles $\delta_r - 2\Delta\delta$, $\delta_r - \Delta\delta$, δ_r . Angle δ_u is then found by solving eqs (9) with $\delta > \delta_r$; finally, the stable margin η_{St} (portrayed in Fig. 2b) is computed using expression (15).

2.3.5 Remark on the approximation of the $P_a - \delta$ curve. Besides assessing the stable margin η_{St} , the above procedure is used to predict the $P_a - \delta$ curve, so as to save time-domain simulations, as will be explained in Remark 3 of § 3.1.3. We also mention that this prediction becomes essential in the context of the emergency SIME proposed in [11].

2.4 Relevant machines and corresponding OMIB

The above paragraphs assume knowledge of the relevant machines of concern. To identify these machines, we observe that on an unstable trajectory, the relevant machines are those which cause the system irrevocable loss of synchronism. Accordingly, we use the following pattern :

(i) compute via a time-domain program the post-fault swing curves of the system machines;

(ii) at each step sort the machines in decreasing order of their rotor angles; identify the first larger angular deviations (larger “gaps”) between any two adjacent machines thus sorted, and consider the candidate relevant machines of concern to be those which are “above these gaps”;

(iii) compute the parameters of the corresponding candidate OMIBs according to § 2.2.2;

Fig. 3 : Illustration of relevant machines identification

(iv) define the “relevant OMIB” to be the candidate OMIB which first reaches its unstable angle δ_u , meeting conditions (9).

Figure 3a illustrates the relevant machines identification in the stability case of Figs. 1 and 2. The unstable angle $\delta_u = 175^\circ$ is reached at time $t_u = 0.51$ s by the OMIB corresponding to the largest gap (of 74°); this latter determines 2 relevant machines and $50 - 2 = 48$ remaining, “backward” machines. The resulting OMIB trajectory is shown by the dotted line in this figure. Incidentally, at t_u the maximum angular deviation (between the two extreme system machines) is of 260° . On the other hand, Fig. 3b corresponds to (the stable case of) Fig. 2b. The considered OMIB has been determined on the unstable trajectory of Fig. 3a. On this stable trajectory, it reaches the return angle $\delta_r = 160^\circ$ (where $\omega_r = 0$), at $t_r = 0.62$ s (see the notation of § 2.3.2).

3 Single Machine Equivalent (SIME)

3.1 Evaluation of stability limits

The stability limits of practical concern are power (transfer or generation) limits (PLs) and critical clearing times (CCTs). Their search relies on the same principle and follows fully equivalent patterns.

3.1.1 Principle SIME assesses transient stability mainly relying on unstable simulations, in particular because unstable simulations are less time consuming than stable ones.

The search uses **pairs of relevant margins** : these are the margin values $\eta(k-1)$ and $\eta(k)$ of the same OMIB at two successive stability simulations. If the two margins are both negative, this is the relevant OMIB of the lesser unstable simulation (i.e. k). However, if the relevant machines of this OMIB are not the most advanced machines in simulation $k-1$, use simulation k together with a new one carried out under lower stability level.

The search will proceed “from the right”, i.e. with successive stability simulations of decreasing severity. It is described below, and illustrated in Fig. 4 in the case of a power limit search.

3.1.2 General procedure. For given operating conditions and contingency scenario (type and location of the contingency; system’s post-fault configuration), the search of a CCT and of a power limit follows similar patterns. However, to make the description as clear as possible we will start with CCTs, then will indicate the necessary adaptations for the search of power limits.

(i) Choose an initial clearing time t_{e1} large enough to yield an unstable simulation. To this end, perform a multimachine time-domain simulation of the system in its fault-on configuration until reaching either a maximum angular deviation between the two extreme system machines, $\delta_{ij\max}$, of 200° , or δ_{OMIB} of 110° ; this latter is the OMIB rotor angle determined in the course of time-domain simulations by the maximum gap.

(ii) With t_{e1} , continue time-domain simulations in the post-fault configuration. At each time step, check whether a candidate relevant OMIB meets conditions (9); stop as soon as these conditions are met. Consider the corresponding $\omega_u = \omega(t_u)$, and compute the unstable margin (η_1) using eq. (13).

(iii) Choose a new clearing time, t_{e2} , lower than the previous one, and compute accordingly the corresponding margin, η_2 .

- If η_2 is negative, extrapolate margins η_1, η_2 to get the critical clearing time t_c corresponding to $\eta = 0$, then go to step (v).

Fig. 4 : Search of stability limits by extra(inter-)polating decreasing margin values. Example of Table 1.

- If η_2 is positive, i.e. if a return OMIB angle is reached, continue the time-domain simulation for the entire integration period in order to explore whether :
 - the relevant OMIB provided by the previous unstable case still keeps valid here
 - another relevant OMIB appears, which leads to first swing instability; compute the corresponding margin η'_2 .
 - multiswing instability appears (with either the same or another relevant OMIB); compute the corresponding margin η'_2 .

In the former case (positive η_2), declare t_c to be the CCT sought and go to step (v).

In the latter two cases ($\eta'_2 < 0$), go to step (iv).

(iv) Choose a new clearing time, t_{e3} , smaller than t_{e2} and proceed as in (iii).

(v) Decide whether t_c is assessed accurately enough, i.e., whether t_c is close enough to t_{e2} . If not, go to (iii).

The above CCT search procedure may be readily transposed to the search of power limits (PLs) with preassigned fault clearing time. It amounts to replacing t_{ei} by PL_i and t_c by PL_c . The initial power level may be chosen as the actual system's upper power level.

3.1.3 Remarks. 1.- On those rare cases where step (i) yields a stable simulation, application of the procedure of § 2.3.4 will provide the corresponding stable margin, after running a new, unstable simulation, with a clearing time larger than t_{e1} .

2.- Under very unstable simulation conditions, it may happen that an OMIB trajectory has no post-fault decelerating power, i.e. no unstable angle δ_u and therefore no margin. Ref. [10] describes the reasons for such situations to arise as well as appropriate procedures to bring the system back to "unstable conditions with margins".

3.- On a stable case, to save computing time (corresponding to about 0.5 to 1 s of time-domain simulation) use the prediction procedure of § 2.3.4.

3.2 Illustrative examples

3.2.1 First illustrative example : power limit assessment. The example is taken from a CIGRE exercise using the IEEE 50-machine system described in Section 4. The purpose of the computation is to determine the power generation limit under the conditions described in § 4.3.1.

The power system is modelled in the standard simplified way. The base case generation power is of 2600 MW.

The result of the considered stability case is summarized in row 3 of Table 3, § 4.3.1. The details of the computation are gathered in Table 1. Column 1 indicates the successive power levels, $P(k)$. The corresponding stability margins are reported in column 3; their extra(inter-)polation provides the successive power limits, PL (column 4). The iterative procedure starts with $P(0) = 3120$ MW (i.e. quite larger than the base case power); it stops after getting a positive margin. The power limit is found to be of 2654 MW which is in good agreement with the reference value provided by a pure time-domain program (2670 MW). This extra- (inter-)polation procedure is illustrated in Fig. 4.

The duration of the time-domain simulation required by SIME is summarized in column 5 and amounts to 3.9 sTDI (seconds of time-domain integration) : 1.9 for the unstable simulations to reach t_u , 2 for the stable simulation, labelled t_s . Actually, here, thanks to the prediction of the $P_a - \delta$ curve, the 2 sTDI

Table 1 : Power limit assessment.

Fault clearing time : 0.108 s.

1	2	3	4	5
$P(k)$ (MW)	Nr of rel.m.	η	PL(k) (MW)	t_u (t_s)
3120	29	-1.75	—	0.8
3120/1.1 = 2836	ditto	-0.53	2712	1.1
2712/1.1 = 2466	—	0.55	2654	(2.0)

Table 2 : Critical clearing time assessment.

1	2	3	4	5
$t_e(k)$ (ms)	Nr of rel. m.	η	$t_c(k)$ (ms)	t_u (t_s)
258	29	-2.60	—	1.03
258/1.1 = 235	—	2.00	245	(2.0)
235	49 (2)	-1.51	—	5.00
213	49 (2)	-1.08	160	4.83

of time-domain simulation covers an overall exploration of about 3 sTDI. Note that the time-domain simulation required by SIME is also its total computing time, since the computations required by SIME per se amounts to a few fractions of ms only. In what follows, we will therefore use sTDI to measure SIME's overall computing requirements.

3.2.2 Second illustrative example : CCT assessment. This example is again taken from the CIGRE exercise, using the IEEE 50-machine system, where part of the machines are equipped with AVRs, suitably modelled (see § 4.3.2).

Table 2 summarizes the simulation results obtained with a maximum time-domain integration period of 5 s. They call for the following observations.

In the first iteration, the system in its during-fault configuration reaches an OMIB angle of 110° at $t = 258$ ms ; hence, the program chooses it automatically to be the initial clearing time (see column 1). In the second iteration ($t_e = 235$ ms), the system shows to be first-swing stable (time-domain integration period of 2 s plus an extra prediction time of about 1 s). The corresponding CCT is computed by interpolation and amounts to 245 ms; note that the reference value of first-swing CCT provided by the corresponding pure time-domain program is of 248 ms.

The following two runs report on multiswing instability exploration. With the same clearing time, extending the time-domain integration period for another 3 s (plus the prediction of the $P_a - \delta$ curve) leads to a second-swing instability (see (2) in column 2) caused by 49 relevant machines; the corresponding margin is of -1.51. Decreasing further the clearing time and integrating for 5 seconds leads again to a second-swing instability with the same relevant machines and a margin of -1.08. Extrapolating these latter two margins provides a second-swing CCT of 160 ms.

3.3 Note on multiswing instability phenomena

The formulation of Section 2 and the general procedure of § 3.1 are also valid for multiswing stability. To compute the margin of the m -th swing, simply consider the angle δ_u (and also δ_r for a stable margin) of this m -th swing.

The example of Table 2 illustrates the procedure. Note that to assess multiswing instability, SIME requires longer time-domain integration periods – but shorter than those required by pure time-domain transient stability programs. Besides, SIME provides the following information based on the OMIB concept :

- identification of the type(s) of multiswing phenomena (second, third,... multiswing instability); this is the number of swings leading to instability; it is provided by the number of oscillations of the relevant OMIB
- for each one of the multiswing phenomena, identification of the actual relevant cluster responsible for the system loss of synchronism.

Figure 5 illustrates the second swing instability reported in Table 2. Notice the admittedly quite intricate swing curves of the 50-machine system and also the way SIME sheds light on the multiswing phenomena; in particular, on the fact that the relevant cluster has 49 machines (actually, one could think of the 50-th machine losing synchronism with respect to 49 others).

Fig. 5: Second swing instability example
Fault cleared at $t_e = 213$ ms (see in Table 2)

Time-domain methods do not provide a clear picture of such phenomena because of the formidable intermixing of the multimachine system swing curves.

3.4 An interesting by-product: the filtering SIME

The definition and straightforward computation of stability margins are exploited in the “filtering SIME” proposed in Ref. [10]. Its aim is to provide an approximate (but reliable) assessment of the stability limit sought, so as to discard or select a stability case according to whether this limit is larger or smaller than a preassigned threshold value. The selected cases (considered to be “severe” enough) are then scrutinized via the “regular” SIME which refines the assessment of the filtering SIME by using additional margin computations. The discarded cases require two (and seldom three) unstable margins corresponding to about 1.5 sTDI per contingency on the average.

The above description suggests that the filtering SIME provides a sound and efficient screening tool. It allows considering hundreds or thousands of contingencies and eventually scrutinizing a few percentage of them. It may be very useful in the context of planning studies; and it makes feasible real-time preventive control.

3.5 Computing gains of SIME

The general procedure of § 3.1 along with the illustrative examples of § 3.2 and the filtering SIME of § 3.4, suggest that SIME owes its attractive computing performances to its margins. The benefits with respect to corresponding time-domain stability assessment come essentially from the following three contributions.

- (i) The fact that margins allow using an iterative rather than a dichotomic procedure.
- (ii) The fact that a stability limit assessment relies mainly on unstable simulations which are little time consuming.
- (iii) Finally, the fact that increasing accuracy generally amounts to merely increasing the number of unstable simulations, unlike time-domain methods.

As already observed in § 3.2.1, a handy measure of computing times required by SIME is the duration of the time-domain integration. This sTDI (for seconds of time-domain integration) essentially depends on the power system size and modelling, and on the very time-domain program with which SIME is coupled. It provides a straightforward comparison with the computing requirements of this time-domain program.

3.6 SIME vs pure time-domain methods

Let us compare SIME with the time-domain transient stability program with which it is coupled (hereafter we shall refer to it as to “the corresponding time-domain program”). We will distinguish the OMIB modelling and its transient stability assessment.

Concerning modelling, the OMIB equivalent is, indeed, a faithful picture of the multimachine system decomposed into two groups, since at each step of the time-domain program it is refreshed with the corresponding multimachine parameters; only minor numerical errors could exist, which would be of the second order, as the numerical errors of the corresponding time-domain program.

As concerning stability assessment, we will distinguish *the moment* the instability is declared and the corresponding *transient stability limit* (critical clearing time or power limit). OMIB declares instability just after passing t_u , i.e. after passing its unstable angle δ_u ; and this is an unambiguous criterion. On the other hand, time-domain programs rely on various pragmatic criteria referring to a maximum angular deviation between extreme machines of the multimachine system of, e.g., 180° or 360° ; or to a the maximum angular deviation between one machine and a reference (e.g. the center of angle or a heavy machine). Notice, however, that *the value* of the transient stability limit is not influenced by *the moment* the instability is declared, i.e. the moment a method declares the system to lose synchronism.

The above two considerations put together lead to the conclusion that if Proposition 1 of § 2.1 holds true, the OMIB will provide the same transient stability assessment (limits) with the corresponding time-domain program even if the two approaches do not declare the system instability at the same moment.⁴

Now, from a physical viewpoint, Proposition 1 seems to be a sound conjecture. The consistently accurate practical results obtained on a very large number of simulations performed on a large variety of power systems corroborate this conjecture.

4 Simulations

4.1 Description

SIME has extensively been tested on various power systems, under various models and various stability conditions, such as the EDF EHV system [10], the Hydro-Québec system [13] and the South–South-East Brazilian system [14].

In this paper we consider two series of simulations performed on IEEE 50-machine test system [15], in the context of a two-phase exercise of the CIGRE Task Force 38-02-09 [16].

The first series concerns computation of CCTs corresponding to 3-phase short circuits; the system is modelled in the standard simplified way (constant electromotive force behind transient reactance; constant impedance loads) (Model M1).

The second series concerns computation of power transfer limits under model M1 and of CCTs under higher-order machine models embedding AVR (Model M2).

In both series, the performances of SIME were compared with those of the corresponding time-domain (SBS) program in terms of accuracy and computing gains. Accuracy is expressed in terms of the relative error, Δ , of SL(SIME) with respect to SL(SBS) in %, and of absolute error, ϵ , in ms or MW as appropriate. (Remember, stability limit (SL) stands for either CCT or PL.) Computing performances are assessed in terms of the mean time-domain integration (TDI) required by SIME and the resulting ratio

$$r = \frac{\text{Mean TDI required by SBS}}{\text{Mean TDI required by SIME}}$$

4.2 First series simulation results

33 stability cases were run. The SIME performances are as follows.

Accuracy :

$$\begin{aligned} \text{mean } |\Delta| &= 2.4 \% ; & \text{mean } |\epsilon| &= 5 \text{ ms} \\ \text{maximum } |\Delta| &= 5 \% ; & \text{maximum } |\epsilon| &= 17 \text{ ms} \end{aligned}$$

Computing performances : mean TDI required by SIME : 5 sTDI.

Considering that SBS would have required 7 iterations, of which 3 are stable (corresponding to $3 \times 5 = 15$ sTDI) and 4

⁴ Actually, for a two-machine system and the classical simplified model the equal-area criterion is just another expression of the Lyapunov direct criterion where, moreover, this latter provides sufficient and necessary stability conditions (rather than solely sufficient conditions as in the general case) [1]. Now, when the two-machine system replaces a multimachine one and, in addition the modelling departs from the classical one, Lyapunov theory stops being rigorously applicable. Validation through real-world examples becomes necessary. This validation has consistently been verified under any stability conditions, any power system modelling, any power system; in short under many thousands of stability cases.

Table 3 : Power limit assessment.
Fault clearing time : 0.108 s . Integration period : 5 s

Case Nr	Base Case	Successive power levels (MW)				PL (MW)		Error	
		P(0)	P(1)	P(2)	P(3)	SIME	SBS	ϵ	$\Delta\%$
1	4000	4800	4364	3928		4019	4010	-8	0.6
2	4000	4800	4364	3928		4102	4070	-32	-0.8
3	2600	3120	2836	2552		2630	2670	40	-1.5
4	2600	3120	2836	2978		2828	2836	8	+0.3
5	4000	4800	4364	3928	3492	3801	3790	-11	-0.3
6	4000	4800	4364	3928	3492	3640	3670	30	0.8
7	2600	3120	2836			2880	2860	-20	-0.7
8	2600	3120	2836			3011	2870	-41	-1.4
9	2600	3120	2836			2893	2910	17	0.6

unstable (corresponding to $1 \times 4 = 4\text{sTDI}$), we assess that the ratio r amounts to $19/5 \simeq 4$.

4.3 Second series simulation results

4.3.1 Power flow limits. Two sets of initial conditions were used [16] :

- the base case with 700 MW load on each generator, i.e. 1400 on the two generators Nos 93 and 110;
- a stressed case with 1300 MW on each generator, i.e. 2600 MW on the two generators.

The objective was to find the maximum power flow that could be supported across a critical boundary for a set of contingencies without instability. The contingencies are 3-phase faults cleared in 108 ms. The model used is M1.

Table 3 describes the results obtained with the 9 stability cases considered. The synthetic performances are found as follows.

Accuracy :

$$\begin{aligned} \text{mean } |\Delta| &= 0.78 \% ; & \text{mean } |\epsilon| &= 23.1 \text{ MW} \\ \text{maximum } |\Delta| &= 1.5 \% ; & \text{maximum } |\epsilon| &= 41 \text{ MW} \end{aligned}$$

The ratio r is again about 4.

Remark. To save computing effort, the procedure of § 3.1 was slightly modified so as to reduce the number of load flows by using, to the extent possible, the same successive load flows for the base case and for the stressed case. Thus, only 11 distinct load flows have been necessary for all 9 different cases.

4.3.2 CCTs; machines equipped with AVRs. In this exercise, where 6 of the system machines are equipped with AVRs, the CCTs of 10 stability scenarios have been assessed. The performances are as follows.

Accuracy :

$$\begin{aligned} \text{mean } |\Delta| &= 3 \% ; & \text{mean } |\epsilon| &= 4 \text{ ms} \\ \text{maximum } |\Delta| &= 14 \% ; & \text{maximum } |\epsilon| &= 18 \text{ ms} \end{aligned}$$

Computing performances : mean integration time required by SIME : 3.3 sTDI. The ratio r is here over 5.

5 Conclusion

We have first presented the fundamentals of the Single Machine Equivalent (SIME) method then the resulting stability procedure. From a conceptual viewpoint, SIME sheds light on the intrinsic mechanism of multimachine transient stability phenomena. From a pragmatic viewpoint, the resulting procedure is a unified approach to the assessment of transient stability margins for preassigned stability and operating conditions, and/or of transient stability limits in terms of critical clearing times or maximum power limits. An important byproduct is the identification of the machines responsible for the system loss of synchronism.

Compared with hybrid multimachine Lyapunov-like functions, SIME shows to be faster and more flexible (in particular in the way of identifying relevant machines). Compared with time-domain methods, SIME is also much faster and conveys additional information in terms of margins and relevant machines; in short,

SIME provides interpretable and more efficient information than the "black-box" type of time-domain methods.

On the whole, SIME provides adequate tools for real-time preventive transient stability assessment; it is now time to explore such avenues. Yet another significant fallout of SIME is the possibilities it opens towards real-time transient stability emergency control. This work is in progress.

(Manuscript received Oct. 29, 1996, revised April 14, 1997)

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