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EXTENDED EQUAL AREA CRITERION REVISITED

Y. Xue *, L. Wehenkel **,
R. Belhomme ***, P. Rousseaux, M. Pavella

University of Liège
Institut Montefiore; B - 4000 Liège, Belgium

E. Euxibie (1), B. Heilbronn (1),
J.F. Lesigne (2)

Electricité de France
1, Av. du Gén. de Gaulle; F - 92141 Clamart, France

Abstract

A case study is conducted on the EHV French power system in order to revisit the extended equal area criterion and test its suitability as a fast transient stability indicator. The assumptions underlying the method are reexamined, causes liable to invalidate them are identified, and indices are devised to automatically circumvent them. The selection of candidate critical machines is also reconsidered and an augmented criterion is proposed. The various improvements are developed and tested on about 1000 stability scenarios, covering the entire 400-kV system; the severity of the scenarios, resulting from the combination of weakened both pre- and post-fault configurations, subjects the method to particularly stringent conditions. The obtained results show that the devised tools contribute to significantly reinforce its robustness and reliability.

Keywords. Transient stability; direct methods; extended equal area criterion; real-time operation; dynamic security indicators.

1 INTRODUCTION

Transient stability is an important but intricate aspect of power systems security, implying the simultaneous satisfaction of quite conflicting requirements, such as fast and accurate stability diagnostic [1]. To meet such requirements, at least to a certain extent, the Liapunov direct approach has widely been investigated during the past three decades [2 to 5].

The extended equal area criterion (EEAC) is a direct type method. It aims at enhancing and broadening the advantages of the Liapunov criterion, by furnishing analytical expressions for ultra-fast analysis, sensitivity analysis and means to preventive control. To reach these objectives, the EEAC uses the conjecture, assumption, and approximation stated below, together with the equal area criterion (or equivalently the Liapunov direct criterion).

Conjecture : The loss of synchronism of a multimachine system, whenever it occurs, is triggered off by the machines' irrevocable separation into two groups; hence, the idea of subdividing the system machines into the "critical group", generally comprising a few machines, and the remaining group, comprising the majority of machines.

Assumption : The stability phenomena may be assessed by replacing the machines of each group by an equivalent; further, the two equivalent machines are replaced by a one-machine-infinite-bus system.

Approximation : The time evolution of the resulting one-machine system may be assessed by means of a limited Taylor series, together with corrective factors to compensate the unavoidable truncation errors.

Initiated in the late eighties [6 to 9], the EEAC has been extensively tested on a large variety of power systems and operating conditions. It yielded very good results, even with relatively large systems as for example a 31-machine American system or the 40-machine EHV Belgian power system [10]. Quite naturally, its first implementation was realized on a Chinese EMS system where it is currently used in a real-time context [11].

These encouraging preliminary results have motivated a case study conducted on the EHV French power system, where the method would be subjected to as stringent stability conditions as possible. This was realized by combining weak operating conditions with severe contingency scenarios, where changes in the post-fault configurations further weaken the system. A first set of simulations yielded globally good results. But at the same time they pointed out the necessity of developing safe-guards, in order to avoid some few, yet harmful diagnostics. Further, they have shown the necessity of reconsidering the criterion used to select candidate critical machines. This paper aims at enhancing the robustness of the method and at making it cope with real-time strategies.

The paper is organized as follows. Section 2 underlines the fundamentals of the EEAC method and recalls its specifics. Section 3 describes the simulations performed on the French system. Section 4 identifies needs of improvements and proposes appropriate means to meet them. Section 5 describes and discusses the simulation results.

N.B. This work addresses questions of analysis type only. Sensitivity analysis or preventive control issues are considered in [8,10].

2 THE STANDARD EEAC

The practical EEAC procedure for transient stability analysis conforms to the following scheme :

(i) for an assigned contingency (or fault, or disturbance) [1] decompose the multimachine system into two subsets : the "cluster of critical machine(s)" called for short the "critical cluster", and the group of the remaining machines;

[1] The terms "disturbance", "fault" or "contingency" will be used interchangeably.

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* On leave from Nanjing Automation Research Inst., P.R.C.
** Research Assistant, F.N.R.S.
*** Senior Research Assistant, F.N.R.S.
(1) Study and Research Division
(2) Power system Operation Division

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(ii) transform the two subsets into two equivalent machines, using their corresponding frame of partial centre of angles;
(iii) reduce these two machines to a "one-machine-infinite-bus" (OMIB) system;
(iv) applying the equal area criterion to the OMIB provides two measures of transient stability : critical clearing angle and stability margin;
(v) using a Taylor series suitably truncated achieves to analytically relate an OMIB angle (e.g. the critical clearing angle) to its corresponding time (e.g. the critical clearing time) and vice versa.

2.1 Basic formulation

The basic formulation of the method outlined below, implies knowledge of the actual critical cluster. This essential question is addressed in § 2.2.

2.1.1 Multimachine system

Let the motion of the i-th machine of an n-machine system be described by

$$\dot{\delta}_i = \omega_i \quad ; \quad M_i \dot{\omega}_i = P_{mi} - P_{ei} \quad i = 1,2,\ldots,n \tag{1}$$

where

$$P_{ei} = E_i^2 Y_{ii} \cos\theta_{ii} + \sum_{j=1, j\neq i}^{n} E_i E_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \tag{2}$$

$\delta_i\,(\omega_i)$; M_i	rotor angle (speed); inertia coefficient
$P_{mi}\,(P_{ei})$	mechanical input (electrical output) power
E_i	voltage behind the direct axis transient reactance
$\boldsymbol{Y}$	admittance matrix reduced at the internal generator nodes
$Y_{ij}\,(\theta_{ij})$	modulus (argument) of the ij-th element of $\boldsymbol{Y}$.

M_i , P_{mi} and E_i are assumed to be constant throughout the transients; all loads are modelled as constant impedances.

2.1.2 Equivalent two machines

Denoting by

$\boldsymbol{S}$ $(\boldsymbol{A})$	the set of critical machines (of all remaining machines)
$s\,(a)$	the equivalent, aggregated machine

moreover, denoting symbolically by $\boldsymbol{G}$ one of the above two groups ($\boldsymbol{S}$ or $\boldsymbol{A}$) and by g its equivalent aggregated machine (s or a), set

$$M_g = \sum_{k\in \boldsymbol{G}} M_k \qquad \delta_g = M_g^{-1} \sum_{k\in \boldsymbol{G}} M_k \delta_k \qquad \gamma_g = \ddot{\delta}_g\big|_{t=0+} \tag{3}$$

where $t = 0^+$ denotes the time immediately following the contingency inception. Applying the standard definition of the partial centre of angles to the set $\boldsymbol{G}$ ($\boldsymbol{S}$ and $\boldsymbol{A}$) yields [2]

$$M_g \ddot{\delta}_g = \sum_{k\in \boldsymbol{G}} (P_{mk} - P_{ek}) \ . \tag{4}$$

Assuming moreover that

$$\delta_k = \delta_s \quad \forall k \in \boldsymbol{S} \qquad \text{and} \qquad \delta_\ell = \delta_a \quad \forall \ell \in \boldsymbol{A} \tag{5}$$

yields P_{ek} (and in a similar way $P_{e\ell}$) :

$$\begin{aligned} P_{ek} \;=\; & E_k^2 Y_{kk} \cos\theta_{kk} + E_k \sum_{j\in \boldsymbol{S},\, j\neq k} E_j Y_{kj} \cos\theta_{kj} + \\ & + E_k \sum_{\ell\in \boldsymbol{A}} E_\ell Y_{k\ell} \cos(\delta_s - \delta_a - \theta_{k\ell}) \qquad \forall k \in \boldsymbol{S} \end{aligned} \tag{6}$$

[2]A similar derivation is proposed in Ref. [12], restricted, however to the particular case of a disturbance consisting of a three-phase short circuit applied at a machine's busbar only, which moreover is supposed to necessarily be the critical one.

2.1.3 The OMIB equivalent

Setting

$$\delta \triangleq \delta_s - \delta_a \tag{7}$$

and using eqs. (4) and (5) yields the OMIB formulation

$$\boxed{M\ddot{\delta} = P_m - [P_c + P_{\max} \sin(\delta - \nu)] = P_m - P_e} \tag{8}$$

where M , P_m , P_e are expressed in terms of the system parameters in its pre-, during- or post-fault configuration as appropriate [9,10].

Note that the above construction preserves the characteristics of topology, *including transfer conductances.*

2.1.4 Equal area criterion (EAC) applied to OMIB

The application of EAC to eq. (8) is schematically portrayed in Fig. 1, which plots the P–δ curves in the pre-fault or original (O), during-fault (D) and post-fault (P) configurations. The original (steady-state) operation is characterized by the rotor angle δ_0 located at the crossing of the horizontal line $P = P_m$ with the original P_{eO} curve, partly drawn. The post-fault stable and unstable equilibrium points, respectively designated δ_P and δ_P^u , are determined by the intersections of P_m with P_{eP} .

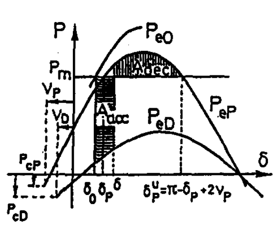

Figure 1
Pictorial representation of the EAC applied to OMIB (from [7])

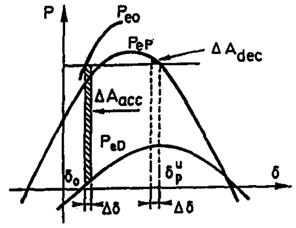

Figure 2
Errors caused by inaccuracies on δ_0 *and* δ_P^u (from [9])

The value that the angle reaches at the fault clearing time delimits the accelerating area, A_{acc} , and decelerating area, A_{dec} , which measure the corresponding transient energies :

$$A_{acc} = (P_m - P_{cD})\,(\delta - \delta_0) + P_{\max\,D}\,[\cos(\delta - \nu_D) - \cos(\delta_0 - \nu_D)] \tag{9}$$

$$A_{dec} = (P_{cP} - P_m)\,(\delta_P^u - \delta) + P_{\max\,P}\,[\cos(\delta - \nu_P) + \cos(\delta_P - \nu_P)] \tag{10}$$

Two alternative transient stability measures readily derive :
(i) transient stability margin relative to a given clearing angle δ_e :

$$\eta = A_{dec}(\delta_e) - A_{acc}(\delta_e) = f(\delta_e) \ ; \tag{11}$$

(ii) the conventional critical clearing angle, δ_c , for which the stability margin vanishes :

$$\eta = 0 \quad \Rightarrow \quad A_{dec}(\delta_c) = A_{acc}(\delta_c) \quad \Rightarrow \quad \delta_c \ . \tag{12}$$

2.1.5 Modified Taylor series

The time corresponding to an OMIB rotor angle (e.g. t_c corresponding to δ_c provided by (12)), may be assessed by a Taylor series expanded about δ_0 , the angle of the OMIB entering its fault-on phase.

In the case the fault-on scenario reduces to a single configuration, the Taylor series contains only even derivatives of δ . Truncating the series after the t^4 term then yields

$$\delta = \delta_0 + \frac{1}{2}\gamma t^2 + \frac{1}{24}\ddot{\gamma} t^4 \tag{13}$$

where γ denotes the second-order derivative of δ, expressed by (7), at $t = 0^+$, and $\ddot{\gamma}$ its fourth-order derivative.

The advantage of the above truncation is to provide an analytical expression of t in terms of δ (by solving (13) with respect to t). This however introduces a truncation error (except for the particular case discussed in § 2.3.2); and the larger the departure of δ from δ_0, the larger the error. Hence, the idea to : (i) apply expression (13) to an angle $(\delta_\alpha - \delta_0)$ smaller than the actual angle $(\delta - \delta_0)$, by introducing a positive parameter $\alpha_1 \leq 1$; (ii) to solve (13) in terms of t_α ; (iii) to amplify the latter by multiplying it by a positive parameter $\alpha_2 \geq 1$, so as to get the actual t corresponding to δ.

Introducing the corrective factors α_1, α_2 in (13), or equivalently the factors α_1, α, yields the modified Taylor series

$$\delta = \delta_0 + \alpha^{-1}\gamma\frac{t^2}{2} + \alpha^{-2}\alpha_1\ddot{\gamma}\frac{t^4}{24} \quad (14)$$

where

$$\alpha = \alpha_1\alpha_2^2 \ . \quad (15)$$

The reason for using the pair (α_1, α) preferably to (α_1, α_2), as well as their proper choice are discussed in § 2.3.2.

2.1.6 Computing candidate Critical Clearing Times (CCTs)

For a given contingency, the candidate CCT corresponding to a candidate critical cluster is computed by : (i) setting $\eta = 0$ and solving eqs. (9)-(12) to determine the critical clearing angle δ_c ; (ii) computing $t = t_c$ for $\delta = \delta_c$ from eq. (14).

Step (i) implies the solution of a non-linear, yet extremely simple algebraic equation; step (ii) is even more trivial. The overall computation is therefore extremely fast and virtually negligible with respect to that required for reducing the complete admittance matrix to $\boldsymbol{Y}$. Note, however, that for a given contingency the reduced $\boldsymbol{Y}$ matrix holds valid whatever the candidate critical cluster : identifying the actual critical cluster by scanning various candidates is therefore quite inexpensive. The usefulness of this remark will appear below.

2.2 Critical cluster identification

For a given contingency, the *identification* of the actual critical cluster conforms to the following procedure :

(i) draw up a list of candidate critical machines;

(ii) consider candidate critical clusters composed of one, two, ... machines and obtained by successively combining the above candidate critical machines;

(iii) compute by turn the corresponding candidate critical clearing times : the smallest one is the actual CCT; the actual critical cluster is precisely that which furnishes the CCT.

The *selection* of such a candidate list may rely on the "initial acceleration criterion"; this consists of : (i) classify the machines in a decreasing order of their initial accelerations; (ii) select those machines which have accelerations close to that of the top machine.

Generally, a significant gap between adjacent machines suggests where to stop the selection. There are, however, several exceptions, calling for appropriate modifications [11,13].

The above procedure relies on the fact that the EEAC provides sufficient *and necessary* stability conditions (see relating discussion, e.g. in [10]). Hence, the above rule identifies unambiguously the actual critical cluster, *provided that all relevant machines are included in the list.*

Remark.- The identification of the Critical Cluster (CC) is a concern common to several energy-type Liapunov approaches (e.g., the "individual machine energy function" [14], the "Mode Of Disturbance" [15], or the "acceleration method" [16]). For general multimachine Liapunov functions, however, the minimum candidate CCT does not necessarily correspond to the actual CC (since the Liapunov criterion provides sufficient but not necessary stability conditions); the EEAC escapes this difficulty, since it is a particular two-machine Liapunov function guaranteeing sufficient and necessary stability conditions. From a computing point of view, on the other hand, considering many candidate CCs may show to be quite heavy in general, while the EEAC is extraordinarily fast and can afford a large number of combinations without corrupting its on-line capabilities (see relating discussion in Section 5).

2.3 Inherent sources of errors

Two types of errors corrupt the EEAC : one relates to the assumptions underlying the derivation of the OMIB, the other to the Taylor series truncation.

2.3.1 Errors linked to the OMIB derivation

The errors relating to the assumption expressed by eq. (5) amounts to neglecting the rotor angle differences of the various machines with respect to the corresponding partial centre of angles (set $\boldsymbol{S}$ or $\boldsymbol{A}$ as appropriate). Fig. 1 shows that these errors affect the values of δ_0, δ_P, and δ_P^u. They may be substantially offset by using the following suggestions [10,13].

1. Instead of δ_0^{E} provided by the OMIB, consider its load flow value, δ_0^{LF}. This does not imply any additional computation, since δ_0^{LF} is available anyhow.

2. Instead of δ_P, use the corrective factor $\Delta\delta_0 = \delta_0^{\mathrm{LF}} - \delta_0^{\mathrm{E}}$, and consider the corrected expression (see Fig.2) $\delta_P' = \delta_P + \Delta\delta_0$.

3. Modify δ_P^u, so that $(\delta_P^u)' = \pi - \delta_P' + 2\nu_P = \delta_P^u - \Delta\delta_0$.

Observe that the overall accuracy depends much more on δ_0 than on δ_P^u (the same $\Delta\delta$ introduces a much larger discrepancy ΔA_{acc} than ΔA_{dec}, see Fig. 2).

2.3.2 Error linked to the Taylor series truncation

This error may be offset by adjusting the values of the parameters introduced in the modified Taylor series (14), [10,13]. Here we merely recall some salient conclusions.

(i) The value of α will generally be chosen close to 1. (In fact, 1 is precisely the value that α assumes in the particular case the critical cluster reduces to the single machine at the busbar of which a three-phase short circuit is presumably applied; indeed, in this case γ becomes constant.) For a given power system, a "learning", off-line stage contributes to better tune α and fix it once and for all. Generally $\alpha = 1.1$ is quite a suitable value for almost all power systems.

(ii) The value of α_1 is fixed by

$$\alpha_1 = \min\left[\alpha_1^*, \bar{\alpha}_1\right] \quad (16)$$

where $\alpha_1^* = 0.3$ (resp. 0.6) when the fault applies at a generator bus (respect. non-generator bus), and where $\bar{\alpha}_1$ is given by

$$\bar{\alpha}_1 = -1.5\,\gamma^2 / \left[\ddot{\gamma}\,(\delta_c - \delta_0)\right] \quad (17)$$

expressing the condition under which eq.(14) solved with respect to t provides a real solution.

Exceptionally, γ may be negative and hence $\tilde{\gamma}$ positive; according to (17), $\bar{\alpha}_1$ is then negative. In such cases, it is advisable to simply take $\alpha_1 \leq 0.2$.

3 SIMULATION DESCRIPTION

The EEAC has been tested under stressed stability conditions on the 400-kV and 225-kV EDF system, comprising 61 machines, 561 buses, 810 lines, and 190 transformers. Overall, this study has considered over 950 stability cases.

The first set of simulations has focused on the area of PALUEL, situated in the north-west part of the network, schematically portrayed in the one-line diagram of Fig. 3 : considering a base case of the overall EHV system, seven additional operating conditions have been created by changes relating to this area; this yielded eight Operating conditions or Points (OPs). These OPs have then been subjected to sixty three-phase short-circuits (3ØSCs), all confined at the 400-kV level of the above area : 30 "single-line" faults where the fault is cleared by opening a single line, 14 "double-line" faults where the fault is cleared by opening a double line, and 16 "busbar" faults where the fault is cleared by opening all elements (lines or transformers) ending up at the busbar of concern. In general, the severer stability conditions are found among the double-line and busbar faults.

The second set of simulations cover 3ØSCs applied at both ends of the 400-kV lines of the entire EDF system. The stability scenarios concern single-line as well as double-line faults, yielding respectively 364 and 134 cases.

The EEAC accuracy is assessed in terms of the fault critical clearing time, denoted CCT (EEAC) (or t_c^E), as opposed to CCT (SBS) (or t_c^S), used here as the benchmark. This latter is obtained by a step-by-step (SBS) numerical integration program, using the system modelling described in § 2.1.1, and as reference a machine representing a large external equivalent.

A first tuning of the EEAC suggested the value 1.1 for parameter α . The values of α_1 , on the other hand, conform to the suggestions of § 2.3.2.

4 IMPROVING THE EEAC

We discuss causes of various difficulties encountered while performing simulations, and propose remedial tools.

4.1 Selection of candidate critical machines

4.1.1 A pragmatic acceleration criterion

We initially used the compromise consisting of choosing the shortest between the list containing all machines having initial accelerations above 50 % of the maximum one (that of the top machine), and the list comprising the first nine machines. This procedure, generally successful, meets however also some failures; in particular :

(a) for contingencies applied at non-generator buses, the Critical Cluster (denoted hereafter CC) may generally be composed of many machines, especially when this bus is located at the centre of a group of machines or nearby weak tie-lines;

(b) often, in such cases, many machines acquire similar, large accelerations, without any significant gap. In general, the actually relevant machines are then classified among irrelevant ones, located too far from the fault to actually belong to the CC.

(c) when the post-fault configuration is significantly different from the pre-fault one, it may happen that some machines not appearing at the top of the initial acceleration list get electrically much closer to the top after the fault clearance.

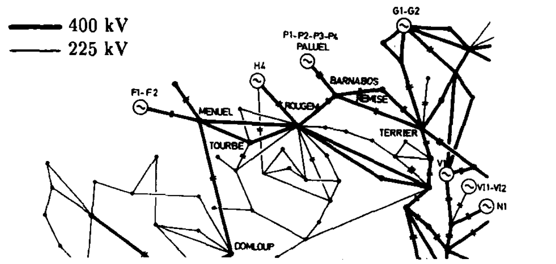

Figure 3 - *One-line diagram of the PALUEL area*

4.1.2 A composite criterion

The above observation (c) suggests that in addition to the initial acceleration, the selection criterion should rely on the post-fault electrical distance of the machines from the fault location. Similarly, observation (b) suggests that the pre-fault electrical distance should as well be taken into account. Combining the above, we propose the following procedure :

1. consider the product $p_i = a_i * Y_{if}^o$, where a_i is the initial acceleration of the i-th machine and Y_{if}^o the pre-fault transfer admittance between machine i and fault location f ; classify the machines in a decreasing order of their p_i value;
2. select as candidate critical machines all those for which $p_i \geq p_{i\,thr.}$; let ℓ_c denote the resulting candidate list;
3. for this list, run the EEAC according to the procedure of § 2.2 to determine a Candidate CC, denoted CCC hereafter;
4. classify the machines in a decreasing order of their post-fault admittance with respect to the faulted area; a certain number of new machines which appear in between machines of ℓ_c provides with these latter a new, "second selection" candidate critical machines, which should tentatively be combined with those of the CCC determined in step 3.

Remarks. 1.- Step (2) of the above composite criterion yields a reduced number of "first selection candidate critical machines", while increasing the probability of encompassing the relevant ones, and while significantly reducing the combinatorial.

2.- The information provided by the "second selection" candidates is particularly useful in stringent stability cases, where it generally succeeds in identifying the right CC, contrary to the sole acceleration criterion which often fails; this is obtained at the expense of almost negligible additional computation effort.

3.- Often, under specified stability conditions, individual machines belonging to the same generating site behave in the same, coherent way. These machines can be identified by comparing their pre- and post-fault transfer admittances as well as their accelerations. Forcing them together in CCCs allows to reduce the combinatorial and increase efficiency.

4.2 Identification of biased diagnostics

Three possible sources of biased diagnostics are identified and explored below.

4.2.1 Post-fault splitting of the critical cluster

This peculiar phenomenon arises when the system post-fault configuration undergoes significant weakening with respect to the pre-fault one. We illustrate it below in Fig. 4, in the case of a double-line three-phase fault.

Considering the critical cluster P2P4F1F2 obtained by the composite criterion, we compute $t_c^E = 0.34\,\text{s}$; the actual CCT is found to be $t_c^S = 0.25\,\text{s}$. The explanation of such a large discrepancy is suggested by Fig. 4, where swing curves are drawn for three clearing times : one very close to the actual CCT, the other a little larger, the third much larger. Figure 4a shows that all four machines of the critical cluster start accelerating together. But the opening of the double-line at $t_e = 0.26\,\text{s}$ makes the electrical distance of P2P4 with respect to F1F2 increase significantly. At the same time, it brings machines P2P4 much closer to some local load, resulting in a transfer of power and a decrease of the machines' kinetic energy : the rotor angles of P2P4 start swinging back, while those of F1F2 steadily continue diverging. In turn, this brings the Partial Centre Of Angles (PCOA) of set $\boldsymbol{S}$ closer to the PCOA of set $\boldsymbol{A}$, and results in a too optimistic diagnostic of the EEAC. The above phenomena are amplified at $t_e = 0.38\,\text{s}$, while they fade for $t_e = 0.50\,\text{s}$ (see respectively Figs. 4b, 4c).

Note that the candidate critical cluster composed of the sole machines F1F2 yields an even more optimistic EEAC diagnostic.

Such post-fault splittings of the CC machines' angular evolution into distinct groups cannot be properly handled by the EEAC. And the necessity of detecting them is imperative, since they naturally yield overoptimistic - and hence dangerous - diagnostic.

A convenient indicator able to identify this splitting should account for the number and the relative size of the machines which, initially belonging to the CC, experience a substantial change of their acceleration with respect to the common, initial acceleration of the CC. Figs. 4 suggest moreover that the indicator should appraise the splitting at a convenient clearing time (see below).

The following normalized standard deviation σ_γ meets the above requirements :

$$\sigma_\gamma = \frac{\left[\sum_{k\in \boldsymbol{S}} M_k \left(\gamma_k(\tau) - \gamma_s(\tau)\right)^2\right]^{1/2}}{\gamma_s(0^+) \left(\sum_{k\in \boldsymbol{S}} M_k\right)^{1/2}} \,.\, 10^2 \qquad (18)$$

where

τ is a time larger than t_c^E

$\gamma_s(0^+) = \ddot{\delta}_s(0^+)$ is the initial acceleration of the CC

$\gamma_k(\tau)$ is the acceleration of the k-th machine of the CC at time τ , corresponding to the OMIB angle $\delta = \delta_c(1+\epsilon)$; $\gamma_k(\tau)$ is obtained by formula (1) where P_{ek} is replaced by its OMIB approximation (6) :

$$\gamma_k(\tau) = M_k^{-1}\,[P_{mk} - E_k\,(\sum_{\ell\in \boldsymbol{S}} E_\ell G_{k\ell} + \sum_{\ell\in \boldsymbol{A}} E_\ell Y_{k\ell} \cos{[\delta_c(1+\epsilon) - \theta_{k\ell}]}\,)] \qquad (19)$$

$Y_{k\ell}, \theta_{k\ell}, G_{k\ell} = Y_{k\ell}\cos\theta_{k\ell}$ are post-fault configuration parameters

$\gamma_s(\tau)$ is the mean acceleration of the CC at τ :

$$\gamma_s(\tau) = \frac{\sum_{k\in \boldsymbol{S}} M_k\,\gamma_k(\tau)}{\sum_{k\in \boldsymbol{S}} M_k} \,.$$

The value of ϵ must be carefully chosen. Indeed, for too small an ϵ , the accelerations of the CC machines are not yet reorganized after the brusque transition from during-fault to post-fault; conversely, for too large an ϵ , the CC machines are definitely out of synchronism and their accelerations too far from the values of concern; in the former case the detection of the CC splittings may be spoiled by false alarms, in the latter by non detections. This is illustrated by the sample of values given in Table 1 in three cases : an actual CC splitting (good detection), a coherent CC (normal case), and a more heterogeneous, complex case.

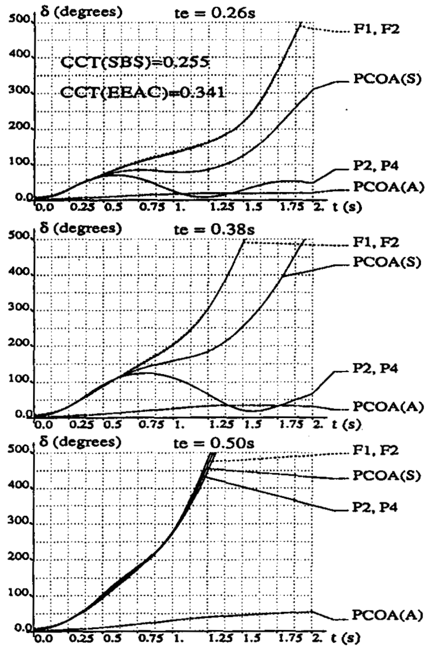

Figure 4 - *Swing curves relating to a double-line fault and three different clearing times*

Finally, observe that the computation of the proposed index σ_γ requires virtually negligible time. Recall also that, in addition to its detection capability, σ_γ warns about the fact that the provided t_c^E value is larger than the actual CCT.

4.2.2 Sensitivity of the OMIB to δ_0

Figure 2 illustrates the observation that the accuracy of the OMIB assessment, δ_c , greatly depends on the accuracy on the initial value, δ_0 (see § 2.3.1). Indeed, the larger the sensitivity of this assessment to δ_0 , the greater the risk of obtaining an erroneous diagnostic; this is particularly dangerous for very small CCTs. Hence, the idea of developing an index appraising this sensitivity. Below, we propose the following normalized index :

$$S_{\delta_o} = \frac{\partial\,(\delta_c - \delta_0)}{\partial \delta_0}(\delta_c - \delta_0)^{-1}.\,10^2 = \left(\frac{\partial \delta_c}{\partial \delta_0} - 1\right)(\delta_c - \delta_0)^{-1}.\,10^2 \,. \quad (20)$$

Table 1

	CC	$\epsilon = 0$		$\epsilon = 0.25$		$\epsilon = 0.50$		$\epsilon = 0.75$		$\epsilon = 1$	
		γ_k	σ_γ	γ_k	σ_γ	γ_k	σ_γ	γ_k	σ_γ	γ_k	σ_γ
A splitting case	F1	-2.9		-3.0		-2.4		-1.1		1.0	
$t_c^S = 0.256$	F2	-1.8		-2.0		-1.5		-0.2		1.7	
$t_c^E = 0.341$	P2	-13.8	20	-14.7	21	-14.3	21	-12.6	21	-9.7	19
$\gamma_s(0^+) = 14.4$	P4	-13.8		-14.7		-14.3		-12.6		-9.7	
A normal case											
$t_c^S = 0.256$	F1	-1.5		-2.6		-3.4		-3.9		-4.1	
$t_c^E = 0.230$	F2	-0.5	3	-1.5	3	-2.2	3	-2.7	3	-3.0	3
$\gamma_s(0^+) = 12.0$											
	F1	0.8		7.9		16.3		24.6		31.2	
A complex case	P1	-0.6		6.8		15.8		24.9		32.2	
	P2	-0.5	34	6.8	24	15.9	10	24.9	5	32.2	19
$t_c^S = 0.805$	P3	-0.7		6.7		15.8		24.9		32.2	
$t_c^E = 0.857$	P4	-0.7		6.7		15.9		24.9		32.2	
$\gamma_s(0^+) = 7.5$	DB1	-13.5		-2.5		11.8		26.8		39.6	
	DB2	-6.7		2.4		14.0		25.7		35.7	

The calculation of $\partial\delta_c/\partial\delta_0$ in terms of the system parameters yields the following analytical expression :

$$\frac{\partial\delta_c}{\partial\delta_0} = \frac{P_{cD} - P_m + P_{\max D}\sin(\delta_0 - \nu_D)}{P_{cD} - P_{cP} + P_{\max D}\sin(\delta_c - \nu_D) - P_{\max P}\sin(\delta_c - \nu_P)} \,. \tag{21}$$

The reason for considering *relative* sensitivity by dividing by $(\delta_c - \delta_0)$ is to get interesting information about the value of δ_c, and hence of CCT; indeed, among all detected "sensitive" EEAC diagnostics, those having significantly larger values S_{δ_0} than normal correspond to very small CCTs, or even to static instability cases.

4.2.3 Sensitivity of CCT to α_1

The discussion of § 2.3.2 and the resulting expression (16) indicate that α_1 is chosen as the smallest between $\bar{\alpha}_1$ and α_1^* values. In general, where α_1^* is chosen, the resulting CCT is quite insensitive to it. But when $\bar{\alpha}_1$ is smaller than α_1^*, and hence automatically selected, the Taylor series becomes quite sensitive to it [10]. In such cases the error on t_c^E may not be negligible. It is therefore necessary to identify and discard these cases, as being likely to provide erroneous diagnostics.

Note, however, that cases relying on $\bar{\alpha}_1$ values correspond to large CCTs, i.e. to less interesting stability assessment. Indeed, the severer the fault, the greater the influence of γ over $\ddot{\gamma}$ on t_c^E, and the smaller the influence of α_1 on t_c^E. A contrario, the more important the $\ddot{\gamma}$, the larger the influence of α_1, and the larger the CCT. (Observe that $\alpha_1 = 0$ corresponds to totally neglecting $\ddot{\gamma}$, $\alpha_1 = 1$ to fully taking it into account, see eq.(14)).

In particular, the "$\bar{\alpha}_1$ cases" detected in our simulations have corresponded to CCTs above 0.7 s, apart from one where $t_c^S = 0.5\,\mathrm{s}$.

Incidentally, the quantitative appraisal of the sensitivity of t_c^E to α_1 could be computed by the following index :

$$S_{\alpha_1} = \frac{\partial t_c^E}{\partial\alpha_1} = -\frac{t_c}{2\alpha_1} - \frac{6\alpha(\delta_c - \delta_0)}{\alpha_1\, t_c\, f\, \ddot{\gamma}} \tag{22}$$

where

$$f = \left[\left(\frac{6\gamma}{\ddot{\gamma}}\right)^2 + \frac{24\,(\delta_c - \delta_0)\,\alpha_1}{\ddot{\gamma}}\right]^{1/2} . \tag{23}$$

The t_c appearing in the RHS of (22) is given the approximate value t_c^E.

Apart from the "$\bar{\alpha}_1$ cases", the Taylor expansion furnishes quite accurate results. Of course, it is always possible to just integrate eq.(8) as for detailed machine models [17]. But the some inaccuracies introduced by the series are largely compensated by its significant benefits to the EEAC : indeed, when sensitivity assessment is sought, the resulting analytical expressions are particularly interesting.

5 SIMULATION RESULTS

We summarize the main results obtained for the 480 cases of the PALUEL area (60 stability scenarios × 8 operating points) as well as the single-line and double-line 3ØSCs (amounting respectively to 364 and 134 cases) run for the entire 400-kV EDF system on a single operating point.

Recall that the benchmark for comparisons is the SBS method; the discrepancy of the EEAC diagnostic is expressed by

$$\Delta = \frac{t_c^S - t_c^E}{t_c^S} \,. \tag{24}$$

The accuracy of the EEAC in terms of CCTs is deemed satisfactory if this discrepancy lies in between ±10 %. Accordingly, we decide to consider as

"bad data" : discrepancies outside the ±10% range,
"good detections": bad data correctly detected by the indicators,
"false alarms" : discrepancies in the ±10% range unduly identified as unreliable by the indicators,
"non detections" : bad data not detected.

Admittedly the above arbitrary definitions might be objectionable; in particular, an error of − 10 % is severer than another of +10 % (overoptimistic vs. overpessimistic diagnostic); it is merely used to ease the comparisons.

Critical clusters (CCs)

Concerning their identification, certain results have already been reported in § 4.1.2. In addition, we observe the following.

In the PALUEL area, they are composed of (some of the) machines of the group (P1,P2,P3,P4), of the group (F1,F2) and/or of H4. The number of machines varies in between 1 and 7. However, some of them may belong to the same site and behave coherently throughout the transients; forcing them together in the candidate CCs during the combinatorial procedure allows substantial savings (see Remark 3 of § 4.1.2).

Note that in this set of 480 cases, the composite selection criterion of § 4.1.2 has identified all but one CC; among them, 38 CCs were unidentifiable by the sole acceleration criterion of § 4.1.1.

In the set of simulations covering the entire 400-kV system, we have been led to lower the thresholds of the composite selection criterion in order to embed a larger number of candidate CCs; in particular, in the Rhône valey area CCs often comprise a large number of machines (as large as 13), not always appearing close enough to the top of the pre-fault or the post-fault lists. In such situations, the above suggestion of combining similar machines becomes a practical necessity.

Error distribution

Figure 5 provides the histogram of the error distribution vs. $\Delta\,\%$. Observe that the majority of the errors are confined in between − 8% and + 10 %, i.e. within acceptable limits. Table 2 shows that among the "bad data", most of them are detected by the indicators σ_γ, S_{δ_0}, $\bar{\alpha}_1$ (see below).

Reliability assessment of the indicators

The thresholds chosen in this study were fixed at $\sigma_{\gamma\mathrm{thr.}} = 18$ (for $\epsilon = 0.5$), and $S_{\delta_0\mathrm{thr.}} = -15$. These values were chosen to realize a compromise allowing to detect all truly dangerous situations while limiting the number of false alarms.

Table 2 gathers the total number of alarms (good detections, false alarms) along with non detections, for the whole set of simulated cases; distinction is made between cases corresponding to actual CCTs smaller and larger than 500 ms. Note that the number of alarms differs from that of detected cases since some of them may be identified by more than one indicator. For each indicator, numbers between brackets specify cases corresponding to a unique indication. Among the 978 simulated cases, we found 46 false alarms and 79 bad data, of which 58 are correctly detected and 21 non detected.

The distribution of these non detected cases is given in Table 3. We note that they don't contain dangerous diagnostics $(\Delta \leq -10\,\%)$: the corresponding errors are comprised in between +10 % and +14 %. Moreover, for CCT < 250 ms there are only two erroneous diagnostics; they amount to + 11 % and + 12 %.

An information additional to that given in Table 2 is that among the good detections provided by S_{δ_0} , 13 correspond to values of S_{δ_0} larger than 10^3 , identifying cases where the actual CCT is almost zero : in addition to its detection capability, S_{δ_0} indeed provides a much more precise assessment.

As a counterpart to this benefit, S_{δ_0} also induces a good deal of false alarms; most of them are found to correspond to errors ranging in between $-10\,\%$ to $-6\,\%$ and $6\,\%$ to $10\,\%$. The histogram of Fig. 6 provides the error distribution of these false alarms.

Finally, the histogram of Fig. 7 portrays the distribution of the σ_γ values . The total number of cases is smaller than 978 since σ_γ is meaningful only for multimachine critical clusters. Observe that according to Table 2, σ_γ introduces much less false alarms than S_{δ_0} .

Overall, the cases detected by the indicators (good detections as well as false alarms) lead to discard about 10.6 % of the EEAC diagnostics.

Computing time requirements

The EEAC computing time results from : (i) the computation of the admittance matrix reduction; (ii) the scanning of candidate CCs obtained by the composite criterion of § 4.1.2, and the computation of the corresponding candidate CCTs.

As an indication, in this study the mean number of candidate CCs was found to be about 230; the mean computing time corresponding to the calculation of a sole candidate CCT was found to be about 0.035 s, leading to an overall computation for step (ii) of 8 s. These times could be further substantially improved with minor programming changes. Overall, the mean computing time for a single contingency assessment was of about 21 seconds. That of a time-domain step-by-step integration with similar modelling was of about 7 minutes.

Observe that the scanning of a list of contingencies makes the comparison even more favorable to the EEAC. Indeed, in the case of multiple contingencies, the use of superposition techniques allows to get successive during- and post-fault $\boldsymbol{Y}$ matrices at much lesser computing effort and thus to realize interesting savings in above step (i) [7].

Discussion

The salient results drawn from the simulations are as follows.

The composite criterion proposed in § 4.1.2 for the selection of candidate critical machines has shown to significantly improve the acceleration criterion used so far, and to work satisfactorily. Yet, there are some few isolated cases, where the number of candidate critical machines is quite large. This suggests that there is still room for improving the identification procedure of the critical cluster.

The three indictors σ_γ , S_{δ_0} and $\tilde{\alpha}_1$ show to suitably detect large errors at the expense of some false alarms; they greatly contribute to render the method robust under extreme conditions. Recall that they were devised to detect specific types of errors (discussed in § 4.2) which have appeared to be the main causes of the bad data (and particularly the largest ones). Besides their ability to detect anomalies, the indicators also carry interesting information : (i) σ_γ detection suggests that the actual CCT is quite smaller than that assessed by the EEAC (about, say, 25%); (ii) large values of S_{δ_0} (e.g. above 800) identify very small CCTs (smaller than, say, 40 ms); (iii) $\tilde{\alpha}_1$ detection corresponds to large CCTs (above 500 ms).

Finally, the EEAC shows to be computationally extremely fast : in the case of single contingency assessment, the gain of the EEAC over a time-domain step-by-step with similar modelling is about 20. This gain becomes even larger when scanning a list of contingencies.

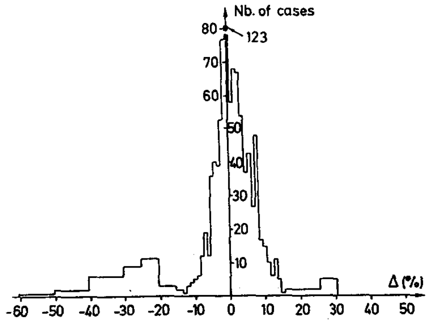

Figure 5 - *Histogram of error distribution*

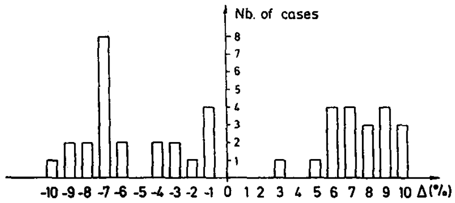

Figure 6 - *Histogram of false alarms induced by* S_{δ_0}

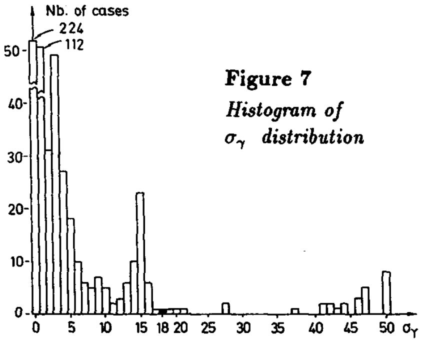

Figure 7
Histogram of σ_γ *distribution*

Table 2 - Reliability assessment of the various indicators

t_c^S range		< 0.5 s	> 0.5 s	Σ
No. of cases		794	184	978
Good detection (unique indication)	S_{δ_0}	23(23)	26(11)	49(34)
	σ_γ	3(3)	22(13)	25(16)
	$\tilde{\alpha}_1$	0	15(8)	15(8)
	All	26(26)	63(32)	89(58)
False alarm (unique indication)	S_{δ_0}	29(29)	17(14)	46(43)
	σ_γ	2(2)	2(1)	4(3)
	$\tilde{\alpha}_1$	0	3(0)	3(0)
	All	31(31)	22(15)	53(46)
non detection		15	6	21

Table 3 - Distribution of all 21 non detected cases

t_c^S (s) \ Δ%	-12	-11	-10	10	11	12	13	14	15	Σ
< 0.25					1	1				2
0.25 - 0.50				1	9	2		1		13
0.50 - 0.75						1	5			6
Σ				1	10	4	5	1		21

6 CONCLUSION

A composite criterion has been proposed to improve the selection of relevant candidate critical machines. It is based on the combination of initial accelerations of the machines, and on their distance from the fault location both in the pre- and post-fault system configurations. Further, three safeguards have been developed to circumvent possible failures of the EEAC. One detects the possible splitting of the critical machines in the post-fault stage; the other concerns the sensitivity of the equivalent one-machine-infinite bus system to its pre-fault angle; the third identifies the sensitivity of the critical clearing time to a parameter of the method. The computation of the above safeguards is virtually negligible, while their detection capabilities contribute to enhance the robustness of EEAC. Overall, they provide a real-time indicator, promising for operation planning or real-time operation.

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Biographies

Yusheng Xue was born in Jiangsu, China, in 1941. He received the BSSB from Shandong Institute of Technology in 1963, the MSSE from EPRI, China in 1981, and the Ph.D. degree from the University of Liège in 1987. He is currently the depute director of the System Engineering Department and in charge of power system application software in NARI (Nanjing Automation Research Institute), China.

Louis Wehenkel was born in Nurnberg, Germany, in 1961. He received the Electrical (Electronics) engineering degree in 1986 and the Ph.D. degree in 1990 both from the University of Liège, Belgium, where he is presently a research assistant of F.N.R.S. (Fonds National de la Recherche Scientifique). His research interests lie mainly in the application of artificial intelligence methodologies to power system security assessment.

Régine Belhomme was born in Waremme, Belgium, in 1963. She received the Electrical (Electronics) engineering degree in 1986 and the Ph.D. degree in 1990 both from the University of Liège, Belgium, where she is presently a senior research assistant of the F.N.R.S. (Fonds National de la Recherche Scientifique). Her research interests lie mainly in power system transient stability.

Patricia Rousseaux was born in Verviers, Belgium, in 1959. She received the Electrical (Electronics) engineering degree in 1982 and the Ph.D. degree in 1988 both from the University of Liège, Belgium, where she is presently an assistant professor in the Department of Electrical Engineering. Her research interests are in the area of power system control and in signal processing.

Mania Pavella received the Electrical (Electronics) engineering degree in 1958 and the Ph.D. degree in 1969 both from the University of Liège, Belgium, where she is presently a Professor. Her research interests lie in the field of electric power system analysis and control.

Edwige Euxibie was born in Amiens, France, in 1962. She received the electrical engineering degree in 1984, and the Electrical DEA degree in 1990 (Diplôme d'Etudes Approfondies), both from the Ecole Nationale Supérieure d'Ingénieurs Electriciens de Grenoble, France. She is presently a research engineer in the "Control and Operation of Power Systems" group, Research and Development Department of EDF. Her research interests lie mainly in the area of power system operation.

Bertrand Heilbronn was born in Paris, France, in 1950. He received his degree of engineer from the Ecole Polytechnique in 1972, and from the Ecole Nationale Supérieure des Télécommunications in 1974. He has been working as a research engineer at EDF since 1978, and since 1985 in the field of power system control. He is presently manager of the research group "Control and Operation of Power Systems", in charge of power system monitoring and control studies.

Jean-François Lesigne was born in Paris, France, in 1958. He received the electrical engineering degree in 1981 from SUPELEC (Ecole Supérieure d'Electricité), Gif-sur-Yvette, France. He is presently manager of the "Power System Dynamics" Division, and in charge of power system transient stability and electromechanical studies. The results of these off-line studies are used by the operators, in the power system national control center.

Discussion

M. A. Pai (University of Illinois, Urbana, IL 61801): This paper is a very useful extension of the earlier work at the University of Liege and will be of interest to industry because of the extensive testing of the algorithm on the EDF system. The important contribution of the paper lies in examining the possible inherent sources of error in the original EEAC approach and applying corrections to the approach which results in better CCT. For example the authors have addressed the need to compute the CC's for faults in the middle of the system (see 4.1) when it may be difficult to group candidate clusters. However the explanation 4.1.1(b) is not quite clear. They may like to elaborate. Is it possible in such cases that there may be more than two clusters? The authors have rightly recognized the post-fault splitting of the critical cluster in some instances. I agree that such cases cannot be handled effectively by EEAC approach. Such cases are best handled by actual fast simulation of detailed model including relay performance.

The simulation results are quite impressive and the authors have pointed the cases where their method did not succeed. This gives a true perspective on the problem. What is interesting from the industry point of view is the computation time that is involved in order that EEAC may become an on-line DSA tool. The section 2.1.6 on computing times is not clear. Given a contingency the modified EEAC method requires steps (i)–(iii) of section 2.2. Do all these steps together take 21 seconds? Also the 7 minute by SBS method will involve repetitive computation to arrive at CCT. How many such repetitive computations were required? These questions are of interest if EEAC method is to become an on-line DSA tool.

On the whole I think the paper is very informative and thorough both on the positive aspects as well as some of the difficult aspects of the EEAC method.

Manuscript received November 7, 1991.

Lamine Mili and Thomas Baldwin (Virginia Polytechnic Institute and State University, Blacksburg, VA): The authors are to be congratulated for their continued work in the development of the Extended Equal Area Criterion (EEAC), and their latest contribution of indices to warn of invalid results. This brings the EEAC method closer to on–line applications. To our knowledge, it is the only candidate that can possibly produce results that are faster than real–time when processing phasor measurements [A1]. The main feature of these measurements is their ability to track fast transients that may take place in the system. This opens the door to dynamic security analysis, thought not only as a tool for computer–aided dispatch, but also as a feedback for automatic monitoring and control of the system. The purpose of this control is to steer away the system from instability following a major contingency. The other competitors to the EEAC are the PEBS methods. Although major advances have been recently made [A2] that overcome the problem of local maxima of the potential surface [A3], these methods remain computationally intensive, which preclude their use in real–time application in their present form.
In order to be able to implement the scheme described in the paper, the authors' comments on the following points will be appreciated.

1. Is the electrical distances Y^{*}_{if} used in p_i are the inverse of the Z^{*}_{if} elements of the bus impedance matrix? In our opinion the electrical distances proposed in [A4] are more reliable than Y^{*}_{if} ; they can handle generator as well as load buses. In contrast, the method suggested in [A5] seems not to be applicable here. A suggestion for a better selection criterion than $p_i = a_i\, Y^{*}_{if}$ is to use a normalized distance weight function, yielding

$$p_i = a_i\,(Y^{*}_{if} / \sum_i Y^{*}_{if}).$$

This will make the threshold p_{th} less dependent on the fault location. Indeed, the determination of this threshold is a critical step for the reliability of the selection. Could the authors give some hints that help us to tune it ? The paper is silent on this important matter.

2. We feel that the whole selection procedure does not guarantee that all of the 'actual' critical machines have been identified for inclusion in the CCC. In fact there is a need for an additional index that tells us with high confidence that none of the critical machines is left out of the CCC list. Presently we are working on such a criterion. The idea is to represent each machine by a point in a multi–dimensional space; this point is identified by the kinetic energy, acceleration, and the derivitives of the acceleration of the associated machine. The bulk of the point cloud is considered to be the stable machine cluster. The other machines are candidates for the critical cluster, and are referred to as outliers. They can be identified through multivariate statistical analysis [A6].

3. Concerning the identification test of other possible post–fault splittings which generate poor results, could the authors give some rules for determining the threshold value, $\sigma_{\gamma thr}$? Can the test be able to handle a splitting of the critical machines during the fault time period ?

4. We commend the authors for proposing the $S_{\delta o}$–test that protects against misleading values for δ_c. This is a very important test that does not only reveal a weakness of the OMIB model, which is otherwise very accurate in a two–machine system, but also indicates an intrinsic impossibility to analyse and to predict the stability of such a system. Indeed, a great sensitivity of δ_c to δ_0 is due to a chaotic behavior of the system. Here chaos is refered to as a small change in the initial condition, δ_0 , leads to a large change in the response, δ_c. Obviously the stability of such a system cannot be analyzed, whatever the method that is used, be it the step–by–step method or the PEBS method. Therefore, we recommend the inclusion of such an index in any transient stability analysis.

5. In the simulation results reported in Section 5, 21 out of the 79 discrepancies outside the ± 10% range that cannot be analyzed by EEAC are not detected by the indices. This represents a percentage of failure of 26.6% , which is too high. Also there are 46 false alarms which result into 104 rejected cases. Obviously there is still some room of improvement in this regard. An important question arises here from a real time application viewpoint: what alternative methods do the authors recommend to use in case of invalidation of EEAC ?

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Y. Xue, L. Wehenkel, R. Belhomme, P. Rousseaux, M. Pavella, E. Euxibie, B. Heilbronn, J.F. Lesigne : We thank the discussers for their interest in our work. Their pertinent comments and questions allow us to clarify and further expand on essential issues of the paper.

Professor Pai. Paragraph 4.1.1 concerns a pragmatic criterion based on the machines' initial accelerations only, used to select the candidate critical machines. Applied to the EDF system, this criterion has met some failures. For example, in cases where many machines acquire large accelerations, no clear distinction or gap may appear between relevant and irrelevant machines; limiting the candidate machines to a reasonable number, say 9, (remember that their combinatorial taken one by one, two by two, ..., leads to $2^9 - 1 = 511$) cannot then consistently select all the critical machines.

Let us illustrate this difficulty in the following particular case : the actual critical cluster (CC) is found to be composed of machines H4 P2 P1 P4 P3 F1 F2, while the acceleration criterion classifies the machines as shown in Table A : note that limiting the candidate critical machines (m) to the first 9 ones, classified according to their initial accelerations (a), prevents machines F1 F2 from being considered in the combinatorial . (Actually F1 F2 are classified 13th and 14th, with accelerations of respectively 6.9 and 6.8). Here many irrelevant machines are inserted in between the interesting ones. The above CC, identified by the EEAC as being that providing the minimum candidate CCT, is also corroborated by the swing curves obtained via an SBS program; these curves, drawn in Fig. C, clearly show the splitting of the system machines into the above 7 and all remaining ones (only a few of these latter are drawn in the figure).

Table A

m	a	CC
H4	18.5	H4
P2	16.3	P2
P1	16.2	P1
P4	16.2	P4
P3	16.1	P3
V1	11.8	F1
B1	9.3	F2
G2	8.1	
G1	8.1	

Table B

m_1	p	m_2	d^P	CC
H4	227.0	**H4**	11.33	H4
P2	180.0	**P1**	6.45	P2
P4	177.0	**P2**	6.41	P4
P1	177.0	DB1	4.51	P1
P3	174.0	F2	4.02	P3
G2	81.5	**P3**	3.91	F1
G1	81.3	**P4**	3.88	F2
DB1	71.2	F1	3.75	

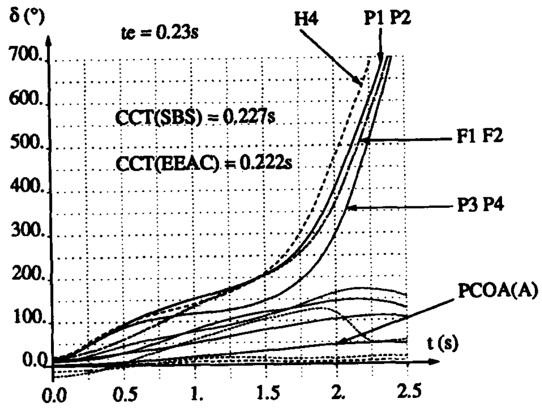

Figure C

The fact that in the above case the acceleration criterion fails to identify the proper CC does not imply the existence of more than two clusters. Rather, it suggests that other parameters, in addition to the initial accelerations, must be taken into account to correctly select the critical machines; this has led us to derive the composite criterion described in §4.1.2. Table B illustrates how this latter works in the previous case and shows its ability to identify the actual CC. In this table, m_1 denotes the machines selected according to the criterion $p_i = a_i * Y_{ij}^0$ (steps 1 and 2 of §4.1.2 of the paper; here $p_{i\,thr.}$ is taken as 0.3 $p_{i\,max}$, where $p_{i\,max}$ is the maximum of the p_i values) ; m_2 denotes the machines selected according to their post-fault admittance d^P with respect to the faulted area (step 4 of §4.1.2); the bold face machines appearing in column m_2 are those obtained according to step 2 of §4.1.2.

Concerning the computing time requirements (section 5), the EEAC process may be divided into 4 main steps.

Step 1 consists of reading the system data. The corresponding computing time is not taken into account in the paper (for the EEAC as well as for the step-by-step numerical integration method).

Step 2 concerns the calculation of the machine electromotive forces behind the transient reactances, the determination of the constant impedances representing the loads, the computation of the pre-fault unreduced admittance matrix and finally its reduction at the machines' internal nodes.

Step 3 takes into account the computation of the during-fault and post-fault reduced admittance matrices, as well as the calculation of the products $p_i = a_i * Y_{ij}^0$ (see §4.1.2 of the paper) needed for the composite selection criterion.

Step 4 relates to the 3 steps [(i) to (iii)] of section §2.2, namely the building of a list of candidate critical machines, the consideration of all their combinations as candidate critical clusters (CCCs), the computation of their corresponding CCTs so as to find the smallest one, yielding the actual CCT, and the actual CC. Step 4 also includes the computation of the indicators for this latter CC.

The computing time for steps 2 and 3 altogether is about 13 s. For step 4, the mean number of CCCs was found to be about 230 and the corresponding computing time for all of them was approximately 8 s. It corresponds to 0.035 s for a single CCC.

The sum of steps 2, 3 and 4 thus gives 21 s. This represents the time needed for a single contingency (when the reading of the data is excluded). Note that step 2 is performed only once per operating condition. Hence, in the multicontingency case, each new contingency implies only steps 3 and 4 and greater computational gains are then obtained. On the other hand, even greater benefits could be obtained from the use of superposition techniques to compute the during-fault and post-fault reduced admittance matrices from the pre-fault one.

The step-by-step numerical integration method is a variable step size, 4th order Runge-Kutta method. The CCT for one contingency is computed iteratively and each iteration requires an integration up to 2 s. For the considered simulations, the mean number of iterations per CCT was about 7 and this corresponds to a time of approximately 7 min.

N.B. The computing times were obtained on a SUN 4/280 RISC computer with 64MB central memory, 10MIPS and 1.6 MFLOPS.

Drs. Mili and Baldwin. Let us first observe that although we are not very familiar with the method proposed in [A1], we believe that this latter might be complementary rather than competitive to the EEAC. Similarly, we don't take the PEBS methods as competitors to the EEAC. This latter has its own potential : it is much faster than PEBS and in addition it provides analytical sensitivity analysis tools as well as means to control (e.g. see Ref. [10] of the paper).

As concerning your specific questions, we consider them below in the sequence they appear in your discussion.

1. The electrical distances proposed in [A4] are designed for the purpose of voltage control, whereas transient stability is mainly concerned with active power. Therefore, distances of your Ref. [A5] are a priori more appropriate; they handle both generator and load buses taken as the fault location. It is precisely the elementary electromechanical distances of Ref. [A5] which have suggested the parameters appearing in the composite criterion of §4.1.2 of the paper.

We agree with you to consider a normalized distance. This is why we take $p_{i\,thr.} = 0.3\ p_{i\,max}$, where $p_{i\,max}$ is the maximum of the p_i values; this corresponds to considering the normalized distance : $p_i/p_{i\,max}$, with a threshold of 0.3 . Anyhow, this threshold is power system dependent; it should be tuned in a first, off-line exploration of the method.

2. Indeed, the whole selection procedure does not guarantee that all of the "actual" critical machines have been identified for inclusion in the candidate critical clusters. There is certainly room for improvement, along either the method you propose or another. We understand that your method is based on kinetic energy, acceleration and its derivatives; we do not see any notion of electrical distance; or maybe it is implicitly taken care of.

3. Once again $\sigma_{\gamma\,thr.}$ is system dependent and should be tuned via a preliminary off-line exploration of the method. As for the splitting of the critical machines during the fault-on period, we believe that since there is no discontinuity during this period, it is much more meaningful to consider this splitting just (say τ sec.) after the fault clearing. Hence, the σ_γ indicator proposed in the paper.

5. The EEAC as all other direct methods is based on a number of conjectures and may occasionally fail. The concern is to avoid overly misleading diagnostics, especially dangerous (i.e. overoptimistic) ones, or otherwise to detect them. The 21 undetected erroneous diagnostics out of the 79 bad data are, without exception, rather mild discrepancies as indicated in Table 3, where one can see that they are neither harmful nor very large. The 26.6% (ratio of 21 over 79) is too crude an indication and should not be taken alone. Rather, one should compare the situation "without bad data identification" (79/978 i.e. 8.1% of not detected bad data) versus "with bad data identification" (only 21/978 = 2.1 % of non detected bad data, but 104/978 = 10.6% of rejected diagnostics).

Overall, the existence of 104 rejected cases over the 978 explored ones (whether rightly or not) might suggest that there is still room for improvements. Anyhow we believe that perfection cannot be expected from any approximate method - and EEAC is such a method. Whenever it fails we would suggest to use a simplified SBS rather than PEBS; this latter was often found in the case of the EDF system to be much less accurate than EEAC and on average much more time consuming than SBS.

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