A CONTINGENCY FILTERING, RANKING AND ASSESSMENT TECHNIQUE FOR ON-LINE TRANSIENT STABILITY STUDIES

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Abstract: A two-block technique is proposed for on-line contingency screening, ranking and assessment in transient stability studies. Its design relies on a hybrid direct - time-domain method called SIME. Basically, SIME assesses stability by transforming the multi-machine power system parameters into those of a one-machine infinite bus system, then by calling upon the equal-area criterion. Stability margins thus obtained are used to classify contingencies, select the "interesting" ones and, finally, rank and assess these latter. An 88-machine EPRI test system illustrates the technique and shows its ability to correctly handle the simulated contingencies, while complying with real-time computational requirements.

Keywords: Power system transient stability; Contingency filtering and ranking; Dynamic security assessment; SIME method.

1. INTRODUCTION

In transient stability studies, contingency filtering and ranking are important but challenging tasks, especially when they must comply with real-time requirements. Time-domain methods can hardly tackle tasks such as determination of adequate stability margins. They can certainly compute stability limits (critical clearing times or power limits); but they would require prohibitive computing times to handle a list of, say, some tens of contingencies. These methods can also classify contingencies into "stable" and "unstable" with respect to a given clearing time, but in a rather crude and inefficient way; indeed, in this case, they cannot rank the "interesting" (i.e., the unstable) contingencies and, in addition, they spend a good deal of CPU time to identify the stable, i.e., the "uninteresting" ones. The technique proposed in this paper provides an alternative solution which besides filtering and ranking contingencies efficiently, it assesses the "interesting" ones in a very informative way.

This "filtering-ranking-assessment" (FRA) technique relies on the hybrid transient stability method called SIME (standing for SIngle Machine Equivalent). In short, SIME transforms the trajectories of a multi-machine system provided by a time-domain program into the trajectory of a One-Machine Infinite Bus (OMIB) equivalent. A detailed description of SIME may be found in earlier publications (e.g., see [1] to [3]), whereas Section 2 glances at its essentials. Let us only stress here that: (i) SIME provides an accurate replica of the stability assessment of the time-domain program that it drives, by refreshing the OMIB parameters at each time step; (ii) SIME does not replace this program; rather, it complements it with multiform information provided by the OMIB together with the equal-area criterion; in particular, with stability margins which are the core of the proposed FRA technique. The resulting two-block procedure is elaborated in Section 3. Section 4 reports on simulation results obtained with the EPRI test system C [4], comprising 88 generators, 434 buses and 2357 lines. In these simulations the time-domain program coupled with SIME is ETMSP. Besides, ETMSP is used alone as a reference for comparisons. 252 contingencies are simulated. It is shown that the technique classifies them reliably (i.e., that it captures all the dangerous contingencies), ranks correctly the "interesting" ones, and finally assesses these latter in terms of critical machines and margins. These various tasks are accomplished within computing times compatible with on-line requirements.

Paper accepted for presentation at the International Conference on Electric Utility Deregulation and Restructuring and Power Technologies 2000, City University, London, 4-7 April 2000.

2. SIME AT A GLANCE

2.1 Foundations

The multi-machine power system parameters provided by a time-domain program are transformed into those of a one-machine infinite bus (OMIB) system at each time step of the simulation. Further, at each time step, the stability of the OMIB is explored by the Equal Area Criterion (EAC); the procedure is stopped as soon as the instability conditions of the EAC are reached.

More precisely, after a contingency inception and its clearance, SIME drives a time-domain program so as to accomplish the following tasks: identify the critical and non critical machines and aggregate them into two groups; replace these groups by successively a two-machine, then an OMIB equivalent system; assess transient stability of this OMIB, using the EAC [1 to 3] [1]. The various steps of the method are briefly described below and illustrated in Figs 1, corresponding to a real stability case.

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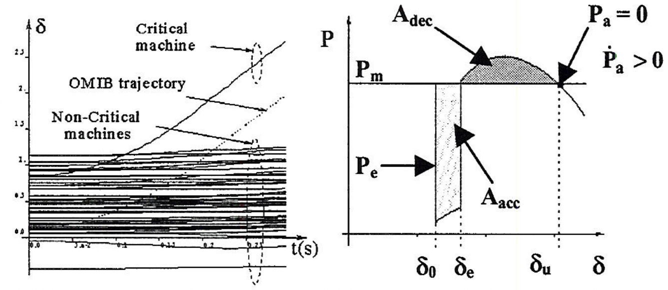
[1] This OMIB transformation generalizes the one used in the EEAC method [5, 6]. In this respect, SIME may be considered as a generalization of the EEAC.



(a) Power system swing curves, critical machine identification, and OMIB swing curve

(b) Equal area criterion application to the OMIB equivalent system.

Fig. 1: Essentials of the SIngle Machine Equivalent (SIME) Method (Taken from [6]).

By definition, the critical machines are those which cause the system loss of synchronism. To identify them, SIME selects candidate OMIBs at each time step of the stability simulation. The procedure is stopped as soon as one of the candidates reaches its unstable angle δ_u (defined below): it is then declared to be the OMIB of concern.

2.2 OMIB parameters, margins, and by-products

The OMIB parameters δ, ω , M, P_m, P_e are computed from the corresponding individual machine parameters, using the concept of partial center of angle [1,2]. Figure 1a portrays the OMIB trajectory plotted from the multi-machine trajectories (swing curves).

According to the EAC, a stability margin is the excess of the decelerating over the accelerating area; this yields the following expressions for unstable and stable margins [1, 2]:

$$\eta_u = -\frac{1}{2} M\omega_u^2$$

$$\eta_{st} = \int_{\delta_r}^{\delta_u} |P_a| d\delta \ .$$

In these expressions,

- P_a is the OMIB accelerating power, i.e., excess of its mechanical over its electrical power: $P_a = P_m - P_e$;
- subscript u (for unstable) refers to the angle δ_u, speed ω_u, and time t_u where $P_a = 0$, $\dot{P}_a > 0$ (OMIB instability *conditions*);
- subscript r (for return) refers to the angle δ_r and time t_r where δ starts decreasing and ω vanishes: $\omega = 0$, $P_a < 0$ (OMIB stability conditions).

Figure 1b illustrates the EAC in the unstable case portrayed in Fig. 1a. Note that the computation of an unstable margin requires a simulation performed until reaching t_u.

Remarks

1. The above descriptions show that the computation of an unstable margin requires t_u sTDI; similarly, the computation of a first-swing stable margin requires t_r sTDI[2]. The acronym sTDI stands for seconds of Time Domain Integration of the transient stability program; see §3.3.
2. A two-margin linear extra- (inter-)polation provides an approximate value of a contingency critical clearing time (CCT). Such procedures are sketched in (II), (III) of Fig.2 and used in Sections 3 and 4.

3. FILTERING RANKING AND ASSESSMENT (FRA) TECHNIQUE

3.1 Definitions

The various contingencies are classified into first-swing stable and unstable; these latter are then classified into (multi-swing) harmless, potentially dangerous and dangerous. Further, the potentially dangerous and dangerous ones are ranked according to their degree of severity (see § 3.2.3). These terms are defined below. A contingency is said to be

- Dangerous (D) if its occurrence drives the system out of step; in other words, a contingency whose critical clearing time is smaller than the operating time of system protections;
- Potentially Dangerous (PD) if it is "almost" dangerous, i.e., milder than a dangerous one but likely to become D under slightly modified operating conditions;
- First-Swing Unstable (FSU) (respectively Stable (FSS)), if under given clearing scenario it drives the system to first-swing instability (respectively stability).

3.2 Design

The FRA technique pursues a threefold objective: to capture without exception all D and PD contingencies; to rank and assess them in a way useful in practice; to discard the "uninteresting" contingencies as fast as possible.

To meet the above objectives, the proposed FRA technique uses the two blocks schematically portrayed in Fig. 2, and commented below. Three clearing times (CTs) are used to classify, rank and assess contingencies:

CT_1 for a first classification into FSS and FSU
CT_2 for deciding whether a FSU contingency is D or not
CT_3 for deciding whether a contingency which is FSU but not D is PD or H.

Note that $CT_1 > CT_3 > CT_2$ .The choice of the above CTs is discussed below.

3.2.1 Filtering block

To discard "uninteresting" contingencies as fast as possible, the filtering block uses a first swing classification which stops the simulation at the end of first swing oscillations (as sketched in case (I) of Fig. 2). To combine computational efficiency with reliability (ability to capture all dangerous contingencies), this classification uses a CT_1 large enough (so as to avoid discarding possible multi-swing unstable cases[3]),

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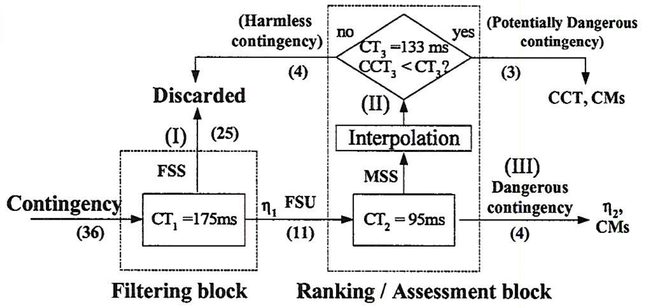
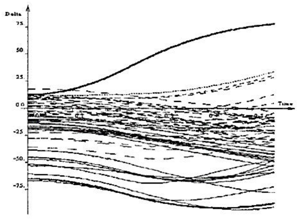
[2] Except when multi-swing instability phenomena are sought, for which an entire stable simulation is necessary.

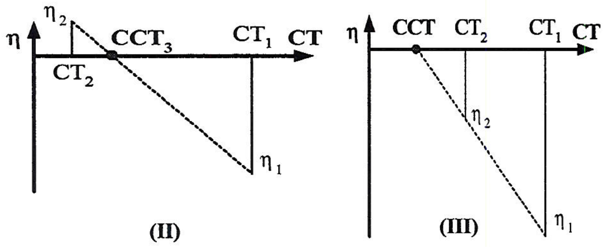
[3] Actually, for a given power system, an offline tuning is needed to choose adequately CTs. This tuning consists of exploring whether the power system, with the considered modeling, has multi-swing instabilities, and if so, to assess the ratio CCT(FS)/CCT(MS). This tuning has to be refreshed only if





(I)

First Swing Stable contingency



(II) Multi-Swing Harmless or Potentially Dangerous contingency

(III) Dangerous contingency

Fig. 2: A realization of the FRA technique. Schematic description of the various contingency classes

yet close enough to CT_2[4] (so as to allow valid linear inter-extra-polation between η_1 and η_2; see cases (II) and (III) of Fig.2). Accordingly, to classify a contingency, a step-by-step simulation is performed by the time-domain program driven by SIME until reaching:

- either a first-swing stability of the multi-machine system (like the one portrayed in (I) of Fig.2) or of the OMIB system (see § 2.2)
- or the unstable condition (see § 2.2) and corresponding δ_u, at t_u.

In the former case, the contingency is declared to be FSS and discarded; in the latter case the contingency is found to be FSU and sent to the second block along with its corresponding, negative margin, η_1.

3.2.2 Ranking/assessment block

For each FSU contingency sent from the first block, a SIME driven time-domain stability simulation is run, in the second block, using CT_2; accordingly, the contingency is said to be

- D, if $\eta_2 < 0$ (see drawing (III) of Fig.2);
- PD or H otherwise, i.e., if $\eta_2 > 0$ (see drawing (II) of Fig.2).

Note that, in this latter case, the simulation is run for the entire integration period since here multi-swing phenomena are taken into consideration. Note also that the CCT_3 resulting from the interpolation of η_1 and η_2 is used to distinguish between PD ($CT_3 > CCT_3$) and H contingencies ($CT_3 < CCT_3$) (see drawing (II) of Fig.2).

Thus, in terms of computing effort, the most expensive simulations of this block concern PD and H contingencies.

3.2.3 Refined ranking and assessment of D contingencies

Besides classifying the contingencies into the aforementioned classes, the ranking/assessment block provides possibilities for finer ranking and assessment of the D contingencies and also of the PD ones, if wished.

Refined assessment of dangerous contingencies relies on unstable simulations using CT_2 as clearing time. Each unstable simulation carries a good deal of information, summarized in the following parameters: size of the unstable (negative) margin; number and identification of the critical machines (CMs), and corresponding generated power; time to instability t_u (i.e., the time for the OMIB to reach instability). The assessment capabilities of these parameters is discussed below.

The approximate CCT obtained by linearly extrapolating margins η_1 and η_2 (drawing (III) of Fig.2), is a good indicator of contingency severity, whenever these margins exist; but, generally, the more severe a contingency and the more unlike the existence of η_1 and even of η_2.

The size of the margin as such is another parameter, which, however, could not rank correctly the corresponding contingency (since different margins generally correspond to different CMs); a more suitable measure appears to be the normalized margin (the margin divided by the OMIB inertia coefficient).

Another parameter for ranking contingencies is the time to instability, t_u. Indeed, it is reasonable to expect that the more unstable a contingency, the faster the system loses synchronism. Note that Ref. [8] uses also the time to instability, though computed in a different way.

To summarize, approximate CCT, time to reach instability, and, to a lesser extent, normalized margin η_2 are three a priori interesting ways of ranking dangerous contingencies. These parameters are tested in the simulations of Section 4. A final remark: the above parameters are direct by-products of the simulations and do not require any computing effort additional to those assessed hereafter.

3.3 Computing effort required by the overall technique

The computations required by SIME per se (computations of OMIB parameters, of margins and their inter- (extra-) polations, etc.) are virtually negligible as compared with the time-domain stability computations (actually, they hardly amount to an iteration of the power flow program). Hence,

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the system undergoes significant changes (e.g., topology, stabilizers, SVCs, FACTS, etc.).

[4] CT_2 is chosen according to the considerations of § 4.3.

virtually, the computing effort reduces to that for running the time-domain program during the short periods required by SIME. Seconds of Time-Domain Integration (sTDI) of this program appears therefore to be a handy measure for assessing computing times of SIME based simulations. Besides, this "unit" is independent of the computer and of the power system size under consideration. Note, however, that for the same power system and stability program, this unit may correspond to different CPU values, depending upon the simulations range. In terms of sTDIs, the computing times required by each one of the 4 different types of contingencies identified so far are as follows:

- FSS : $t_r(CT_1)$
- D : $t_u(CT_1) + t_u(CT_2)$
- PD : $t_u(CT_1) + MIP$
- H : $t_u(CT_1) + MIP$.

In the above notation, $t_r(CT_1)$ denotes the time to reach the first-swing stable conditions. Similarly, $t_u(CT_1)$ (respectively $t_u(CT_2)$) is the time to reach the unstable conditions for $CT = CT_1$ (respectively CT_2). Finally, *MIP* denotes the "Maximum Integration Period" (e.g., below $MIP = 5s$).

4. SIMULATIONS

4.1 Simulation conditions

The ETMSP time-domain program is used alone as the benchmark for comparisons, and as a subroutine of SIME in the FRA technique. The reliability of the FRA technique and its ranking capabilities are assessed by means of reference critical clearing times (CCTs) provided by the ETMSP program. Their computation is obtained by a binary search using an upper bound of 500 ms, and a maximum integration period of 5 s; further, an angular deviation of 360 degrees between extreme machines is used for detecting instability during the iterative process, with a tolerance of 5 ms (the difference between the clearing times of the last unstable and the last stable simulations).

Actually, for assessing performances of the sole FRA technique, an upper bound of 175 ms for the binary search would be sufficient. The purpose for using 500 ms is to test also the accuracy of the very SIME method on the whole contingency set, by comparing its CCTs with those of the ETMSP program run alone.

4.2 Test system

The proposed technique was investigated on the EPRI test power system C [4]. Its total power is about 350,000 MW. Other characteristics are displayed in Table 1.

Table1: Main characteristics of the EPRI test system C [4].

System	Contingency
Number of buses: 434 Number of lines: 2357 Number of generators with classical model: 74 Number of generators with detailed model: 14 Load model: constant impedance	Number of contingencies/operating state: 36 Number of pre-contingency operating states: 7 Total number of cases: 252 Type: 3-ϕ fault on one bus, and tripping one or several lines when clearing the fault

4.3 Choosing threshold clearing times (CTs)

As already mentioned, the various CTs of the FRA scheme are set up by the user and are system-dependent, since the actual clearing times (or the operating times of the protective equipment) vary for the different contingencies and from one power system to another. For example, engineers can use a "security margin" and choose a CT_2 larger than the actual operating time of the protective devices of all contingencies which here ranges from 81.5 ms (8 contingencies) to 91.2 ms (28 contingencies). Hence, $CT_2 = 95$ ms (5.7 cycles) seems to be a value suitable for all contingencies.

As mentioned above, CT_1 should be larger than but not too far from CT_2, and CT_3 set at an intermediate value. Accordingly, the following values were chosen in the simulations: $CT_1= 175$ ms; $CT_2=95$ ms; $CT_3=133$ ms.

4.4 Simulation results

Table 2 provides a sample of results obtained with the 36 contingencies and one operating state. This table is subdivided into three blocks:

- the first gathers the benchmark CCTs obtained by the ETMSP program run alone;
- the second gives the CCTs obtained by the SIME method, and their comparison with the above;
- the third reports on results obtained with the FRA technique.

4.4.1 ETMSP results

- Column 1 identifies the contingency number;
- Column 2 displays the CCTs;
- Column 3 ranks contingency severity relying on CCTs.

4.4.2 SIME results

- Column 4 lists the CCTs of the various contingencies as computed by SIME;
- Columns 5 and 6 display respectively the difference in ms and in percentage between the CCT values computed by the ETMSP alone and by the SIME-ETMSP program. The accuracy is assessed by:

$$\Delta CCT = CCT(ETMSP) - CCT(SIME) \qquad (ms)$$

$$\Delta CCT(\%) = [\Delta CCT / CCT(ETMSP)] \, x100 \qquad (\%)$$

Obviously, SIME is in a very good agreement with ETMSP: apart from few exceptions, the discrepancies are within the tolerance range of ETMSP and SIME (± 4 ms). Note that this goes along the general observation: the agreement of SIME with the time-domain program that it uses has been obtained consistently, whatever this program, the power system, and its modeling. Actually, SIME gives an even more reliable and unbiased assessment than the time-domain program[5].

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[5] SIME's (in)stability criteria are unambiguously defined (see the conditions of §2.2), while those of a time-domain program are system- and operator-dependent, see related discussion in Ref. 2.

4.4.3 Results of the FRA technique

The results are gathered in columns 7 to 9 of the table:

- Column 7 shows the number of simulations required of the FRA technique;
- Column 8 displays the corresponding sTDIs;
- Column 9 gives the contingency classification under the conditions specified so far, namely:
  - Dangerous (D), if the contingency is (multi-swing) unstable for $CT_2 = 95$ ms;
  - Potentially Dangerous (PD), if it is (multi-swing) unstable for $CT_3 = 133$ ms;
  - Harmless (H), if it is (multi-swing) stable for $CT_3 = 133$ ms;
  - First-Swing Stable (FSS), if it is first-swing stable for $CT_1 = 175$ ms.

Comparing the classification of column 9 with the actual CCT (columns 2 or 4), one observes that the FRA scheme provides consistently reliable results, i.e., it captures all dangerous contingencies and, in addition, it classifies correctly the remaining contingencies into FSS, PD and H.

4.4.4 Refined ranking and assessment

The refined ranking/assessment is carried out according to the considerations of §3.2.3. Table 3 gathers the resulting information, organized as follows:

- First part (first 4 rows): relative to the contingencies classified D in Table 2
- Second part (last 3 rows): relative to the contingencies classified PD in Table 2 (optional)
- Column 1: contingency identification
- Column 2: stability margin, η_2, normalized by the OMIB inertia coefficient. Note that contingency Nr 1 does not have a stability margin. This corresponds to a very unstable case for which curves P_m and P_e, do not intersect: there is no solution for the post-fault operating condition of the system
- Column 3: number of CMs. (For obvious space reasons their names are not specified here)
- Column 4: time to reach instability, t_u, for D contingencies (to reach stability, t_r, for PD contingencies)
- Column 5: approximate CCT provided by extra- (or inter-) polating linearly the two margin values computed at CT_1 and CT_2. Observe that here the extrapolation is impossible for the dangerous contingencies, because they don't have a margin for CT_1
- Column 6: Reference CCTs provided by the full SIME transient stability program, used as a reference for contingency ranking
- Column 7: resulting ranking.

4.4.5 Discussion

Comparing columns 2, 4, and 7 of Table 3 shows that the ranking provided by η_2 and t_u are in good agreement with the "reference" CCTs.

Table 2 – Simulation Results for Model C – Case 6.

1	2	3	4	5	6	7	8	9
ETMSP program			SIME			FRA Technique		
Cont. Nr.	CCT (ms)	Rank	CCT (ms)	ΔCCT (ms)	ΔCCT (%)	Nr. Sim.	sTDI	Class
1	0	1	0	0	0.0	2	0.88	D
2	113	5	115	-2	-1.8	2	5.7	PD
3	156	11	161	-5	-3.2	2	6.36	H
4	145	10	147	-2	-1.4	2	6.32	H
5	172	16	179	-7	-4.1	1	1.49	FSS
6	277	22	280	-3	-1.1	1	1.15	FSS
7	320	25	316	4	1.3	1	1.13	FSS
8	430	32	426	4	0.9	1	1.09	FSS
9	297	23	308	-11	-3.7	1	1.13	FSS
10	70	4	72	-2	-2.9	2	1.79	D
11	66	3	69	-3	-4.5	2	1.69	D
12	172	17	174	-2	-1.2	1	1.51	FSS
13	172	18	174	-2	-1.2	1	1.51	FSS
14	168	12	173	-5	-2.9	1	1.64	FSS
15	168	13	173	-5	-2.9	1	1.64	FSS
16	168	14	173	-5	-2.9	1	1.64	FSS
17	168	15	173	-5	-2.9	1	1.64	FSS
18	316	24	324	-8	-2.5	1	1.13	FSS
19	324	26	325	-1	-0.3	1	1.12	FSS
20	434	33	436	-2	-0.5	1	1.08	FSS
21	434	34	436	-2	-0.5	1	1.08	FSS
22	113	6	116	-3	-2.7	2	5.72	PD
23	113	7	116	-3	-2.7	2	5.72	PD
24	172	19	174	-2	-1.2	1	1.51	FSS
25	172	20	174	-2	-1.2	1	1.51	FSS
26	328	27	331	-3	-0.9	1	1.12	FSS
27	328	28	331	-3	-0.9	1	1.12	FSS
28	434	35	436	-2	-0.5	1	1.08	FSS
29	438	36	463	-25	-5.7	1	1.08	FSS
30	0	2	0	0	0.0	2	1.56	D
31	328	29	332	-4	-1.2	1	1.14	FSS
32	328	30	332	-4	-0.2	1	1.14	FSS
33	332	31	333	-1	-0.3	1	1.14	FSS
34	215	21	218	-3	-1.4	1	1.19	FSS
35	137	8	141	-4	-2.9	2	5.9	H
36	137	9	141	-4	-2.9	2	5.9	H

Table 3: Ranking and assessment of D and PD contingencies.

1	2	3	4	5	6	7
Cont. Nr	η_2 $(rad./s)^2$	Nr of CMs	t_{u2}, (t_r) (s)	App. CCT (ms)	Ref. CCT (ms)	Rank
1	---	6	0.395	< 95	0	1
30	-1.20	28	1.010	< 95	0	2
11	-0.81	37	1.325	< 95	69	3
10	-0.70	39	1.395	< 95	72	4
2	0.782	38	(1.030)	109	115	5
22	0.884	38	(1.005)	110	116	6
23	0.884	38	(1.005)	110	116	7

4.4.6 Synthetic assessment

The FRA technique has been applied to the 7 different operating states (see Table 1). The results obtained are very similar to those of Tables 2 and 3 in all respects. Below we merely provide their global classification and ranking for the whole set of 252 contingencies:

Nr of FSS contingencies:172; Nr of H contingencies: 31
Nr of PD contingencies: 25; Nr of D contingencies: 24.

This classification is fully validated by the reference CCT values.

4.5 Computing performances

The mean computing time required of the FRA technique to simulate 1 contingency is about 2.2 sTDI (79.55/36; see column 8 of Table 2). Note, however, that this is a quite overestimated value; indeed, generally, the number of FSS contingencies is much larger, while their computing time is much smaller than that of FSU ones.

Finally note that comparing these times with those required by a time-domain program would be hazardous for many reasons. Indeed, several classification schemes may be thought of, furnishing several types of classification. For example, one could think of:

- using a CT of 175 ms to classify the contingencies as FSS/FSU
- using a CT of 175 ms to classify the contingencies as multi-swing stable/unstable
- the same as above except that the FSS/FSU contingencies are further assessed in terms of their CCT
- the same as above 3 schemes with another CT value, e.g., 95 ms.

The CPU times of these variants would range between values slightly smaller than that required of the FRA technique and 10 times as much. But the main point is that *there is no ground for comparing outcomes of a time-domain program with those of the FRA technique: the latter are incomparably more informative and powerful than the former.*

5. CONCLUSIONS

This paper has proposed a filtering, ranking and assessment (FRA) approach to on-line transient stability assessment. The approach derives from the hybrid transient stability method called SIME, and retains, like SIME, the advantages of time-domain and of the direct methods while evading their drawbacks. It is thus able to combine accuracy and flexibility of time-domain methods with respect to power system modeling, contingency scenarios and modes of (in)stability, with straightforward computation of stability margins and unambiguous identification of critical machines provided by the direct method.

The approach was applied to the EPRI test system and key requirements were scrutinized, in order to examine its ability to: (i) readily identify and discard most of the uninteresting contingencies; (ii) classify the potentially interesting ones; (iii) rank the actually interesting contingencies according to their degree of severity; (iv) assess the dangerous contingencies in terms of their stability margin and critical machines.

The technique was found to be fully reliable (i.e. able to capture without exception the dangerous contingencies), very informative (thanks to its classification, ranking and assessment possibilities), finally computationally efficient, able to comply with on-line requirements. Moreover, globally, a good deal of the computing time was devoted to the assessment of the "interesting" contingencies, while the "uninteresting" ones were readily discarded.

Finally, thanks to the information provided by the assessment block, the technique is able to open avenues towards transient stability control. Results on this aspect of paramount importance will be reported soon.

Acknowledgements. The first author gratefully acknowledges the financial assistance given by the Consejo Nacional de Ciencia y Tecnología, México for his PhD studies. The financial support of the Electric Power Research Institute (project WO#3103-10) for developing the filtering part of the FRA scheme and for performing investigations on the EPRI system is thankfully acknowledged

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