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Transient Stability Emergency Control Combining Open-Loop and Closed-Loop Techniques

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Abstract– An on-line transient stability emergency control approach is proposed, which couples an open-loop and a closed-loop emergency control technique. The open-loop technique uses on-line transient stability assessment in order to adapt the settings of automatic system protection schemes to the current operating conditions. On the other hand, the closed-loop technique uses measurements in order to design and trigger countermeasures, after the contingency has actually happened, then to continue monitoring in a closed-loop fashion. The approach aims at combining advantages of event-based and measurement-based system protection schemes, namely, speed of action and robustness with respect to uncertainties in system modeling. It can also comply with economic criteria.

***Index Terms*– Transient stability, SIME method, Transient stability control, Emergency Control, Closed-loop Emergency Control, Open Loop Emergency Control.**

1 INTRODUCTION

Preventive control aims at modifying the operating conditions of a power system so as to make it able to withstand severe contingencies that would drive it to instability, whenever they occur. However, the preventive countermeasures advocated for very severe contingencies may be so expensive that the system operator usually refuses to trigger for enhancing the system stability against contingencies that may not occur. Besides, the stability cases that actually occur are generally different from those for which the countermeasures are designed. An interesting alternative to preventive control is emergency control. Here, the countermeasures are automatically triggered after a contingency has actually occurred and possibly cleared by appropriate protective devices.

Emergency control can broadly be classified into two categories: closed-loop and open loop [1], [2]. Closed-loop emergency control aims at assessing, ***on the basis of real-time measurements****,* whether the contingency, which has actually occurred, is driving the system to instability; if so, at designing and triggering appropriate control actions and, further, at following-up the system evolution so as to make proper re-adjustments (additional control), if necessary.

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A ***closed-loop emergency control*** method, named **E-SIME**, was proposed some years ago [3] to [5]. Its complete closed-loop cycle comprises the following steps: predictive assessment of the instability and its size; design of corresponding control action; decision-making and decision triggering. Although very appealing, this technique may be too slow to contain effectively the extremely fast developing transient instability phenomena (loss of synchronism may arise as quickly as, say, 150 ms). In such cases, open-loop control may be an interesting alternative. Indeed, its purpose is to trigger automatically the corrective action ***just after*** the contingency inception, by assessing the severity of the anticipated contingency ***on the basis of simulations*****,** and by arming the appropriate devices.

Such an Open-Loop Emergency Control (**OLEC**) technique was recently proposed [6], [7]. It aims at realizing a tradeoff between preventive and open-loop emergency control by ***combining preventive with emergency actions.*** Besides, it uses systematic assessment, able to reach a satisfactory solution of sufficiently moderate emergency control and economically acceptable preventive control.

Both E-SIME and OLEC techniques rely on the general SIME-based control approach. Hence the idea to couple them so as to combine their complementary features, in particular the rapidity of OLEC action with the closed-loop capability of E-SIME.

Next sections describe in a sequence the fundamentals of the general SIME-based control (Section 2), OLEC (Section 3) and E-SIME (Section 4). Section 5 illustrates these two techniques by real-world examples and, finally, Section 6 proposes the OLEC–E-SIME coupled approach.

2 SIME-BASED TRANSIENT STABILITY CONTROL

2.1 SIME: direct products

To analyze an unstable case, SIME starts driving a time-domain (T-D) program as soon as the system enters its post-fault configuration. At each step of the T-D simulation, SIME transforms the multi-machine system furnished by this program into a suitable One-Machine Infinite Bus (OMIB) equivalent, defined by its angle δ, speed ω, mechanical power P_m, electrical power P_e and inertia coefficient M. (All OMIB parameters are derived from multi-machine system parameters.) Further, SIME explores the OMIB dynamics by using the equal-area criterion

(EAC). The procedure stops as soon as the OMIB reaches the EAC ***instability conditions*** assessed by the closed-form expressions

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

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

$$\eta_u = A_{dec} - A_{acc} = -\frac{1}{2} M\omega_u^2 \, . \tag{2}$$

On the other hand, if the case is stable, the OMIB will reach the EAC ***stability conditions***

$$\omega(t_r) = 0 \quad ; \; P_a(t_r) < 0 \tag{3}$$

where time t_r is the "time to first-swing stability"; the corresponding stability margin can be computed by

$$\eta_{st} = \left| \int_{\delta_r}^{\delta_u} P_a \, d\delta \right| \, . \tag{4}$$

Note that the OMIB of concern here is the one defined on an unstable case "close to the considered stable case" [2].

2.2 SIME's salient parameters and properties

1. Calculation of stability margins, identification of the critical machines and assessment of their degree of criticality (or participation to the instability phenomena)[2] are parameters of paramount importance.
2. The "**time to instability**", t_u**,** is another important parameter. It indicates the time an unstable simulation is stopped, and measures its severity.
3. The margin expressed by eq. (2) or (4) is often "normalized" by the OMIB inertia coefficient. In what follows, we will refer to this latter as the "standard" stability margin.
4. Under very unstable conditions, it may happen that the standard margin does not exist, because the OMIB P_m and P_e curves do not intersect (there is no post-fault equilibrium solution). A convenient substitute is the "minimum distance" between post-fault P_m and P_e curves. Note that here the "time to instability" is the time to reach this minimum distance and to stop the simulation. To simplify, we will still denote it "t_u".
5. A very interesting property of the stability margins (standard as well as substitute ones) is that they vary quasi- linearly with the stability conditions [2]. This justifies extra- (inter-)polating margins linearly. The SIME-based control techniques benefit considerably from this property.

2.3 SIME-based preventive control

To stabilize an unstable case (defined by the pre-fault operating conditions and the contingency type and clearing scenario), SIME furnishes the following two-part information.

- *Size of instability (margin) and critical machines* along with their *degree of criticality or involvement*;
- *Suggestions for stabilization*. These suggestions are obtained by the interplay between OMIB–EAC (Equal-Area Criterion) and time-domain multi-machine representations, according to the following procedure:
  - stabilizing an unstable case consists of modifying the pre-contingency conditions until the stability margin becomes zero. According to EAC, this implies increasing the decelerating area and/or decreasing the accelerating area of the OMIB $P-\delta$ representation. Generally, this may be achieved by decreasing the OMIB equivalent generation power. Ref. [2] derives a relationship between the margin η and the amount of the OMIB generation decrease, ΔP_{OMIB}:

$$\eta = f(\Delta P_{OMIB}) \, ; \tag{5}$$

  - further, Ref. [2] shows that to keep the total consumption constant, the following multi-machine condition must be satisfied, when neglecting loses:

$$\Delta P_{OMIB} = \Delta P_C = \sum_{i \in CMs} \Delta P_{C_i} = -\Delta P_N = -\sum_{j \in NMs} \Delta P_{N_j} \tag{6}$$

  where ΔP_C and ΔP_N are the changes in the total power of the group of critical and non-critical machines, respectively.
  - Application of eqs (5) and (6) provides a first approximate value of ΔP_C.

Remark. Obviously, the above generation re-dispatch goes along engineering reasoning: for stabilizing a system, bring the machines' angle trajectories closer to each other. However, SIME provides important additional information: it quantifies the amount of generation to be shifted and determines the machines from which it should be shifted.

2.4 E-SIME emergency control

Two main differences characterize the E-SIME emergency control from the preventive one, namely:

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

[2] the degree of involvement of a critical machine is proportional to its angular deviation assessed at t_u.

- the information about the multi-machine system is provided by real-time measurements, rather than T-D simulations;
- the decrease in generation of critical machines is made here by shedding generation; besides, it is not compensated by an appropriate increase in generation on non-critical machines, at least in a short period following the control action.

Apart from these differences, the principle remains the same. This is clarified in the following sections.

3 THE OLEC TECHNIQUE

The leading idea is to mitigate preventive actions (generation shifting) by complementing them with emergency actions (generation tripping) that would automatically be triggered only if the postulated contingency actually occurs. The procedure realizing this idea is summarized in the following steps [6], [7].

1. For an initially unstable scenario (operating condition subject to a pre-defined harmful contingency and its clearing scheme), compute the corresponding (negative) margin and determine the corresponding critical machines.
2. Assuming that (some of) these machines belong to a power plant equipped with a generation tripping scheme, select the number of units to trip in the emergency mode.
3. Starting with the initial scenario, perform SIME's simulations up to reaching the assumed delay of generation tripping; at this time, shed the machines selected in step 2, and pursue the simulation until reaching instability or stability conditions (see eqs (1) and (3)). If stability is met, stop; otherwise, determine the new stability margin and corresponding critical machines (to check whether they are the same or not with the previous simulation).
4. Run the transient stability control program to increase to zero this new (negative) margin [6] to [8]. To this end, perform generation shifting in the usual way, from the remaining critical machines to non-critical machines.
5. The new, secure operating state results from the combination of the above generation rescheduling taken preventively, and the consideration of the critical machines, previously chosen to trip correctively.
6. Repeat the above steps 1 to 5 with each one of all possible patterns of critical machines to trip, until getting an operating condition, which realizes a good compromise between security and economics.
7. After the "optimal" number of machines to trip is determined, the settings of the special protection activating the generation tripping scheme in the plant is adapted so as to automatically disconnect these machines in the event of the contingency occurrence.

Remark. OLEC refers to no feedback control. Admittedly, this term might suggest, "a man is into the loop" while, actually, "there is no man". "Feed-forward emergency control" might be an interesting alternative. However, the term "OLEC" has been chosen to emphasize the specific meaning of a mixture of pre-determined preventive countermeasures and emergency actions.

4 E–SIME

Following a disturbance inception and its clearance, the Emergency SIME aims at predicting the system transient stability behavior and, if necessary, at deciding and triggering control actions early enough to prevent loss of synchronism. Further, it aims at continuing monitoring the system, in order to assess whether the control action has been sufficient or should be reinforced. The method relies on real-time measurements, informing about machines parameters, see below, §4.1.2

The various tasks are realized in the way succinctly described below.

4.1 Predictive transient stability assessment

4.1.1 Principle

The prediction relies on real-time measurements, acquired at regular time steps, t_i ***'s,*** and refreshed at the rate Δt_i. The procedure consists of the following steps.

(i) *Predicting the OMIB structure:* use a Taylor series expansion to predict (say, 100 ms ahead), the individual machines' rotor angles; rank the machines according to their angles, identify the largest angular distance between two successive machines and declare those above this distance to be the "candidate critical machines", the remaining ones being the "candidate non-critical machines". The suitable aggregation of these machines provides the "candidate OMIB".

(ii) *Predicting the* $P_a - \delta$ *curve:* compute the parameters of this "candidate OMIB", and in particular its accelerating power and rotor angle, P_a and δ, for three successive data sets acquired at $t_i - 2\Delta t_i$, $t_i - \Delta t_i$, t_i. Write the equation

$$P_a(\delta) = a\delta^2 + b\delta + c \quad (7)$$

for the three different times and solve for a, b, c [3].

(iii) *Predicting instability:* search for the solution of

$$P_a(\delta_u) = a\delta_u{}^2 + b\delta_u + c = 0 \quad (8)$$

to determine whether the OMIB reaches the unstable conditions

$$P_a(\delta_u), \quad \dot{P}_a(\delta_u) > 0 .$$

If not, repeat steps (i) to (iii) using new measurements sets. If yes, the candidate OMIB is the critical one, for which the method computes successively [3] to [5]

[3] Subsequently, using newly acquired sets of measurements and processing a least squares technique, which shows to be particularly robust, refine the estimated curve. A further improvement consists of using a weighted least-squares (WLS) technique, by giving more important weights to the last sets of measurements.

– the unstable angle δ_u

– the unstable margin

$$\eta = -\int_{\delta_i}^{\delta_u} P_a \, d\delta - \frac{1}{2} M \omega_i^2 \qquad (9)$$

– the time to instability

$$t_u = t_i + \int_{\delta_i}^{\delta_u} \frac{d\delta}{\sqrt{(2/M)\int_{\delta_i}^{\delta} -P_a \, d\delta + \omega_i^2}} \qquad (10)$$

where δ_i stands for $\delta(t_i)$ and ω_i for $\omega(t_i)$.

(iv) *Validity test.* The validity test relies on the observation that under given operating and contingency conditions, the value of the (negative) margin should be constant, whatever the time step. Hence, the above computations should be repeated at successive Δt_i's until getting a (almost) constant margin value.

4.1.2 Salient features

- The method uses real-time measurements acquired at regular time intervals and aims at controlling the system in less than, say, 500 ms after the contingency inception and its clearance.
- The prediction phase starts after detecting an anomaly (contingency occurrence) and its clearance by means of protective relays. Note that this prediction does not imply identification of the contingency (location, type, etc.).
- The prediction is possible thanks to the use of the OMIB transformation; predicting the behavior (accelerating power) of all of the system machines would have led to totally unreliable results.
- There may be a tradeoff between the above mentioned validation test and time to instability: the shorter this time, the earlier the corrective action should be taken, possibly before complete convergence of the validation test.

Finally note that the above descriptions aim at giving a mere flavor of the method. Detailed developments may be found in [2] to [5].

4.2 Emergency control

4.2.1 Structure of the emergency control scheme

On the basis of real-time measurements taken at the power plants, the method pursues the following main objectives:

- to assess *whether* the system is stable or it is driven to instability; in the latter case
- to assess *"how much"* unstable the system is going to be; accordingly,
- to assess *"where"* and *"how much corrective action"* to take (pre-assigned type of corrective action);
- to continue assessing whether the executed corrective action has been sufficient or whether to proceed further.

Block 2 of Fig. 1 covers the two first steps: prediction of instability, and appraisal of the size of instability, in terms of margins and critical machines. Block 3 takes care of the design of control actions. For example, when generation shedding is of concern, the action consists of determining the number of generators to shed.

Further, the method sends the order of triggering the action, while continuing to monitor and control the system in closed-loop fashion, until getting power system stabilization.

4.2.2 Discussion

- The prediction of the time to (reach) instability may influence the control decision (size of control; time to trigger it; etc).
- The hardware requirements of the emergency control scheme are phasor measurement devices placed at the main power plant stations and communication systems to transmit (centralize-decentralize) this information. These requirements seem to be within reach of today's technology [9], [10].
- The emergency control relies on purely real-time measurements (actually a relatively small number of measurements). This frees the control from uncertainties about power system modeling, parameter values, operating condition, type and location of the contingency.

5 Illustration

5.1 Simulation conditions

We use the EPRI test system C [11], having 434 buses, 2357 lines and 88 machines (of which 14 are modeled in detail), and consider two contingencies.

These contingencies represent a 3-ϕ short-circuit applied

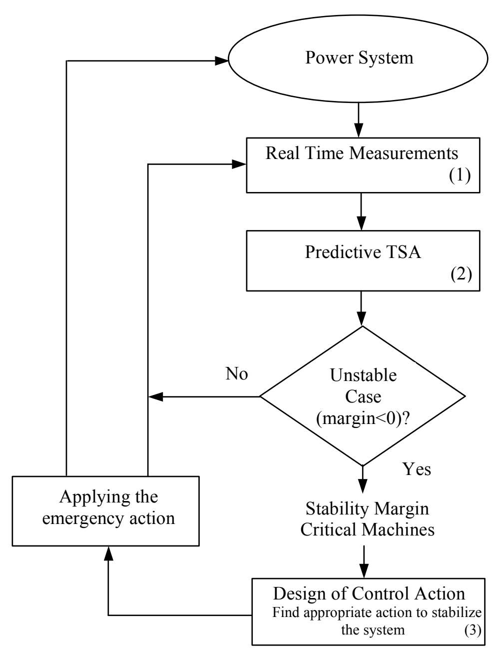

Fig. 1. General framework for closed-loop transient stability emergency control

TABLE 1: CONTINGENCIES MAIN FEATURES

Contingency 1a	Contingency 1b
tu = 1. 19 s	tu = 0. 395 s
CMs	CMs
Preventive SIME = 7	Preventive SIME = 7
P_{C0} = 24 623 MW	P_{C0} = 5600 MW
Emergency SIME = 7	Emergency SIME = 7
P_{C0} = 5600 MW	P_{C0} = 5600 MW
Stabilization by preventive SIME: ΔPc = - 627 MW	Stabilization by preventive SIME: ΔPc = - 3177 MW

at bus #15 (500kV), and cleared 100 ms after their inception, either by opening one line (contingency # 1a) or two lines (contingency # 1b) [6].

Table 1 summarizes contingencies' main features. Note that the 7 critical machines are the same for both contingencies.

Below, we consider these two contingencies and attempt to stabilize them by OLEC and E-SIME.

5.2 Stabilization by OLEC

Contingency # 1a

In the purely preventive mode, this contingency may be stabilized in a rather inexpensive way (see Table 1).

Hence, using OLEC to stabilize it is not very interesting, inasmuch as the countermeasures required for stabilizing contingency # 1b by OLEC stabilize also contingency # 1a (see below).

Contingency # 1b

According to Table 1, stabilizing this contingency in a purely preventive mode would have been inadmissible. Below we stabilize it by OLEC, using the following parameters:

- number of critical machines (CMs) to trip: two; their stability-unconstrained pre-fault generation is: 821 + 769 = 1590 MW [8];
- time delay for tripping these CMs: 150 ms from the fault inception.

The design of the control action follows the procedure described above (Section 3). First, it is found that, because the case is very unstable, tripping 2 critical machines 150 ms after the fault inception would not be sufficient to stabilize it. Figures 2a and 2b portray, respectively, the multi-machine swing curves and the δ-P OMIB curves of the totally stability-unconstrained system. Obviously, this is an extremely stressed system. Since the emergency action is insufficient to stabilize the case, the procedure of Section 3 continues with step 3: the new substitute margin is computed and the appropriate preventive generation rescheduling is decided in order to stabilize the operating conditions. The final result of the preventive stabilization procedure of the system with 5 critical machines indicates that their generation should be reduced from 4010 MW to 2415 MW.

Figures 2c and 2d display the multi-machine and OMIB δ-P curves corresponding to this stabilized case. They clearly show the effectiveness of the combined action of

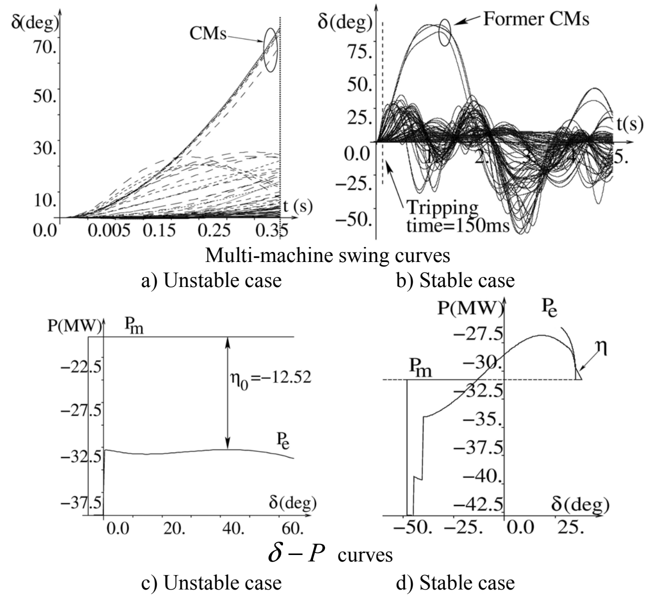

Fig. 2: Stabilization process of contingency #1b by OLEC

generation shifting (preventive) and generation tripping (emergency) controls.

5.3 Stabilization by E-SIME

Contingency # 1a

For want of real-time measurements, the simulations have been run with E-SIME coupled with the ETMSP program [12]. Fig. 3 illustrates the system response for uncontrolled and controlled case.

The contingency is stabilized by shedding CMs. The size of this control action, assessed according to Section 4, is found to be 3 units among the 7 most advanced ones, corresponding to 2,463 MW. The machines shed are #1855 (835 MW), #1771 (793 MW), and #1877 (835 MW). Because of the proximity of predicted instability, it is decided to take control action quite early (at $t_i = 415ms$). The control action is applied at $t_i = 575ms$ (the communication delay is supposed to be 50 ms both for data acquisition-transmission and order transmission for the control room to the power plants to be controlled).

Contingency # 1b

E-SIME cannot stabilize this contingency effectively: its time to instability is so short (395 ms) that the control action would be triggered after the system loss of synchronism.

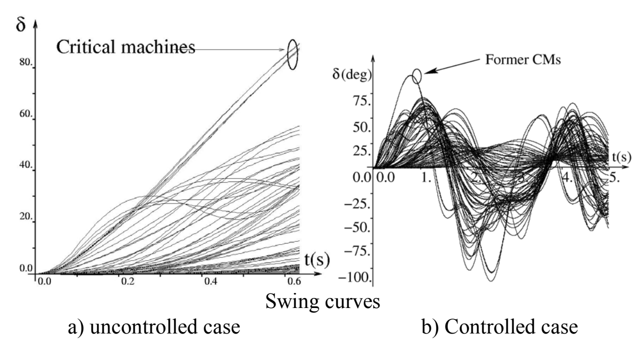

Fig. 3: Stabilization process of contingency. #1a by E-SIME [2].

6 SIME-BASED ADAPTIVE EMERGENCY CONTROL

6.1 Generalities

Converting a remedial scheme in an adaptive system protection is a very hard task, because their action should consider the **overall system dynamic behavior**. One of the solutions to this problem consists in using pre-calculated arming tables (computed off-line in the operation planning context) for updating the settings of the generation tripping device [13], [14]. Solutions to compute **on-line** the settings of the remedial scheme can be classified into the following two main approaches:

- System protection scheme (SPS) becomes response-based[4], and use (almost) instantaneous real measurements to assess system stability and adapt their control action depending on the current dynamics, after the contingency has actually occurred [15], [16]
- System protection scheme remains as an event-based device[5], automatically triggered by system protections when a pre-selected contingency takes place, but their settings (like the amount of generators to shed and the time to perform the control), are updated by simulations performed on-line at the EMS (or other location) under changing system operating conditions, on a periodical basis [14] to [16]

SIME-based control is now able to perform, and combine, both types of system protection schemes against transient instabilities:

- E-SIME as a response-based system protection scheme.
- OLEC as the event-based system protection scheme.

This combination is described below.

6.2 Coupling E-SIME with OLEC

Generally speaking, closed-loop and open-loop controls have more or less complementary features and assets. Hence the idea of combining closed-loop with open-loop emergency control techniques. The idea is even more appealing when the two techniques rely on the same basic method.

Indeed, despite important assets, E-SIME needs some delay (say, 450 ms from the disturbance inception) before triggering the control action, and the larger this delay, the larger the generation shedding needed. This delay can even become fatal to the system integrity, if the contingency is very severe, as in the example of Section 5.

On the other hand, OLEC is likely to act much faster (say, 150 ms after the disturbance inception) since the automatic protection activating the generation tripping scheme uses only local measurements to detect the fault and act, in contrast to E-SIME, which- at least in principle- needs all machines' rotor angles and powers. But the suggested action may be incorrect, at least partly, given the uncertainties about the anticipated operating conditions.

Coupling the above two techniques may combine their advantages while avoiding part of their weaknesses, at least from a theoretical viewpoint. In short, this combination yields the following scenario of events.

• **At t_0**: disturbance inception.
• **At t_1 = 150 ms**: triggering the generation shedding pre-defined by OLEC.
• **At t_2 = 180 ms:** based on sets of real-time measurements (supposed to arrive every 20 ms): E-SIME predicts instability size (margin); time to instability (when the system will lose synchronism irrevocably in the absence of control action); CMs) and decides about control action (number of CMs to shed).

Further, E-SIME compares the above control action based on the measurements with the one decided by OLEC and already triggered 30 ms earlier, and:

- if E-SIME assesses the latter to be sufficient, it does not take any additional action but simply continuous monitoring the system, based on incoming sets of measurements;
- if, on the contrary, it deems the OLEC action insufficient, it predicts the system new transient stability status (new instability size and time to instability), given the action already triggered. Note that the new time to instability is larger than the one assessed under the assumption of no OLEC action; hence, there is more time left to refine its assessment, if necessary, and/or to make the delay of 300 ms sufficient for preserving the system integrity.

Figure 4 sketches the main steps of the above procedure.

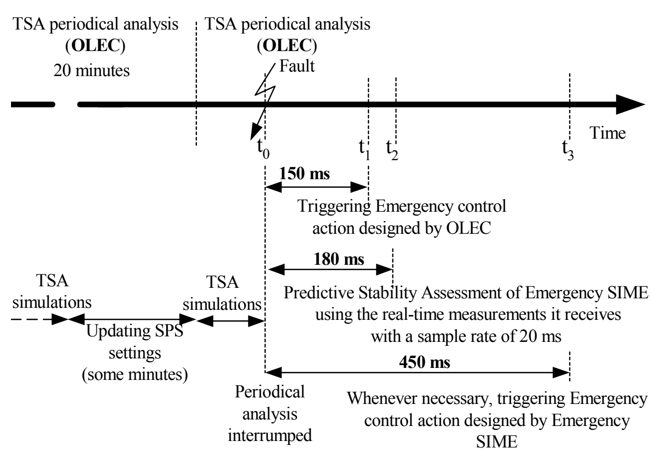

Fig. 4: SIME-based emergency control actions against transient stability (Adapted from [7].)

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[4] "A response based system protection scheme use electric variables and initiate non-continuous stabilizing actions after the disturbance has caused the measured variables to significantly degrade. The objective is to correct the deterioration of these variables by an action, which is generally local" [13].

[5] "Event-based system protection scheme are designed for operation only upon the recognition of a particular combination of events and are thus based on the direct detection of the event (e.g. loss of several lines in a station). This type of scheme is generally used for events whose severity largely exceeds the robustness of the system or when the phenomena concerned are too fast to allow the use of a response based system protection scheme. They are generally high-speed because their actions must be carried out before system behavior becomes overly degraded and system instability cannot be prevented" [13].

7 Conclusion

This paper has addressed the issue of on-line transient stability emergency control. Three SIME-based approaches have been considered: the OLEC, the E-SIME, and an adaptive emergency control that combines these two approaches. While OLEC aims to relieve preventive control actions (generation rescheduling) by complementing them with generation tripping (assessed preventively but triggered only if the anticipated harmful contingency actually occurs), the E-SIME uses real-time measurements following the actual occurrence of a contingency to appraise corrective countermeasures indispensable for the system integrity.

Coupling OLEC and E-SIME in order to combine their complementary features, in particular the rapidity of OLEC and closed-loop capability of E-SIME, comes quite naturally thanks to the fact that they rely on the same basic method. This coupling constitutes a SIME-based adaptive emergency control discussed in this paper.

Of course, the above preliminary study should be adjusted to cope with technical performances and requirements. Obviously, this would worth a careful and in-depth evaluation, which, however goes beyond the scope of this paper.

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10 Biographies

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