Undervoltage load shedding using distributed controllers

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***Abstract*—A new load shedding scheme against long-term voltage instability is proposed. It uses a set of distributed controllers, each monitoring transmission voltages in a zone and controlling a group of related loads. Each controller acts in closed-loop, shedding amounts that vary in magnitude and time according to the evolution of its monitored voltage. The whole system can operate without information exchange between controllers, the latter being implicitly coordinated through network voltages. The operation, design and robustness features are illustrated through simulations of a real system.**

***Index Terms*—Voltage stability, system protection scheme, undervoltage load shedding, distributed control**

I. INTRODUCTION

Load shedding is the ultimate countermeasure to save a voltage unstable system, when there is no other alternative to stop an approaching collapse [1], [2]. This countermeasure is cost effective in the sense that it can stop voltage instability triggered by large disturbances, against which preventive actions would not be economically justified (if at all possible) in view of the low probability of occurrence [3]. Load shedding is also needed when the system undergoes an initial voltage drop that is too pronounced to be corrected by generators (due their limited range of allowed voltages) or load tap changers (due to their relatively slow movements and also limited control range).

The automatic load shedding considered in this paper belongs to the family of System Protection Schemes (also referred to as Special Protections Scheme) (SPS) against long-term voltage instability. An SPS is a protection designed to detect abnormal system conditions and take predetermined corrective actions (other than the isolation of the faulted elements) to preserve as far as possible system integrity and regain acceptable performances [4].

The following SPS design has been chosen in this work:

- *response-based*: load shedding will rely on voltage measurements which reflect the initiating disturbance (without identifying it) and the actions taken so far by the SPS and by other controllers. On the contrary, an event-based SPS would react to the occurrence of specific events [5];
- *rule-based*: load shedding will rely on a combination of rules of the type:

$$\text{if } \; V < V^{th} \; \text{ during } \tau \text{ seconds, shed } \; \Delta P \; \text{ MW} \qquad (1)$$

  where V is a measured voltage and V^{th} a corresponding threshold value;
- *closed-loop operation*: an essential feature of the scheme considered here is the ability to activate the rule (1) several times, based on the measured result of the previous activations. This closed-loop feature allows the load shedding controllers to adapt their actions to the severity of the disturbance. Furthermore, it increases the robustness with respect to operation failures as well as system behaviour uncertainties [6]. This is particularly important in voltage instability, where load plays a central role but its composition varies with time and its behaviour under large voltage drops may not be known accurately;
- a *distributed* scheme is proposed for its ability to adjust to the disturbance location, as will be explained in the next section.

As an alternative to the above rule-based scheme, some researchers have proposed more involved analysis of a real-time model of the system to control generator voltages, shunt compensation and load shedding in emergency conditions. Among them, let us quote the approaches inspired of Model Predictive Control [7]-[10]. Some strengths and limitations of this approach are discussed in [11]. More investigations are needed to ascertain that these more complex and computationally intensive schemes meet the reliability and robustness requirements of an SPS.

Other input signals than voltage magnitudes may be monitored in the rules (1). Reactive reserve (or field current) on key generators has been considered [12], for instance to deal with situations where voltages drop abruptly after the activation of OverExcitation Limiters (OELs). An alternative consists in trying to detect a condition that corresponds to loss of stability, instead of observing its consequences, the objective being to obtain an earlier emergency signal. This is the purpose of the voltage instability predictor initially proposed in [13] and improved in [14], [15]. However, several issues need to be addressed regarding the use of this predictor after a severe disturbance (instead of during a smooth load increase) and its anticipation capability compared to low voltage detection.

It is well-known that time, location and amount are three important and closely related aspects of load shedding against voltage instability [16].

The time available for shedding is limited by the necessity to avoid [2]:

- reaching the collapse point corresponding to generator loss of synchronism or motor stalling;
- further system degradation due to undervoltage tripping of field current limited generators, or line tripping by

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protections;

- the nuisance for customers of sustained low voltages. This requires to act fast, even in the case of long-term voltage instability, if the disturbance has a strong initial impact [6].

As far as long-term voltage instability is concerned, if none of the above factors is limiting, one can show that there is a maximum delay beyond which shedding later requires shedding more [2], [17]. On the other hand, it may be appropriate to activate other emergency controls first so that the amount of load shedding is reduced [6].

The shedding location matters a lot when dealing with voltage instability: shedding at a less appropriate place requires shedding more. In practice, the region prone to voltage instability is well known beforehand. However, within this region, the best location for load shedding may vary significantly with the disturbance and system topology [18].

There are proven sensitivity techniques to identify which parameters have most influence on load power margin [19]; they can be straightforwardly applied to load shedding. Furthermore, this analysis can be coupled to time simulation in order to find the best corrective actions in a post-disturbance unstable situation [20], [21], [17], [22]. More recently Ref. [23] proposed a simple sensitivity computation encompassing unstable as well as low but stable voltage situations. Once a ranking of loads has been set up, the minimal amount of power to shed can be easily computed [17].

While easily performed off-line, for predefined contingencies, the above computations can hardly be embedded in an SPS facing an unknown disturbance. Instead, the latter must be provided with a possibly sub-optimal but simple and robust logic to chose the shedding location. The distributed scheme proposed in this paper tends to act first where voltages drop the most. Even if it may lead to shedding some more load, this criterion makes sense in terms of reducing the nuisance caused to customers by low voltages.

This paper is organized as follows. The principle of the proposed scheme is presented in Section II, while the optimization of its parameters is explained in Section III. Section IV reports on various tests performed on a real-life system. The paper ends up with conclusions and perspectives for future work.

II. THE PROPOSED LOAD SHEDDING SCHEME

A. Overall principle

The proposed scheme relies on a set of controllers distributed over the region prone to voltage instability. Each controller monitors the voltage V at a transmission bus and acts on a set of loads located at distribution level and having influence on V. A sub-transmission network may exist in between the monitored and the controlled buses, as sketched in Fig. 1. Note that not all transmission buses need to be monitored, and not all loads need be controlled.

Each controller operates as follows:

- it acts when its monitored voltage V falls below some threshold V^{th};
- it can act repeatedly, until V recovers above V^{th}. This yields the already mentioned closed-loop behaviour;

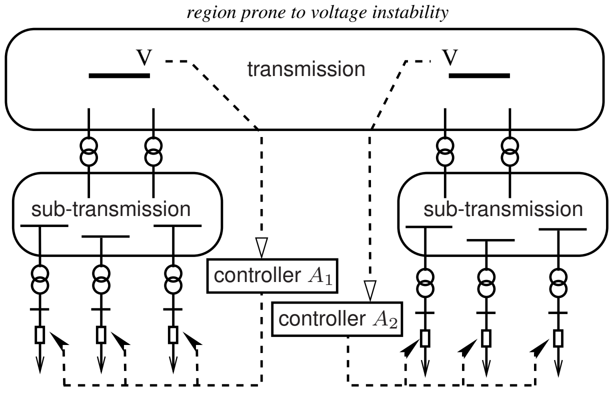

Fig. 1. Overall structure of the proposed scheme

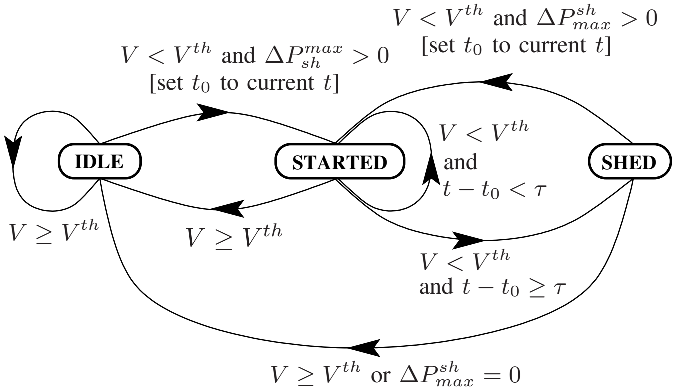

Fig. 2. Logic of an individual load shedding controller (within brackets: action taken when the transition takes place)

- it waits in between two sheddings, in order to assess the effect of the actions taken both by itself and by the other controllers;
- the delay between successive sheddings varies with the severity of the situation;
- the same holds true for the amount shed.

B. Individual controller design

The operation of an individual controller is described in Fig. 2 in the form of an automaton.

As long as V remains above the specified threshold, the controller is idle, while it is started as soon as a (severe) disturbance causes V to drop below V^{th}. Let t_0 be the time where this change takes place. The controller remains started until either the voltage recovers, or a time τ is elapsed since t_0. In the latter case, the controller sheds a power ΔP^{sh} and returns to either idle (if V recovers above V^{th}) or started state (if V remains smaller than V^{th}). In the second case, the current time is taken as the new value of t_0 and the controller is ready to act again (provided of course that there remains load to shed).

The delay τ depends on the time evolution of V as follows. A block of load is shed at a time $t_0 + \tau$ such that:

$$\int_{t_0}^{t_0+\tau} \left(V^{th} - V(t)\right) dt = C \tag{2}$$

where C is a constant to be adjusted. This control law yields an inverse-time characteristic: the deeper the voltage drops, the less time it takes to reach the value C and, hence, the faster the shedding. The larger C, the more time it takes for the integral to reach this value and hence, the slower the action.

Furthermore, the delay τ is lower bounded:

$$\tau_{min} \leq \tau \tag{3}$$

to prevent the controller from reacting on a nearby fault. Indeed, in normal situations time must be left for the protections to clear the fault and the voltage to recover to normal values.

Similarly, the amount ΔP^{sh} of power shed at time $t_0 + \tau$ depends on the time evolution of V through:

$$\Delta P^{sh} = K \cdot \Delta V^{av} \tag{4}$$

where K is another constant to be adjusted, and ΔV^{av} is the average voltage drop over the $[t_0 \; t_0 + \tau]$ interval, i.e.

$$\Delta V^{av} = \frac{1}{\tau} \int_{t_0}^{t_0+\tau} \left(V^{th} - V(t) \right) dt \tag{5}$$

The above relationships transpose voltage drop severity into load shedding amplitude: the larger $V^{th} - V$, the larger ΔV^{av} and, hence, the larger the amount of load shed. The same holds true when the gain K increases.

The controller acts by opening distribution circuit breakers and may disconnect interruptible loads only. Hence, the minimum load shedding corresponds to the smallest load whose breaker can be opened, while the maximum shedding corresponds to opening all the manoeuvrable breakers. Furthermore, to prevent unacceptable transients, it may be appropriate to limit the power disconnected in a single step to some value ΔP^{sh}_{tr}. The above limitations are summarized as follows:

$$\min_k P_k \leq \Delta P^{sh} \leq \Delta P^{sh}_{max} \tag{6}$$

$$\text{with} \quad \Delta P^{sh}_{max} = \min \left(\sum_k P_k, \, \Delta P^{sh}_{tr} \right) \tag{7}$$

where P_k denotes the individual load power behind the k-th circuit breaker under control, and the minimum in (6) and the sum in (7) extend over all manoeuvrable breakers.

The control logic focuses on active power but load reactive power is obviously reduced together with active power. In the absence of more detailed information, we assume that both powers vary in the same proportion.

C. Cooperation between controllers

The various controllers interact in the following way.

Let us consider two close controllers: C_i monitoring bus i and C_j monitoring bus j ($j \neq i$). Let us assume that both controllers are started by a disturbance. When C_i sheds some load, this causes the voltages to increase not only at bus i but also at neighbouring buses, in particular at the monitored bus j. Since V_j increases, the integral $\int \left(V^{th} - V_j(t) \right) dt$ grows more slowly with time, thereby leading to a larger delay τ before C_j can act. For the same reason, ΔV^{av} decreases and C_j will shed less load once its delay τ is elapsed. For larger voltage increases, V_j may even become larger than V^{th} making C_j return to idle state. In other words, when one controller sheds load, this slows down or inhibits the controllers that compete with him to restore voltages in the same area. This cooperation avoids excessive load shedding.

Moreover, the whole system will tend to shed first where voltages drop the most. This location changes with the disturbance. Hence, the proposed scheme automatically adjusts the shedding location to the disturbance it faces.

Note that the above features are achieved without resorting to a dedicated communication network. The controllers do not exchange information, but are rather informed of their respective actions through the power system itself. This is made possible by the fact that voltages have no “inertia”: the effects of shedding are felt almost instantaneously. Neither do the controllers require a model of the system. This and the absence of communication makes the protection scheme definitely simpler and hence more reliable.

D. Extensions and variants

1) Centralized variant of SPS: The proposed scheme is meant to operate in a fully distributed way, each controller using local information and taking local actions, as underfrequency load shedding controllers do [25]. The objective of this paper is to demonstrate that such a decentralized SPS could operate reliably. Now, one may think of implementing this scheme in a centralized way, by collecting all voltage measurements at a central point, running the computations involved in Eqs. (2-7) in a single processor, and sending back load shedding orders (with some communication delays to be taken into account). In this case, additional information exchanges and interactions between controllers may be envisaged without further penalizing the scheme. An example is provided in Section IV-J.

2) Redundant measurements: In order to protect the SPS against erroneous measurements, it is desirable for each controller to rely on several voltage measurements, taken at closely located buses. Some filtering can remove outliers from the measurements, and the average value of the valid ones can be used as V in Eqs. (2,5). If all data are dubious, the controller should not be started; other controllers will take over, as illustrated in Section IV-I.

3) Average voltage drop: One reason for averaging the voltage drop over time in Eq. (5) is the necessity to filter out transients and measurement noise. However, the average need not be computed over the τ seconds elapsed since the last shedding. Instead, a shorter time window may be considered:

$$\Delta V^{av} = \frac{1}{\tau'} \int_{t_0+\tau-\tau'}^{t_0+\tau} \left(V^{th} - V(t) \right) dt \tag{8}$$

with $\tau_{min} < \tau^{'} < \tau$, so that ΔP^{sh} relies on more recent voltage values. This may lead to shed less power in some cases.

III. TUNING THE CONTROLLER PARAMETERS

The tuning of the controllers should rely on a set of scenarios combining different operating conditions and disturbances, as typically considered when planning SPS [6].

The basic requirements are:

1) protection security: the SPS does not act in a scenario with acceptable post-disturbance system response. This is normally the case following any N-1 contingency;
2) protection dependability: all unacceptable post-disturbance system responses are saved by the SPS, possibly in conjunction with other available controls;
3) protection selectivity: in the latter case, as few load power as possible is interrupted.

The tuning mainly consists of choosing the best values for V^{th}, C and K. The bounds τ_{min} and ΔP_{tr}^{sh} can be chosen by engineering judgement.

First, attention must be paid to V^{th}. This threshold should be set high enough to avoid excessive shedding delays, which in turn would require to shed more and/or cause low load voltages. On the other hand, it should be low enough to obey requirement 1 above. It should thus be set a little below the lowest voltage value reached during any of the acceptable post-disturbance evolutions.

Next, C and K should be selected so that, for all scenarios:

- the protection sheds as few load as possible and
- some security margin is left with respect to values causing protection failure.

Using the same C and K values for all controllers makes the design definitely simpler. In the tests we performed so far, there has been no evidence that individual values would yield substantial benefits. Therefore, this simplification is adopted throughout the remaining of the paper.

These guidelines are illustrated in detail in the next section.

IV. SIMULATION RESULTS

A. Test system

The proposed SPS has been tested on a detailed planning model of a region of the French transmission system, operated by RTE [18], where security is on some occasions constrained by voltage stability. A one-line diagram of the transmission (380 and 225-kV) grid is shown in Fig. 3.

The model includes 1244 buses, 1090 lines and 541 transformers. This involves the main transmission grid of France and, for its Western region, a detailed representation of the (90 and 63-kV) sub-transmission networks as well as 341 transformers feeding 20-kV distribution buses. The overall structure is sketched in Fig. 1.

The sub-transmission system is subdivided into 16 non connected zones, whose boundaries are shown with dotted lines and labeled $Z_1, \ldots, Z_{16}$ in Fig. 3. In the same figure, the arrows indicate connections to lower voltage levels (mainly sub-transmission except for a few loads directly fed from transmission).

Loads are connected at the distribution buses and represented by the well-known exponential model: $P = P_o V_\ell^\alpha$, $Q = Q_o V_\ell^\beta$, where V_ℓ is the corresponding bus voltage.

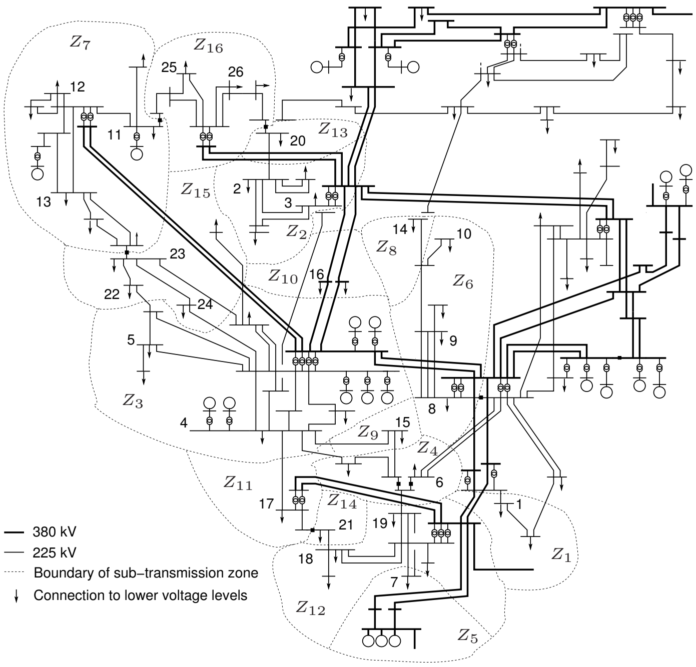

Fig. 3. One-line diagram of the studied region within RTE system

Following a disturbance, the long-term dynamics are driven by 341 load tap changers with various delays, by overexcitation limiters of generators, and by secondary voltage regulators controlling 11 pilot nodes [24]. Two levels of tap changers control sub-transmission and distribution voltages (the 380/225 kV transformers having fixed ratios). The system responses have been obtained by Quasi Steady-State (QSS) simulation [2], using a time step of 1 second and a simulation interval of 1000 seconds. Hence, electromechanical transients are not simulated; this is acceptable considering that the protection is not going to act in less than 4 seconds, according to the tuning detailed in Section IV-D. Obviously, detailed time simulation can be used instead of the QSS approximation; it is even recommended for final verification of the protection behaviour.

The criterion to accept a post-disturbance evolution was that all transmission voltages remain above 0.8 pu. It may happen that voltages recover after reaching this low value, thanks to secondary voltage control, but this was not accepted considering the nuisance for customers and the lack of reliability of the load model. In addition, it was checked that no field-current limited generator had its voltage below the value imposed by plant auxiliaries.

The examples provided in this paper relate to four disturbances:

D1: loss of two transmission lines in zone Z_7 (see Fig. 3);
D2: loss of two transmission lines connecting Z_{15} to Z_3;
D3: loss of two transmission lines connecting Z_2 to Z_{16};
D4: loss of two transmission lines connecting Z_7 to Z_3 with automatic reclosure of a switch between Z_7 and Z_{15}.

all leading to voltages lower than 0.80 pu.

B. Choosing the load shedding controller location

No attempt was made to optimize the location of the controllers. Instead, the previously mentioned geographical zones were re-used, all of them being provided with at least one controller. Some zones with a large load power received several controllers, each taking care of a cluster of loads based on topology. By so doing, a total of 26 controllers were considered, which are denoted C_i $(i = 1, \ldots, 26)$ in

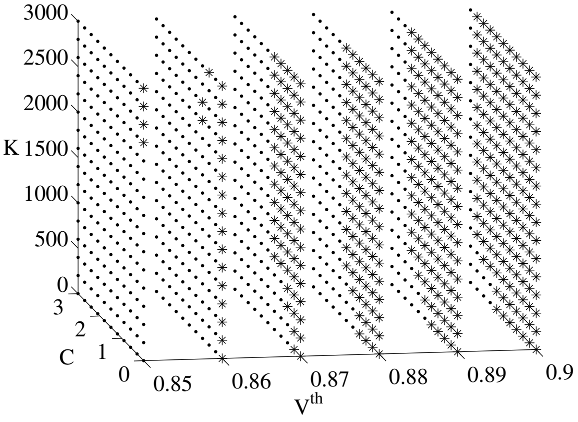

Fig. 4. Performance of load shedding scheme for different C, K and V^{th} settings

TABLE I
MINIMUM VOLTAGE REACHED AFTER ACCEPTABLE DISTURBANCES

zone	controller	min. volt. (pu)	zone	controller	min. volt. (pu)
Z_1	C_1	1.02	Z_8	C_{14}	0.94
Z_2	C_2	0.97	Z_9	C_{15}	1.00
	C_3	0.98	Z_{10}	C_{16}	1.01
Z_3	C_4	1.00	Z_{11}	C_{17}	1.02
	C_5	1.00	Z_{12}	C_{18}	0.98
Z_4	C_6	0.94		C_{19}	0.93
Z_5	C_7	0.93	Z_{13}	C_{20}	0.99
Z_6	C_8	1.00	Z_{14}	C_{21}	1.01
	C_9	0.96	Z_{15}	C_{22}	0.93
	C_{10}	0.95		C_{23}	0.95
Z_7	C_{11}	0.99		C_{24}	0.95
	C_{12}	0.98	Z_{16}	C_{25}	1.00
	C_{13}	0.94		C_{26}	1.00

the sequel. They are identified in Fig. 3 by their numbers i ($i = 1, \ldots, 26$) displayed next to the transmission bus they monitor. For instance, the figure shows that zone Z_7 received the controllers C_{11}, C_{12} and C_{13}, respectively. As individual loads at distribution level were not known from the available data, power was shed homothetically in each cluster, with a lower limit of 10 MW.

C. Choosing V^{th}

As already mentioned, the voltage threshold V^{th} should be set high enough in order to avoid delaying the controller actions. This is best seen from Fig. 4, which relates to disturbance D4. In this figure, the dots indicate protection failures, i.e. cases where a 0.80 pu voltage was temporarily or permanently reached at a transmission bus. On the contrary, the stars indicate settings for which the post-disturbance voltage evolution is accepted. For clarity, the figure does not show results for $V^{th} > 0.90$ pu, which correspond to all stars.

These results confirm that V^{th} should be taken as high as possible in order the protection to operate reliably. However, above 0.90 pu, the gain in reliability becomes marginal.

On the other hand, as also mentioned, V^{th} should be low enough so that no load is shed when the system post-disturbance response is acceptable. According to standard operating rules, this should be the case for any single contingency. Hence, all single outages were simulated, and the lowest voltage reached in the post-disturbance period was recorded at each bus monitored by a load shedding controller. Table I gives the minimum over all disturbances, for each controller. As can be seen, setting $V^{th} = 0.92$ pu for all controllers would be acceptable.

N-2 or more severe disturbances *with acceptable system responses* could be also involved in the choice of V^{th}. This is a matter of design criterion. If it is not allowed to shed load (considering that the system response is acceptable), then V^{th} has to be decreased in order to cope with the lower voltages reached after these more severe disturbances. In this case it was found more appropriate to select non uniform values of V^{th} ranging from 0.86 to 0.90 pu.

As a compromise between protection security and selectivity, V^{th} was set to 0.90 pu. This leaves some margin with respect to the 0.93 pu ceiling corresponding to N-1 contingencies without affecting the protection performance. By so doing, we accept to shed load after *some* N-2 or more severe contingencies which do not cause unacceptable voltages. The same value V^{th} is used for all controllers for the sake of simplicity.

Note finally that in highly compensated (or capacitive) systems, the same procedure will naturally lead to higher V^{th} values, since after acceptable disturbances voltages will settle to higher values. Critical voltages will be also higher and hence V^{th} will remain close to the latter, thereby avoiding undue delays that would lead to shedding more load. A similar procedure led to values of V^{th} in the range $[0.9 \;\; 0.95]$ pu when devising the undervoltage load shedding scheme of the 735-kV system detailed in [6].

D. Choosing C and K

The next step is to determine the best (C,K) combination. To this purpose, for each scenario necessitating load shedding, it is appropriate to consider plots of the type shown in Figs. 5 and 6. These plots show the total amount of power shed (by all controllers until all monitored voltages recover above V^{th}), for various values of C and K, under the chosen V^{th}. The gray parts represent successful protection operation, the darkest points corresponding to the smallest amount of power cut.

Figure 5 corresponds to disturbance D2 (see Section IV-A), which is "mildly" unstable, while Fig. 6 refers to D4, which is "more severe". Both figures confirm that choosing a larger C (i.e. a slow responding protection) requires to also set K to a larger value, but leads to shedding more load. Beyond some value of C, the protection is so slow that it fails, whatever the value of K.

From such plots, a (C,K) combination suitable to all scenarios can be identified by minimizing the total load shedding over all scenarios [6]. However, other aspects and engineering judgement have to be taken into consideration when tuning such an SPS. For instance:

- for reliability reasons, it does not sound appropriate to choose a point in the (C,K) space close to the limit of protection failure. With reference to Figs. 5 and 6, the

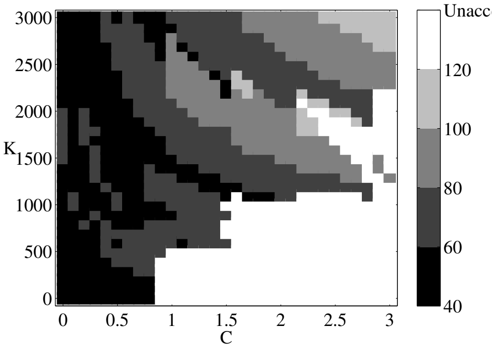

Fig. 5. Total power shed for various (C, K) values; disturbance D2

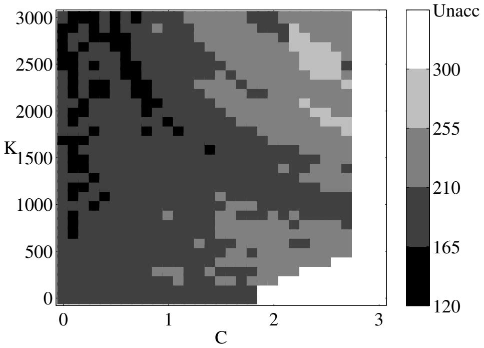

Fig. 6. Total power shed for various (C, K) values; disturbance D4

chosen point should be at a minimum distance of the white areas;

- too small C values are not recommended because the integral in Eq. (5) would be computed over a short interval where transients may deteriorate accuracy;
- too small K values are not realistic because it may not be feasible to disconnect small blocks of loads.

Taking into account the above mentioned recommendations, the settings in Table II have been adopted for all controllers. According to Eqs. (2, 4, 5), these values of C and K mean that if V settles at 0.86 pu, for instance, 80 MW are shed after 10 seconds. The shortest shedding delay would correspond to a case where, right after the disturbance V settles a little above 0.80 pu (the lowest accepted value). The value is easily obtained from (2) as $\tau = \frac{0.4}{0.9-0.8} = 4$ seconds.

TABLE II
CONTROLLER SETTINGS

V^{th}	C	K	τ_{min}	$\min_k P_k$	ΔP_{tr}^{sh}
0.9 pu	0.4 pu·s	2000 MW/pu	3 s	10 MW	250 MW

E. Detailed example of performance

It can be seen in Figs. 5 and 6 that the zones of equal shedding are not limited by smooth boundaries. This is attributable to the discrete nature of the controllers. A small change of a parameter may lead to a smaller or larger load shedding by one controller which will delay or reset the action of a nearby controller. In this section, precisely, we illustrate how the controllers interact with each other.

We consider disturbance D2. In the absence of load shedding, the unstable voltage evolution observed by controller C_{24} is shown with dotted line in Fig. 7. The heavy line in the same figure corresponds to the system stabilized by the proposed protection.

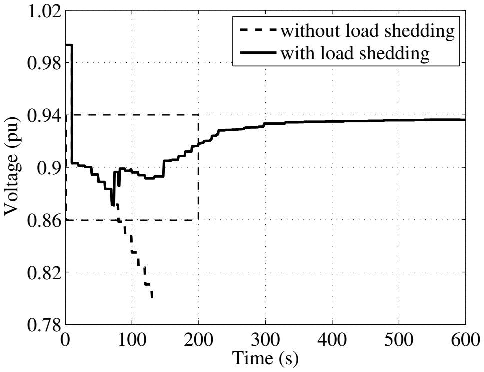

Fig. 7. Voltage evolution without and with load shedding

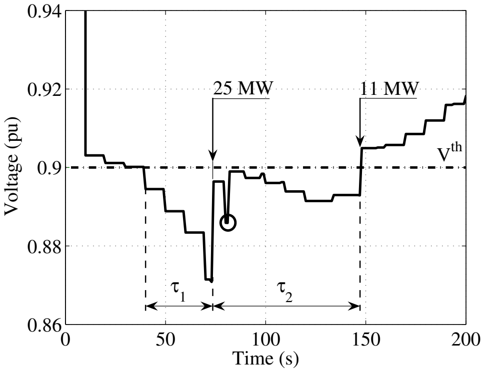

Fig. 8. Monitored voltage and actions of controller C_{24}

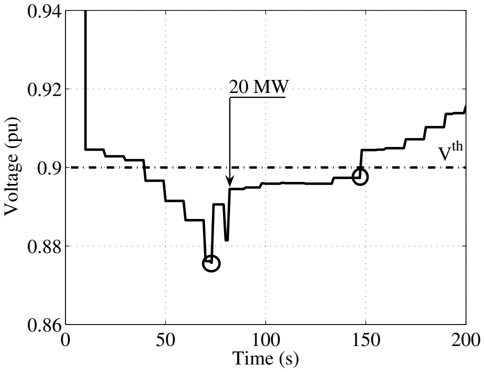

Fig. 9. Monitored voltage and actions of controller C_{22}

In this example, C_{22} and C_{24} respond to the disturbance. In order to illustrate their interactions, a zoom on the dashed area of Fig. 7 is provided in Fig. 8, while Fig. 9 shows the voltage monitored by C_{22} over the same time interval. In both figures, the MW values refer to the power shed by the controller of concern while the circles indicate shedding by the other one.

As can be seen, the voltage jump experienced when C_{24} sheds 25 MW, has the effect of delaying and reducing the first load shedding by C_{22}. Similarly, the 11 MW shed by C_{24} make both voltages recover above $V^{th} = 0.90$ pu and both controllers return to idle state.

Consider now a case (not shown with figures) where $K =$

3000 MW/pu. As a result, the first block shed by C_{24} is larger, which makes its voltage recover above V^{th}. As the voltage of C_{22} is still below V^{th}, the latter acts, as in Fig. 9, but at a later time. As a result, its voltage also recovers above V^{th} and no third shedding is needed.

Figure 8 also illustrates the previously mentioned inverse-time characteristic. The two areas between the V and V^{th} curves, of respective widths τ_1 and τ_2, have the same surface C. Since the voltage has increased under the effect of the 25-MW shedding, the controller waits a longer time before shedding the next 11 MW ($\tau_2 > \tau_1$).

F. SPS Selectivity in terms of location

This section illustrates one aspect of SPS selectivity, i.e. the ability of the distributed protection to adjust the shedding location to the disturbance it faces. This relates to the fact that the area experiencing the largest voltage drops changes with the disturbance, and different controllers are activated.

For each of the four disturbances, Table III provides the most affected zones, the controllers that were activated, and the blocks of power that were sequentially shed, for the V^{th}, C and K settings chosen in the previous sections. Let us recall that different settings may lead to different combinations of controller actions. A zero value in the table indicates that the corresponding controller was temporarily started but switched back to idle state before acting (see Fig. 2).

As can be seen, the affected zones and the activated controllers change significantly from one disturbance to another.

TABLE III
CONTROLLERS ACTIVATED BY THE FOUR DISTURBANCES

disturb.	zone	controller	shedding steps (MW)
D1	Z_7	C_{13}	35 + 25
	Z_7	C_{11}	0
D2	Z_{15}	C_{22}	20
	Z_{15}	C_{24}	25 + 11
	Z_{15}	C_{23}	0
D3	Z_{13}	C_{20}	32
	Z_{16}	C_{26}	48
	Z_7	C_{13}	20
	Z_{16}	C_{25}	0
D4	Z_7	C_{12}	27
	Z_7	C_{13}	26 + 37
	Z_{15}	C_{22}	20 + 17
	Z_{15}	C_{23}	22 + 24
	Z_7	C_{11}	0

G. SPS selectivity in terms of total power cut

Another aspect of selectivity is the ability to adjust the load shedding amount to the severity of the disturbance.

Let us stress that the proposed distributed controller structure is not claimed to yield minimum load shedding, although the controllers settings have been chosen so as to meet this objective. Tests have thus been performed to assess the degree of sub-optimality in terms of amount of power cut.

As a benchmark, a method inspired of [17] has been used to compute the minimal power that should be shed *in a single step* to save the system.

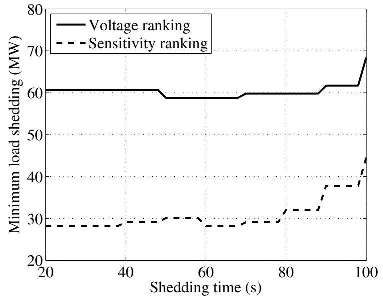

Fig. 10. Minimum (single-step) shedding vs. time; disturbance D2

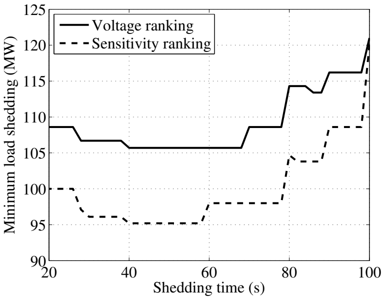

Fig. 11. Minimum (single-step) shedding vs. time; disturbance D4

First, loads are ranked with respect to their efficiency in restoring voltages. Two criteria have been used. The first one is based on the sensitivities detailed in [23], while in the second one loads are ranked by increasing order of post-disturbance transmission voltages. A snapshot of voltages is taken when one of them reaches 0.8 pu. The voltage ranking has some similarity with what the distributed controllers do, *except that here load is shed in a single step*, which results in shedding less [6]. Then, for a given shedding time, a binary search is used to find the minimum total power to cut. For a given value of power, shedding is distributed over the loads by decreasing order of the ranking. Finally, the procedure is repeated for various shedding delays.

Figures 10 and 11 shows the so obtained minimum shedding as a function of shedding time, for disturbances D2 and D4, respectively. The curves confirm that beyond some delay, shedding later requires to shed more [2]. Also, as expected, sensitivity-based ranking yields lower load shedding. Thus, the minimum shedding (unfortunately not known when facing the disturbance!) is 29 MW for disturbance D2 and 95 MW for disturbance D4.

These amounts are to be compared to those shed by the distributed controllers. Figures 5 and 6 show that they can shed as few as 40 MW for disturbance D2 and 120 MW for disturbance D4. These values are not far from the benchmark values, if one considers that each shedding is lower limited to 10 MW. When the settings of Table II are used, the distributed controllers shed 56 MW (respectively 173 MW) after disturbance D2 (respectively D4), as can be checked from the last column of Table III. These values are less close to the optimum. The reason is that the settings of Table II were not optimized for D2 and D4 but are a compromise over a larger set of disturbances.

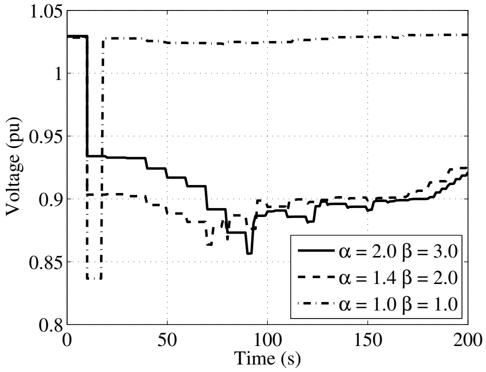

Fig. 12. System response with load shedding, for various load behaviours

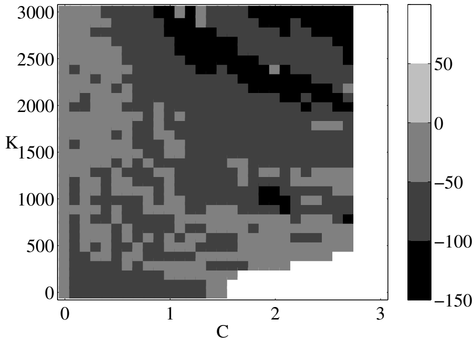

Fig. 13. Difference in power shed when load exponents change from $(\alpha = 1.4, \beta = 2.0)$ to $(\alpha = 1.0, \beta = 1.0)$

H. SPS robustness with respect to load model uncertainty

As already mentioned, the closed-loop nature of each controller compensates for uncertainties in dynamic system behaviour. This section aims at illustrating the robustness of the proposed scheme with respect to load modelling inaccuracies.

The controllers' ability to adapt to unforeseen load characteristics is illustrated by Fig. 12, showing the evolution of the lowest transmission voltage for different load exponents α and β, after disturbance D4. Although the controllers were tuned from simulations performed with $(\alpha = 1.4, \beta = 2)$, they respond very satisfactorily (if not better) when facing different load characteristics.

One can also see that the smaller α and/or β, the faster and the deeper the voltage drop below $V^{th} = 0.90$ pu, and hence the faster the shedding and the voltage restoration.

Different load characteristics lead to different shedding amounts. Figure 13 shows the *difference* in power cut when the load exponents change from $(\alpha = 1.4, \beta = 2.0)$ to $(\alpha = 1.0, \beta = 1.0)$. Positive values correspond to cases where less load is shed when $(\alpha = 1.0, \beta = 1.0)$; this tends to occur for small values of C or K. The white region of the diagram corresponds to (C, K) settings for which the protection failed for at least one of the two load characteristics. In fact, a comparison with the diagram in Fig. 6 shows that the region of successful operation of the protection remains almost the same in spite of the large difference in load behaviours.

Other tests were made assuming a smaller or even no reactive power counterpart when dropping active power. An example is provided in Fig. 14, relative to disturbance D2.

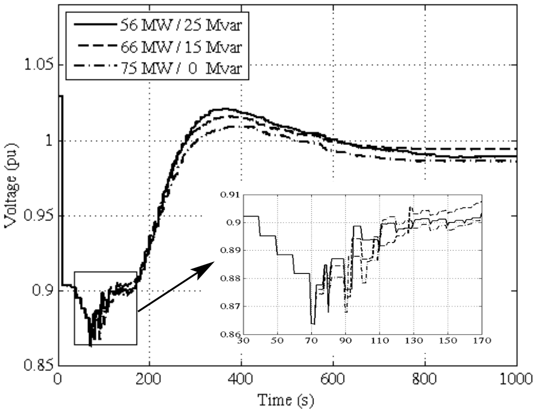

Fig. 14. Effect of shedding under unexpected load power factors

In the simulation shown with heavy line, the load power power factor was left unchanged after shedding. In the other two cases, 50 % and 0 % of the reactive power were cut, respectively. As can be seen, although the C and K parameters were tuned under the assumption of constant power factor, the controllers adjust to the changing conditions by shedding more active power (see caption in Fig. 14). Nevertheless, the voltage evolution is hardly affected.

I. SPS robustness with respect to component failure

Another aspect of robustness has to do with the possible failure of some controllers. This section aims at demonstrating the performance of the proposed scheme in this respect.

Table IV shows the power shed by each controller in response to disturbance D2, in various scenarios. Case 1 corresponds to the simulation shown in Figs. 7 to 9 while the other cases correspond to failures, as detailed hereafter.

TABLE IV
LOAD SHEDDING AMOUNTS (MW) IN VARIOUS SCENARIOS

	Case					
controller	1	2	3	4	5	6
C_{22}	20	15	62	-	62	-
C_{23}	0	0	21	0	-	58
C_{24}	36	44	-	54	-	-
Total	56	59	83	54	62	58

In Case 2 the voltage measurement used by controller C_{24} was assumed to be systematically 0.01 pu smaller than the correct value, causing this controller to act faster and shed more power. This is compensated by a smaller action of C_{22}.

Case 3 simulates a full failure of C_{24} (identified with a "-" in the table); this is covered by a stronger action of C_{22}, while C_{23} comes into play. Similarly, Case 4 corresponds to failure of C_{22}; it causes C_{24} to take a stronger action, but the help of C_{23} is not needed.

Cases 5 and 6 correspond to the failure of two controllers at the same time. In both cases, the remaining controllers succeed stabilizing the system with a little more effort than in Case 1.

One can conclude that the redundancy among controllers makes the protection scheme very reliable. Furthermore, substituting one controller with another does not significantly

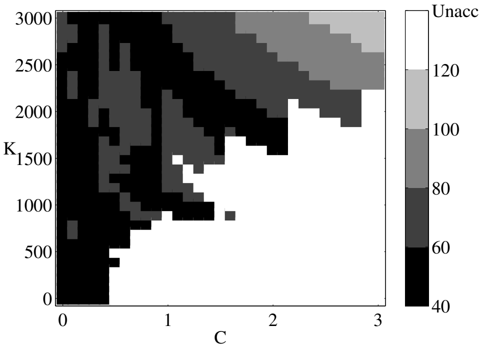

Fig. 15. Total power shed for various (C, K) values; disturbance D2

increase the amount of power shed. It may even decrease a little bit. Case 3 appears as an exception and is discussed in the next section.

J. Variant with communicating controllers

Comparing Case 3 with Case 5 shows that C_{22} alone could have saved the system, without the intervention of C_{23}. In Case 3 more load has been shed because both controllers acted at the same time, not knowing about their respective actions. This is the price to pay for not having communication between controllers, other than through network voltages.

One may think of a variant with communicating controllers (for instance in the context of a centralized SPS, as mentioned in Section II-D), allowing controllers to send signals which accelerate, inhibit or even reset the actions of other controllers. To this purpose, a variant was considered in which: (i) all controllers are reset when one is acting, and (ii) if the integrals (2) of two controllers reach the C value at the same time, only the one observing the greater voltage drop is acting.

Figure 15 show the results obtained with the above variant in the case of disturbance D2. A comparison with the corresponding diagram in Fig. 5 shows that some load shedding can be avoided, for some combinations of C and K. There is no systematic decrease though. On the contrary, for small values of C, the non-communicating scheme had a better behaviour. Also, the region of successful operation of the protection shrunk for some disturbances; this is attributable to the delays introduced by the resets.

Although communication between controllers could bring some improvements, a scheme remains to be found in order to obtain substantial benefits that would compensate for the increased complexity.

V. CONCLUSION

A new undervoltage load shedding scheme has been proposed and realistic tests have been reported demonstrating:

- its response-based and closed-loop operation allowing to adjust to the severity of the situation;
- its distributed structure allowing to adjust to the disturbance location;
- its robustness with respect to unexpected load behaviours or controller failures;
- its simplicity, since there is no dedicated communication between controllers and no system model is needed.

Of course, the paper only tackled the control logic. Validation with full time simulation, design measurement filtering schemes, number of controllers, clustering of loads, etc. are important aspects to be considered before implementing such a system protection scheme. Variants of the proposed scheme may be also thought of, for use in a centralized protection allowing the controllers to exchange information.

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