Decentralized tap changer blocking and load shedding against voltage instability: prospective tests on the RTE system [1]

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Abstract

This paper reports on prospective tests of a system protection scheme against long-term voltage instability relying on a set of distributed controllers, each monitoring a transmission voltage, blocking tap changers and shedding loads in a zone. The emergency actions adjust in magnitude and location to the disturbance. Each controller acts in closed-loop, which guarantees robustness. The method is illustrated on a real-life model of the Western region of the RTE system. The choice of the controller settings is discussed in some detail and examples of performance are given, combining the above remedial action with capacitor switching and secondary voltage control.

Key words: voltage stability, emergency control, system protection schemes, tap changer blocking, load shedding

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1 Introduction

There are two lines of defence against voltage instability and the associated risk of system blackout [1,2]:

- preventively: check system security margins with respect to “credible” (typically N-1) events. To this purpose, it is quite common to compute load power margins, i.e. the largest load increase that the system can accept in its present configuration, so that its response to the incident remains acceptable;
- correctively: face more severe disturbances leading to emergency conditions through System Protection Schemes (SPS), i.e. protections designed to detect abnormal 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 [3].

This paper deals with the second aspect and focuses on long-term voltage instability. In this context, several actions can be taken in emergency conditions:

- switching shunt compensation;
- raising generator voltages, which increases the maximum power deliverable to loads but obviously becomes ineffective once the generators reach their excitation limits;
- blocking transformer Load Tap Changers (LTCs) on their current positions. Alternatively, the taps can be moved and locked to predetermined positions or their voltage setpoints can be decreased [4,5]. All these techniques aim at stopping the load power restoration and take advantage of load sensitivity to voltage;
- shedding load, which is very effective if performed at the right location and in due time and amount [6–9].

The first three actions listed above have been in use at RTE for some time [3,10]. Shunt capacitors are automatically switched at HV buses of EHV/HV transformers, upon detection of a low voltage condition at the corresponding EHV bus. Generator voltages are controlled in a coordinated way by secondary voltage control [11]. The latter aims at keeping the voltages of pilot buses near setpoint values while sharing the reactive effort among the generators according to their capabilities. Although mainly designed to operate in normal conditions, secondary voltage control contributes to increasing generator voltages in emergency situations and helps restoring transmission grid voltages. Finally, the taps of the HV/MV transformers controlling the MV distribution buses are blocked on their current position upon detection of low voltage conditions at EHV buses. Under the same conditions, the taps of EHV/HV transformers that normally control HV bus voltages are moved to a pre-determined position aimed at preserving EHV voltages to the detriment of HV ones. The same taps, however, are merely blocked if their current position is more favourable to the EHV voltages than the predefined locking position. This blocking/locking scheme was shown in many simulations to be a successful countermeasure, and indeed helped preserving system operation on a few occasions.

The present prospective study was performed in order to assess the performance of load shedding as an additional line of defence. To this purpose, the design proposed in [9] was investigated. It consists of a set of distributed controllers, each monitoring transmission voltages in a zone and controlling a group of related loads. In the course of testing this scheme, the possibility was considered to also perform tap changer blocking/locking in a distributed manner, which represents an improvement with respect to [9].

The main features of the proposed scheme are as follows:

- *response-based* protection: load shedding relies on voltage measurements which reflect the initiating disturbance and the actions taken so far by the SPS and by other controllers;
- *closed-loop* protection: the SPS can be activated several times, on the basis of the measured result of 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 [7]. This is 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;
- *distributed* protection: load is shed first where voltages drop the most. This location changes with the disturbance, allowing the scheme to automatically adjust the shedding location to the disturbance it faces. Similarly the tap changers are blocked only where needed, allowing distribution voltages to be restored in the zones that are less effective in protecting the system. Furthermore, the multi-controller nature of the scheme brings some redundancy that increases robustness against individual controller failures [9].

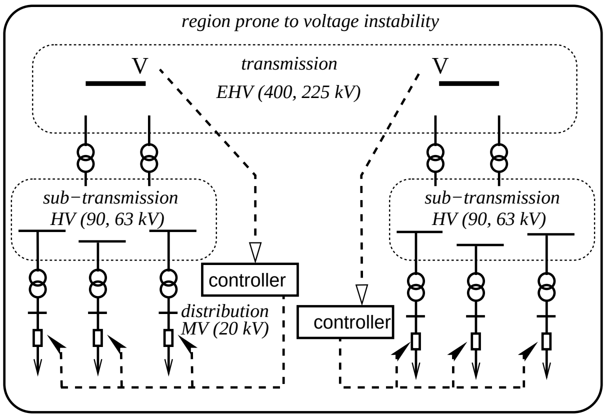

Fig. 1. Overall structure of the distributed scheme (voltage levels relate to RTE system)

2 Principle of the system protection scheme

2.1 *Load shedding scheme*

The load shedding 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. Sub-transmission networks 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 to be controlled.

The decision by a controller to shed load is based on the comparison of V with a threshold value V^{sh}. If a (severe) disturbance causes V to become smaller than V^{sh}, the controller sheds an amount ΔP^{sh} of load power after a delay τ. Both ΔP^{sh} and τ depend on the dynamic evolution of V, as detailed hereafter.

Let t_0 be the time where measurement V becomes smaller than V^{sh}. A first block of load is shed at a time $t_0 + \tau$ such that:

$$\int_{t_0}^{t_0+\tau} \left(V^{sh} - V(t)\right) dt = C \tag{1}$$

Thus, the C constant has to do with the shedding delay τ. The larger C, the more time it takes for the integral to reach this value and hence, the slower the action. Furthermore, the deeper the voltage drops, the less time it takes to reach the value

C and, hence, the faster the shedding.

The delay τ is lower bounded:

$$\tau_{min} \leq \tau \tag{2}$$

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

The amount of load shed by the controller at $t_0 + \tau$ is given by:

$$\Delta P^{sh} = K \cdot \Delta V^{av} \tag{3}$$

where ΔV^{av} is the average voltage drop over the $[t_0 \; t_0 + \tau]$ interval, i.e.

$$\Delta V^{av} = \frac{1}{\tau} \int_{t_0}^{t_0+\tau} \Big(V^{sh} - V(t) \Big) \, dt \tag{4}$$

The above relationships transpose voltage drop severity into load shedding amplitude: the larger $V^{sh} - V$, the larger ΔV^{av} and, hence, the larger the amount of load shed. The same holds true when the gain K increases. Through (4) the voltage drop is averaged over time in order to filter out transients and measurement noise. Another reason for having τ large enough is the accurate computation of the integral in (1) and (4).

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}. These limits are summarized as follows:

$$\min_k P_k \leq \Delta P^{sh} \leq \min \left(\sum_k P_k, \; \Delta P^{sh}_{tr} \right) \tag{5}$$

where P_k denotes the individual load power behind the k-th circuit breaker under control, and the minimum and sum extend over all manoeuvrable and not yet opened breakers.

Note that the sequence is repeated until the voltage is restored above the threshold. At the time the controller sheds load, the integral in (1, 4) is reset to zero, t_0 is set to the current time, and the controller is ready to act again as long as $V < V^{sh}$, and provided that load is available to do so. This repeated action capability yields the closed-loop behaviour in the sense explained in the Introduction. Another role of the delay τ is to leave time for the controller to assess the effect of the actions taken both by itself and by the other controllers.

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. In [9] the scheme was shown to be robust with respect to unexpected changes of load reactive power.

2.2 Tap changer blocking scheme

The tap changer blocking scheme is assumed to operate in the same zones as load shedding. This is, however, a one-shot control. Namely the taps of a zone are blocked or locked once the monitored voltage V drops and remain below a threshold V^{bl} for some time $\tau^{'}$.

2.3 Overall architecture

The proposed scheme was initially meant to operate in a fully distributed way, each controller using local information and taking local actions, as for underfrequency load shedding. In particular, the scheme operates without resorting to a dedicated communication network. The controllers do not exchange information, but are rather informed of their respective actions through the system itself. Indeed, when a controller sheds load, the resulting voltage increase slows down or inhibits the nearby controllers. This is made possible by the fact that voltages have no “inertia”.

Neither do the controllers require a model of the system. This and the absence of communication makes the protection scheme simpler and hence more reliable.

This purely distributed scheme was shown in [9] to 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. (1-5) in a single processor, and sending back emergency orders. In this case, additional information exchanges and interactions between controllers may be envisaged without further penalizing the scheme. However, telecommunication delays and possible failures should then be considered when evaluating performance and reliability.

2.4 Tuning the controller parameters

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

First, attention should be paid to choosing proper values of V^{sh} and V^{bl}. Several conflicting requirements have to be satisfied. Namely V^{sh} should be:

- low enough so that it does not act in a scenario with acceptable post-disturbance system response
- high enough so that post-disturbance voltages remain at an acceptable value
- high enough to avoid shedding too late, which in turn may require to shed more
- low enough to let other stabilizing controls act, such as tap changer blocking.

while V^{bl} should be:

- sufficiently higher than V^{sh} to favour tap changer blocking with respect to load shedding
- low enough so that it does not act in a scenario with acceptable post-disturbance system response (same as above).

Next, C and K should be chosen so that, over the whole set of scenarios, the protection sheds as few load as possible, while keeping these parameters away from values that could cause protection failure.

Using the same C and K values for all controllers makes the design definitely simpler. We did not find practical evidence that individual values would yield substantial benefits. Therefore, this simplification is adopted throughout the remaining of the paper.

Further aspects are considered in the next section.

3 Design of the controllers

Preliminary tests of the above described scheme have been performed on the Western region of the RTE system. The assumptions made in these tests are discussed in the present section, while illustrative examples are given in the next one.

3.1 System model

The model includes 4563 buses, 148 synchronous generators, 2 Static Var Compensators, 3904 lines and 2028 transformers. It 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 the transformers feeding the 20-kV distribution buses. Loads at these MV buses are represented with an exponential model.

The long-term dynamics are driven by 1346 LTCs with various delays, by overexcitation limiters of generators, and by secondary voltage regulators. The Western region is equipped with coordinated secondary voltage control, while in the remaining of the system, the older PI controllers are used to this purpose [11]. LTCs control both sub-transmission and distribution voltages, as shown in Fig. 1. Finally, 37 shunt capacitors at sub-transmission level are automatically switched on, each upon detection of low voltage at the nearest transmission bus.

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 900 seconds. Thus, electromechanical transients are not simulated, which is acceptable considering that the protection scheme will not act in less than 3 seconds.

3.2 Criterion of acceptable evolution

The criterion to accept a post-disturbance evolution was that all transmission voltages remain above 0.8 pu. It may happen that voltages recover even 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 verified that no field-current limited generator had its voltage below the minimum imposed by plant auxiliaries.

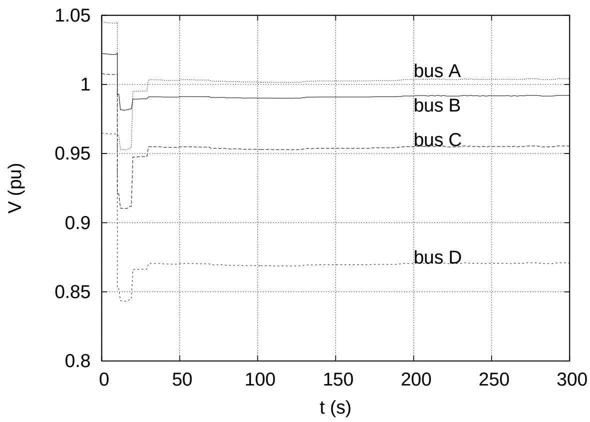

Fig. 2. Example of centralized tap changer blocking

3.3 Existing tap blocking scheme

The existing tap changer blocking/locking scheme can act in 4 areas within the Western region. In each area, it is activated after the voltage at a pre-defined 380-kV bus drops below a pre-specified threshold. The whole scheme involves 528 transformers and the taps are controlled as described in the Introduction.

As an illustration, Fig. 2 shows the evolution of voltages at four 225-kV buses after a line outage in severe conditions. The disturbance, applied at $t = 10$ s, triggers the blocking which is effective 30 seconds later. In the meantime no LTC has started to act yet and hence load power restoration through LTCs is avoided. On the contrary, transmission voltages increase after the disturbance under the effect of shunt capacitor switching and secondary voltage control.

The stabilization effect is clear from the figure but it must be stressed that this emergency control affects the voltages of all loads inside the area (and the areas are much larger than the zones considered in the distributed scheme). Moreover, there is no further line of defence against voltage decrease. Finally, a possible failure of the scheme should be envisaged. This motivates to resort to load shedding as a complementary line of defence.

3.4 Assigning loads to the distributed controllers

To locate the controllers, an existing decomposition of the region into 79 load zones, corresponding to distribution districts, was considered. This initial partition was simplified to eliminate small zones, avoid having EHV monitored buses radially connected to the remaining of the transmission system, etc. This led to 51 zones, with load power ranging from 61 to 475 MW. Each of them was assigned to an EHV bus, whose voltage is monitored as explained previously. The total load in the 51 zones is 10600 MW.

Furthermore, while enumerating all combinations of pre-contingency state, contingency and (V^{sh}, C, K) parameters, it was observed that only 25 of the controllers were effectively responding. The zones of these 25 controllers are denoted $Z_1, \dots, Z_{25}$ in the sequel.

Finally, when the (V^{sh}, C, K) parameters are set to their optimal values, only 14 out of these 25 controllers act. This yields a valuable indication of the minimal number and location of controllers to install in the system, at least for the set of scenarios considered.

As can be seen, no attempt was made to define the zones according to the voltage behaviour of the system.

As regards the controllability of distribution circuit breakers, the following simplifying assumptions were made. Load is shed in steps of 2.5 % of the power initially consumed in the zone. Thus, the amount of power cut at one time is determined from (3) and rounded to the nearest larger multiple of the 2.5 % step. All loads in a zone are decreased homothetically. A maximum interruptible fraction of 40 % of the initial power has been assumed. Reactive power reduction preserves the initial power factor. As shown in [9], a strength of the proposed closed-loop scheme is the ability to compensate for unforeseen load (and load shedding) behaviour. The minimum delay before shedding τ_{min} has been set to 3 seconds.

As already mentioned, the same zones were used for the blocking/locking of LTCs. The scheme presently used by RTE at the region level and outlined in the Introduction, was assumed inside each zone. The delay τ' before blocking/locking the taps has been set to 3 seconds, as there is no point in further delaying this one-shot control.

These delays, significantly shorter than those presently in effect, would require new communication equipments. The latter would serve the twofold objective of tap blocking/locking and load shedding.

3.5 Scenarios used to tune the SPS

A set of 361 contingencies was considered, including 350 single outages (N-1 incidents) and 11 busbar faults (cleared by opening all equipments connected to the bar) affecting the Western region.

Only two (busbar fault) contingencies led to voltage instability at the base case operating point. Therefore, to include further stressed situations, we computed for each contingency the maximum pre-disturbance load power increase that can be accepted before the contingency yields unacceptable system response. To this purpose, load was increased uniformly over the region, up to a maximum of 500 MW/100 Mvar. Nine additional contingencies were found to have a margin lower than this maximum. This led to designing the protection scheme on the basis of:

- 359 stable scenarios : 350 with the system at maximum stress, and 9 at marginally acceptable stress;
- 22 unstable scenarios : 2 in base case, 9 at marginally unacceptable stress and the same 11 at maximum stress.

3.6 Setting V^{sh} and V^{bl}

V^{sh} and V^{bl} were chosen to meet the requirements listed in Section 2.4 in the best possible way.

First, we determined the lowest voltage reached at the 51 monitored EHV buses after each of the N-1 contingencies, with the system operating at either maximum or marginally stable stress. This minimum voltage was found to be 0.92 pu, except for two contingencies with local effects leading to respectively 0.87 and 0.86 pu in one zone. Hence, to avoid shedding load following N-1 events with acceptable system response, V^{sh} should be set a little below 0.92 pu, except in that zone, where it should be chosen a little below 0.86 pu.

On the other hand, it was found that V^{sh} should not be set below 0.85 pu to leave the controllers a chance to shed load before the unacceptable value of 0.80 pu is reached.

If the protection consisted of load shedding only, there would be some advantage in setting V^{sh} to - say - 0.90 pu instead of 0.85 pu as it would lead to shedding a little less power in most (but not all) of the 22 unstable scenarios.

However, when combining LTC blocking/locking and load shedding, much less load is shed (as will be shown in the next section) and hence there is no significant drawback in setting V^{sh} to 0.85 pu. On the contrary, this allows to set V^{bl} to 0.90 pu, and hence give precedence to LTC blocking/locking. With $V^{bl} = 0.90$ pu, LTC will be blocked/locked in one zone following the two acceptable N-1 contingencies already mentioned. The impact is much lower than load shedding, but if it was not deemed acceptable, a lower V^{bl} threshold could be taken in those two zones.

3.7 Setting C and K

The best (C, K) pair can be defined as the one minimizing the average load shedding over all scenarios:

$$\bar{P}^{sh} = \frac{1}{s} \sum_{j=1}^{s} P^{sh}(s_j, C, K) \tag{6}$$

where $P^{sh}(s_j, C, K)$ denotes the power shed in the j-th scenario $s_j \;\; (j = 1, \ldots, s)$ with the protection parameters set to C and K. Since a convex optimization method cannot be used, discretized values of C and K were enumerated, with $C \in \{0, 0.1, ..., 0.5\}$ and $K \in \{0, 100, ..., 3000\}$. Out of 186 so-defined values, 15 led to violating the 0.8 pu minimum voltage criterion after at least one contingency, and hence were no longer considered. The best values according to this criterion are $C = 0$ pu.s and $K = 1000$ MW/pu.

As an illustration, Figure 3 shows the variation of $\bar{P}^{sh}$ (computed over the $s = 22$ unacceptable scenarios) as a function of C and K. The gray parts represent successful protection operation, the darkest points corresponding to the smallest amount of power cut. This diagram confirms that choosing $C = 0$ and $K = 1000$ leads to shedding less load on the average. More importantly, it shows that this combination is far enough from the white area corresponding to protection malfunction, which guarantees robustness.

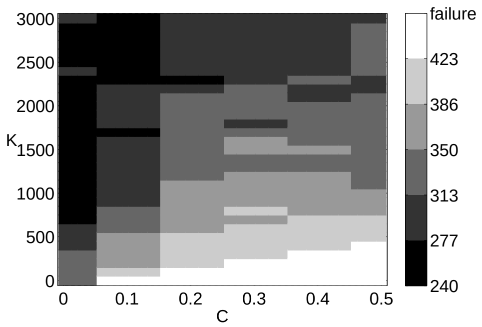

Fig. 3. Average load shedding $\bar{P}^{sh}$ (in MW) for various values of C and K

Note that weighting factors could be entered in (6) to account for the fact that a busbar fault is less probable than an N-1 outage, that it is more probable to operate at lower stress, etc.

An alternative way of assessing the performance for given values of C and K consists in counting the total number of scenario and parameter combinations in which more load is shed when using different values for these two parameters. Thus, the performance index I of a (C_i, K_j) pair is the number of combinations (s_m, C_k, K_l) such that:

$$P^{sh}(s_m, C_k, K_l) > P^{sh}(s_m, C_i, K_j) \qquad m = 1, \ldots, s;\ k \neq i \text{ or } l \neq j$$

Table 1 lists the best (C, K) pairs ranked by decreasing value of I, which is shown in the second column. One can observe that many pairs perform better than ($C = 0.0, K = 1000$), the pair that led to minimum $\bar{P}^{sh}$.

A comparison between both criteria is provided by Table 2, which shows the power shed in 22 scenarios (MU stands for "Marginally Unstable" and MS for "Maximum Stress"). Compared to $(C = 0, K = 1000)$, $(C = 0, K = 2500)$ leads to shed less in 13 scenarios, more in 7 scenarios and the same amount in 2 scenarios. On the other hand, both settings lead to almost the same value of $\bar{P}^{sh}$. Hence, $(C = 0, K = 2500)$ may be preferred.

It is interesting to note that both criteria lead to a load shedding protection that acts fast once the V^{sh} threshold is crossed. Indeed, $C = 0$ means that the delay τ was set at its minimum $\tau_{min} = 3$ seconds.

Table 1
Ranking of (C, K) pairs by decreasing value of index I

pair	number of (s_m, C_k, K_l) combinations with		
(C_i, K_j)	more power shed	less power shed	same power shed
$(0.0, 2500)$	1951	476	169
$(0.0, 1600)$	1928	496	172
$(0.0, 2600)$	1924	498	174
$(0.0, 2700)$	1911	515	170
$(0.0, 1700)$	1853	572	171
⋮			
$(0.0, 1000)$	1791	601	204

3.8 Suboptimality of the SPS tuning

Clearly, by tuning the protection over a set of scenarios, its performance in a particular scenario is lower than if it was tuned for that particular scenario. This is confirmed by Table 3 which provides the amount of load shed in response to 8 contingencies, with the system operating at marginally unacceptable and maximum stress, respectively. No tap changer blocking was considered in this case.

The columns labeled "GO" relate to the global optimization (i.e. over the whole set of scenarios) while the columns labeled "IO" relate to the protection optimized for each scenario individually. The differences between "GO" and "IO" results remain acceptable, and even small in some cases. They are the price to pay for having a single response-based protection dealing with many situations (as opposed to an event-based protection relying on the identification of the disturbance).

The table shows that the amount of shed load increases with the system pre-contingency stress, which is also to be expected.

Table 2
Amount of load shed (MW) with the best (C, K) pair of each criteria

contingency	$(C = 0, K = 1000)$		$(C = 0, K = 2500)$	
	MU	MS	MU	MS
1	43	65	43	62
2	245	322	466	754
3	211	454	150	373
4	261	417	263	472
5	29	363	23	345
6	315	387	153	328
7	48	147	42	116
8	222	269	176	307
9	344	320	300	322
10	344	320	300	322
11	18	128	18	98
$\bar{P}^{sh}$	240		247	

4 Examples of protection performance

4.1 Distributed load shedding alone

Figure 4 shows the evolution of the voltage at one of the EHV buses monitored by the protection scheme, without and with load shedding, respectively. No tap changer blocking has been considered in this case. This situation could correspond to a failure of the existing tap blocking scheme, compensated by load shedding.

The dotted curve in the figure shows that, without emergency control, the voltage drops very quickly under the effect of the contingency (applied at t =10 s). With load shedding, on the other hand, several controllers act and prevent voltage from approaching the 0.80 pu lower limit. Instead, it remains around V^{sh} = 0.85 pu, before increasing under the effect of secondary voltage control. The latter stops

Table 3
Total power (in MW) shed by individually or globally optimized protection

contin-gency	at marginally unacceptable stress		at maximum stress	
	IO	GO	IO	GO
1	33.6	43.6	55.4	65.7
2	153.1	245.5	260.4	322.2
3	126.8	211.7	240.2	454.5
4	170.3	261.0	281.5	417.7
5	24.0	30.0	159.3	363.6
6	153.8	315.2	239.4	387.7
7	42.3	48.3	104.2	147.1
8	90.6	222.0	256.2	269.5

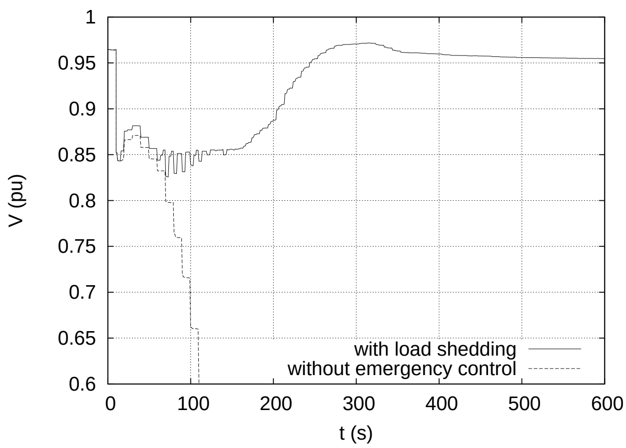

Fig. 4. Evolution of voltage at one monitored EHV bus without emergency control and with load shedding

operating when the local generators switch under field current limit and regains control when they switch back under voltage control thanks to load shedding.

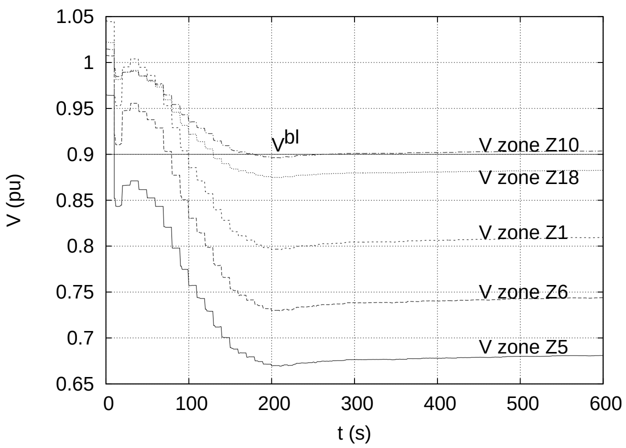

Fig. 5. Evolution of voltages at monitored EHV buses with distributed LTC blocking/locking

4.2 Distributed tap changer blocking/locking alone

We consider now the operation of the distributed tap changer blocking/locking scheme alone (i.e. without load shedding). Figure 5 shows the evolution of voltages at the EHV buses monitored by five controllers reacting to the disturbance. The latter is the same as in Fig. 4 but, here, the system evolution is unacceptable.

The explanation is easily found from the figure. Immediately after the disturbance, the taps are blocked in zone Z5, under the effect of the voltage falling below 0.90 pu. Elsewhere, the taps keep on moving and EHV transmission voltages keep on decreasing, which leads other zones to block their taps, for instance Z6 at $t = 80$ s, Z1 at $t = 99$ s, etc. In the meantime, however, voltages have decreased in the already blocked zones since in tap blocking/locking no attempt is made to preserve transmission voltages (unlike the reverse control proposed in [12]). Even if a large number of taps are eventually blocked, in the meantime the voltages have dropped dramatically.

This indicates that distributed tap blocking/locking alone is not a sufficient measure against voltage instability.

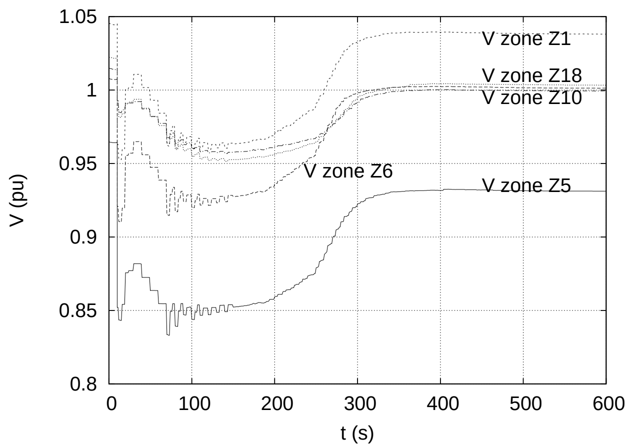

Fig. 6. Evolution of voltages at monitored EHV buses with distributed LTC blocking/locking and load shedding

4.3 Combined distributed tap changer blocking/locking and load shedding

Figure 6 shows the evolution of the same voltages when combining tap blocking/locking and load shedding, both in their distributed form. The system is stabilized very effectively, and voltages regain acceptable values.

The real benefit of emergency tap control is disclosed in Table 4, which compares the power shed with and without tap blocking/locking, for the contingencies and stress levels already considered in Table 3.

As can be seen, the control of tap changers allows to shed significantly less load, especially when the disturbance is severe. Increasing V^{bl} further reduces the load shedding but the implication of setting this threshold too high has been already discussed.

In the case of Fig. 6, the taps were blocked only in Z5 and two other zones (not shown in the figure). The corresponding contingency is the seventh one, at maximum stress. Table 4 shows that this incident is comparatively milder. The other disturbances lead to controlling taps in more zones.

Table 4
Total power (in MW) shed with and without distributed tap changer blocking/locking

contin-gency	marginally unacceptable stress		maximum stress	
	block + shed	shed only	block + shed	shed only
1	40.3	43.6	58.8	65.7
2	78.6	245.5	154.4	322.2
3	79.5	211.7	153.5	454.5
4	124.3	261.0	176.9	417.7
5	0.0	30.0	202.2	363.6
6	125.3	315.2	154.5	387.7
7	12.1	48.3	98.0	147.1
8	115.3	222.0	215.8	269.5

4.4 SPS Selectivity in terms of location

Finally we illustrate the ability of the distributed protection to adjust to the disturbance it faces. This relates to the fact that the zones experiencing the largest voltage drops change with the disturbance, and different controllers are activated.

Figure 7 shows the zones in which load shedding took place after three different contingencies. As can be seen, the affected zones and the power shed change significantly from one disturbance to another.

5 Conclusion

The present blocking/locking scheme in operation at RTE was shown to be a successful countermeasure and helped preserving system operation on a few occasions. On the Western region, all taps are blocked upon detection of a low voltage at one EHV bus.

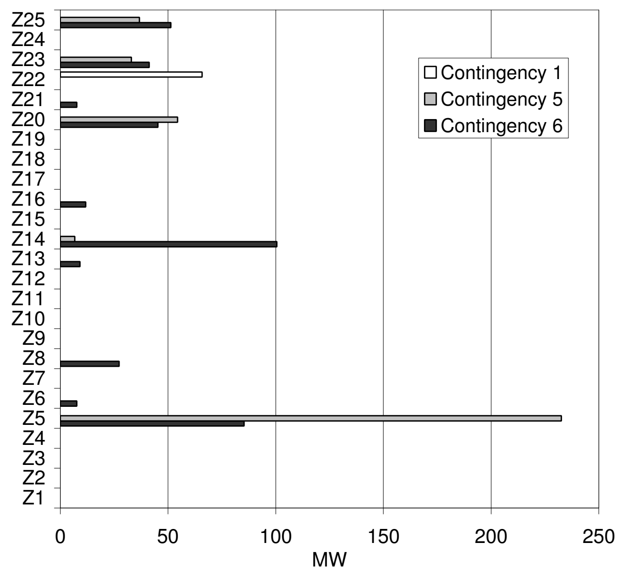

Fig. 7. Load shedding in various zones for 3 contingencies

As an additional line of defence, a prospective study of an SPS involving a set of distributed controllers operating in closed-loop was made and preliminary tests of this system on a detailed model of the Western region of the RTE system are reported in this paper. Load shedding is performed in various predefined zones and can be supplemented by tap changer blocking/locking in the same zones.

The results show that in case of failure of the existing tap changer control scheme, distributed load shedding alone can prevent system collapse. Its combination with distributed tap changer blocking/locking allows to reduce the amount of load shed. On the other hand, the results point out that distributed tap changer blocking/locking alone is not sufficient.

It is thus possible to focus tap changer control on a smaller part of the system, automatically adjusted to the disturbance faced, but at the price of a limited load shedding, and with an adequate communication system.

On the other hand, the closed-loop load shedding scheme potentially offers some advantages: (i) bringing transmission voltages back to normal values, (ii) actively preserving the system against further degradation, and (iii) acting as backup protection in case of failure of the tap changer control procedure.

References

[1] C. W. Taylor, *Power system voltage stability*, EPRI Power Engineering Series, Mc Graw Hill, 1994

[2] T. Van Cutsem, C. Vournas, *Voltage Stability of Electric Power Systems*, Boston, Kluwer Academic Publishers (now Springer), 1998

[3] D. H. Karlsson, convener, “System Protection Schemes in Power Networks”. Final report of CIGRE Task Force 38.02.19

[4] F. Carbone, G. Castelano, G. Moreschini, “Coordination and Control of Tap Changers Under Load at Different Voltage Level Transformers”, Proc. Melecon ’96 conference, Bari

[5] C.D. Vournas, A. Metsiou, M. Kotlida, V. Nikolaidis, M. Karystianos, “Comparison and Combination of Emergency Control Methods for Voltage Stability”, Proc. IEEE PES General Meeting, Denver, June 2004

[6] C. W. Taylor, “Concepts of undervoltage load shedding for voltage stability”, IEEE Trans. on Power Delivery, Vol. 7, 1992, pp. 480-488

[7] D. Lefebvre, C. Moors, T. Van Cutsem, “Design of an undervoltage load shedding scheme for the Hydro-Québec system”, Proc. IEEE PES General Meeting, Toronto (Canada), July 2003

[8] S. Imai, “Undervoltage load shedding improving security as reasonable measure for extreme contingencies”, Prof. IEEE PES General Meeting, San Francisco, 2005

[9] B. Otomega, T. Van Cutsem, “Undervoltage load shedding using distributed controllers”, IEEE Trans. on Power Systems, Vol. 22, 2007, pp. 1898-1907

[10] “Power System Reliability Memento”, RTE publication available at www.rte-france.com/ htm/an/mediatheque/vie_publi_annu_memento.jsp

[11] J.-P. Paul, J.-Y. Leost, J.-M. Tesseron, “Survey of the Secondary Voltage Control in France: Present realization and investigations”, IEEE Trans. on Power Systems, Vol. 2, 1987, pp. 505-511

[12] B. Otomega, V. Sermanson, T. Van Cutsem, “Reverse-logic control of load tap changers in emergency voltage conditions”, Proc. IEEE Power Tech Conf., Bologna, June 2003