Wide-Area Adaptive Load Shedding Control to Counteract Voltage Instability

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Abstract: A two-level adaptive load shedding scheme against voltage instability is proposed, adjusting its actions to the severity of the situation. The lower level includes a set of distributed controllers which curtail loads once the voltages at monitored transmission buses fall and stay for some time below threshold values. The adaptive nature of the proposed scheme comes from the upper level adjusting those thresholds in real-time. At the time instant the upper level detects that the system enters an emergency condition, it sends a signal to the lower-level controllers requesting them to take their currently measured voltages as threshold values. The upper-level emergency detection can be based on various criteria, the key-point being that it takes advantage of a wide-area monitoring of the system. In particular, the paper illustrates the use of a voltage instability detection scheme based on sensitivity computation. In case the upper level fails sending its signal, the lower-level controllers act in purely distributed mode, each using its pre-set threshold voltage. The capabilities of the proposed scheme are illustrated on a small but realistic test system.

Keywords: Voltage instability, corrective control, system integrity protection scheme, load shedding, distributed control, wide-area monitoring, wide-area protection, adaptive systems

1. INTRODUCTION

Load shedding is an effective countermeasure against voltage instability and collapse, as documented for instance in Taylor (1994, 1992); Van Cutsem and Vournas (1998); Feng et al. (1998); Nikolaidis and Vournas (2008). It should be used in the last resort, when other available corrective controls have been exhausted. It must be actuated automatically, through a System Integrity Protection Scheme (SIPS), see Karlsson (2001); Ingelsson et al. (1996); Madani et al. (2010).

Undervoltage load shedding controllers preferably rely on local measurements only, and involve a combination of rules of the type :

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

where V^{th} is a threshold value and τ is an intentional delay.

Several rules of type (1) may be used, see f.i. Van Cutsem and Vournas (2007); Moors et al. (2001). Also, other input signals than voltage magnitudes may be monitored. For instance, reactive reserve on key generators has been considered in Ingelsson et al. (1996) to deal with situations where voltages drop abruptly after the activation of OverExcitation Limiters (OELs).

The simplicity of the rule-based undervoltage load shedding controllers contributes to SIPS reliability. On the other hand, resorting to constant values of V^{th}, τ and ΔP may not be the most appropriate: for instance, a developing instability might not be stopped in some situations, while an excessive load curtailment can take place in some others. Hence, the parameters involved in (1) must be optimized over a large set of scenarios, as illustrated in Moors et al. (2001). The alternative considered here is to resort to an adaptive load shedding scheme, in which controllers adjust their action to the emergency situation they are facing.

The continuous development of communication and measurement technologies (most notably Phasor Measurement Units (PMUs)) have opened new perspectives for designing wide-area monitoring, detection, protection and control systems (see Phadke and Thorp (2008)), including load shedding control (see Glavic and Van Cutsem (2010)). In this paper we focus on an algorithm that would exploit these new technologies to make undervoltage load shedding adaptive.

To this purpose, we consider a two-level structure. The lower level is made up of a set of distributed load shedding controllers, relying on voltage measurements, acting in closed-loop according to the simple logic (1). It has been shown in Otomega and Van Cutsem (2007) that a set of such controllers can collectively adjust their response to the location of the disturbance. The upper level, on the other hand, involves wide-area monitoring to early detect a developing instability. The efficient sensitivity computation detailed in Glavic and Van Cutsem (2009a,b) can be used to this purpose. The information sent by the upper to the lower-level controllers is merely a signal that resets the voltage threshold V^{th} in each controller.

The rest of the paper is organized as follows. Section 2 and 4 summarize previous developments dealing with distributed undervoltage load shedding and wide-area voltage instability detection, respectively. The two-level adaptive load shedding scheme is presented in Section 3. Simulation results obtained with the Nordic32 test system are reported in Section 5, while Section 6 offers some conclusions.

2. DISTRIBUTED UNDERVOLTAGE LOAD SHEDDING

The load shedding scheme introduced in Otomega and Van Cutsem (2007) relies on a set of controllers distributed over the region prone to long-term 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. With respect to a single centralized load shedding, this distributed scheme offers the advantage of adjusting the load curtailment to the location of the disturbance.

The decision of each controllers to shed load is based on the comparison of the measured voltage magnitude V with a threshold value V^{th}. A first block of load is shed at $t_0 + \tau$ such that

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

where t_0 is the time when $V < V^{th}$ and C is a constant to be adjusted. τ is lower limited to avoid responding to voltage transients that result from normally cleared faults.

The amount ΔP^{sh} of power shed is not fixed but depends on the time evolution of V through:

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

with:

$$\Delta P^{sh}_{min} \leq \Delta P^{sh} \leq \Delta P^{sh}_{max} \tag{4}$$

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.

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

When a controller sheds load, the integral in (2) and (5) is reset to zero, t_0 to the current time, and the controller is ready to act again as long as measured voltage magnitude is below the threshold. Repeated action capability yields a closed-loop design. The controllers do not exchange information, but interact through the measured voltages which reflect without delay the nearby load shedding. Each controller curtails load in steps of at least ΔP^{sh}_{min} MW and at most ΔP^{sh}_{max} MW. The latter bound prevents unacceptable transients.

3. TWO-LEVEL ADAPTIVE LOAD SHEDDING SCHEME

In spite of their advantages, the distributed controllers still rely on pre-determined values of V^{th}, C, and K. As already mentioned, it is desirable to make them more adaptive to the situation they are facing.

A first step in this direction was made in Otomega and Van Cutsem (2011) with the aim to react fast in the presence of induction motor loads, while avoiding undue shedding after normally cleared faults. To this purpose, a signal from neighboring generators, indicating they are going to have their field current limited, is sent to the local controllers enabling them to shed load faster after V has dropped below V^{th}. Thus, the signal sent by the overexcited generators is used by the local controllers to adapt their shedding delay τ.

This work goes farther by proposing a dedicated second-level controller, with a wide-area view of the system evolution. The aim of an upper-level controller in any hierarchical control scheme is either to coordinate the efforts of lower-level controllers or adaptively provide parameters to these controllers. The latter option is considered in this work.

The proposed two-level structure is shown in Fig. 1. The lower level includes a set of distributed controllers, as described in the previous section (two of them are sketched in the figure). The purpose of the upper level is to provide the lower-level controllers with parameters adjusted in real time to the situation of concern. Out of the three above mentioned parameters, the voltage threshold V^{th} is probably the most delicate to adjust, and the emphasis is put on that parameter.

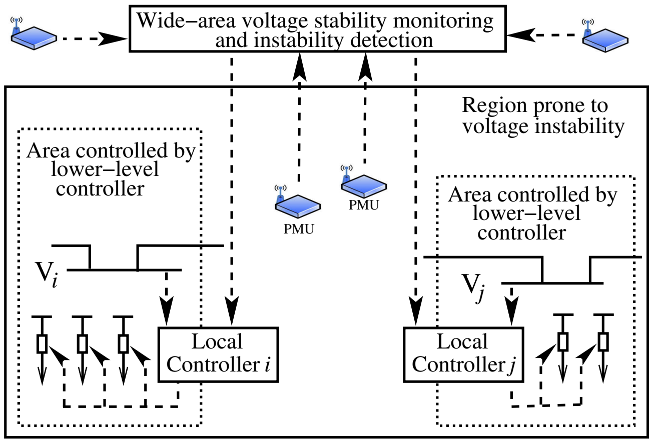

Fig. 1. Structure of two-level adaptive load shedding scheme

The very principle of the upper level can be summarized as follows. We assume that wide-area monitoring is performed at this level, based on appropriate real-time measurements, including PMUs if available. Following a large disturbance, we assume that it is possible to detect that the system is evolving towards long-term voltage instability, more precisely to identify that the system has crossed a “critical voltage profile”. The latter defines minimum acceptable voltages at the various buses monitored by the lower-level controllers. Therefrom, the role of the distributed load shedding controllers will be to restore and maintain their monitored voltages at or slightly above the critical voltage profile.

This can be performed with very little information sent from upper to lower level (virtually a single bit of information !). Indeed, at the time instant the upper level detects that the system has crossed the critical voltage profile, it sends a signal to the lower-level controllers requesting each of them to take its currently measured voltage V as threshold value V^{th}. Each local controller will then shed load in successive blocks, with delays before the first and between successive curtailments. Of course, the local controllers keep on interacting through the network voltages as in the purely distributed (single-level) scheme of Otomega and Van Cutsem (2007). Namely, when one controller acts, the immediate voltage rise is sensed by the other controllers who either delay their actions or even reset.

Finally if, for any reason, the upper level monitoring scheme fails providing the signal to the local controllers, the latter may use their original (pre-determined) thresholds. This redundancy increases the reliability of the load shedding protection.

4. WIDE-AREA VOLTAGE INSTABILITY DETECTION

A method for the early detection of a developing voltage instability from the system states provided by synchronized phasor measurements was proposed in Glavic and Van Cutsem (2009a,b). The method fits a set of algebraic equations $\boldsymbol{\varphi}(\mathbf{z}, \mathbf{s}) = \mathbf{0}$ to the sampled states, where $\mathbf{z}$ denotes the state vector and $\mathbf{s}$ is the vector of load active and reactive powers. These equations are obtained under the following assumptions:

- the network is represented by its bus admittance matrix, using real-time breaker status information;
- the short-term dynamics of generators, automatic voltage regulators, speed governors, static var compensators, etc. are not tracked but replaced by accurate equilibrium equations;
- the long-term dynamics driven by OELs, Load Tap Changers (LTCs) and restorative loads are reflected through the change in measured voltages from one snapshot to the next;
- whether a generator is voltage controlled or field current limited is known or detected. Equations are adjusted accordingly.

Sensitivities are used to identify when a combination of load active and reactive powers passes through a maximum, which is taken as indicator of emergency situation. The critical voltage profile mentioned in the previous section relates to that point (which can be seen intuitively as a generalization of the "knee-point" of a PV curve).

Note that this requires knowing only the consumed powers: no information about load behaviour with voltage is needed. We consider the sensitivities of the total reactive power generation to individual load reactive powers. They are obtained from a general sensitivity formula Van Cutsem and Vournas (2007) as:

$$S_{Q_g\mathbf{q}} = -\boldsymbol{\varphi}_{\mathbf{q}}^T \left(\boldsymbol{\varphi}_{\mathbf{z}}^T\right)^{-1} \nabla_{\mathbf{z}} Q_g \qquad (6)$$

where $\mathbf{q}$ is the vector of load reactive powers, $\nabla_{\mathbf{z}} Q_g$ denotes the gradient of Q_g with respect to the state vector $\mathbf{z}$, $\boldsymbol{\varphi}_{\mathbf{z}}$ is the Jacobian of $\boldsymbol{\varphi}$ with respect to $\mathbf{z}$, and $\boldsymbol{\varphi}_{\mathbf{q}}$ the Jacobian of $\boldsymbol{\varphi}$ with respect to $\mathbf{q}$. These sensitivities can be computed very efficiently.

In theory these sensitivities change sign through infinity at the sought maximum load power point. In practice, what is sought is a sudden change in sign at a discrete time k such that:

$$S_{Q_gQ_j}(k-1) > d_+ \quad \text{and} \quad S_{Q_gQ_j}(k) < d_- \qquad (7)$$

where $d_+ > 0$ and $d_- < 0$ are thresholds.

Attention is paid to generator reactive power limits. An estimate of E_q, the e.m.f. proportional to field current, is used to identify whether a synchronous generator operates under control of its Automatic Voltage Regulator (AVR) or has been already limited by its OEL. Under AVR control, an equation such as:

$$kE_q^s - G(V^o - V) = 0 \qquad (8)$$

is used, while under OEL control, it is replaced by an equation of the type:

$$E_q - E_q^{lim} = kE_q^s - E_q^{lim} = 0 \qquad (9)$$

where G is the open-loop static gain of the AVR, E_q^s is the e.m.f. behind saturated synchronous reactances, k is the saturation factor, V is the terminal voltage, V^o is the AVR voltage setpoint, and E_q^{lim} corresponds to the field current forced by the OEL. E_q and k are components of $\mathbf{z}$ together with the (rectangular components of) bus voltages and other variables.

Furthermore, it is of interest to anticipate the effect of an approaching OEL activation. To this purpose, when $E_q > E_q^{lim} + \epsilon$, the OEL equation (9) is anticipatively substituted to the AVR equation (8) when evaluating the Jacobian $\boldsymbol{\varphi}_{\mathbf{z}}$. This remains in effect as long as the OEL is acting, which is identified by $E_q^{lim} - \epsilon \le E_q \le E_q^{lim} + \epsilon$.

5. SIMULATION RESULTS

5.1 Test system

The proposed load shedding scheme is illustrated on the Nordic32 test system. This system has been used and is documented in several publications, for instance Glavic and Van Cutsem (2009b). The one-line diagram of this 52-bus, 20-machine system is shown in Fig. 2. Its detailed dynamic model (under the standard phasor approximation) has been simulated in the MATLAB/Simulink environment with a variable time-step integration method.

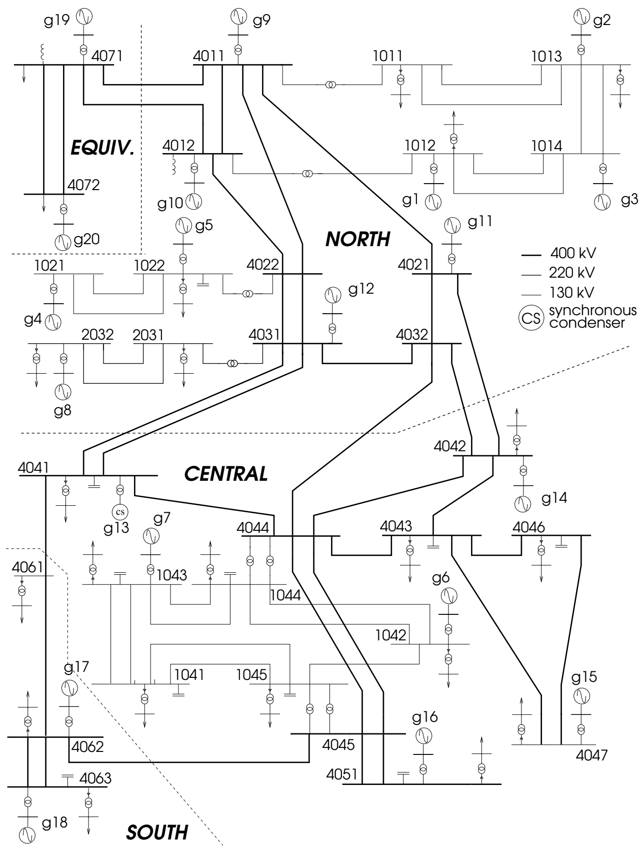

Fig. 2. Nordic32 test system

The disturbance of concern is a short-circuit at $t = 1$ s on the line 4032-4044, close to bus 4044. This fault is cleared after 0.1 s by opening the line. This line outage makes the system long-term voltage unstable. The long-term degradation caused by LTCs and OELs acting with various delays ends up in the loss of synchronism of the field current limited generator g6. The unstable evolution of the voltage at bus 1041 is shown in Fig. 3.

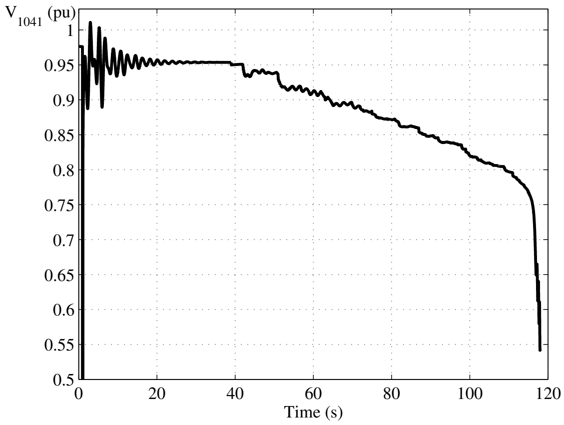

Fig. 3. Unstable evolution of voltage magnitude at bus 1041

To counteract voltage instability, the system has been provided with 5 load shedding controllers, located in the Central area, which is undergoing low voltages. The controllers monitor voltages at buses 1041, 1042, 1043, 1044, and 1045, respectively, and act on the corresponding loads at distribution level.

Two cases have been considered:

- *Case 1* : purely distributed load shedding scheme;
- *Case 2* : two-level control scheme proposed in this paper.

5.2 Results for Case 1

First, the settings of the distributed controllers have been optimized as explained in Otomega and Van Cutsem (2007). Based on extensive simulations, the voltage threshold V^{th} has been set to 0.9 pu, a constant delay of 3 s has been used for τ, while K has been set to a very low value, which leads to curtailing the minimum interruptible power ΔP^{sh}_{min} (see (4)) each time a controller acts. ΔP^{sh}_{min} has been set to 10 MW for all controllers. No constraining limit ΔP^{sh}_{max} has been considered.

The same settings are used in all controllers. With these parameters the total amount of curtailed power is 330 MW. This is the overall minimum obtained over a large number of (τ, K) combinations. The stabilized voltage evolution is shown with dashed line in Fig. 4, where the unstable evolution has been reproduced (with dash-dotted line) for easy comparison.

5.3 Results for Case 2

At the upper level, the sensitivities (6) have been used to detect the onset of instability. They have been computed every 0.1 second from the bus voltage phasors provided by time simulation. Their evolution is shown in Fig. 5. For the disturbance of concern, the change in sign is detected at $t = 51$ s, as can be easily seen from the figure, relative to bus 1041 (Ref. Glavic and Van Cutsem (2009a) shows that sensitivities change sign at the same time at all buses).

Thus, at $t = 51$ s, a signal is sent to the load shedding controllers for them to take the transmission voltage they currently measure as new threshold. This leads the controller of bus 1041

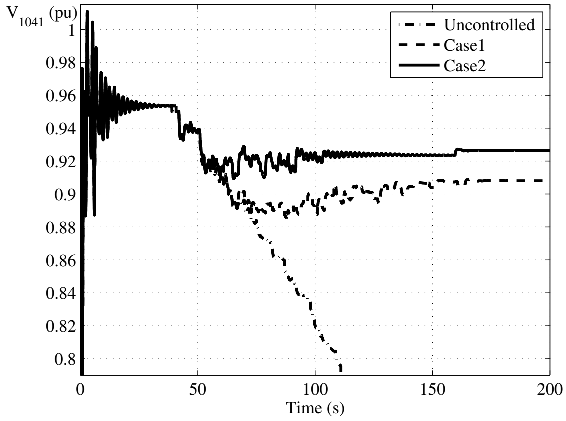

Fig. 4. Voltage magnitude at bus 1041 with load shedding

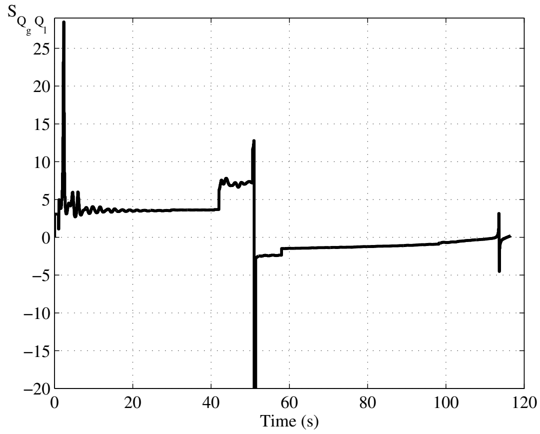

Fig. 5. Sensitivity $S_{Q_gQ_j}$ at bus 1041

to set its V^{th} value to 0.93 pu, and the one of bus 1044 to 0.94 pu. Since the sensitivities give an early warning of instability, the voltages monitored by the other three controllers are still well above 0.95 pu. To avoid shedding at such high voltages, V^{th} bas been upper limited to 0.95 pu for these controllers.

The system response obtained with the two-level controller is shown with solid line in Fig. 4. As a general remark, the evolution is smoother because load shedding starts earlier.

The total curtailed power for this case is 210 MW, thus leading to a 120 MW reduction with respect to Case 1. The total power shed for various values of ΔP^{min}_{sh} is shown in Fig. 6. In all cases, the two-level scheme curtails less load. Table 1 shows the total power shed by each controller. Compared to Case 1, the shedding starts earlier and due to the short delay $\tau = 3$ s, the variation of ΔP^{min}_{sh} does not much influence the total amount of load shed.

5.4 Simulation of inter-level communication failure

In case the alarm signal issued by the upper level is not received by the distributed controllers, the latter operate with their predefined setting: $V^{th} = 0.90$ pu. To illustrate the resulting behaviour, the following two variants have been considered:

- *Case 2.a*: the controller of bus 1044 does not receive the signal;

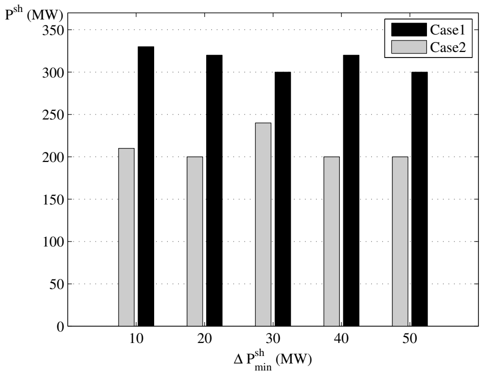

Fig. 6. Total load power shed for various values of ΔP^{sh}_{min}

Table 1. Load power shed (MW) by each controller for various values of ΔP^{sh}_{min}

Bus	V^{th} (pu)	ΔP^{sh}_{min} (MW)				
		10	20	30	40	50
1041	0.93	50	60	60	40	50
1042	0.95	0	0	0	0	0
1043	0.95	0	0	0	0	0
1044	0.94	130	120	150	120	150
1045	0.95	30	20	30	40	0
Total (MW)		210	200	240	200	200

- *Case 2.b*: the controllers of buses 1044 and 1045 do not receive the signal.

The results are given in Table 2, assuming $\Delta P^{sh}_{min} = 10$ MW. They illustrate that the proposed scheme is fault-tolerant since the controllers receiving the upper-level signal take stronger actions to compensate for the controllers not acting due to their lower value of V^{th} (set by default to 0.90 pu). Note that if all controllers fail receiving the signal, they react as in Case 1 (see Section 5.2).

Table 2. Load shedding with communication failures

Bus	Case 2		Case 2.a		Case 2.b	
	V^{th} (pu)	ΔP^{sh} (MW)	V^{th} (pu)	ΔP^{sh} (MW)	V^{th} (pu)	ΔP^{sh} (MW)
1041	0.93	50	0.93	80	0.93	200
1042	0.95	0	0.95	0	0.95	0
1043	0.95	0	0.95	0	0.95	50
1044	0.94	130	0.90	0	0.90	0
1045	0.95	30	0.95	150	0.90	0
Total (MW)		210		230		250

5.5 Results in the presence of induction motor loads

The capabilities of the proposed protection scheme have been tested in stringent conditions, assuming that the loads fed by buses 1041, 1042, 1043, 1044, 1045, 4043, 4046, and 4047 include 50 % of induction motors (represented by a single equivalent motor at each bus). This causes the voltage to collapse earlier (when the voltage support of key generators is lost) and to drop sharply under the effect of motor stalling. This is illustrated in Fig. 7 showing the voltage response to the same disturbance.

The challenge in such a case is to shed load very fast, while avoiding to react to normally cleared faults. To reach this objective, the technique proposed in Otomega and Van Cutsem (2011) can be re-used: when the emergency signal is received from the upper level, the local controllers reduce their shedding delay to $\tau = 0.3$ s (in addition to adjusting V^{th}). In case of normal fault, no signal being received from the upper level, τ would remain at its default value of 3 seconds.

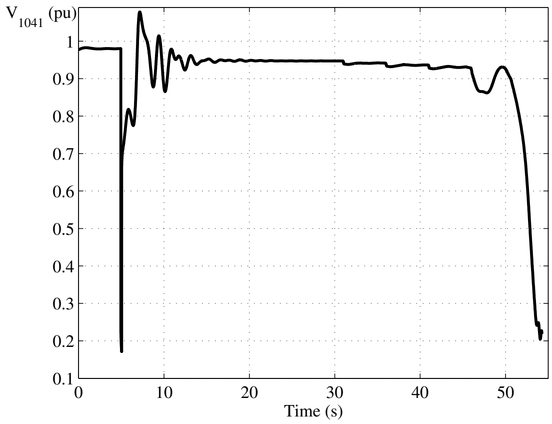

Fig. 7. Unstable evolution of voltage at bus 1041 with 50 % motor load

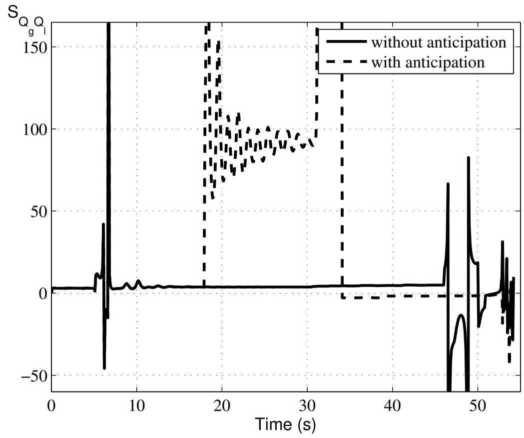

Fig. 8. Sensitivity $S_{Q_gQ_j}$ at bus 1041 with 50 % motor load

The evolution of sensitivities is shown with solid line in Fig. 8. First, a change in sign is observed at $t = 7$ s, but the sensitivity remains negative for a little less than 1 second, before getting back to positive. This results from the delayed voltage recovery after fault clearing, caused by motors. This short-lasting change in sign has to be ignored. The significant change takes place at $t = 46.5$ s. Assuming a 1 second delay to ascertain that the sensitivities settle to negative values, the emergency signal is sent by the upper level at $t = 47.5$ s. The resulting system response is shown in Fig. 9 with dashed line.

Another possibility consists in relying on a sensitivity computation that anticipates the near-future limitations of generators, as outlined in the last paragraph of Section 4, and detailed in Glavic and Van Cutsem (2009a,b). The evolution of the same sensitivity computed with anticipation is shown with dotted line in Fig. 8. The change in sign takes place at $t = 34$ s, when the field current of generator g15 starts exceeding its limit, whose enforcement is anticipatively reflected in the Jacobian $\boldsymbol{\varphi}_{\mathbf{z}}$. The signal would be send to the local controllers 1 second later. With this anticipation, τ can be left at its default value of 3 seconds.

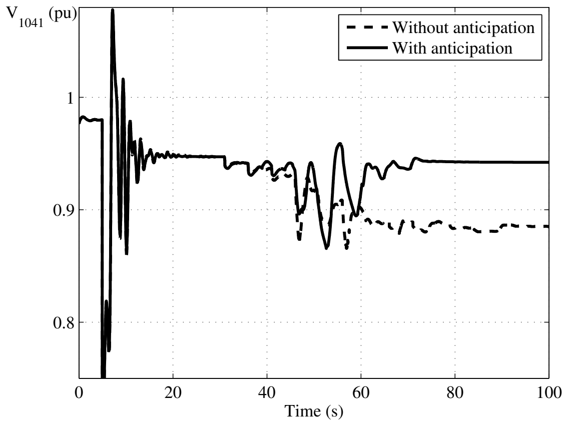

Fig. 9. Voltage at bus 1041 with 50 % motor load and load shedding

The corresponding stabilized voltage evolution is shown with solid line in Fig. 9.

The load shedding amounts, obtained with $\Delta P^{sh}_{min} = 10$ MW, are summarized in Table 3. Without anticipation in the sensitivity computation, besides the fact that emergency control takes place "at the very last moment", significantly more load is curtailed. The main reason is that the controllers start acting all together within a very short time interval.

Table 3. Load shedding with 50 % motor load

Bus	sensitivities computed			
	without anticipation		with anticipation	
	V^{th} (pu)	ΔP^{sh} (MW)	V^{th} (pu)	ΔP^{sh} (MW)
1041	0.88	160	0.94	140
1042	0.95	0	0.95	0
1043	0.92	115	0.95	0
1044	0.90	40	0.95	40
1045	0.91	20	0.95	20
Total (MW)		335		200

6. CONCLUSION

A two-level adaptive load shedding scheme, which adjusts its action to the severity of the situation has been presented.

At the lower level, the scheme relies on a set of distributed controllers, aimed at shedding load as long as monitored transmission voltages are not restored above threshold values. Upon detection of an emergency situation, the upper level sends a signal to the distributed controllers, for the latter to set their threshold values at the currently measured voltages. The objective is to keep the system operating above the critical voltage profile corresponding to the emergency detection.

The emergency signal is obtained from wide-area monitoring by the upper level. To this purpose, an advanced but efficient sensitivity computation has been considered. These sensitivities should be computed from synchronized phasor measurements.

From the results obtained with the small but realistic Nordic32 test system, the following conclusions can be drawn:

- proper adaptation of the voltage thresholds in real time yields a more dependable protection;
- the proposed scheme is fault-tolerant since it can accommodate failures to receive the emergency signal;
- anticipating the generator limitations in sensitivity computation yields higher robustness in the stringent situations with sharp voltage drops caused by motor loads.

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