Implementation and Comparison of Different Under Frequency Load-Shedding Schemes

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Abstract: In the context of power system restructuring, the maintaining of adequate levels of security and reliability will be operated also through direct load control, thus considering load as the potential provider of ancillary services such as Regulation, Load-following, Frequency Responsive Spinning Reserve. In any case load-shedding still remains the ultimate resource for emergency conditions. In the paper several load-shedding schemes for under-frequency operation are examined. Both traditional schemes, based only on frequency thresholds, and adaptive schemes, based on frequency and on its rate of change, are considered. An IEEE test system for reliability analysis is used to compare the behavior of the proposed schemes when selecting different thresholds and percentages of load to be disconnected. Results are reported into detail and considerations on possible advantages and drawbacks also related to the framework provided by the electricity market are presented.

Keywords: Load-shedding, emergency conditions, spinning reserve, frequency rate of change, adaptive power system control, ancillary services.

I. INTRODUCTION

Reliable and secure operation of large power systems has always been a primary goal for system operators. The new system structure following unbundling and deregulation requires very strong efforts in real-time assessing of system conditions and in the subsequent actions to protect power system [1], [2].

The analysis that is required for maintaining system security includes both "diagnosis" and "therapy". A preventive analysis of the possible contingencies, system configuration and protection characteristics can lead to the definition of adequate plans to prevent system degradation and to minimize outage wide-spreading.

Power-load unbalance is the most dangerous condition for power system operation. Every unbalance between generation and load causes a deviation of the frequency from its steady state which - if not properly counteracted - can lead to system black-out. Typical contingencies that may affect power system security are the loss of generators and/or of large interconnection lines.

In the vertically integrated utilities of past memory, generators were put into operation with adequate margin for regulation, load-following, spinning reserve, etc. In restructured power systems these services are provided on a market basis. It is rather evident that load can play a role very similar to generator real power control in maintaining the power system equilibrium [3]. While the most efficient approach in emergency conditions is to instantaneously disconnect load, in a wider perspective, when the contingency that affects the system does not require very fast remedial action, load can also be curtailed or reduced thus implicitly supplying energy-balancing services[4].

The focus of the paper will be predominantly on emergency load-shedding for preventing frequency degradation. Under the circumstances that can originate severe power-load unbalances, system frequency can go below unacceptable values and this can also originate the cascading disconnection of other generating units. The diagnosis phase previously mentioned and usually performed by means of frequency measurements can be improved by including the Rate of Change of Frequency (ROCOF).

Several practices and options are available for load-shedding schemes. The following sections will examine a good number of them based on frequency thresholds and on both frequency and its derivative thresholds. The implementation of the different strategies and the comparison of their performances obtained through simulations performed on an IEEE Reliability Test system [5] are reported and commented.

II. LOAD SHEDDING SCHEMES: PRINCIPLES AND IMPLEMENTATION

A. Load-shedding fundamentals

When dealing with load-shedding, several items must be taken into account. The most important of them are [6]: the definition of a minimum allowable frequency for secure system operation, the amount of load to be shed, the different frequency thresholds, the number and the size of steps.

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The minimum allowable frequency is imposed by the limitations of operation of system equipment. Specifically, the elements that are more sensitive to frequency drops are generators, auxiliary services and steam turbines [7]. In the following and with reference to 60 Hz, the frequency values proposed by [7] will be quoted. The corresponding values for 50 Hz systems will be reported within brackets. All evaluations reported in Section III have been carried on for 50 Hz systems.

Generators can operate at speeds much lower than steady state one, provided their MVA output is reduced. Power plant auxiliary services are more demanding than generators in terms of minimum allowable frequency: in fact, they begin to malfunction at a frequency of 57 Hz (47.5 Hz), while the situation becomes critical at 53-55 Hz (about 44-46 Hz). In that case, there is a cascade effect: the asynchronous motors of the auxiliary services are disconnected by their protections.

Anyway, the steam turbine is the equipment more sensitive to frequency drops. Turbine natural frequencies are kept - by design - far from the nominal speed, so that they are not likely to operate in a situation of resonance, which could destroy the turbine or cause a reduction of its life.

It is safe to avoid that the frequency falls below 57 Hz (47.5 Hz): in fact, every commercial turbine can sustain up to 10 contingencies at 57 Hz (47.5 Hz) for one second without being jeopardized [7].

The economical limitations mentioned in Section I in the amount of spinning reserve, regulation and the intrinsic technical limits of some plants in terms of their ramping capability call for immediate remedial actions based on load-shedding.

The main features that a load shedding scheme must provide are [8]:

- The action has to be quick, so that the frequency drop is halted before a situation of danger has occurred
- Unnecessary actions have to be avoided
- The protection system has to be liable and redundant, as a malfunction of it would surely lead to a major failure of the whole system
- The amount of load to be shed should always be the minimum possible, but anyway sufficient to restore the security of the grid and to avoid the minimum allowable frequency being overcome

Basically, a load shedding scheme acts whenever it diagnoses a situation of danger for the system. The most intuitive method for checking the level of danger is measuring the average frequency of the grid: when the frequency falls below certain thresholds it is possible to obtain an indication on the risk for the system and consequently to shed a certain amount of load.

The two main reasons for improving this simple scheme are that, if the disturbance is very large, the consequent frequency transient will be very quick. For load-shedding to be effective, it is wise to recognize the emergency situation as quickly as possible. On the other side, in case of small disturbances, the methodologies based only on frequency thresholds may result in an excessive amount of load shed.

For the two above reasons it is advisable to consider a new element of diagnosis, which is the derivative of the frequency (df/dt) or *Rate of Change of Frequency* (ROCOF). This value has the meaning of speed at which the frequency is declining. By measuring the speed at which a certain frequency threshold is reached it is possible to estimate the danger of the current contingency and so to provide different load-shedding alternatives depending on the value of df/dt.

Moreover, by knowing the initial value of df/dt (that is to say its value when the frequency begins to decline soon after a contingency) it is possible to estimate the disturbance and so to provide an adequate load-shedding.

B. *Load-shedding schemes*

It is possible to identify three main categories of load shedding schemes: (a) traditional, (b) semi-adaptive and (c) adaptive.

The *traditional load shedding* is definitely the most diffused, because it is simple and it does not require sophisticated relays, such as ROCOF relays whose accuracy is often questionable. The traditional scheme sheds a certain amount of the load under relief when the system frequency falls below a certain threshold. This first shed may be insufficient; in that case, if the frequency keeps on falling down, further sheds are performed when lower thresholds are passed. The values of the thresholds and of the relative amounts of load to be shed are decided off-line, on the base of experience and simulations.

The *semi-adaptive scheme* [9] provides a step forward. In fact, it measures df/dt when a certain frequency threshold is reached. According to that value, a different amount of load is shed. In other words, this scheme checks also the speed at which the threshold is exceeded: the higher this speed is, the more load is shed. Usually, the measure of the ROCOF is evaluated only at the first frequency threshold, the following ones being traditional.

The next improvement in load-shedding is the so called adaptive method which makes use of the frequency derivative and is based on the *System Frequency Response* (SFR) model developed in [10]. This model is obtained from the complete block diagram representation of a generic generating unit, along with its governor.

A reduced order SFR model for the whole electrical system can be obtained on the basis of commonly adopted hypotheses [11]. From the reduced order SFR model it is possible to obtain a relation between the initial value of the ROCOF and the size of the disturbance P_{step} that caused the frequency decline. This relation is:

$$\left.\frac{df}{dt}\right|_{t=0} = \frac{P_{step}}{2H} \tag{1}$$

where f is expressed in per unit on the base of the nominal system frequency (50 or 60 Hz) and P_{step} is in per unit on the total MVA of the whole system.

The initial value of the ROCOF is proportional, through the inertia constant H, to the size of the disturbance. Thus, assuming that the inertia of the system is known, the measure of the initial ROCOF is - through H - a backward estimate of the disturbance and consequently an adequate countermeasure in terms of load-shedding can be operated. A drawback of this method is that if generators or large synchronous motors are disconnected during the disturbance, the inertia of the system should be accordingly adapted. For large systems, this can be overcome by the consideration that only a small percentage of the total inertia has been lost. For small systems, this may generate an underestimation of the actual perturbation. A brief recall of the method proposed by P.M. Anderson and M. Mirheydar is reported below for better understanding the comparison carried on in the next section. Details are fully covered in [10], [11].

The measure m_0 of the initial value of the frequency derivative permits to estimate the disturbance P_{step} which caused the frequency drop. Obviously, it is not necessary to shed an amount of load equal to P_{step}: as a matter of fact, the system has a spinning reserve of its own, so it is able to sustain different disturbances without being affected too much. In particular, the system has a m_0 critical and a relative $P_{step\ critical}$ which correspond to the maximum allowable disturbance, that is the one which would bring the system frequency to its minimum allowable value. On the basis of the comparison between the measured m_0 and $m_{0\ critical}$ the adaptive scheme decides whether to act or not. If the measured $|m_0|$ is smaller than $|m_{0\ critical}|$, no load is shed, as the actual contingency is less dangerous than the maximum allowable one. Otherwise, if the measured $|m_0|$ is greater than the critical one, an amount of load P_{shed} equal to P_{step} - $P_{step\ critical}$ is candidate for shedding. It can be decided that P_{shed} is distributed locally among the buses of the grid and it is not shed in one stroke, but at different steps based on the frequency (e.g.: 40% of P_{shed} is shed when frequency falls down 49.5 Hz, 30% at 49 Hz, 30% at 48.5 Hz.).

Due to the simplifying hypotheses adopted to develop the SFR model, the shedding of a load amounting exactly to P_{shed} may be insufficient. Thus authors in [10] suggest the adoption of a correction factor (equal to 1.05) for P_{shed}.

This load shedding method is called adaptive because its behavior fits with the contingency that is affecting the system: the disturbance is estimated from the value of m_o and consequently an appropriate load shedding is provided.

There are several load-shedding solutions available worldwide. A collection of them is reported in Table I together with the main characteristics and parameters involved for each of them (both 50 Hz and 60 Hz frequency values and thresholds are reported according to the quoted references). Table I has been the base for simulations carried on and reported in the next section.

Table I – Considered load shedding schemes (LUR in column 2 stands for "load under relief" in % of total system load)

Ref.	LUR	Traditional load shedding thresholds	Use of df/dt	Notes
[12]	60%	First threshold at 49.1 Hz		Min. f: 47.5 Hz
[13]	30%		f=49.5 Hz, df/dt=0.10 Hz/s f=49.5 Hz, df/dt=0.33 Hz/s f=49.5 Hz, df/dt=0.50 Hz/s	Where: At each bus, proportionally to the amount of load of each bus in the pre-contingency load-flow
[9]	50%	f=59.2 Hz ⇒ 10% of total load f=58.8 Hz ⇒ 15% of total load f=58.0 Hz ⇒ 20% of total load	f=59.5 Hz, df/dt=0.4 Hz/s ⇒ 10% tot. load f=59.5 Hz, df/dt=1.0 Hz/s ⇒ 25% tot. load f=59.5 Hz, df/dt=2.0 Hz/s ⇒ 35% tot. load f=59.5 Hz, df/dt=4.0 Hz/s ⇒ 50% tot. load f=58.8 Hz ⇒ 50% of total load	
[14]	80%	20 steps of 0.1 Hz between 48.5 and 46.5 Hz		
[11]		1. 59.5 Hz ⇒ 0.0625 pu 59.2 Hz ⇒ 0.0625 pu 58.9 Hz ⇒ 0.0625 pu 58.6 Hz ⇒ 0.0625 pu TOTAL: 0.25 pu of total load 2. 59.5 Hz ⇒ 0.048 pu 59.3 Hz ⇒ 0.048 pu 59.1 Hz ⇒ 0.042 pu 58.8 Hz ⇒ 0.040 pu 58.5 Hz ⇒ 0.036 pu 58.2 Hz ⇒ 0.030 pu TOTAL: 0.25 pu of total load	Adaptive method: 1. 59.5 Hz ⇒ 0.5*Pshed The rest of Pshed is shed at equal steps, for instance every 0.5 Hz 2. 59.5 Hz ⇒ 0.475*Pshed 59.2 Hz ⇒ 0.15*Pshed 58.9 Hz ⇒ 0.15*Pshed 58.6 Hz ⇒ 0.15*Pshed 58.3 Hz ⇒ 0.075*Pshed	Min. f: 57 Hz Max. f: 61.5 Hz
[15]	60%			Where: At each bus, proportionally to voltage reductions through the factor $k_i = \frac{\Delta V_i \cdot \delta Q_i / \delta V_i}{\sum_{i=1}^{N} [\Delta V_i \cdot \delta Q_i / \delta V_i]}$ where ΔV_i = voltage reduction at node "i" $\delta Q_i / \delta V_i$ = sensitivity of voltage at node "i" to change of reactive power
[6]	80%	Between 49.2 Hz and 48.4 Hz, using a reduced number of steps to avoid overlapping and to have a limited number of relays		

[16]	25%	f=59.5 Hz ⇒ 3.33% of total load f=59.4 Hz ⇒ 3.33% of total load f=59.3 Hz ⇒ 3.33% of total load f=59.1 Hz ⇒ 5% of total load f=59.0 Hz ⇒ 5% of total load f=58.9 Hz ⇒ 5% of total load		

III. SIMULATIONS AND RESULTS

A. The test network

In order to examine the behavior of the three different load-shedding schemes, a test network has been set up, starting from the IEEE RTS test network [5]. This network is made up of 24 buses, 33 synchronous generators located at 11 buses. The total amount of active load in the network is 3135 MW, while the reactive load is 638 MVAR. All the loads in the system are modeled as constant loads, i.e. they are not dependent on frequency and voltage variations. This may be an important limitation in correctly reporting individual behavior of load-shedding schemes but it was felt to be less significant when comparisons are carried on for different schemes all operating under the same simplifying hypothesis.

Two main areas can be identified in the network: a "northern" one, where most of the generating plants are installed, and a "southern" one, which is mainly a load area. The tie lines between these two zones are 220 kV heavily loaded lines.

Some of the generators of the grid take part in the primary f/P regulation, while small generators are excluded and large slow units participate with ramping capability limitations. The resulting total spinning reserve available on the grid is 495 MW. This means that every disturbance greater than 495 MW will not be fully recovered by the system. Also disturbances slightly smaller than 495 MW may be dangerous for the system because of the mentioned limitations. Secondary f/P regulation was not considered in the simulations, as it is very slow (full response in the order of 100 s).

Moreover, in order to obtain a larger degree of security and according to common practice, the minimum allowable frequency has been chosen at 48 Hz, although for 50 Hz systems the technical limit is 47.5 Hz.

B. Results of simulation for some selected cases

The load shedding solutions described in Section II have been tested on a commercial power system analysis code.

The load-shedding schemes have been implemented by means of the user defined model facilities of the code. Four different traditional schemes have been compared, in order to show how the combined choice of the frequency thresholds and of the relative amounts of load to be shed affects the performances of the scheme. Then, a semi-adaptive scheme and an adaptive one have been proposed and compared with the traditional ones. Some parameters have been kept fixed for each scheme, with the aim of facilitating the comparison:

- The total load under relief is 1000 MW, about 30% of all the active load of the system. The total load to be shed is distributed among the buses in amounts proportional to the pre-contingency load flow.
- The applied contingency consisted of a significant and instantaneous load increment. The relay delay time is set equal to 0.2 s, which is a typical value for common relays.

The four considered traditional load-shedding schemes are reported in the following Table II, where the percentage of load to be shed is referred to the total 1000 MW load under relief.

Table II – Different traditional load shedding schemes

Traditional scheme	frequency thresholds	% Load to shed
(a1)	49.5 Hz	40%
	49.0 Hz	30%
	48.5 Hz	30%
(a2)	49.5 Hz	25%
	49.0 Hz	40%
	48.5 Hz	35%
(a3)	49.5 Hz	33%
	49.0 Hz	33%
	48.5 Hz	33%
(a4)	49.1 Hz	40%
	48.8 Hz	30%
	48.5 Hz	30%

The semi-adaptive scheme chosen for the simulations is represented in Fig. 1 (a) by the typical representation used in the literature. The amount of load to be shed at 49.5 Hz depends on the ROCOF magnitude at 49.5 Hz. At 49 Hz, a further 25% of 1000 MW is shed, no matter how much load was shed at 49.5 Hz. At 48.5 all the load under relief is shed.

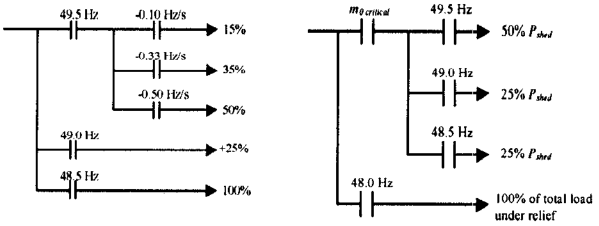

Fig. 1 – (a) Semi-adaptive, (b) Adaptive load-shedding schemes

The adaptive scheme is reported in Fig. 1 (b). The load amount P_{shed}, determined on the basis of (1), is shed into three steps occurring at 49.5, 49 and 48.5 Hz. At 48 Hz, a back-up relay sheds all the remaining load under relief.

Three different contingencies have been analyzed: load step increments of 200 MW, 450 MW and 750 MW. The first disturbance is less than half of the total spinning reserve of the system. The second one (450 MW) is close to the total amount of spinning reserve (495 MW). The largest one (750 MW) is representative of the total power flow from the northern area to the southern area.

B.1 Small system disturbance: 200 MW

This contingency can be recovered with no need to shed load: the minimum frequency resulting from this disturbance is about 49.26 Hz, which is largely acceptable by system equipment. Thus, in this case, the correct choice for each load-shedding scheme is to avoid any intervention.

Three of the four traditional schemes - (a1), (a2) and (a3) - do not behave in the best way, as they perform an unnecessary load shedding with a consequent contained over-frequency. This happens because the frequency falls below their first threshold, which was set at 49.5 Hz. The last traditional scheme (a4) does not shed any load, as its first threshold is set at 49.1 Hz, whereas the minimum frequency peak is 49.26 Hz. Results are reported in Fig. 2.

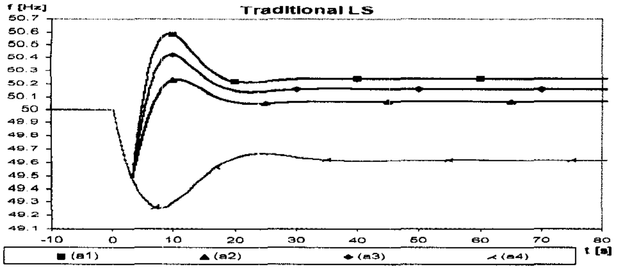

Fig. 2 – Comparison among the four traditional load-shedding schemes for a disturbance of 200 MW

The semi-adaptive scheme has better performances than methods (a1), (a2) and (a3), because it checks also the ROCOF when the frequency has declined to 49.5 Hz. Being |df/dt| smaller than 0.33 Hz/s, this scheme sheds just 150 MW, that is to say much less than (a1), (a2) and (a3) schemes (which shed 400 MW, 250 MW and 330 MW respectively). Yet, although the amount of load-shedding is reduced in this case, it is anyway unnecessary. Thus, the behavior of this scheme too is not the desirable one.

The adaptive scheme, just like the traditional scheme (a4), operates the best choice, as it sheds no load at all. Although the way these two schemes come to this decision is different, it is based on the same physical reasons. The traditional scheme does not act because the disturbance is such that the first threshold of 49.1 Hz was not overcome. The adaptive scheme avoids any load shedding because the initial value of the ROCOF is smaller than the critical one and so the contingency is estimated as less dangerous than the critical one. The transient behavior of system frequency is shown in Fig. 3.

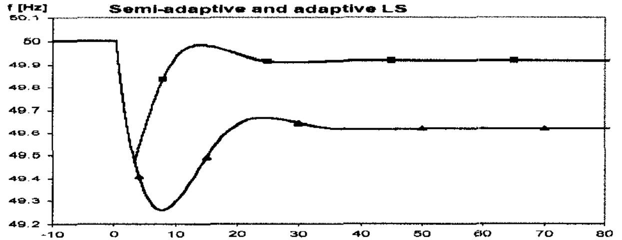

Fig. 3 – Comparison between the semi-adatpive and the adaptive schemes for a disturbance of 200 MW

B.2 Medium size disturbance: 450 MW

This contingency is slightly smaller than the total spinning reserve of the system, which is about 495 MW, and so it might have been recovered by the f/P primary regulation. Anyway, the emergency procedure operates a load shedding because the recovery is so slow that a minimum frequency of 46.76 Hz is reached. The reasons for this slowness have already been recalled and are due to ramping constraints on some large generating units.

As shown in Fig. 4, for this case, the best traditional scheme is (a2), as it sheds less (250 MW) than schemes (a1) (400 MW), (a3) (330 MW) and (a4) (400 MW). Moreover, the traditional scheme (a4), which previously had the best behavior, is now the worst one as it begins to shed only when the frequency is at 49.1 Hz and thus the minimum frequency peak is more severe.

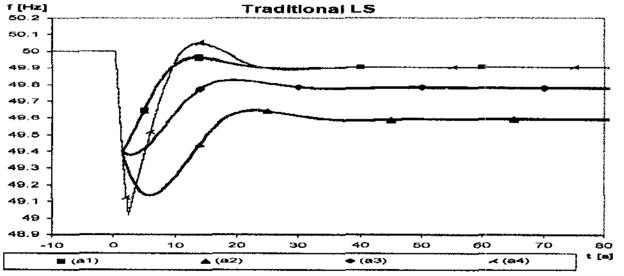

Fig. 4 – Comparison between the four traditional schemes for a disturbance of 450 MW

The semi-adaptive solution sheds 350 MW, that is to say the amount of load correspondent to a value of |df/dt| at 49.5 Hz between 0.33 and 0.50 Hz/s (see Fig. 5). Its performance is similar to the traditional schemes.

The best performance is achieved by the adaptive scheme, which sheds the smallest amount of load (64 MW). Obviously, shedding a smaller amount of load means accepting a lower minimum frequency. Anyway, the minimum frequency is correctly larger than the minimum allowable one (48 Hz).

B.3 Disturbance of 750 MW

A contingency of 750 MW would bring the system to a complete frequency collapse, as not enough spinning reserve is present in the system to cover the mismatch between the load and the generated power.

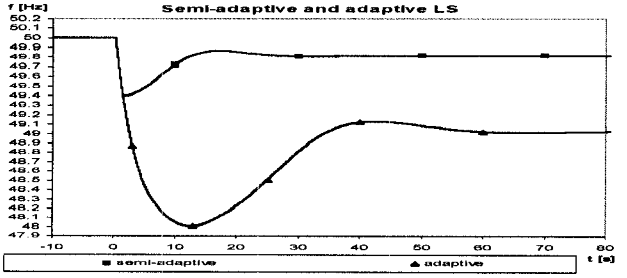

Fig. 5 – Comparison between the semi-adatpive and the adaptive schemes for a disturbance of 450 MW

The four traditional schemes show almost the same performances (see Fig. 6), as they shed comparable amounts of load, respectively 700 MW – (a1), 650 MW – (a2), 660 MW – (a3), and 700 MW – (a4). The fourth traditional scheme (a4) has a slightly worse response than the other three, because it starts shedding at 49.1 Hz instead of 49.5 Hz. This delayed action allows the minimum frequency peak to go down to 48.74 Hz against 48.94 Hz of scheme (a1), which sheds the same amount of load but starting at 49.5 Hz.

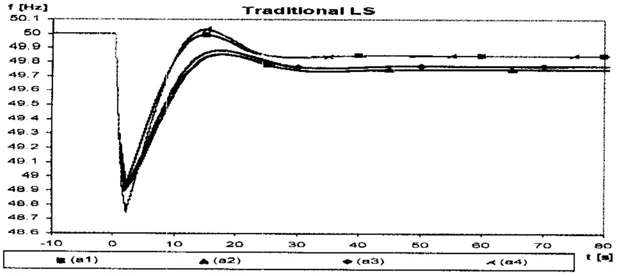

Fig. 6 – Comparison between the four traditional schemes for a disturbance of 750 MW

The semi-adaptive scheme sheds 750 MW, thus not providing any benefit over the traditional ones. The reason for this is that the disturbance of 750 MW is so large that some load must be shed even at frequency thresholds below the first one. Being these thresholds traditional (i.e. with no check on df/dt), the scheme behaves almost exactly as the traditional schemes.

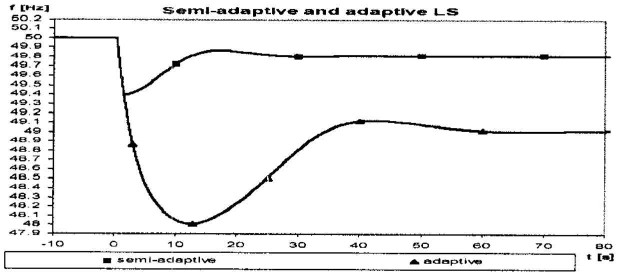

Fig. 7 – Comparison between the semi-adatpive and the adaptive schemes for a disturbance of 750 MW

On the contrary, again the adaptive method shows good performances: the quantity of load-shedding is the smallest (424 MW), by obviously paying the cost of a deeper frequency peak and of a lower steady state frequency. Results are in Fig. 7.

IV. CONCLUSIONS

The paper has examined the current situation and the perspectives for under frequency load-shedding. Several schemes have been investigated: from traditional approaches based on frequency thresholds to semi-adaptive methodologies based on frequency an its derivative. A fully adaptive technique has been also used because of its potential interest in the current context of deregulation.

The performances of the different examined methods, pointed out through dynamic simulations on the IEEE RTS network, show that traditional methods tend to be rather conservative in the amount of load effectively shed.

Several questions are posed by power system engineers if such stringent performances are still necessary in the field of frequency control [17]. If the frequency excursion range is not required anymore to be so thin, the adaptive load-shedding method can contribute to matching the combined exigency of maintaining system security and shed the minimum amount of load.

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