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.

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:

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

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.