ADVANCED LOAD-SHEDDING FUNCTIONS IN DISTRIBUTION PROTECTION RELAYS

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ABSTRACT

The paper analyzes the requirements and methods for load-shedding in distribution systems and discusses frequency and voltage based functions in protection relays. Centralized and distributed load-shedding schemes are described. The impact of IEC 61850 on load-shedding is considered as well. Testing of advanced load-shedding functions is discussed at the end of the paper.

INTRODUCTION

Even with significant efforts from planning and protection engineers working on improvements in the design and operation of electric power systems, wide area disturbances remain a fact of life that we need to deal with. Load shedding plays an extremely important role by preventing the complete collapse of the system and reducing the number of customers affected by the event.

The blackouts in North America and Europe in 2003, as well as the recent disturbance in Europe in November 2006 [1] showed again the role of load shedding and the need for improvements in its design and implementation.

In the evening of 4 November 2006, cascading overloads and tripping lead to the splitting of Europe in three large separate systems. The Western area faced significant supply-demand imbalance which resulted in a quick drop (in 8s) of frequency down to about 49 Hz.

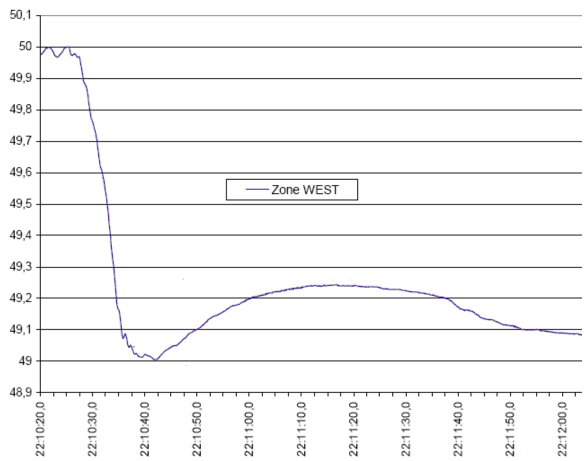

Fig. 1 Frequency change in Western Europe 4/11/2006

Such a frequency drop resulted in a sequence of events and activation of the defense plans in each TSO area that led to automatic load shedding and tripping of pump storage units when the frequency dropped under the pre-defined thresholds. All this occurred in a very short time - 8 seconds during the frequency drop.

Figure 2 shows the load shedding in different parts of the West European system.

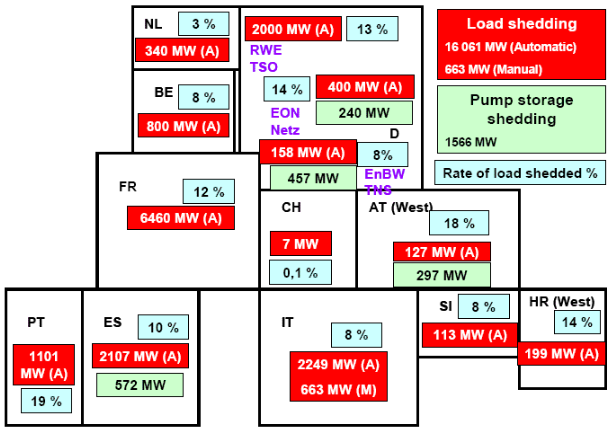

Fig. 2 Load-shedding in Western Europe 4/11/2006

According to the UCTE Operation Handbook, these automatic actions should prevent the system collapse as a result of significant power imbalance. The amount of load shedding in each TSO area defined in the defense plan depends on the frequency threshold and sometimes on the speed of frequency decrease. For every TSO, the general rule is to trip the pumped-storage units when the frequency drops to 49.5 Hz and start the load shedding step by step at a frequency near 49 Hz with thresholds every 0.4 Hz or 0.5 Hz. A total of about 1 600 MW of pumps were stopped and 17 000 MW of load was shed and (see Figure 2).

The values in green squares show the automatic pumps shedding. Automatic (A) and manual (M) load shedding is in red squares, while the values in the blue squares is the rate of load shedding and pump shedding related to the estimated total load [1].

The defense plan actions triggered by each TSO helped to restore the frequency close to its nominal value. However, in some TSOs (Italy and Austria), the automatic load shedding was completed by manual load shedding actions due to the low stable frequency near 49.2 Hz a few minutes after the incident.

The need for manual load shedding and the differences between the expected and actual load shedding show that it is possible to achieve better performance using the advanced load shedding functions available in modern distribution protection relays.

LOAD SHEDDING IN SUBSTATIONS

Load shedding in substations can be executed based on several different principles. It also can be triggered by different system events and can serve different purposes. In the case of the European disturbance described above underfrequency load shedding was used to restore the load – generation balance in the separated parts of the European system. The load shedding in this case was executed locally in the distribution substations and triggered by the drop of frequency below the pre-defined thresholds in accordance with the defensive plans.
Load also can be shed in order to prevent the separation of the system. In this case it is triggered by criteria implemented at the system level in a remedial action scheme and executed in substations when they receive commands for load shedding from the upper level of the system.
The load shedding in the substation can be based on two main principles described below.

Centralized Load Shedding

Centralized load shedding has been the method of choice since the first implementations of underfrequency load shedding and was mainly driven by the technology at the time – electromechanical underfrequency relays. In this case a single relay in the substation is performing frequency measurement at one point in the substation and acting as one step of the load shedding scheme. If more than one step is needed, additional underfrequency relays will be used.
The outputs of the relay are wired to trip the breakers of the distribution feeders included in the load shedding system.

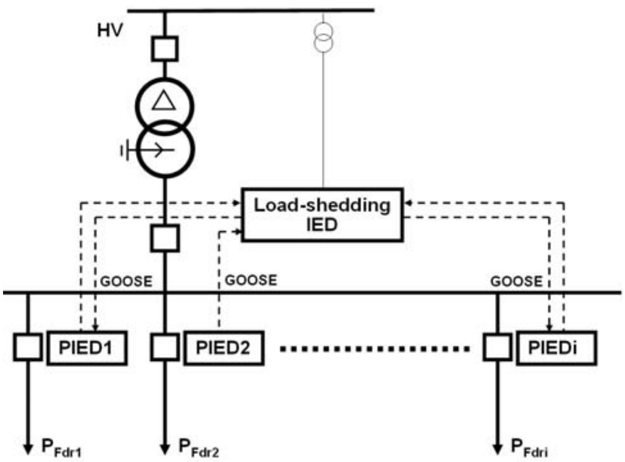

Fig. 3 Centralized load shedding using GOOSE messages

Centralized load shedding systems are used also today in the world of microprocessor based relays. An advanced, specialized frequency and voltage relay can be used to perform complex load shedding functions in multiple steps and based on different criteria as defined by the defense plan. The tripping of the breakers can be achieved through hard-wiring or using the defined in IEC 61850 high-speed peer-to-peer communications GOOSE messages.
The decision to use centralized load shedding also is affected by the capabilities of the distribution feeder relays. If the feeders are protected by electromechanical or solid state overcurrent relays, they obviously do not perform frequency measurements and it is more economical to add only a single multifunctional load-shedding IED instead of replacing all distribution feeder protection relays.
Even if the feeders are protected by multifunctional microprocessor based relays, they may not have voltage inputs and frequency monitoring capabilities, thus defining the need for a central load shedding IED.
In both cases the load-shedding device will determine the group of loads that need to be shed, usually starting with the loads with lower priority. If GOOSE messages are used, it will send a message to the network indicating which step has operated and the distribution feeder IEDs subscribing to this message will trip their associated breakers.
Centralized load shedding is used in substations also when it is executed as the result of operation of a remedial action scheme as shown in Figure 4.

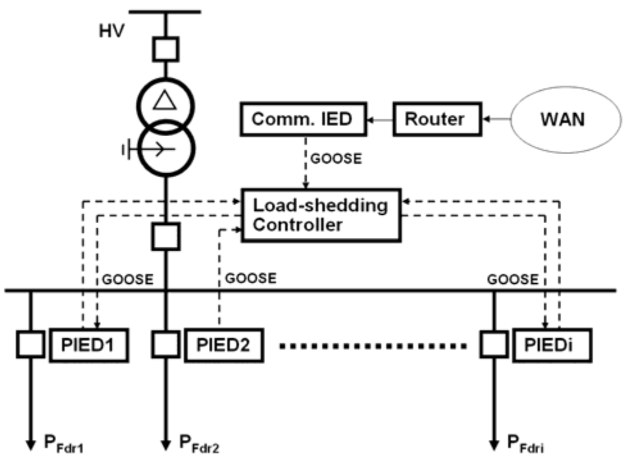

Fig. 4 Centralized adaptive load shedding

In order to achieve adaptive load shedding the substation level controller receives GOOSE messages from the distribution feeder relays every time when there is a change in the load outside of the user defined tolerance setting. The load shedding controller uses this information to determine an optimal combination of loads to be shed based on the optimization criteria.
In case of a wide area disturbance the remedial action scheme send a command through a communications IED to the substation controller to shed a specific amount of load. This amount of load is matched with the possible groups of feeder loads and a GOOSE message is sent to the network indicating which feeders need to tripped in order to shed an amount of load as close as possible to the required value. Any distribution feeder IEDs that belongs to the load

shedding system and subscribes to GOOSE messages from the substation controller will receive the message and if it indicates that it belongs to the group of feeders to be shed, it will trip its associated breaker.
Since a centralized load shedding system is subject to the failure of the load shedding device, a second backup IED may be required to ensure the reliability of operation in case of system disturbance.

Distributed Load Shedding

Distributed load shedding is a relatively new concept since it requires each individual distribution feeder to be equipped with an IED that measures the frequency and can perform the load shedding function. This means also that each of the distribution feeder relays needs to have voltage inputs which indicates in general a high end device with a higher cost. However, such a device provides not only protection, but also measurements, recording and other required functions, as well as increased reliability of the load shedding system.
Figure 5 shows a distributed load shedding system with each protection IED connected to a feeder current transformer and a common distribution bus voltage transformer.

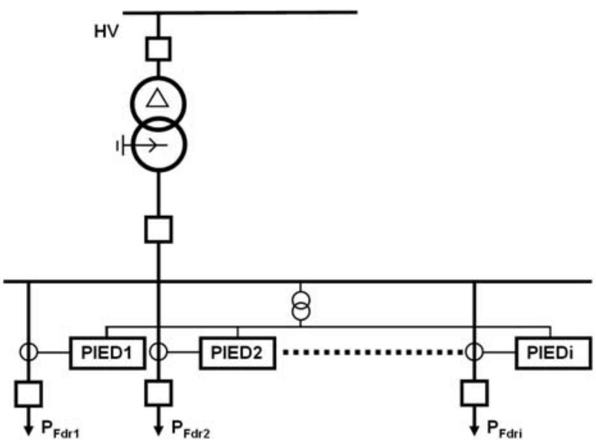

Fig. 5 Distributed load shedding system

In case of distributed load shedding each individual relay belongs to a specific step of the load shedding system and usually has a more limited functionality compared to specialized IEDs used in centralized systems.
The fact that each feeder can be controlled by a separate step in the load shedding system with a different setting allows the implementation of a more flexible system that will shed load closer to the requirement for balancing load and generation in the area separated after a disturbance. Two types of settings will need to be implemented – one for stopping the frequency decay and the second to bring back the frequency to normal if it hangs at below nominal level. In order to be able to support the above requirements, the modern distribution protection relays include advanced protection functions described below.

LOAD SHEDDING FUNCTIONS IN IEDS

Load shedding functions in multifunctional protection IEDs can be achieved using deferent methods and their combination in complex schemes using the programmable scheme logic that such devices typically have. Following is a description of several functions that can ensure optimal performance of an underfrequency load shedding device under different system disturbance conditions.

Underfrequency

The basic underfrequency protection (f+t) is the most commonly used and is available with multiple independent definite time delayed stages – up to six in some relays. Although the elements are described as definite time delayed, they can be also used as instantaneous by setting the time delay to zero.
In order to minimize the effects of underfrequency on a system, a multi stage load shedding scheme may be used with the substation loads prioritized and grouped. During an underfrequency condition, the load groups are disconnected sequentially depending on the level of underfrequency, with the highest priority group being the last one to be disconnected.
The time delay setting range should be sufficient to override any transient dips in frequency, as well as to provide time for the frequency controls in the system to respond. This should be balanced against the system survival requirement since excessive time delays may cause the system stability to be in jeopardy. Time delay settings of 5 – 20s are typical. The relatively long time delays are intended to provide time for the system controls to respond and will work well in a situation where the decline of system frequency is slow. For situations where rapid decline of frequency is expected, the load shedding scheme above should be supplemented by rate of change of frequency protection elements.

Frequency supervised rate of change of frequency

If the load to generation imbalance is considerable this may result in relatively rapid changes of the system frequency(as in Figure 1). In such case maintaining the system stability is an important task, and requires a quick corrective action.
High speed load shedding cannot be achieved by monitoring the system frequency alone and the rate of change of system frequency becomes an equally critical parameter to use.
There is no intentional time delay associated with this element although using the Programmable Scheme Logic (PSL), time delays could be applied if required.
It may be possible to further improve the speed of load shedding in critical cases by changing the frequency setting on the frequency supervised rate of change of frequency element. If the frequency settings for the “f+df/dt” element have been set slightly higher than the frequency settings for the “f+t” element, this difference will allow for the slow frequency decline and fast frequency decline scenarios to be independently monitored and optimized without sacrificing

system security.

Independent rate of change of frequency

This element is a plain rate of change of frequency monitoring element, and is not supervised by a frequency setting. However, a timer is included to provide a time delayed operation. The element can be used to provide extra flexibility to a load shedding scheme in cases of severe load to generation imbalances.
Since the rate of change monitoring is independent of frequency, the element can identify frequency variations occurring close to nominal frequency and thus provide early warning to the operator on a developing frequency problem. Additionally, the element could also be used as an alarm to warn operators of unusually high frequency variations.
The output of the element would normally be given a user-selectable time delay, although it is possible to set this to zero and create an instantaneous element.
Considerable care should be taken when setting this element because it is not supervised by a frequency setting. Setting of the time delay will lead to a more stable element but this should be considered against the loss of fast tripping capability as the time delay is extended.

Average rate of change of frequency

Owing to the complex dynamics of power systems, variations in frequency during times of generation – load imbalance do not follow any regular patterns and are highly non-linear. Oscillations will occur as the system seeks to address the imbalance, resulting in frequency oscillations typically in the order of 0.1Hz to 1Hz, in addition to the basic change in frequency.
The rate of change of frequency elements discussed above use an "instantaneous" measurement of "df/dt" based upon a fixed, for example 3 cycle measurement. Due to the oscillatory nature of frequency excursions, this instantaneous value can sometimes be misleading, either causing unexpected operation or excessive stability. For this reason, the relays provide an element for monitoring longer term frequency trend, thus reducing the effects of non-linearity in the system and providing increased security.

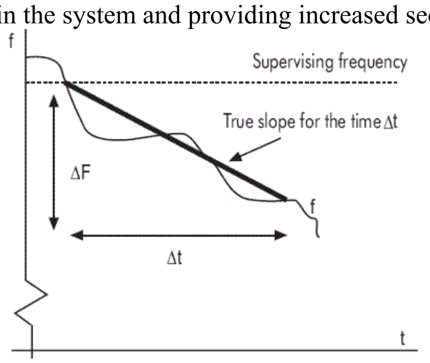

Fig. 6 Average rate of change of frequency

As for the other rate of change of frequency elements, it is recommended that the ”f+ Δf/Δt” element is used in conjunction with the ”f+t” element. The average rate of change of frequency element can be set to measure the rate of change over a short period as low as 20ms or a relatively long period up to 2s. With a time setting of Δt towards the lower end of this range, the element becomes similar to the frequency supervised rate of change function, "f+df/dt". With high Δt settings it acts as a frequency trend monitor.

TESTING OF LOAD SHEDDING FUNCTIONS

Testing of advanced load shedding functions and complex schemes requires the use of advanced testing tools to ensure that the relays will operate as expected under real system disturbance conditions. New testing technology allows much more comprehensive testing where both protection functions and control logic can be tested using automated test routines or dynamic simulations. Some relays will not respond well to a step-change-in frequency test. They have a supervisory feature that resets the measurements, thinking a step change in system frequency is not possible. These relays require a ramped test. Testing of the basic frequency elements follows the usual principles for pickup and dropout accuracy verification based on frequency ramping with a minimum step size of 0.01 Hz with a minimum resolution of 0.005 Hz. Rate-of-change and average rate-of-change functions, which may be supervised by voltage or current elements plus additional PSL makes their testing much more complicated.

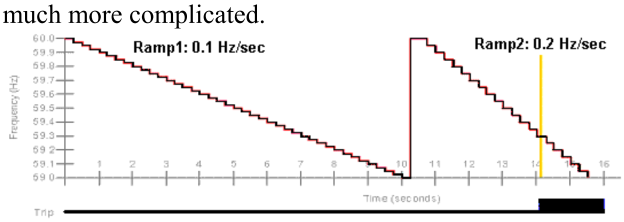

Fig. 7 Rate-of-change test

CONCLUSIONS

Load shedding is one the main actions that can be used to prevent further spread of a wide area disturbance and restoration of the load-generation balance in a separated part of the system.
State-of-the art distribution protection IEDs can be used for the implementation of advanced centralized or distributed multi-step load shedding schemes based on frequency, rate-of-change or average rate-of-change of frequency and their different combinations using PSL.
Support of IEC 61850 high-speed peer-to-peer GOOSE messages allows the development of more flexible and efficient load shedding solutions.

REFERENCES

1. UCTE, Interim Report - System Disturbance on 4 November 2006, 30.11.2006