OPERATIONAL EXPERIENCE OF LOAD SHEDDING AND NEW REQUIREMENTS ON FREQUENCY RELAYS

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This paper summarises experience and analysis of underfrequency load shedding and power generator islanding. Most power systems can withstand the loss of a single generating unit or a single transmission line. Simultaneous loss of several power system components may cause a severe deficit in active and reactive power. The action of overexcitation limiters on the remaining generators may further aggravate the situation. Such infrequent events may cause severe drop in system frequency and voltage magnitude. Frequency relays for load shedding and power generator islanding must operate correctly even if the system frequency decays and the voltage magnitude decays rapidly at the same time.

INTRODUCTION

Power system engineers plan power systems so that the intended systems can withstand credible contingencies. Such contingencies may include: (1) the loss of a single generating unit, (2) the loss of a single transmission line or (3) the loss of more than one power system component. It is common practice to use system protection schemes to mitigate the consequences of infrequent contingencies beyond the planning criteria.

A system protection scheme must cope with two types of severe events. One event is the loss of several generating units in the power system. Another event is the loss of several transmission lines running from a production area to a consumption area. One example of a system protection scheme is underfrequency load shedding used to stop the frequency drop after loss of generating units. Another example is undervoltage load shedding used to avoid voltage collapse. System protection schemes may initiate load shedding as a final action to mitigate the consequences of severe faults. Ingelson et al (1996) describe a protection scheme to prevent voltage collapse. System protection schemes may also comprise generator tripping to avoid transient instability after loss critical transmission lines.

System protection schemes may also comprise zero-voltage protection used to open circuit breakers upon complete loss of voltage. Such an action makes it possible to avoid inadvertent energisation of large network sections. This means that the network restoration can start at once from a well defined switching state. Underfrequency generator tripping to houseload operation may also expedite the power system restoration. The generation unit is then ready for synchronisation.

OPERATIONAL EXPERIENCE

The Swedish power generating system has a mixture of hydro, fossil and nuclear units. Many large hydro power plants are located in the northern part of Sweden. The big thermal power plants are located near the load centres in the southern part of Sweden. The early plans, from 1955, for the Swedish 400 kV transmission network called for transportation of 8 500 MW over an average distance of 700 kilometres. The transmission system has a number of bottlenecks where the power transfer capacity is limited. Such a bottleneck is Section 2 running at latitude 61°N.

In the late 1960's, Swedish utilities south of Section 2 installed a distributed under-frequency load shedding system. The system has five steps with settings from 48.0 to 49.0 Hz. Each step has two frequency settings with different time delays. Each step disconnects about 10% of the load south of Section 2. Nuclear power units have an underfrequency protection that disconnects the unit at 47.5 Hz after a short delay. It should be short enough that to trip to houseload operation.

On 27 December 1983, a serious event occurred in the Swedish power system. The total load in Sweden at that time was about 18 300 MW. A busbar fault near Stockholm caused cascade tripping of transmission lines in the critical Section 2. Protection systems automatically tripped some tie-lines to neighbouring countries and separated the Nordel system into several subsystems. The subsystem south of Section 2 had a power deficit of about 7 000 MW. Frequency and voltage dropped quickly. The underfrequency load shedding system did not act as expected and no load shedding took place. All nuclear power plants, except one failed to trip to houseload operation. A total blackout occurred in the southern part of Sweden. Kearsley (1987) and Walve (1986) give further information.

In 1982, a utility installed a Power System Swing Recorder (PSSR) in a nuclear power station in the very south of Sweden. The recordings were valuable for the analysis of the disturbances in that part of the system. Figure 1 shows the frequency drop recorded at the power plant during the blackout in 1983. Some 50 seconds elapsed after the primary busbar fault until the PSSR started. The PSSR started to record at $t = 0$ seconds local time in the recorder. The system probably separated at $t = 2$ s. Two seconds later, the blackout was a fact. The rate-of-change of the local frequency increased gradually and was more than 3 Hz/s at $t = 3$ s.

Developments in Power System Protection, 25–27th March 1997, Conference Publication No. 434, © IEE, 1997

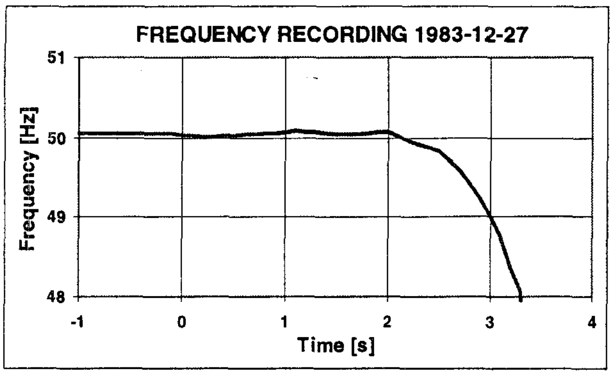

Figure 1: Frequency drop during the blackout.

Figure 2 shows the corresponding voltage drop. At $t = 3$ s, the rate-of-change of the magnitude of the voltage was about 200 kV/s (-0.5 pu/s).

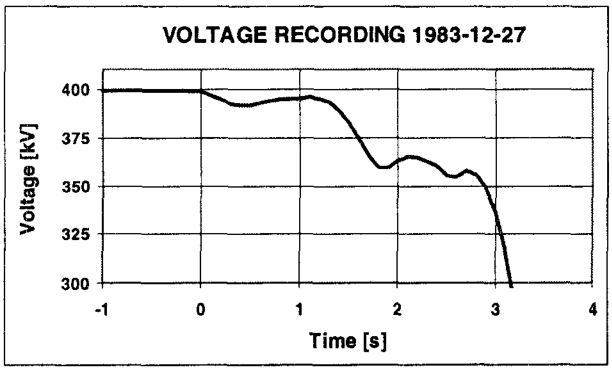

Figure 2: Voltage drop during the blackout.

Figure 3 shows a typical frequency drop in the Nordel system after the loss of a generation unit with a rated capacity of 1 050 MW. The loss of the generating unit occurred on 15 September 1988. The rate-of-change of system frequency is much lower than during the blackout on 27 December 1983.

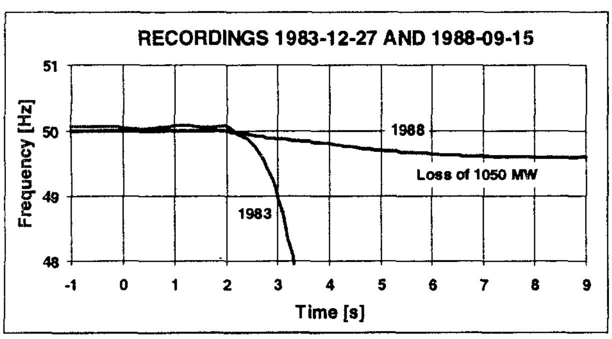

Figure 3: Comparison of two frequency responses.

The blackout in 1983 lead to a very fast frequency **and** voltage drop. It was so rapid that neither the underfrequency load shedding system nor the generator underfrequency protection system reacted. The disturbance developed in a way that it is not certain that underfrequency load shedding alone could have saved the system. The frequency and voltage were already so low at that time so islanding of nuclear power production should take place (loss of more than 5 000 MW). The first step of the underfrequency load shedding system had the setting of 48.8 Hz and a delay of 0.15 seconds. When the frequency crosses this level the rate-of-change is very big. To stop the progressing system collapse one would have to use some other criteria than just a frequency level.

SIMULATION STUDY

This section contains a simulation study comprising both a large power system and an industrial system. The aim is to calculate the response of the local frequency and voltage magnitude caused by the islanding of a subsystem and by the loss of a big generating unit.

We have used a simple model with two generating units and a multi-circuit transmission system connected to the high voltage side of the generator step-up transformers. The model also comprises loads connected to the high voltage side of the step-up transformers. The active and reactive load depends on local frequency and voltage magnitude. We have used a generator model based on the work by Heffron and Phillips (1952) as described by DeMello and Concordia (1969).

The large system is a simplified version of the Nordel power system. The receiving subsystem represents the subsystem south of the critical Section 2 in Sweden. In the receiving system the total load is 16 000 MW and the total installed capacity 12 000 MVA. The transmission from north to south comprises eight 400 kV series compensated lines with a total length of 500 kilometres. The power transfer from north to south is close to 6 000 MW. Below we show the response of local frequency and voltage magnitude for two events: (1) the disconnection of the transmission lines supplying almost 40% of the local load and (2) the loss of a big generation unit. Figure 4 shows the frequency drop and Figure 5 shows the voltage drop.

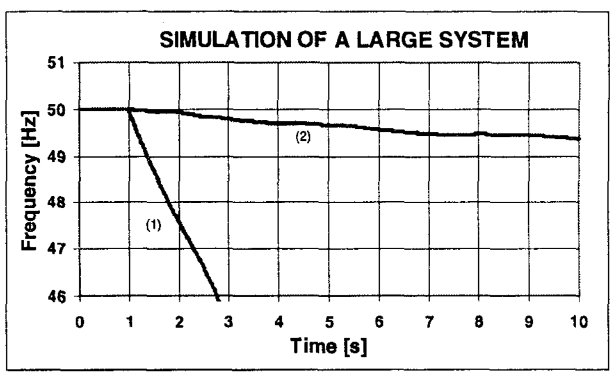

Figure 4: Frequency Drop in a Large System.

The calculated rate-of-change of local frequency is more than 2 Hz/second at the disconnection of all transmission circuits from north to south. The rate-of-change and the total frequency drop are much smaller in case of loss of a big generating unit. The calculated rate-of-change of voltage magnitude is faster than 0.1 pu/second at the loss of the entire transmission from north to south. The response of voltage magnitude is a complex interplay between the voltage dependent load at large excursions, the generators and their excitation system including overexcitation limiters. Our simple model therefore underestimates the real rate-of-change of voltage magnitude that has been recorded.

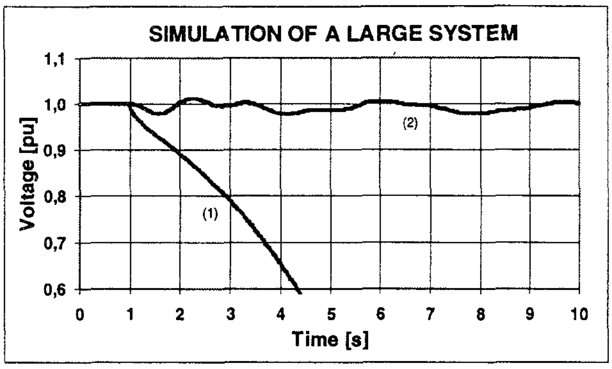

Figure 5: Voltage Drop in a Large System.

The second system is a simplified version of an industrial system mainly supplied from a power supply system. In the industrial system, the total load is 200 MW and the total installed capacity is 100 MVA. The transmission from the power system comprises two 130 kV lines with a total length of 100 kilometres. The power transfer to the industrial system is close to 120 MW. Below we show the response after the disconnection of the two power lines. They supply 60% of the local power demand. Figure 6 shows the frequency drop and Figure 7 shows the voltage drop.

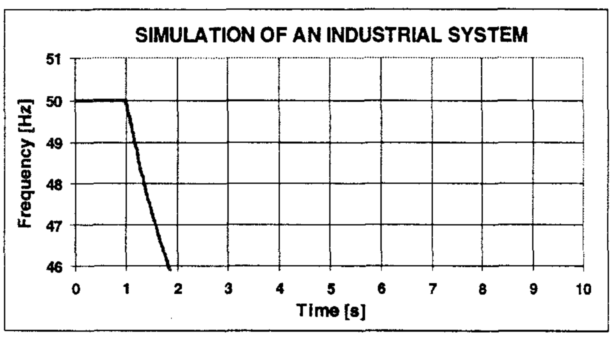

Figure 6: Frequency Drop in an Industrial System.

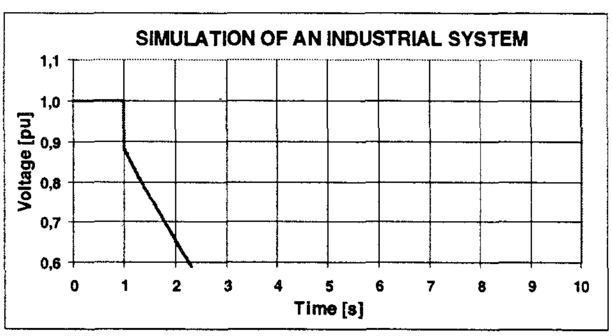

Figure 7: Voltage Drop in an Industrial System.

The calculated rate-of-change of local frequency is more than 4 Hz/second. The calculated rate-of-change of voltage magnitude is about 0.4 pu/second. The islanding of a subsystem with power deficiency will cause a rapid drop in frequency **and** voltage. The rate-of-change of frequency and voltage increases with the relative power deficit in the receiving subsystem. Analysis supported by experience show that we have to consider rate-of-change in frequency in the order of 2 to 5 Hz/second. It is also necessary to consider a rate-of-change in voltage magnitude of 0.1 to 0.5 pu/second.

LABORATORY TESTS

Laboratory tests were performed to check operate time of one of the underfrequency relays used for islanding of nuclear power plants during the blackout in 1983. This was part of the work to improve the probability of successful islanding. Figure 8 shows the result of tests where the relay was exposed to voltage and frequency drop at the same time.

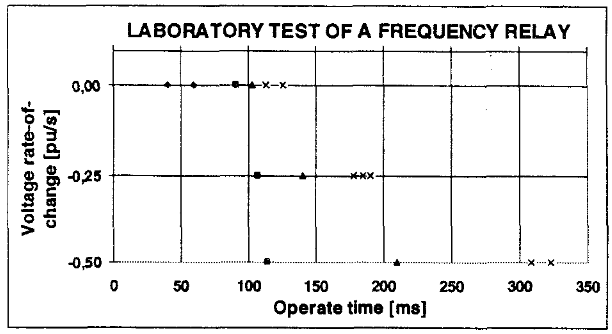

Figure 8: Test results (◆: frequency step 50→45 Hz, ■: -8 Hz/s, ▲: -4Hz/s, ✖: -2 Hz/s).

The relay performed well and had an operate time less than 130 ms when the magnitude of the energising voltage was kept constant. The operate time increased significantly and was in the interval from 90 to 330 milliseconds when the frequency **and** the magnitude of the voltage both decreased like a ramp. Recent papers on testing of frequency relays do not mention the need to test them with decaying voltage, see Stringer (1996).

NEW REQUIREMENTS

The operational experience led to the conclusion that underfrequency relays for islanding of nuclear generating units must operate without significant delay. Frequency relays for load shedding applications should meet similar requirements. The operate time of frequency relays for such applications must not increase even if the magnitude of the energising voltage decrease with a rate-of-change of -0.5 pu/second. In some power systems there are possibilities of using df/dt relays in order to speed up emergency actions to avoid blackouts.

REALISATION

This section describes the principle and properties of a new frequency relay. The product implementation comprises hardware and software elements. In the relay, they are combined in an optimum way based on the new requirement. Since the requirements for frequency measurement functions differ depending on application range and needed accuracy for load shedding and generator islanding, two models were created.

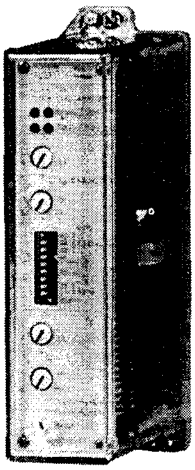

Figure 9: The New Frequency Relay.

Model 1 has two discrete frequency-measuring steps settable in the range of 5 Hz and 10 Hz off the rated frequency respectively. Each step can be set either as an over- or an under-frequency element. The second step can be set to measure absolute frequency or alternatively as a df/dt function. It is possible to set response to a negative df/dt or absolute rate of change, i.e. an output is then achieved for both increasing and decreasing frequency changes. It is of course also possible to control the response of the df/dt output contact via the change over contact elements of the first frequency step. The setting resolution for the two frequency levels of this model is 25 mHz. A df/dt setting range of 0.2 10 Hz/second is available in this model.

Model 2 also has two discrete frequency-measuring steps but settable in a narrower range to yield a finer resolution, i.e. 10mHz steps. The two ranges permit settings up to 4 Hz over or under nominal frequency.

The frequency measurement is based on accurate timing measurements between 3 or 2 power system periods for model 1 and 2 respectively. Trip decisions are made based on several calculation loop reaffirmation in order to achieve security. The start signal may be used as an instantaneous output when high speed is of the outermost essence. The normal trip-output may be delayed. The delay setting range from 0 to 20 seconds.

An adaptable measuring principle is implemented for the df/dt function in order to secure best possible stability for the trip decision. The period of measurement required for tripping is therefor made dependent on the set df/dt level. In the range 0.2-0.45 Hz/second, 14 periods are used. For larger settings of rate-of-change of frequency, shorter measuring periods are used. A minimum of 2 periods is used in the 4-10 Hz/second range. Filtering of the sampled input from the power system as well as the calculated result are performed via averaging of 4 sets of data. Jitter in the power system is effectively eliminated in this way.

Another feature is the total independence of the magnitude of input voltage level as long as the voltage remains within the defined range. As simultaneous changes in input voltage magnitude and frequency occur during system disturbances, this was part of the type test procedure. The relay was tested for 1, 2, and 4 Hz/second frequency changes simultaneous with 0, 1, 2 and V/second of a 20 V nominal voltage setting. No effects could be observed. A sudden dip in voltage will not cause erratic frequency measurement since the measuring principle has been made independent of the absolute voltage level . The input voltage may be set between 20-320 V. Undervoltage blocking is performed at 50% of the set input voltage.

CONCLUSIONS

The 1983 blackout in Sweden lead to a very fast frequency **and** voltage drop. It was so rapid that neither the underfrequency load shedding system nor the generator underfrequency islanding system reacted. Analysis supported by operational experience shows that we have to consider a rate-of-change in local frequency in the order of 2 to 5 Hz/second. It is also necessary to consider a rate-of-change in voltage magnitude of 0.1 to 0.5 pu/second. Laboratory tests shows that the operate time of some frequency relays increased significantly when the frequency **and** the magnitude of the voltage both changed like a ramp. The operate time of frequency relays for such generator disconnection and load shedding applications must not increase even if the magnitude of the energising voltage decrease with a rate-of-change of -0.5 pu/second. There are frequency relays available on the market that meets these new and more demanding requirements.

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