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Sub-Synchronous Resonance (SSR) in existing and future networks
Detection and appropriate measures

Design Challenges for Numerical SSR Protection

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Summary

We report on the development of a modern numerical SSR protection to replace an existing analogue relay that no longer could be adapted to changing operating conditions. The development is based on knowledge gained from field recordings of SSR events at the prospective site. From this and some theoretical considerations, it was possible to design a new protection function that is more reliable than previous generations of SSR relays.

Keywords

Sub- and super-synchronous current and voltage, torsional vibration, field measurements, SSR protection.

1. Introduction

Sub-synchronous resonance (SSR) can cause a growing pulsating torque on the generator and turbines shaft. SSR can appear in thermal power units which have a long shaft and where the generator is connected to a long radial transmission network with series capacitors. It is considered as an unstable and dangerous condition that can cause fatigue and damage to the shaft, in the worst case the shaft could even break. SSR in hydro power units are very unlikely because the inertia of the generator is very dominant and the inertia of the turbine is only 5 to 10 % of the total inertia of the hydro power unit [1].

The initial interest in sub-synchronous resonance, caused by the first two famous catastrophic events in 1970 and 1971 [2], has in the past decades diminished considerably. Nevertheless there are still major generating plants located in vicinity of series compensated transmission lines and/or HVDC converter stations which may be vulnerable to this phenomenon.

Even in cases where protection already exists, any changes in the power system may raise SSR-specific concerns again. Such changes include changes or replacement of the generator or any turbine section (HP-, IP- or LP-section). The changes may also include changes of the network structure or degree of compensation of adjacent series compensation transmission lines or an unusual switching state in the transmission network. In such a case, an existing SSR protection system may need re-tuning which may be a delicate process.

In this paper, we report on such a case, where the detailed know-how on the tuning procedures for the existing protection were no longer available, as it was designed and installed around

1985. Furthermore, suitable replacements could not easily be found on the market. Therefore an entirely new SSR protection had to be developed.

In the following, the development process is discussed in some detail. First we give an overview of the prospective site and then describe observations from captured SSR events which led to some theoretical derivations. The total information gathered enabled a rather unconventional design of the final protection function.

2. The Swedish Power System

In the Swedish national grid there are ten series compensated lines. Eight of them are transmission lines connecting the north to the southern part of Sweden. The other two lines are connections between Sweden and Finland. Studies have shown that three of these ten series compensated lines can cause sub-synchronous resonance (torsional interaction) between a generator unit in Forsmark Nuclear Power Plant (NPP) and the electrical grid, see Figure 1.

Figure 1: Network around Forsmark

The length of these three series compensated lines is around 300 km and the compensation degree is between 70-85 %. They are connected to Ängsberg and Stackbo 400 kV substations, which are located at a distance of around 70 km from the Forsmark NPP. A 400 kV converter station for HVDC link to Finland is also located in the vicinity of Forsmark NPP.

At the Forsmark NPP-site there are three boiling water reactors designed by Asea-Atom. Forsmark 1 entered into commercial operation in 1980, while Forsmark 2 began operating commercially in 1981. Forsmark 3 began commercial operation in August 1985. The only unit that is sensitive to the sub-synchronous resonance is the 3rd unit which is the largest, rated around 1240 MWe and producing 9 TWh annually. During last years a modernization project has been ongoing. Due to foreseen shaft changes the original shaft mechanical torsional frequency will change and corresponding changes in the presently used SSR relays are unavoidable.

The existing SSR protections were installed in the middle of the 1980:s. They are installed at the three series capacitor stations and at the NPP [3]. Relays at 400 kV monitor currents in two phases and have a filter with pass-band of 17–36 Hz. The filter is connected to an over-current function with inverse time characteristic. This old protection has limited setting ranges and the filter characteristic is not adjustable. Currently the following approach for long lasting SSR events is used in Swedish power system: First the SSR relay in the 400 kV station shall operate in order to bypass the series capacitors. However, if this action do not stop the SSR oscillation, the relay at the NPP shall give a trip command to the affected generator in order to save the unit shaft from fatigue.

Steelworks with arc furnaces are also situated close to Ängsberg and Stackbo substations. These arc furnaces cause a lot of noise in measured voltage and current signals below 50 Hz which can cause unwanted operation of the SSR relays. The Swedish railway system operates at 16.7 Hz which also has to be taken into account when designing new numerical SSR protection relay.

3. SSR field observations

The design of any protection function requires deep insight into the addressed phenomenon which can be obtained from literature, simulations and site measurements. When the project to develop a new SSR protection relay was formed, it was possible to mainly rely on the last approach. Thus two modern protection Intelligent Electronic Devices, IEDs, where installed, one at the generating plant and one at the 400 kV substation. Initially, these two IEDs where only functioning as disturbance recorders trigged by the start signal from the existing SSR relays. When the new software functionality, discussed in Section 5, became available, this was also used to trig disturbance records. This enabled a first comparison between the performance of the existing and the conceived numerical SSR protection. The numerical design of the new relay also allowed logging of SSR quantities over longer period of time (months) on a stand-alone PC. In a final stage of the project a new numerical SSR protection functionality with all desired logics was installed.

This section intends to give some brief highlights of the observations made from disturbance records and logs. Examples will be provided that shows active SSR phenomena, how they may be initiated and how long they can persist. A comparison of the existing and new SSR relay will be presented. Also an example of a non-SSR disturbance that may cause an unwanted operation of the SSR relay is given.

3.1 Transient-initiated SSR event

Many of the observed SSR events are initiated by relatively fast load changes or network transients. Such transients have namely a very wide frequency content and if they are strong enough, they may initiate mechanical torsional oscillations of the unit shaft. These events are good examples of how an SSR event can be identified, as initially there are no SSR current and voltage components present while they are observed after the transient. An example with a known cause is chosen here; it is caused by a quick and large ramp-down of the nearby HVDC link due to a system contingency in Finland.

In Figure 2 the voltage and current frequency spectrum, as recorded at the generator terminals, before and after the switching transient are presented. Amplitudes are given in percent of CT and VT rating. The peaks appearing around 17, 83 and 117 Hz are caused by the Swedish railway system, operating at 16.7 Hz. Note that several new peaks, caused by SSR, have appeared around the fundamental frequency after the switching transient.

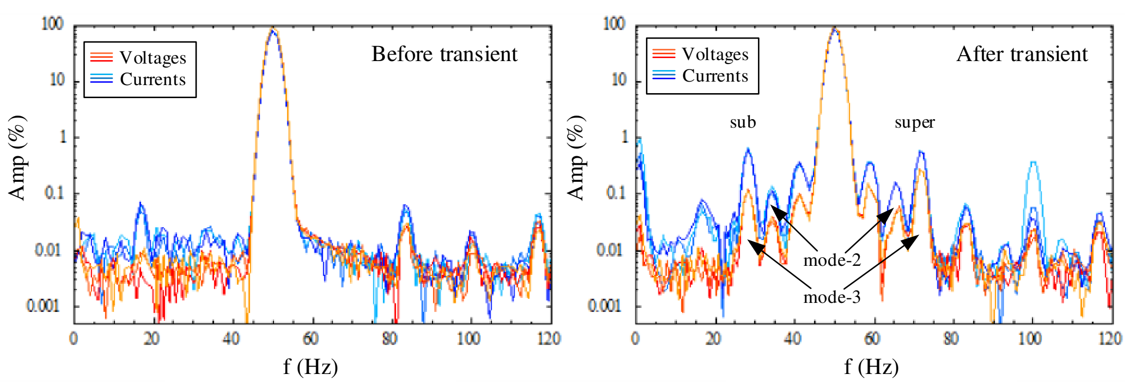

Figure 2: Short-time frequency spectra from U and I captured at the generator terminals

The figure shows that initially the frequency region between 20 and 40 Hz is without any detectable peak magnitude. However, after the transient, the spectra to the right in Figure 2 is obtained. Here, several peaks symmetrically distributed above and below the fundamental frequency have appeared. The symmetrical distribution is a natural consequence of the modulation caused by torsional vibrations in the generator shaft, as will be shown in Section 4 below. This is thus a good indicator of an on-going SSR phenomenon while the symmetric peaks have not attracted much attention in the existing literature [2,3,4]. Several peaks appear because a unit shaft with multiple turbines will have a number of torsional resonance modes, see references [2,4] for a detailed discussion.

The torsional oscillation modes have different damping characteristics so that only the strongest can be observed in a disturbance record trigged half a minute later. This mode, mode-3 in Figure 2, has the largest potential to cause dangerous SSR events and will be the main focus of the further discussion in the paper. The other two modes, especially mode-2, should not be totally neglected, however.

Most of the SSR events initiated by transients decay rather quickly, the present example is rather unusual in that it persist for more than 30 seconds as proven by the subsequent disturbance record. Figure 3 show the initial decay of the torsional mode-3 as seen by sub- and super-synchronous currents and voltages. From these figures, it is notable that the sub- and super-synchronous current components have almost identical amplitude, whereas the super-synchronous voltage component has about twice the amplitude of the sub-synchronous voltage component. This observation will be further exploited in Section 4.

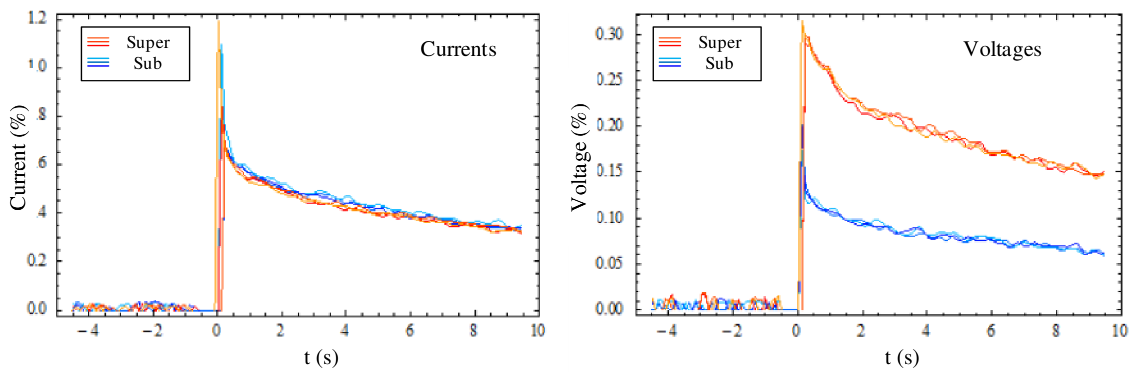

Figure 3: Sub- and super-synchronous U and I magnitudes during the SSR event

The disturbance records were generally trigged by a high current in the frequency range below the fundamental. There are however other phenomena that may cause high sub-fundamental currents as shown in Figure 4. The broadness of the current peak below fundamental frequency and the lack of a mirror peak above, clearly indicate that this is not caused by SSR. A possible cause may be a steelwork using an electric furnace in the vicinity of the substation.

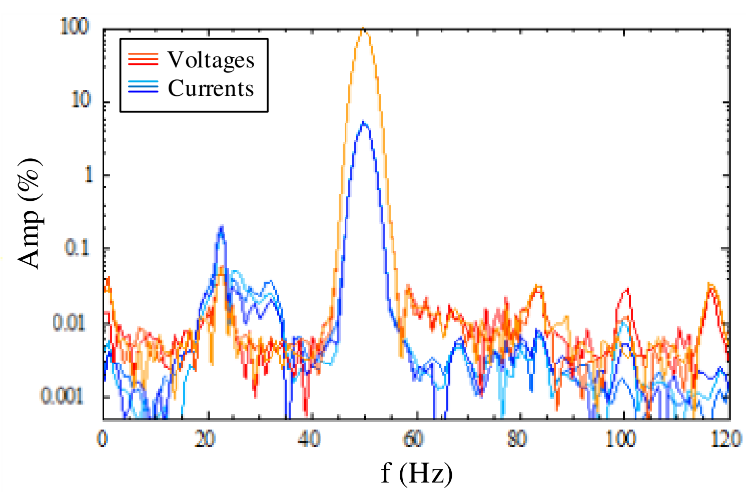

Figure 4: Spectra, similar to Figure 2, from a disturbance record trigged at the 400 kV substation that shows increased current below fundamental frequency that does not seem to be caused by SSR

Disturbances such as this may cause an unwanted operation of the SSR protection and must thus be considered in the new relay design.

3.2 More persistent SSR events

A transient-induced SSR event was discussed in some detail above, such events generally do not cause very large SSR currents and usually decay within a few seconds, inducing limited strain on the unit shaft. Indeed, the transient itself is often a much larger ordeal. However, disturbance records with almost constant SSR activity are also recorded. Many of these are from relatively short time periods, while there are much longer spans between these bursts of SSR recordings. This is understood as a persistent SSR event and durations up to 10 hours are indicated by some disturbance record sequences. As disturbance records only give a few seconds snapshot when the SSR level has passed a trigger criterion, they are not well suited for studying persistent SSR. Most importantly, persistent SSR with amplitude that is always above any trigger criterion may only give a disturbance record at start and thus pass largely unnoticed.

It is thus interesting to log the sub-synchronous amplitudes continuously and with the new numerical IED design, this became possible. A computer connected to the same communication network as the IED can then read the sub- and super-synchronous voltage, current and frequency from the new functionality and write them to a time-stamped log file. Such logging systems where installed both at the Forsmark NPP and the 400 kV substation. One prolonged SSR event that is logged in both places will be discussed below.

As seen from Figure 5, the selected SSR event lasted more than 30 minutes. In contrast to the previous example, there is no clear indication of an initiating transient or any hint of why it ended from the captured disturbance records. The observations from the two sites are remarkably similar while the SSR amplitudes are relatively smaller at the 400kV substation.

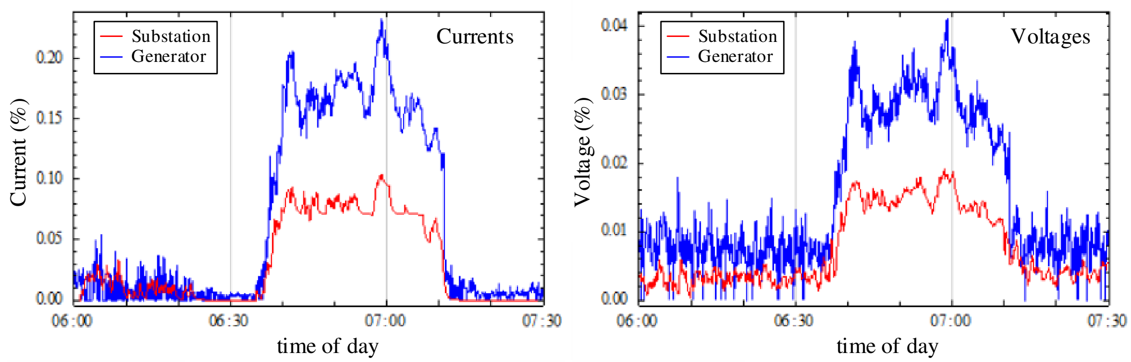

Figure 5: Sub-synchronous current and voltage components at the generator terminals and at the 400 kV substation during a prolonged SSR event

In view of the sub- and super-synchronous amplitude relations at the generator terminals for the transient event shown above, it is interesting to compare spectra from the 400kV substation and from the generator terminals, such are shown in Figure 6. Here it is obvious that the sub- and super-synchronous components propagate quite differently in the power grid and the SSR voltage peaks may not be so clearly visible at the 400kV substation.

3.3 Comparison of new and old protection

When an existing protection function is to be replaced, it is of course important to verify that the new function has at least the same capabilities as the old SSR relay. This may become a very complex task if all aspects of the functionality, such as bandwidths, time delays, etc., are to be compared. Thus, only the sensitivity to SSR currents is evaluated in the paper.

The evaluation is based on disturbance records captured by the IED with the new software functionality running. The estimated amplitudes for SSR currents and voltages are saved in the record together with digital channels reflecting trigger criteria from over-voltage or over-current based on the estimated amplitudes. From the existing SSR protection, only the start signal via a contact was available, thus the only information is that the existing analogue SSR over-current relay has seen a larger SSR signal than its set start threshold. Start levels for the new design and the existing SSR relay were set to the same current level, about 0.12% at the generating plant, whereas the trip level is about 0.45%. The start level of the existing protection at the 400 kV substation is somewhat higher. Start signals from both the existing protection and the new SSR functionality could trig disturbance records.

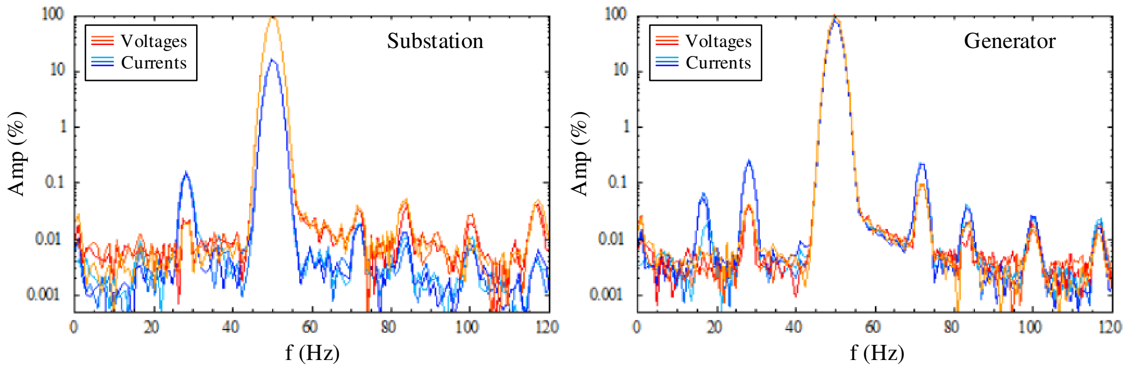

Figure 6 : Voltage and current spectra, from the 400 kV substation and the generator terminals during the prolonged SSR event shown in Figure 5

From the analysis of a large number of disturbance records from the generating plant it is found that both functions issue start signals if the current is large enough, larger than 0.4%. A case was found where the existing protection issued a start signals for an SSR current as low as 0.05% as estimated by the new SSR relay whereas it did not react to a case with 0.38% estimated current. No case was found where the existing protection had issued a start signal and the new SSR relay could not find a significant SSR current. It is no surprise that the two functions estimate the SSR current somewhat differently as they are based on very different principles: the existing protection use analog filters whereas the new SSR relay is a numerical algorithm with no direct analog correspondence.

Thus it is assured that the new numerical SSR protection is designed to react for SSR currents with the same sensitivity as the existing protection. Appropriate time delay in the form of inverse time characteristics can easily be provided with numerical design. Furthermore, the findings from this investigation present possibilities to design a more reliable SSR protection.

3.4 Conclusions from observed SSR events

To summarize the observations made:

- Sub-synchronous resonances have been observed both at the generator terminals and at 400kV transmission substation.
- The existing and new numerical protection reacts reasonably consistent to SSR currents.
- Both sub-synchronous and super-synchronous peaks are observed for SSR currents and voltages. The relation between these peaks seems to have a simple relationship at the generator terminals, whereas at the 400kV substation a predictable pattern is not as obvious.
- SSR events are often initiated by sudden load changes but these events usually decay rapidly; in some cases more persistent resonances are initiated. An SSR protection function should thus not react too rapidly as the presence of a resonance cannot be established while a system transient occurs.
- SSR activity may last for a long time, several hours. It may appear and disappear without any obvious external reason.
- SSR protection purely based on sub-synchronous current level may be affected by other system disturbances and noise.

4. Theoretical SSR amplitudes

The apparent relation between the sub- and super-synchronous amplitudes observed in Figure 3 demands a theoretical study. Consider thus a simple model of a single-phase synchronous machine and assume that the field-winding generates an air-gap magnetic field with the peak value B_m and that the air-gap flux varies sinusoidally in tangential direction around the periphery of the rotor body. Assume also that the mechanical angular velocity of the rotor varies sinusoidally around the average angular velocity ω_n with the angular velocity ω_p (a torsional mechanical resonance). The instantaneous angular velocity is then given by:

$$\omega(t) = \omega_n + \Delta\Omega \cos(\omega_p t) \tag{1}$$

where $\Delta\Omega$ is the peak value of the deviation of the instantaneous mechanical angular velocity from the average angular velocity ω_n. After integration of the argument of the sinusoidal function and application of Faraday's law of induction, the induced voltage $u(t)$ in the stator is given by:

$$u(t) = \frac{d}{dt}\left\{ A \cdot B_m \sin\left[\omega_n t + \frac{\Delta\Omega}{\omega_p}\sin(\omega_p t)\right]\right\} \tag{2}$$

where A is a constant depending on the area of the stator winding and the number of turns. Expanding the derivatives and performing a series expansion gives an expression for the stator voltage to first order in $\Delta\Omega$:

$$\begin{aligned} u(t) = \omega_n A \cdot B_m &\left\{ \cos(\omega_n t) + \frac{\Delta\Omega}{2\omega_n\omega_p}(\omega_n + \omega_p)\cos[(\omega_n + \omega_p)t] - \right. \\ &\left. - \frac{\Delta\Omega}{2\omega_n\omega_p}(\omega_n - \omega_p)\cos[(\omega_n - \omega_p)t] \right\} \end{aligned} \tag{3}$$

From this expression we note that there is a relation between the sub- and super-synchronous voltage component amplitudes and their respective frequencies as per the following equation:

$$\frac{Amplitude_{\sup}}{Amplitude_{sub}} = \frac{\omega_n + \omega_p}{\omega_n - \omega_p} = \frac{Frequency_{\sup}}{Frequency_{sub}} \tag{4}$$

The voltage components amplitude ratio is hence equal to the ratio of the frequencies, which is roughly what is observed for the SSR voltages in Figure 3. Such a relation is thus a simple evidence that SSR is observed which can be exploited to design a more reliable SSR protection. Furthermore, the ratio of SSR amplitude to the fundamental frequency voltage is only dependent on the involved frequencies and the vibration amplitude $\Delta\Omega$. The voltage SSR amplitudes can thus be used as a direct measurement of the torsional vibration amplitude.

If the generator load at off-nominal frequencies is dominantly inductive, the absolute load impedance will linearly increase with frequency. Thus the currents at sub- and super-synchronous frequencies will be approximately equal, again as observed in Figure 3.

It must be strongly emphasized that this derivation only holds for sub- and super-synchronous voltage and current components at the generator terminals. In the transmission grid, these relations become much more complicated and depends on the particular network details.

5. Design of numerical SSR protection

The biggest challenge for any type of SSR relay is its capability to accurately measure the SSR current and/or voltage components. As shown in this paper these components can be extremely small (less than one percent of the CT and VT rating). However it shall be noted that the fundamental frequency current and voltage, which are always present during an SSR event, serve as a carrier signal for the SSR components throughout the whole measurement chain including input CTs and/or VTs of the numerical IED. Thus their presence effectively enables the SSR relay to measure at all such small current and voltage quantities. At the same time the measurement/filtering part of the SSR relay itself must be capable to suppress the fundamental frequency component in order to extract the SSR component with high precision.

Therefore a special digital filter was implemented in the new SSR relay. By using long measurement windows (about one second) and special window filtering technique it was possible to design a digital filter which is capable of extracting the sub- or super-synchronous voltage or current components [5]. The new filter delivers the phasors (magnitude and the phase angle) and the frequency of the extracted components for all three phases from the connected CT and/or VT circuits. Then, in order to realize a SSR protection, these SSR component phasors are given to the standard over-current or over-voltage functions which provide the required timing for the SSR relay operation. Note that over-current and/or over-voltage functions are readily available in the modern numerical IEDs. Typically a special Inverse Definite Minimum Time (IDMT) curve is used for SSR protection [3]. The required inverse timing operating characteristic is easily provided by the programmable IDMT curve of the standard over-current or over-voltage protection functions. The frequency of the SSR component which need to be extracted by the filter is only a setting parameter. Thus the new numerical relay [5] can easily be adapted to any SSR installation.

5.1 New SSR protection scheme used in Forsmark 3 NPP

The observation found from the field studies is that the SSR voltage magnitude at the generator terminal is directly proportional to the shaft torsional vibration amplitude, while the SSR current magnitude is dependent on the impedance of the connected power system. Therefore it was decided to use the SSR voltage components within the new SSR protection relay for tripping logic. As stated previously the standard over-voltage functions are used to provide necessary IDMT time delay. The following figure provides simplified logic diagram used within the new SSR relay installed at the generator terminals on Unit 3 in Forsmark NPP. The logic shown in Figure 7 can be summarized in words as follows. The first two filters are used in order to extract mode-2 super- and sub-synchronous SSR voltage components. The mode-2 super-synchronous voltage component (U_{SUP_2}) is then given to the standard over-voltage function in

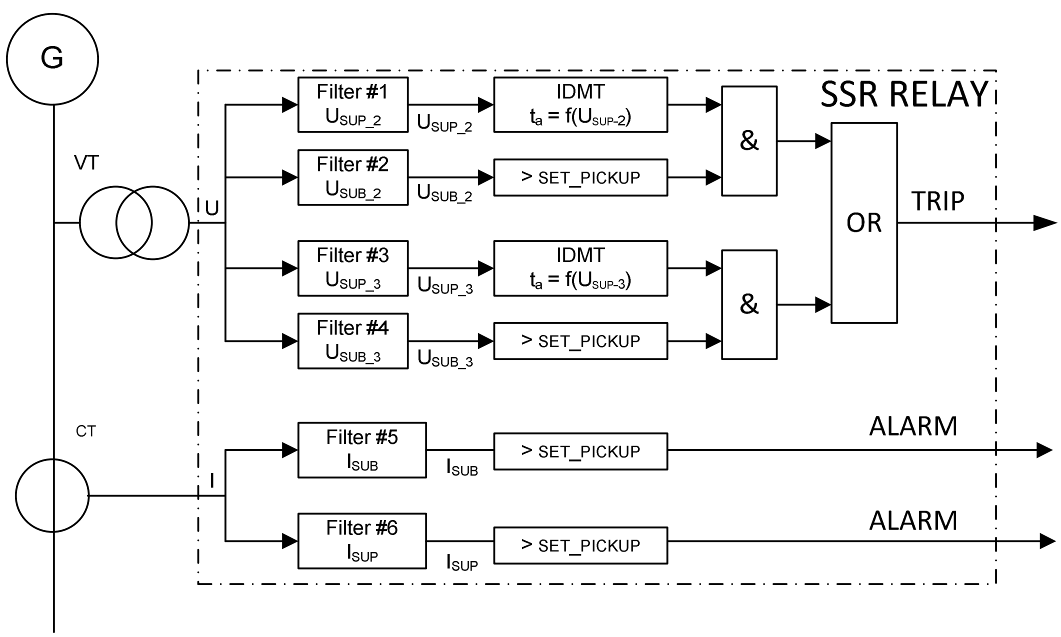

Figure 7: Logic used within the new SSR relay installed at the generator terminals

order to provide the IDMT time delay. Once this IDMT time delay has expired and at the same time the mode-2 sub-synchronous voltage component (U_{SUB_2}) is bigger than the set threshold the Trip command will be given from the new SSR relay.

Filter number three and four are used to provide the same functionality for mode-3 super- and sub-synchronous SSR voltage components. Finally the fifth and sixth filter are used to extract super- and sub-synchronous SSR current components. These current components are not used for tripping logic but only for alarm purposes.

However, it should be noted that the logic presented in Figure 7 will only be used for the new SSR relay installed at the generator terminals. For reasons explained previously in this paper, the new SSR relay installed in the 400kV substation will still use only the sub-synchronous current components for its operation.

6. Conclusion

This project has proven that it is possible to design a numerical SSR protection relay on a standard hardware platform. The new SSR relay has shown performance practically identical or even better than the old analogue SSR relay. Due to modular numerical design the new SSR relay can be easily adapted in different installations. The numerical SSR relay [5], utilizing the logic presented in Figure 7, is installed on Unit 3 in the Forsmark NPP. The protection panel used in this installation is shown in Figure 8.

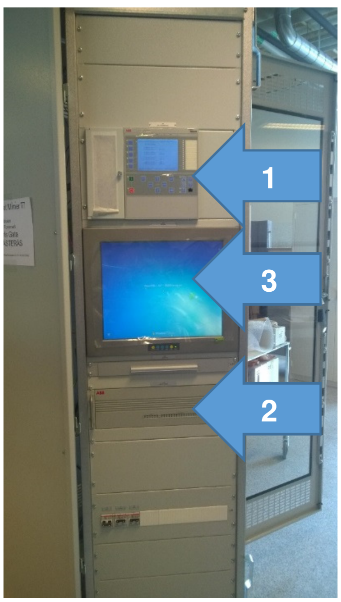

Figure 8: New SSR protection panel for Forsmark NPP

In addition to the new SSR relay (indicated by number one in Figure 8), a separate logging system is also installed (indicated by number two in Figure 8). This logging system writes continuously (once every two seconds) the SSR sub- and super-synchronous current and voltage components as well as their frequencies to the industrial PC hard disk. Additionally, the system provides trending features which can be displayed directly on the screen available in the panel (indicated by number three in Figure 8). This will enable the Forsmark NPP personnel to get a quick overview of the SSR activities in the Swedish power network in the future.

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