

CHALLENGES AND SOLUTIONS FOR NUMERICAL SUB-SYNCHRONOUS RESONANCE PROTECTION

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Abstract

This paper will review the sub-synchronous oscillation phenomena and the interactions between the electrical power system and the mechanical turbine generator system. The paper presents captured field data of sub-synchronous and super-synchronous resonance at the generator terminals of a nuclear power plant and at a transmission substation from a field study lasting several years. It describes the relationship between sub- and super-synchronous currents and voltages, such as frequencies, dependencies, duration, time constants and magnitudes. From this study a protection scheme was devised that can easily be incorporated into a numerical relay using standard protection functions and a numerical multi-purpose filter.

Keywords

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

I. INTRODUCTION

The use of series compensated lines has proven to be the most economical method for transmitting ac power over long distances. As the amount of compensation has been increased, the associated difficulties have become more troublesome. One of the difficulties is sub-synchronous oscillations which lead to the sub-synchronous resonance (SSR) of the electrical system at a frequency corresponding to a torsional resonance frequency of a turbine generator shaft. This type of phenomena has caused a failure of a turbine-generator in the early 1970s at the Mohave generator plant. Analysis determined that the failure was caused by a near coincidence of the first torsional oscillation mode of the turbine-generator and the electrical resonance of the series capacitor and 500kV transmission network. In the 1980s sub-synchronous torsional interaction was observed between the Square Butte generators and a nearby HVDC terminal. Related phenomena have recently been associated with modern wind turbine generator technologies. SSR filters, dynamic stabilizers, Statcoms, FACTS controllers, and series capacitor controls have been used to solve the sub-synchronous oscillation problem. In the early 80s relays were developed by Westinghouse [5, 7] and others to detect this type of phenomena before significant damage occurred in the turbine-generator shaft. Detection techniques are now available in microprocessor relays.

Sub-synchronous resonance (SSR) can cause a growing pulsating torque on the generator axis. SSR can appear in thermal power plants which have a long shaft, and where the unit is connected to a long radial transmission network with series capacitive compensation. It is considered as an

unstable and dangerous condition that can cause fatigue and damage to the generator shaft. In the worst case it can even break the generator shaft. SSR in hydro power units is 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 has, in the past decades, diminished considerably. Nevertheless, there are still major generating plants located in the vicinity of series compensated transmission lines and/or HVDC stations which may be vulnerable to this phenomenon. Even in cases where SSR protection already exists, any changes in the power system may raise SSR-specific concerns again. Such changes include changes to or replacement of the generator or any turbine section (HP-, IP- or LP-section). The changes may also include changes to the network structure or degree of compensation of adjacent series compensation transmission lines, or unusual switching states in the transmission network. In such a case, an existing SSR protection system may need re-tuning, which may be a delicate process.

Such a case arose, 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, a suitable replacement could not be found. Therefore an entirely new SSR protection had to be developed. In this paper the development process is discussed in some detail, starting with an overview of the prospective site, and then describing 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.

II. THE SWEDISH POWER SYSTEM

In the Swedish national grid there are ten series compensated lines. Eight of them are transmission lines connecting the northern part 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 between a generator unit in Forsmark Nuclear Power Plant (NPP) and the electrical grid, see Figure 1 [8].

The length of these three series compensated lines is around 300km and the compensation degree is between 70-85%. They are connected to Ängsberg and Stackbo 400kV substations, which are located at a distance of around 70km from the Forsmark NPP. A 400kV station for the HVDC link to Finland is also located in the vicinity of the 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 Forsmark 3 unit. Forsmark 3 is the largest unit. It is rated around 1240MWe and produces 9TWh annually. During the last several years, a modernization project was initiated. Due to foreseen shaft changes, the original shaft mechanical frequency will change and corresponding changes in the presently used SSR relays are unavoidable.

The existing SSR protection relays were installed in the middle of the 1980s. They were installed at the series capacitor stations and at the NPP. Relays at 400kV monitor currents in two phases and have a filter with pass-band of 17–36Hz. The filter is connected to an overcurrent 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 400kV station shall operate in order to bypass the series capacitors
- if this action does not stop the SSR oscillation, the relay at the NPP shall give a trip command to the affected unit in order to save the generator 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 50Hz, which can cause unwanted operation of the SSR relays. The Swedish railway system operates at 16.7Hz which also has to be taken into account when designing new SSR protection relays.

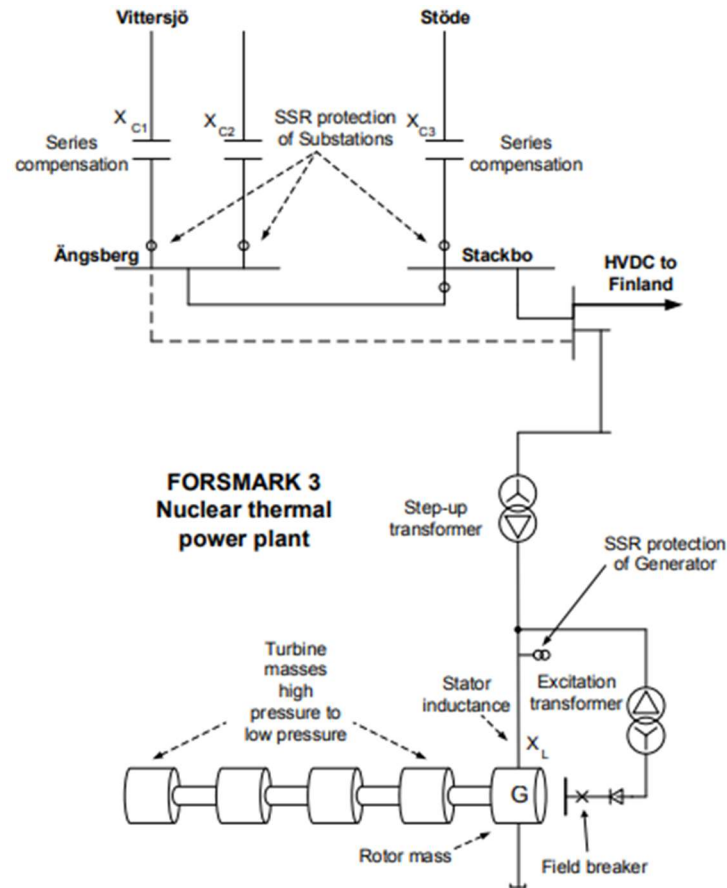


Figure 1: network around Forsmark

III. 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 IEDs were installed, one at the generating plant and one at the 400 kV substation. Initially, these two IEDs were only functioning as disturbance recorders triggered by the start signal from the existing SSR relays. When the new software functionality, discussed in Section V, became available, this was also used to trigger disturbance records. This

enabled a first comparison between the performance of the existing SSR protection and the conceived numerical SSR protection. The numerical design of the new relay also allowed logging of SSR quantities over longer periods of time (months) on a stand-alone PC. In the final stage of the project a new numerical SSR protection functionality with all desired logics was installed.

The intent of this section is to give some brief highlights of the observations made from disturbance records and logs. Examples will be provided that show active SSR phenomena, how they may be initiated and how long they can persist. Also an example of a non-SSR disturbance that may cause an unwanted operation of the SSR relay is given.

A. Transient-initiated SSR event

Many of the observed SSR events were initiated by relatively fast load changes. Such transients have very wide frequency content and, if they are strong enough, they may initiate mechanical oscillations on the generator shaft. These events are good examples of how an SSR event can be identified, as initially there are no SSR currents and voltages 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 on 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 117Hz are caused by the Swedish railway system, operating at 16.7Hz. Note that several new peaks, caused by SSR, have appeared around the fundamental frequency after the switching transient.

Figure 2 shows that initially the frequency region between 20 and 40Hz is without any detectable peak magnitude. However, after the transient, the right spectrum in Figure 2 is obtained where 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 IV. This is thus a good indicator of an on-going SSR phenomenon while the symmetric peaks have not attracted much attention in the standard literature [2,3,6,9]. Several peaks appear because a generator shaft with multiple turbines will have a number of torsional resonance modes – see reference [2] for a detailed discussion.

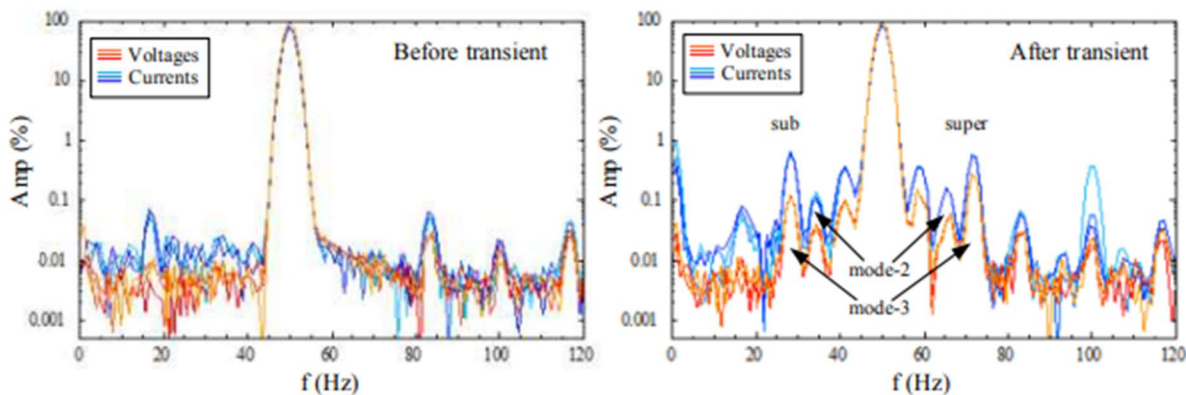


Figure 2: short-time frequency spectra from voltage and current captured at the generator terminals

The vibration modes have different damping characteristics so that only the strongest can be observed in a disturbance record triggered half a minute later. This mode (i.e. Mode-3) which has potential to cause dangerous SSR events is the one furthest from the fundamental frequency and will be the main focus of the further discussion in the paper.

Most of the SSR events initiated by transients decay rather quickly. The present example is rather unusual in that it persists for more than 30 seconds as proven by the subsequent disturbance record. Figure 3 shows the initial decay of the main torsional mode as seen by sub- and super-synchronous currents and voltages. From Figure 3, 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 exploited further in Section IV.

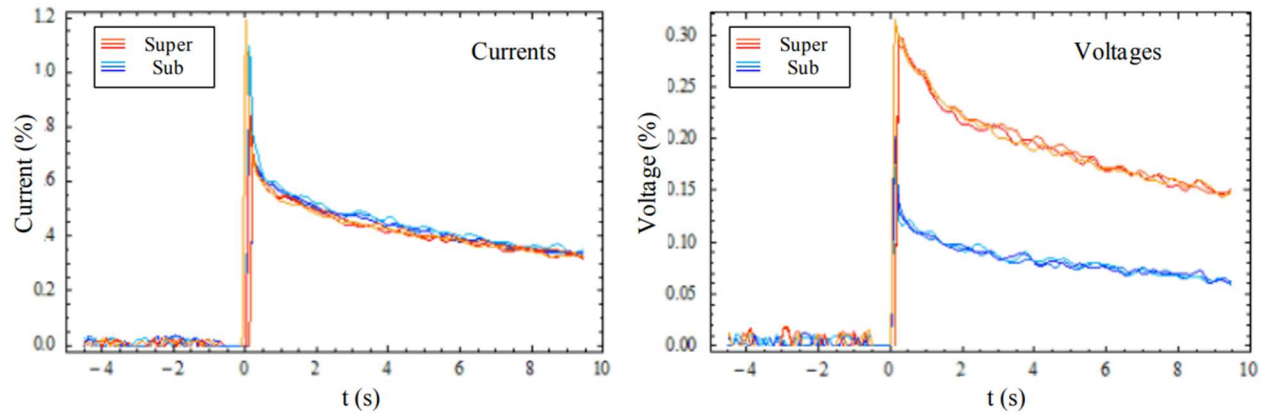


Figure 3: sub- and super-synchronous voltage and current magnitudes during an SSR event

The disturbance records were generally triggered by a high current in the frequency range below the fundamental. Other than an SSR event, there are other phenomena that may cause high sub-fundamental currents as shown in Figure 4. The broadness of the current peak below the 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. Disturbances such as this may cause an unwanted operation of the SSR protection and must thus be considered in the new relay design.

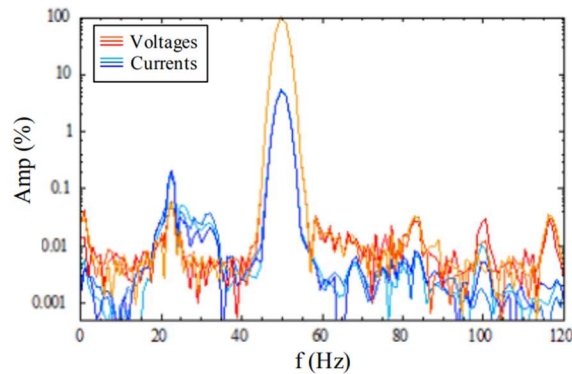


Figure 4: frequency spectrum, similar to Figure 2, from a disturbance record triggered at the 400kV substation that shows increased current below the fundamental frequency not caused by SSR

B. 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 generator 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 of 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 were installed at both the Forsmark NPP and the 400kV substation. One prolonged SSR event that is logged in both places will be discussed below.

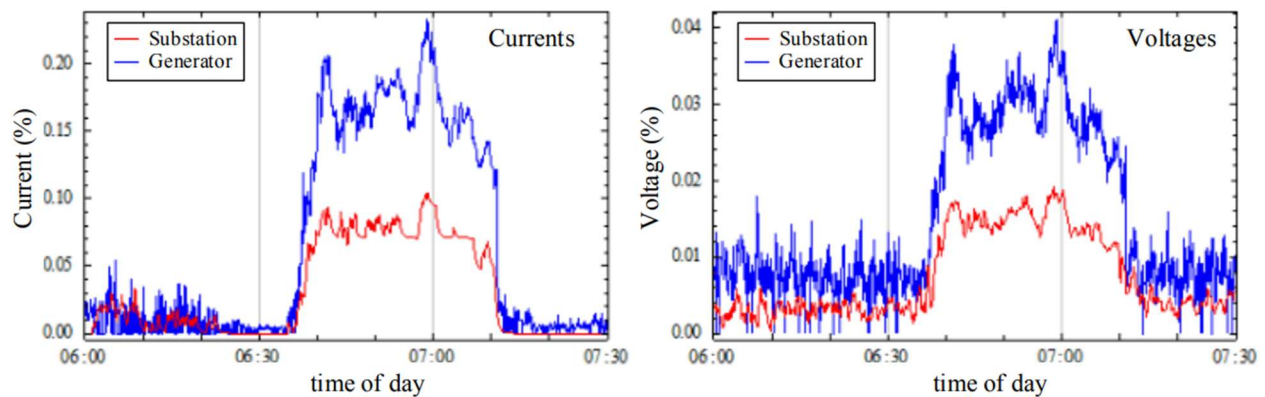


Figure 5: sub-synchronous current and voltage components at the generator terminals and at the 400kV substation during a prolonged SSR event

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.

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. This is 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 peak is not so clearly seen at the 400kV substation.

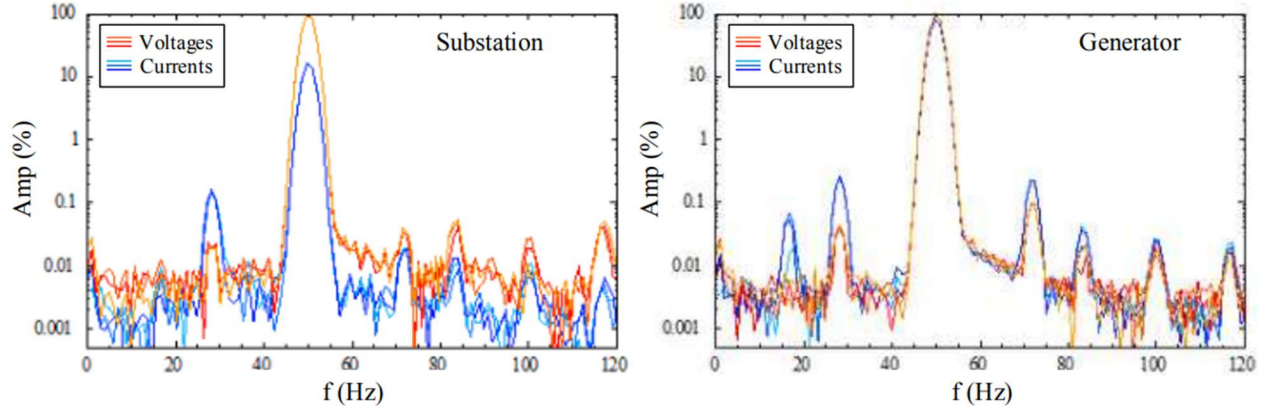


Figure 6: voltage and current spectra from the 400kV substation and the generator terminals during the prolonged SSR event shown in Figure 5

C. Conclusions from observed SSR

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, whereas 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 disturbances.

IV. THEORETICAL SSR AMPLITUDES

The relation between the sub- and super-synchronous amplitudes observed in Figure 3 demands a theoretical explanation. 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 sinusoidal in tangential direction around the periphery of the rotor body. Assume also that the mechanical angular velocity of the rotor varies sinusoidal 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

$$\omega(t) = \omega_n + \Delta\Omega \cos(\omega_p t) \quad (1)$$

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 $v(t)$ in the stator is given by

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

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 $\Delta\Omega$

$$v(t) = \omega_n \cdot A \cdot B_m \left\{ \cos(\omega_n t) + \frac{\Delta\Omega}{2\omega_n \omega_p} (\omega_n + \omega_p) \cos[(\omega_n + \omega_p)t] - \frac{\Delta\Omega}{2\omega_n \omega_p} (\omega_n - \omega_p) \cos[(\omega_n - \omega_p)t] \right\} \quad (3)$$

From (3) note that there is a relation between the sub- and super-synchronous voltage component amplitudes and their respective frequencies as per the following equation

$$\frac{\text{Amplitude}_{\text{sup}}}{\text{Amplitude}_{\text{sub}}} = \frac{\omega_n + \omega_p}{\omega_n - \omega_p} = \frac{\text{Frequency}_{\text{sup}}}{\text{Frequency}_{\text{sub}}} \quad (4)$$

The amplitude ratio is hence equal to the ratio of the frequencies which is roughly what is observed for the voltages in Figure 3. Such a relation is thus simple evidence for SSR 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, however, that this derivation only holds for sub- and super-synchronous voltages and current components at the generator terminals. In the transmission grid, these relations become much more complicated and depend on the network details.

V. 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 (e.g. less than one percent of the CT and VT rating). However note that the fundamental frequency (i.e. 50Hz or 60Hz) currents and voltages serve as a carrier signal for these SSR components throughout the whole measurement chain. Thus their presence effectively enables the SSR relay to measure such small current and voltage quantities. At the same time the measurement/filtering part of the SSR relay itself must be capable to filter out the fundamental frequency component in order to extract the required SSR component with high precision.

Therefore a special digital filter was implemented in the new SSR relay. By using long measurement windows (e.g. one second) and special window filtering technique it was possible

to design a digital filter which is capable to extract the sub- or super-synchronous voltage or current components [4]. The new filter delivers the phasors (i.e. magnitude and the phase angle) and the frequency of the extracted components for each of the three phases from the connected CT and/or VT circuits. Then, in order to obtain the SSR protection, these SSR current or voltage component phasors are then given to the standard overcurrent or overvoltage functions which provide the required timing for the relay operation. Typically a special IDMT curve is used for SSR protection [5,7]. Note that overcurrent or overvoltage functions are readily available in modern numerical IEDs. The required inverse timing operating characteristic is easily provided by the programmable IDMT curve of the standard overcurrent or overvoltage protection functions. The frequency of the SSR component which needs to be extracted by the filter is a setting parameter. Thus the new numerical relay [4] can be easily adapted to any SSR installation.

A. 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 movement/twisting, 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 overvoltage functions are used to provide necessary IDMT time delay.

Figure 7 provides a simplified logic diagram used within the new SSR relay installed at the generator terminals on Unit 3 at Forsmark NPP.

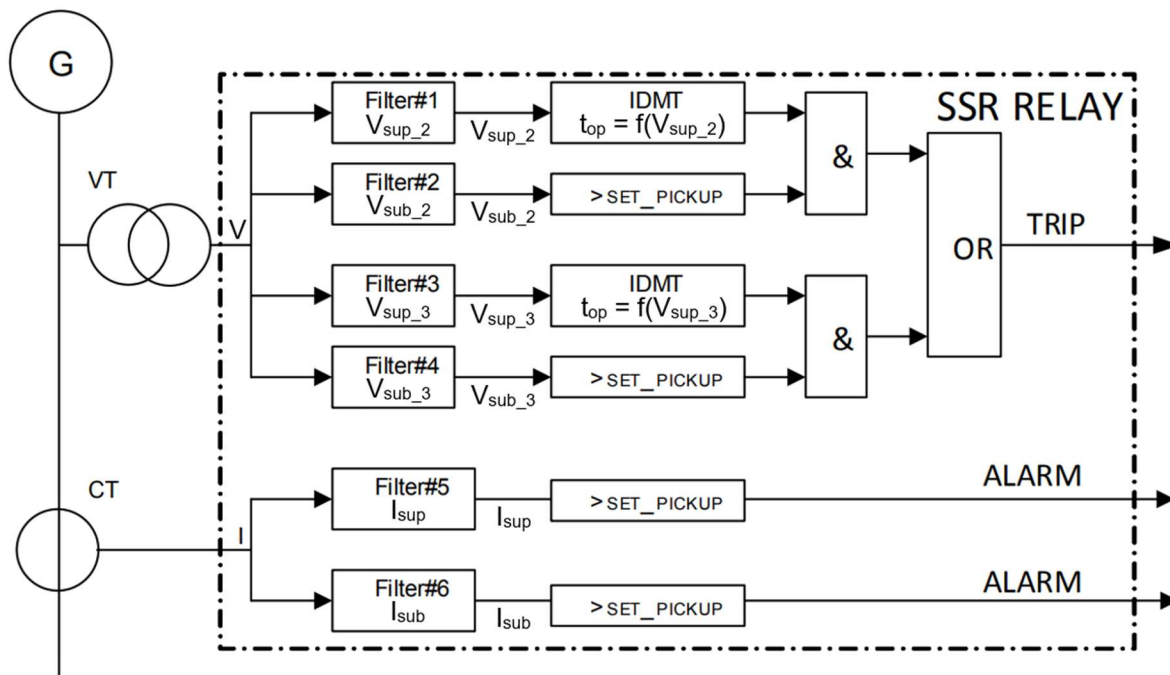


Figure 7: logic used within the new SSR relay installed at the generator terminals

The logic shown in Figure 7 can be summarized as follows

- filters 1 and 2 are used to extract mode-2 super- and sub-synchronous SSR voltage components
 - the mode-2 super-synchronous voltage component (V_{sup_2}) is then given to the standard overvoltage function in order to provide the IDMT time delay

- once this variable IDMT time delay has expired and at the same time the mode-2 sub-synchronous voltage component (V_{sub_2}) is bigger than the set threshold, the trip command will be given from the new SSR relay
- filters 3 and 4 are used to provide the same functionality for mode-3 sub- and super-synchronous SSR voltage components
- filters 5 and 6 are used to extract super- and sub-synchronous SSR current components
 - the current components are not used for tripping, but just for alarming purposes

Note that the above presented logic 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.

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 new SSR relay, utilizing the logic presented in Figure 7, is installed on Unit 3 in the Forsmark NPP. The new SSR protection panel used in this installation is shown in Figure 8.

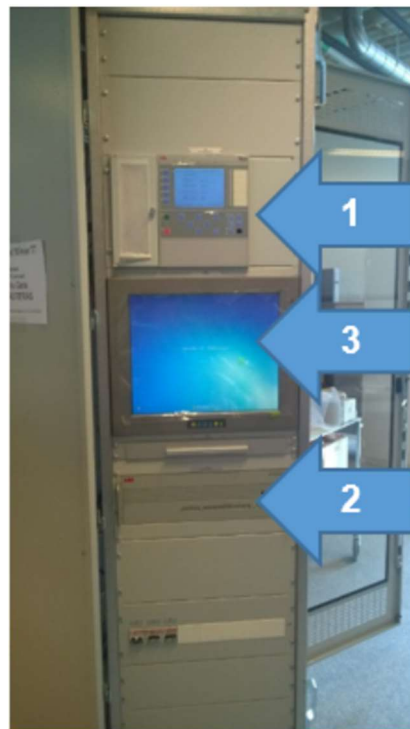


Figure 8: new SSR protection panel for Forsmark NPP

In addition to the new SSR relay (indicated by 1 in Figure 8), a separate logging system is also installed (indicated by 2 in Figure 8). This logging system writes-down continuously (e.g. 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. The system provides trending features as well,

which can be displayed directly on the screen available in the panel (indicated by 3 in Figure 8). This will enable the NPP personnel to get quick overview of the SSR activities in the Swedish power network in the future.

VI. CONCLUSION

This paper has reviewed the sub-synchronous resonance phenomena. How this SSR relates to thermal generating plants, and wind turbines connected to nearby series compensated lines was discussed. The effects of FACTS devices, and various electronic controls were discussed with respect to sub-synchronous torsional interaction, and sub-synchronous control instability. A vintage SSO relay was discussed along with properties of the SSR waveforms that are available for use in detection with a numerical relay. Finally, a new approach was described to detect an SSR event which has been installed and in service for the past several years. Relays are now available with SSR detection capability.

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