Subsynchronous Oscillation Detection Using Microprocessor Relays

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Abstract:

This paper will review the Subsynchronous oscillation phenomena and the interactions between the electrical power system and the mechanical turbine generator system. Past relays used to detect SSO will be discussed, and a new detection technique will be described which can be easily incorporated into a microprocessor relay. Finally, some results will be given showing the application and field experience in several power systems.

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 subsynchronous oscillations which lead to the subsynchronous resonance (SSR) of the electrical system at 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 1970's 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 500 kV transmission network. In the 1980's Subsynchronous 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 subsynchronous oscillation problem. In the early 80's relays were developed by Westinghouse and others to detect this type of phenomena before significant damage occurred in the turbine generator shaft. Detection techniques are now available in a microprocessor relay.

Subsynchronous Phenomena

As shown in figure 1. A turbine generator can be represented by a group of masses on a shaft that can be between 100 feet to 300 feet long. Each of these masses can interact with each other to set up their own modes of oscillation. If there are n masses, then there will be n-1 modes of oscillation. Perturbations of the mechanical system will stimulate these modes. These perturbations can come from sudden changes in input torque from actions of the governor system, or sudden changes in electrical torque caused by faults or sudden load changes. The energy put into the mechanical system will exchange between the Kinetic (mass-speed) and potential energy (shaft twist – spring). When perturbed, the masses oscillate against each other at the natural frequencies of the mechanical system. These natural modes of oscillation modify the generator speed resulting in currents at the new frequencies.

They follow the following equation:

$$f_{SSR} = f_{Rated} \pm f_{Mechanical} \tag{0.1}$$

or

$$f_r = f_0 \pm f_{er} \tag{0.2}$$

Where: f_o is the average synchronous frequency

f_{er} is the resonant frequency of the electrical system

f_r is the frequency of the rotor current as a result of f_{er}

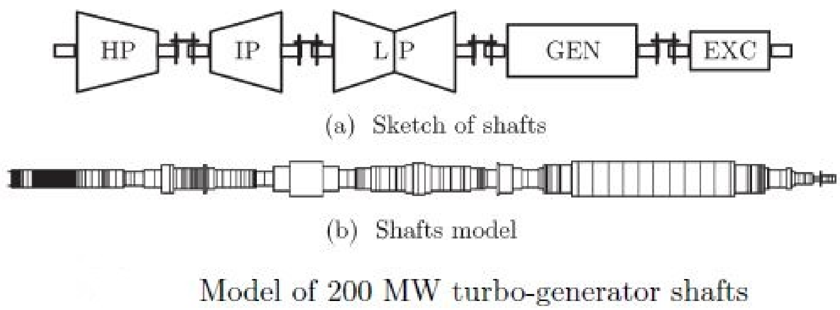


Figure 1

Thus, the mechanical frequency is modulated on the rated frequency. The component above the rated frequency is called the super-synchronous component, and the frequency below the rated frequency is called the sub-synchronous component. This is shown in figure 2. Note the log scale on the Y axis, SSR currents are more than 100 times smaller than the fundamental current.

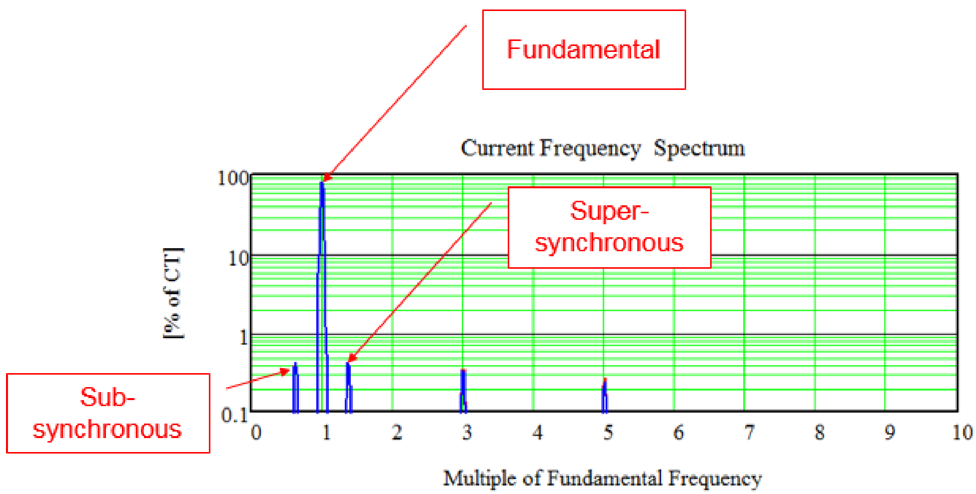


Figure 2

This is an electro-mechanical system in that the generator is connected to an electric power system as shown in figure 3. Overhead lines with series compensation will have their own natural frequency of oscillation given by the equation:

$$\omega L = 1/\omega C \tag{1.3}$$

Where L is the inductance of the transmission line and C is the capacitance of the series capacitor. The electrical system subsynchronous natural frequency can be determined by:

$$f_{er} = f_0 \sqrt{X_S / (X'' + X_l + X_T)} \tag{1.4}$$

$fer = electrical\ system\ subsynchronous\ natural\ frequency$

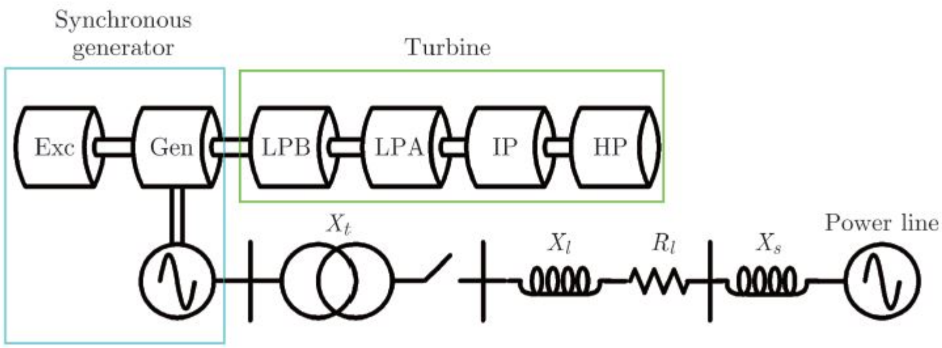
f0 = frequency corresponding to average rotor speed

Xs = System capacitive reactance

X" = generator subtransient reactance

X_l = transmission line reactance

X_T = transformer reactance



Electromechanical Power System
Figure 3

If the system conditions at these new off nominal frequencies are just right because of series capacitors or active devices, these oscillations may be sustained or even grow for significant durations.

Subsynchronous Oscillations (SSO) fall into several subcategories, including: Induction Generator Effect (IGE), Torsional Interaction (TI), and Torque Amplification (TA).

IGE is purely an electrical phenomena that results from an electrical resonance between a series capacitor and a generator. Problems with IGE are fairly uncommon with thermal plants. Subsynchronous torsional interaction (SSTI) occurs when the electrical system operation results in mechanical damping at the generator that is negative and sufficiently large to exceed the inherent mechanical damping of the shaft at a natural torsional frequency of the mechanical system. This can occur because of a resonance with a series capacitor or because of the control action of devices such as HVDC converters, SVC's and STATCOMS. Torque Amplification occurs when the resonance between a series capacitor and a machine results in shaft stresses following a disturbance that are higher than would be without resonance.

Series capacitors are not the only source of torsional interaction. Controls of HVDC converters, power system stabilizers, FACTS devices, and other power electronics based equipment have the potential to interact with the torsional modes of nearby turbine generators.

In the past torsional concerns have been limited to conventional thermal power plants. Hydro plants are less susceptible to this due to the higher inertia of the generator and higher mechanical damping in the turbine.

A related phenomena concerns the potential interaction between a series compensated line and the same fast acting control used in HVDC systems, FACTS systems, and some power electronic based wind turbine generators. It is called subsynchronous control interaction (SSCI) since there is no mechanical or torsional component to the interaction.

The primary electrical phenomena of concern with Type 1 and Type 2 directly connected induction generators is that of self- excitation. An example of self-excitation on a Type 1 WTG is shown in Figure 4. One phase of the currents and the speed of the WTG are shown. This figure is from a 2012 paper by Daniel, Wong, Ingstrom, and Sjoberg. [3]

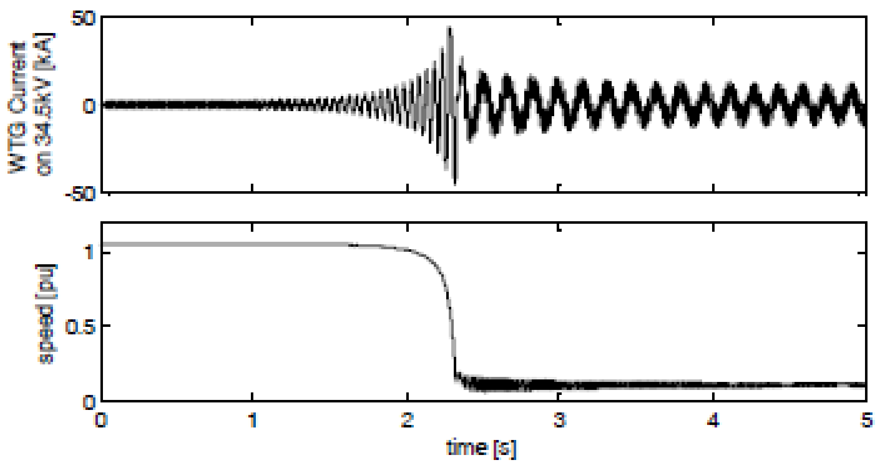


Figure 4

Self- excitation of a 100Mw type 1 wind plant connected radially through A 60% compensated line

In order to demonstrate the effects of self-excitation protective functions have been disabled for this figure. Parameters used in this example result in subsynchronous resonant frequencies of 6 and 20 Hz. The 20 Hz appears first and grows exponentially, overwhelming the fundamental frequency excitation and slowing the machine. The machine is eventually slowed enough to be pulled into a stable 6Hz operating mode. In practice, the wind turbine generator protection would trip the generator off line early in the growth of the 20Hz currents.

Type 3 wind turbine generators are doubly-fed, wound rotor induction machines. Partial size voltage source converters are placed in parallel to the machine and connected to the machine stator terminals and wound rotor windings. The grid side converter is used to control the dc link voltage, while the rotor side converter provides a control voltage source to the rotor and allows a broad range control of the machine operating point with regard to power production and speed.

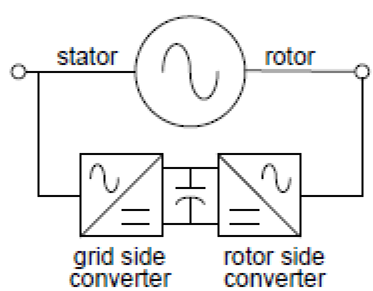


Figure 5

Type 3 Wind Turbine Generator

The subsynchronous phenomena experienced by Type 3 WTG's is related to self-excitation, but also a function of the controls. That is, the controls are unstable in the presence of the series capacitors. This is called subsynchronous control instability. The converter and the controls also exacerbate the self - excitation of the induction machine. This is shown in figure 6. [3]

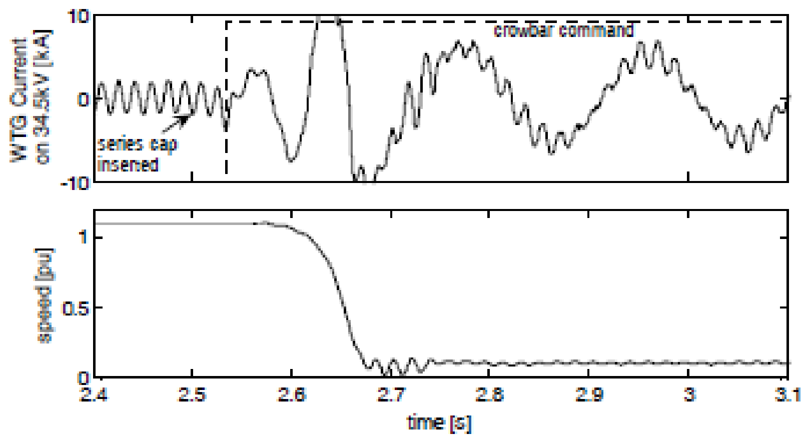


Figure 6

Control interaction and self- excitation of a 100Mw Type 3 wind plant connected to a Simplified radial test system with 60% compensation of a 345Kv line.

The wind farm is started with the series capacitor bypassed and the bypass breaker opened after 2.5 seconds. High currents trigger the crowbar approximately 2 cycles after insertion of the series capacitor. Following the initiation of the crowbar action, classic self-excitation occurs as seen in figure 6 by the dominant frequency between 2.7s and 3.1 seconds.

The presence of a WTG can alter the system resonances thereby influencing other generators. The WTG controls can provide a destabilizing influence on the mechanical torsional modes of other generators.

Type 4 wind turbine generators have been found to be immune to direct subsynchronous issues. The use of a full converter provides an effective isolation from system resonance created by the series compensation so the induction machine itself does not experience self-excitation, and the controls are quite stable in the presence of series capacitors.

Effects from SSR

The main concern with SSR is the possibility of rotor damage due to excessive shaft torques. Generally, the analysis for potential shaft failure is divided into two areas. For high torque levels in which the steel has reached the yield point, the resulting shaft deformation can result in shaft misalignment. The resultant lateral bending stresses could ultimately lead to shaft failure if not corrected. For lower torque levels, in which the endurance limit has been exceeded, the main concern is cyclic torques causing fatigue in the shaft. The amount of fatigue life expended is calculated using a stress life or S-N curve.

Detection of Subsynchronous Oscillations

This first relay for SSO detection based on measurement of electrical quantities was developed in the late 1970's by Westinghouse.[4] It was called the SSO relay. It detected a signal that was either growing or decaying with time. A decaying signal was detected by a transient trip (TT) module. A signal whose magnitude was constant or growing and whose frequency corresponds to a torsional natural frequency of the turbine-generator was detected by a self- excited trip (SET) module. Partial logic for the TT and SET modules is shown in figure 7. The relay was a custom design per site. That is, the frequencies the relay was tunes to were fixed. Modules had to be changed to change frequencies.

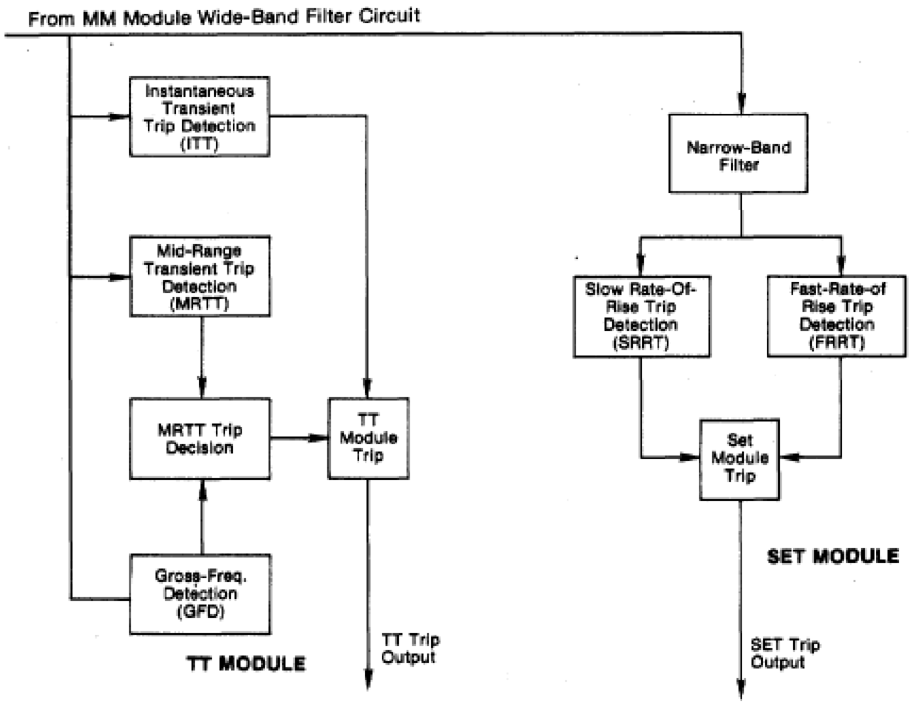


Figure 7

SSO Signal Detection

As was the norm in relays manufactured in the 1980's. the SSO relay occupied an entire 19' x 90' relay panel. A picture of the relay is shown in figure 8.

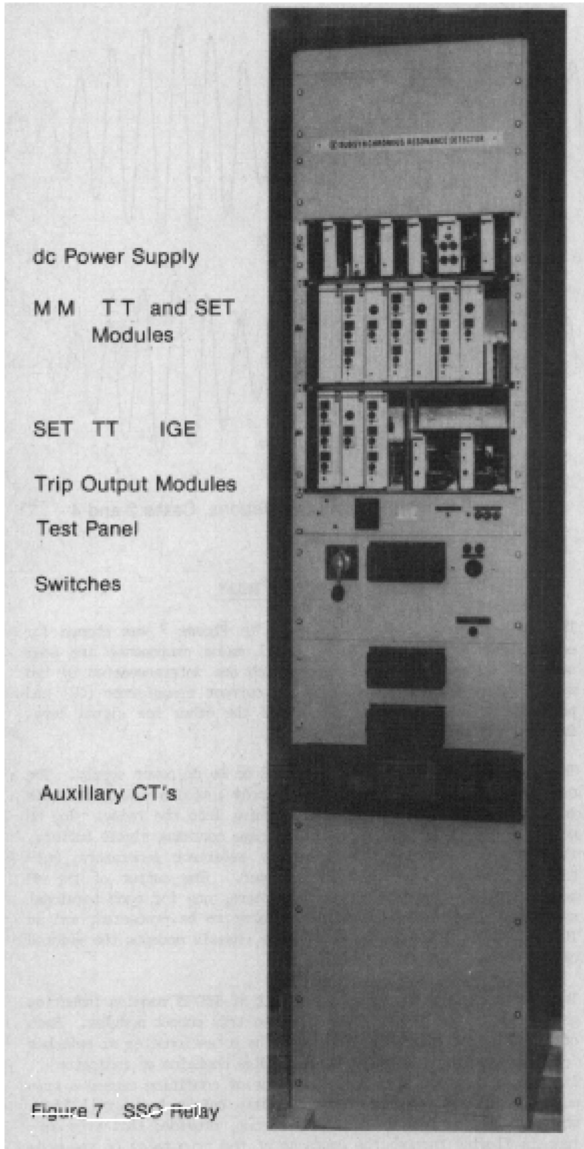


Figure 8

Westinghouse SSO Relay

Today's microprocessor technology makes the design of the highly accurate band pass filter that is settable to a given frequency much easier.

A few observations of the SSO frequency spectrum make the detection of an SSO event from other low frequency noise events plausible. First, even though the subsynchronous frequency current is very small, in the order of 0.1% to 7% of the 60 Hz rated current, the subsynchronous frequency current is modulated on the 60Hz current. This makes measurement of the low frequency signal a matter of extracting it via a band pass filter. Second, the subsynchronous frequency current is always accompanied by a super synchronous frequency current. If the super frequency current or voltage is not present, then this isn't an SSR event. This is illustrated in figures 9 for current, and figure 10 for voltage. Also note that the high and low frequencies also show up on the voltage spectrum analysis.

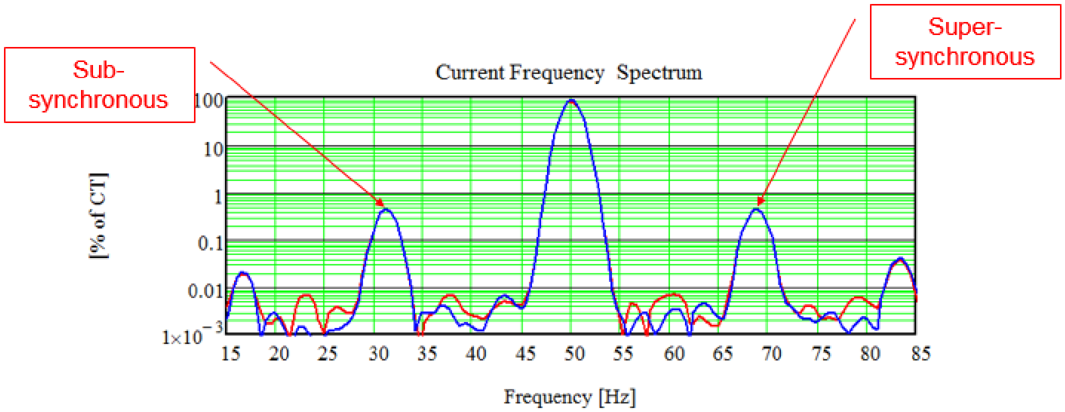


Figure 9

Current Frequency Spectrum for SSR Event

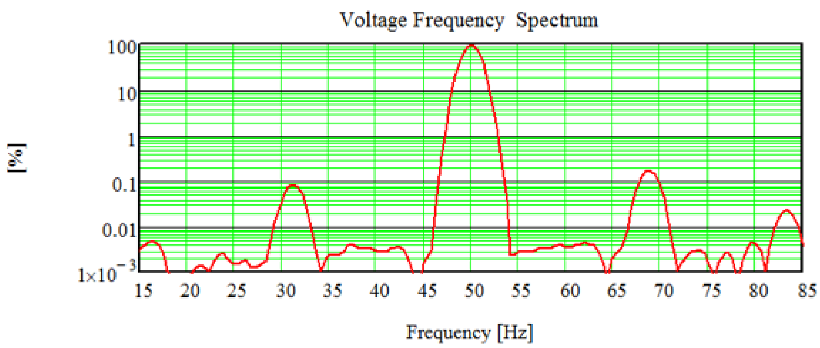


Figure 10

Voltage Frequency Spectrum for SSR Event

Some further field observation of SSR phenomena were made at a Swedish 1240 MWe nuclear power plant that has an HVDC link to Finland nearby. The occurrence was caused by a quick ramp down of the HVDC link doe to a problem in Finland. Figure 11 shows the voltage and current frequency spectrum as recorded at the generator terminals both before and after the transient. Initially, there are no SSR current and voltage components present while they are observed after the transient. Amplitudes are given in percent of current transformer and voltage transformer rating. Peaks around 17, 83, and 117 Hz are caused by the Swedish railway system operating at 16.7 Hz.

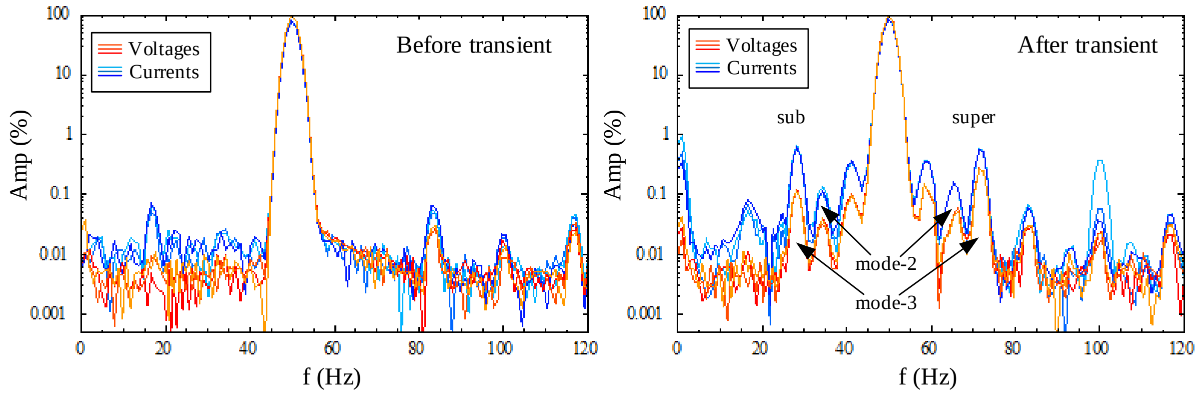


Figure 11

Short time frequency spectra form V and I captured at 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 11 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.

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 11, has the largest potential to cause dangerous SSR events. The other two modes, especially mode-2, should not be totally neglected.

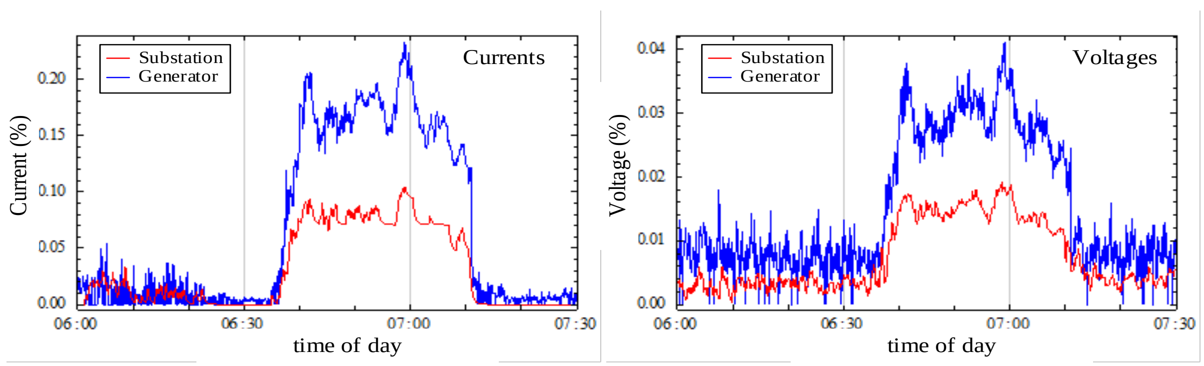


Figure 12

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

As seen from Figure 12, 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, 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.

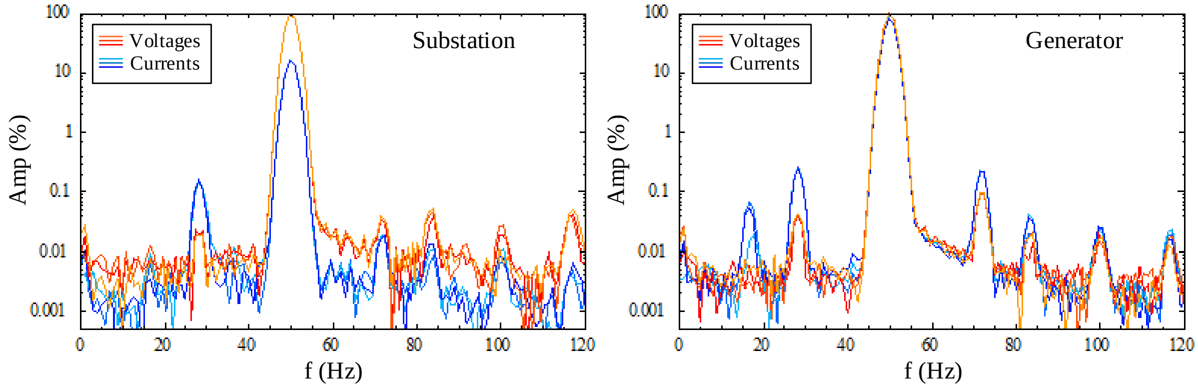


Figure 13

Voltage and current spectra, from the 400 kV substation and the generator terminals during the prolonged SSR event shown in Figure 12

From the field studies it was observed 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. This is the case for measurements are made at the generator terminal. Whereas current should be used when measuring from a nearby substation. Using all the aforementioned observations, relay logic can be constructed. This is shown in the simplified logic for the function shown in Figure 14.

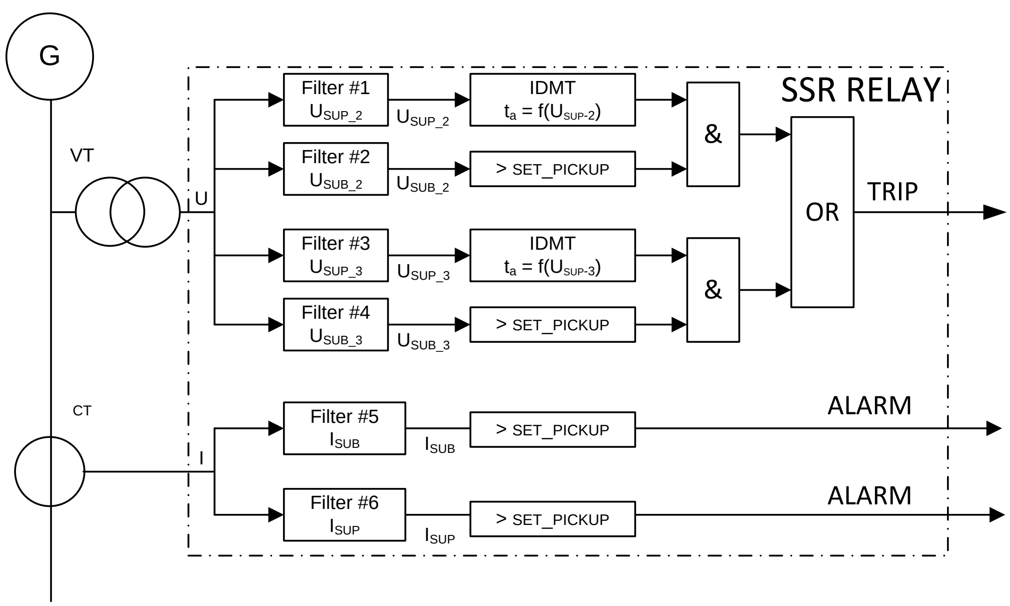


Figure 11
Logic used within the new SSR relay when installed at Generator Terminals

Voltages and currents are fed into a band-pass filters set to the torsional sub and super synchronous resonant frequencies for Mode 2 and mode 3. If after a time delay the voltage at desired frequency is still above the pickup level, the relay trips. If the installation is at the substation rather than the generator terminals, sub synchronous and super-synchronous current is used for detection and tripping. Note that in both instances super-synchronous and sub synchronous frequencies must be present before tripping.

Conclusion

This paper has reviewed the subsynchronous 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 Subsynchronous torsional interaction, and subsynchronous control instability. A vintage SSO relay was discussed along with properties of the SSR waveforms that are available for use in detection with a microprocessor relay. Finally, a new approach was described to detect an SSR event which has been installed and in service for the past two years. Relays are now available with SSR detection capability.

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Biographies

***Roger* Hedding** graduated with a BSEE from Marquette University, and a Masters degree in Electrical Engineering from the University of Pittsburgh. Roger a Senior Consultant for ABB. He guides the development and application of relay products for the North American market. Roger is an IEEE senior member, and Past Chair of the IEEE PES Power Systems Relay Committee. Roger has authored many papers in power systems protection. His hobbies include travel with his wife, playing golf, and playing with his grandchildren.

Stefan Roxenborg was born in Sweden 1970. He did his master thesis in University of Sydney Australia 1996, and received his MScEE at the Royal Institute of Technology (KTH) 1996, in Stockholm, Sweden. Since 1997 he has been working for ABB Substation Automation Products as an application development

engineer for transformer and generator protection. Currently he has a position of a research project leader and developer. He is a member of CIGRE, and been convener or the CIGRE B5.WG37 and special reporter for "Protection, Monitoring and Control of Shunt Reactors and Special Transformers" in CIGRE B5 colloquium Brazil 2013. Stefan has published several technical papers in the relay protection area and is a co- and core- holder of several patent applications in the power system area.