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A New Subsynchronous Oscillation (SSO) Relay for Renewable Generation and Series Compensated Transmission Systems

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SUMMARY
The interaction between the control system of renewable energy generation and series compensated transmission lines can potentially create subsynchronous oscillations (SSO) that damage the power system's primary equipment. This paper presents the characteristics of SSO based on an actual event. Different from conventional digital relay signal processing, a special signal processing technique is designed to effectively extract the subsynchronous component from the voltage and current signals. Additional protection algorithms utilize the subsynchronous component and power system fundamental frequency component to quickly detect the SSO. Both off-line simulations and RTDS-based hardware in the loop tests validate the speed, reliability, and security of SSO relay. The relay may be deployed at series capacitor bank locations and the interconnection point to mitigate the effect of SSO.

KEYWORDS

Subsynchronous Oscillation (SSO), Series Compensated Line, Renewable Generation, Wind Generation, Protection, RTDS

Introduction

The rapid growth of the renewable energy industry, especially wind energy, demands new transmission infrastructure to move the electricity generated by renewable energy sources from ~~a~~ remote area to a more heavily populated area. Series compensated transmission line is an economical candidate for long distance power transmission because it provides expanded power transfer capability as compared to the uncompensated transmission line with the same voltage level. However, the series capacitor banks, coupled with transmission line reactance, create natural resonance frequencies on the transmission networks. If the natural resonance frequency of the transmission network is the synchronous frequency complement of any of the natural mechanical frequencies of the turbine-generator spring-mass system, the system may experience subsynchronous resonance (SSR) that can damage the turbine-generator shaft. There are different ways the system and generator may interact to produce SSR. The Torsional Interaction (TI), Induction Generator Effect (IGE), and Torque Amplification (AI) are known causes of SSR when the series compensated line is in the vicinity of traditional fossil fuel generators [1].

The event that ERCOT experienced in October 2009 revealed a new type of power system subsynchronous interaction. Such interaction is between wind generators, particularly the Type-3 wind turbine-generators (WTG), and a series compensated transmission line. A Type-3 WTG includes the wind turbine shaft system, Double Fed Induction Generator (DFIG), and converter control system based on power electronics. The WTG control systems reacted so fast to system disturbance that they created modes of oscillation in series compensated transmission networks. In that event, the subsynchronous oscillation was clearly demonstrated in the recorded signals as the system voltage reached 1.45 pu within 200 milliseconds to destroy numerous WTG crowbar circuits before the series capacitor banks were bypassed. Detailed simulation also revealed that the frequency of oscillation could range from 10Hz to 45 Hz in power systems with 60Hz normal frequency. This type of SSR is specifically labeled as Subsynchronous Control Interaction (SSCI) by the industry.

Protective relays are important components of the overall strategy of SSR protection for utilities that may encounter an SSR problem. The torsional stress relay (TSR), based on shaft speed measurement, has been developed and widely applied to protect generator shafts since the first significant SSR event. However, the TSR cannot address the challenges brought by SSCI. The SSCI also poses challenges to modern digital relays because most relays' signal processing algorithms are designed to extract fundamental frequency signals and filter out non-fundamental frequency signals [2]. Efforts have been made to reconstruct the sub-harmonic operational quantities by compensating the attenuation of digital filters that were originally designed to extract fundamental frequency [3]. Such a method can utilize a traditional relay platform, but its effectiveness is questionable because of signal processing limitations. The limitation of these existing relaying solutions has elicited the effort reported in this paper to develop a new relay to protect the power system from SSCI oscillation.

The rest of this paper is organized in the following sections: (1) Detailed analysis of the recorded line voltage and current signal to reveal the characteristics of SSCI oscillation; (2) A proposed relaying solution that includes the signal processing, designation of operation quantities, and SSO detection logics; and (3) Performance validation using Real-Time Digital Simulator (RTDS) with hardware-in-the-loop testing of the relay unit.

The Characteristics of SSCI Type of Oscillation

The aforementioned SSCI event that occurred in 2009 was triggered by a fault on one of two series compensated 345-kV transmission lines that export power generated by two wind farms. The protection system correctly tripped the faulted line according to the design to isolate the fault within 3 cycles. However, the loss of one transmission line left the two wind farms to be radially connected to the other series compensated transmission line and, consequently, the oscillation started. Figure 1 shows the line currents and bus voltages recorded by the digital relay at the interconnection point. The dedicated digital fault recorder at the series capacitor bank site recorded the series capacitor current through the complete sequence of the event as shown in Figure 2. After about 200 milliseconds into the oscillation, the bus voltage at the interconnection point reached 1.45 pu, the current magnitude of the combined two wind-farms' output swung up 9 times the pre-fault current magnitude, and the damage to the wind turbine crowbar was estimated to have started. During the whole oscillation process that lasted approximately 1.5 seconds, the only protection system that reacted was that the series capacitor bank bypass breaker was closed by the capacitor bank control system when the Metal Oxide Varistors (MOVs) started conducting excessively, as shown in Figure 3. The prolonged 1.5 second oscillation accompanied by the overvoltage caused damage to several wind generators and had an adverse effect on the fatigue life expenditure of other system equipment.

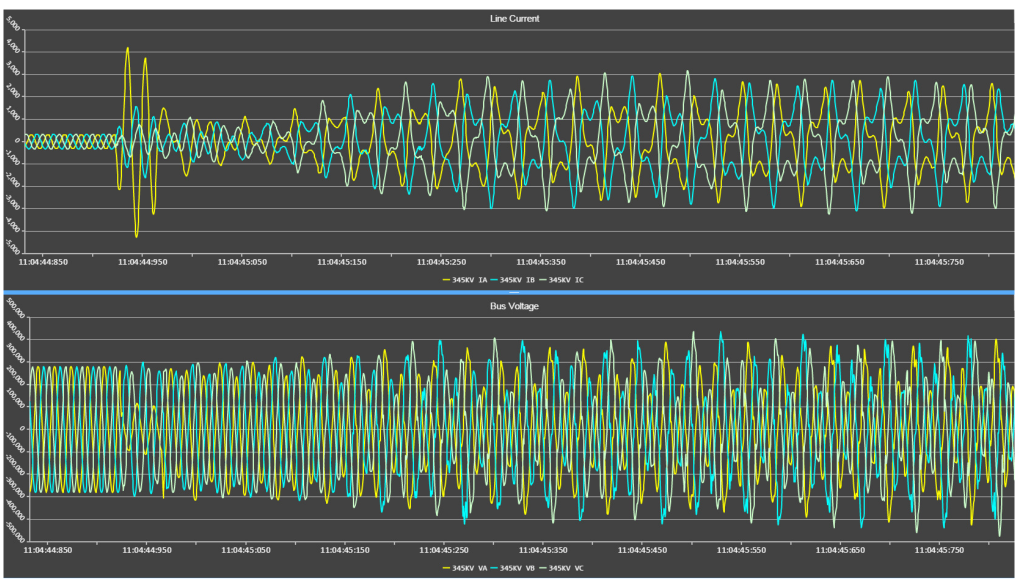

Figure 1 Line current and bus voltage at the interconnection point

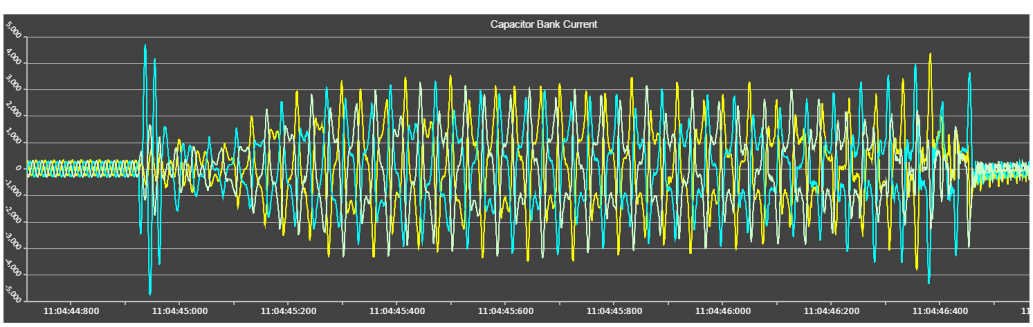

Figure 2 Series Capacitor Bank Current

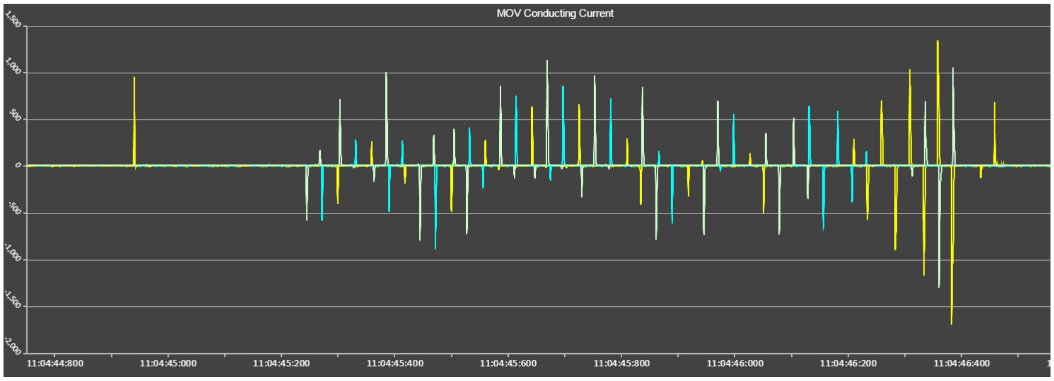

Figure 3 Series Cap Bank MOV Conducting Currents

The spectrum analysis of the recorded line current and bus voltage after the line fault reveals significant subsynchronous oscillation (SSO). Figures 4 and 5 below show the spectrum of the phase currents and the voltages respectively. The spectrum plots of all three phases show a very similar spectrum signature and they almost overlap each other. The frequency of the subsynchronous component is around 24 Hz. The spectrum of the line currents shows the magnitude of the subsynchronous component is larger than 250% of the fundamental frequency component. The magnitude of the subsynchronous component of the bus voltage is about 30% of the fundamental frequency component. The subsynchronous component shown in the current signal is more obvious than in the voltage signal.

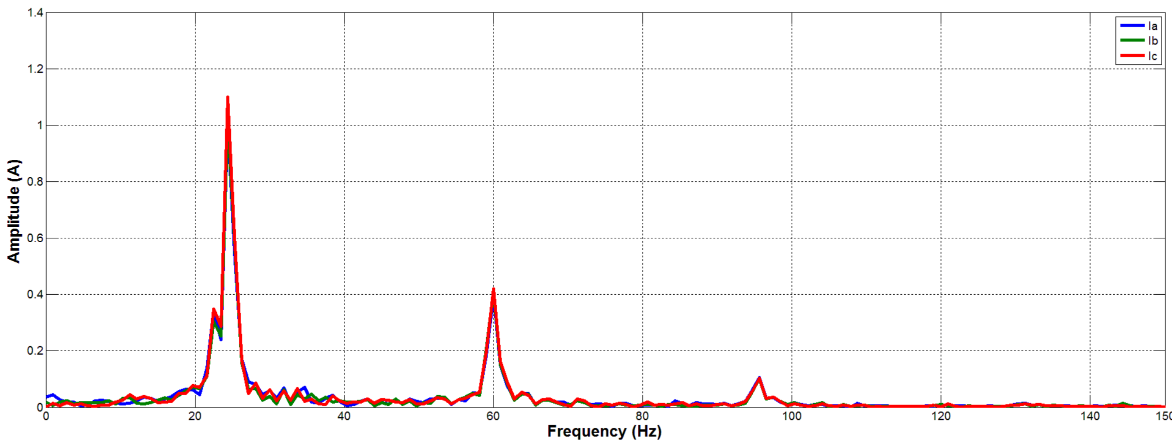

Figure 4 the Spectrum of Line Phase Currents at Interconnection Point

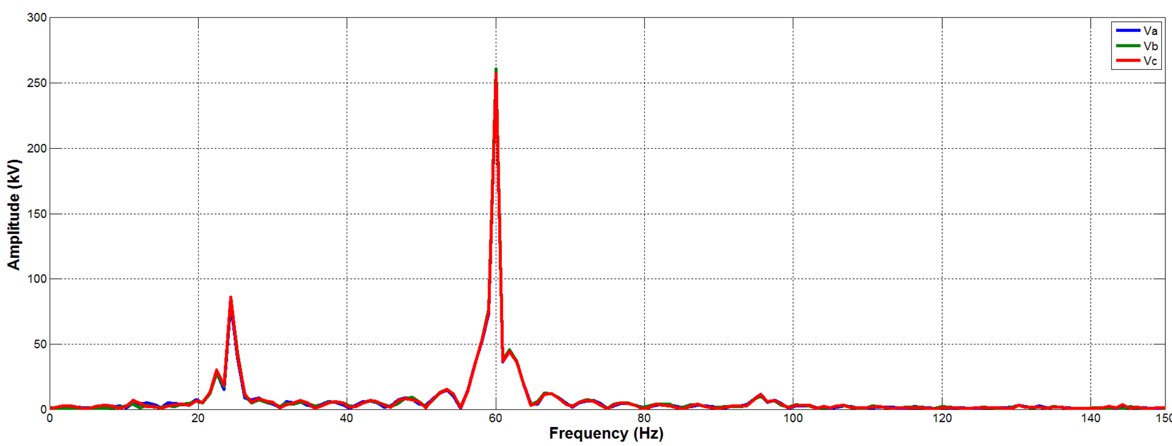

Figure 5 the Spectrum of Phase Voltages at Interconnection Point

Signal Processing Design for SSO Relay

For power system transient faults, such as line to ground fault, the measured line currents contain mainly the fundamental frequency current and the decaying DC component. The traditional digital relay design applies digital signal processing to filter the DC component and other non-fundamental frequency components. Figure 6 shows the frequency response of the typical Fourier filtering method that applies sine and cosine filters to respectively extract the real part and the imaginary part of current or voltage phasors at the fundamental frequency. It is noted that these filters provide unit gain at the fundamental frequency and remove the DC and other high order harmonic components. The characteristics of the Fourier filtering work excellently for traditional protection functions that are based on fundamental frequency quantities. However, this type of signal processing scheme does not work well with subsynchronous oscillation detection because the filtering provides significant attenuation at the subsynchronous frequency range from 10Hz to 50Hz. Although modern digital relay platforms provide powerful programming flexibility to allow end users to develop customized protection functions, the limitation of their signal processing implementation prevents the generic digital relay platforms from being effectively used to tackle the SSO problem.

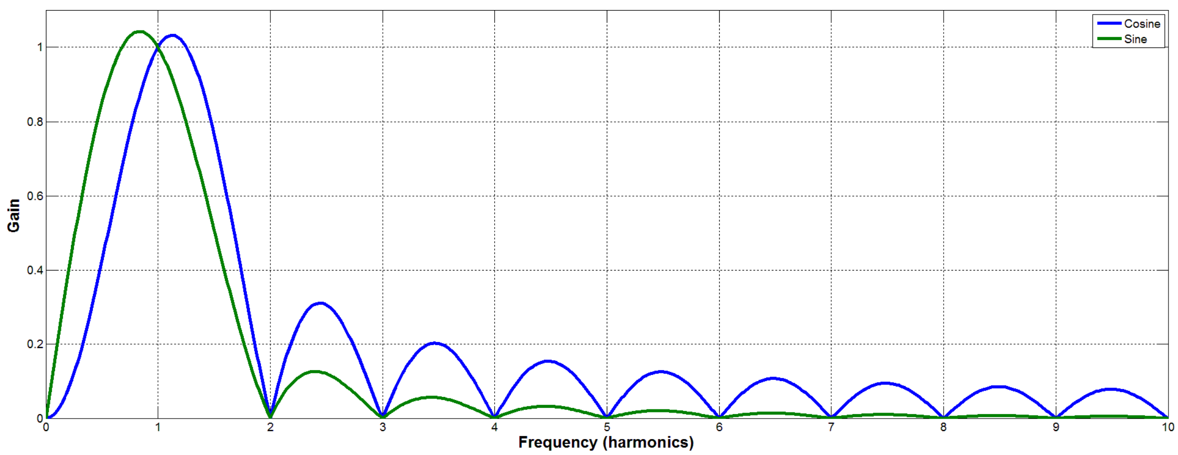

Figure 6 Frequency Response of Traditional Relay Signal Processing

In our effort to design the new SSO relay, we used a generic hardware platform that can facilitate bottom-up software design in a relatively easy fashion. The companion advanced signal processing design toolbox is used to design a digital bandpass filter to effectively extract the subsynchronous oscillation signal that ranges from 10Hz to 50Hz. Figure 7 shows the frequency response of the bandpass filter that we chose for the SSO detection function. This digital filter has over -60 dB attenuation at the fundamental frequency for 60Hz power system. It also provides unit gain over the frequency range from 10Hz to 50Hz. By passing the voltage and current signals through the bandpass filter, we can obtain the instantaneous subsynchronous oscillation component. Figures 8 and 9 show the extracted subsynchronous oscillation component (red dash line) side-by-side to the fundamental 60Hz component (green double-dash line) in the recorded current and voltage signal respectively. By examining the instantaneous values in Figure 8, we can observe that the magnitude of subsynchronous component magnitude is significantly larger than the 60Hz component, which matches the magnitude of the spectrum plot as shown in Figure 4. Under normal power system operation, it is not expected to observe any signal with significant magnitude coming out of this bandpass filter.

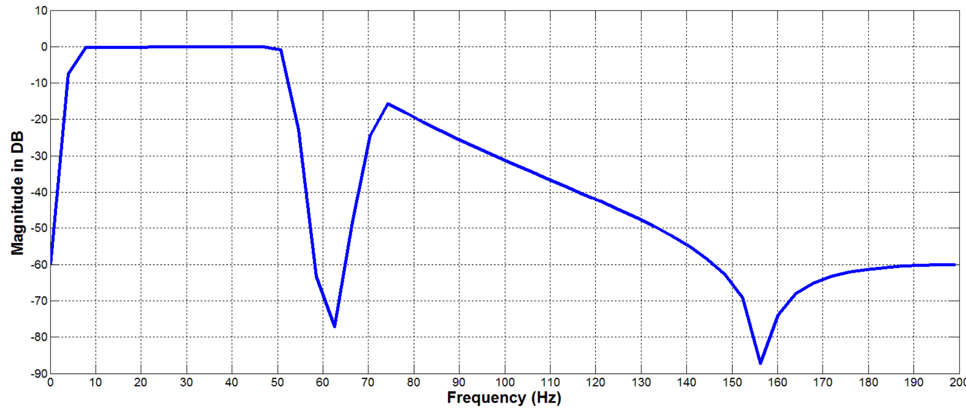

Figure 7 Frequency Response of the Bandpass filter for SSO relay

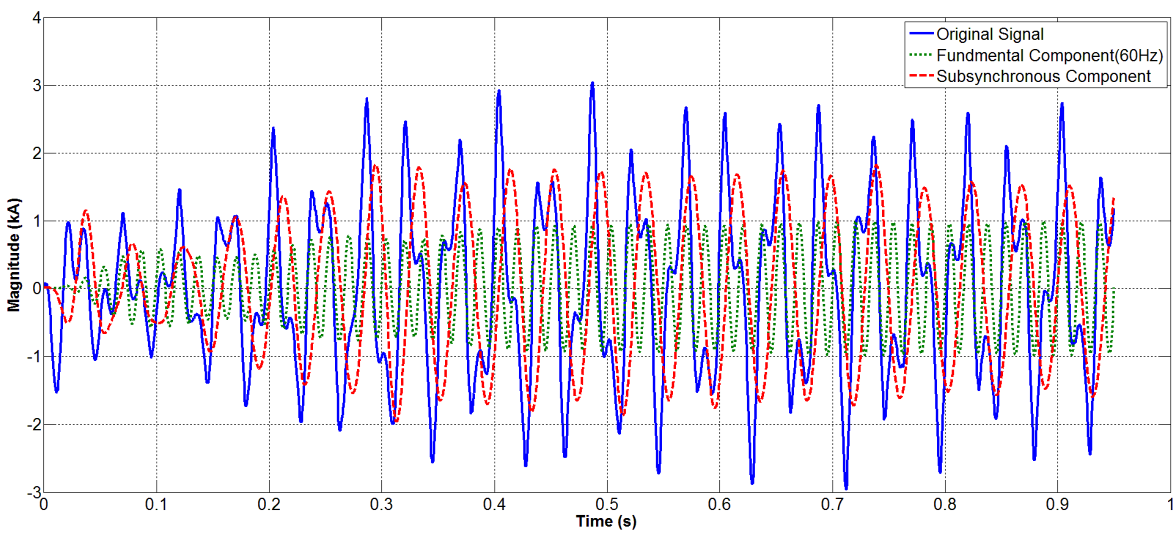

Figure 8 Phase Current with filtered Subsynchronous Component and 60Hz Component

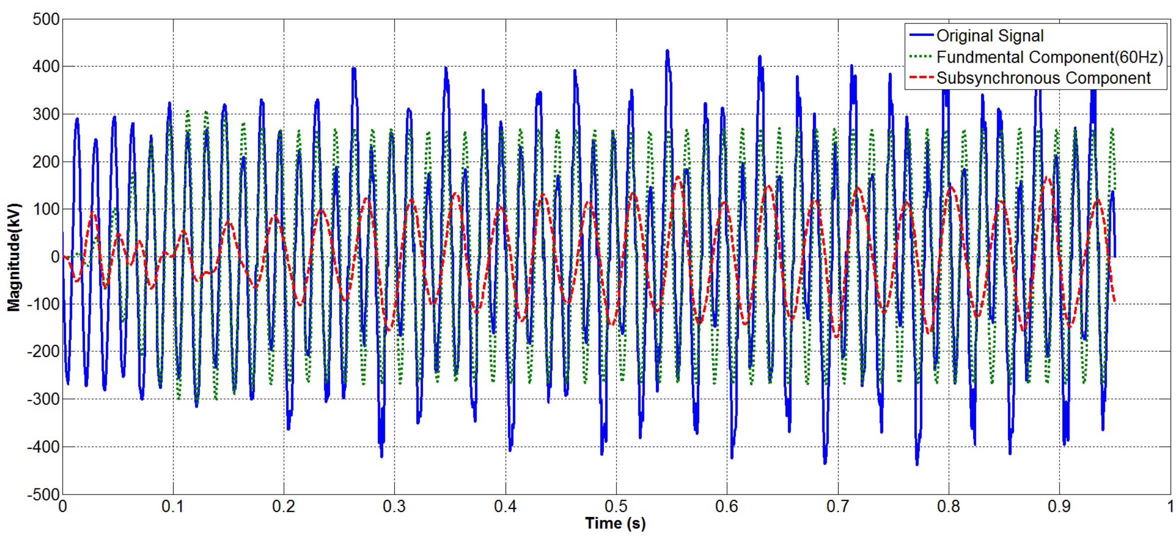

Figure 9 Phase Voltage with Filtered Subsynchronous Component and 60Hz Component

SSO Protection Algorithm

Different from traditional protection algorithms that use fundamental frequency quantities, the SSO protection algorithms involve using quantities from both the subsynchronous component and the fundamental frequency component. A simple oscillation detection method would be comparing the magnitude of the low frequency signal to a predefined threshold to determine whether action needs to be taken. However, the system studies and simulations revealed that the magnitude of SSO depends on various system operation conditions, including the base load conditions. It is challenging to determine a universal threshold. Instead, we used the ratio of the magnitude of subsynchronous component to the magnitude of the fundamental component as an operation quantity. To bridge the gap between two components with different frequencies, the Root Mean Square (RMS) method was used to calculate the magnitude of each component. For discrete sampled values, the RMS value was calculated according to Equation 1, where n is the number of samples.

$$X_{rms} = \sqrt{\frac{1}{n}(x_1^2 + x_2^2 + \cdots + x_n^2)} \quad (1)$$

The SSO protection function is designed to detect SSO with frequency from 10Hz to 50Hz. The default RMS calculation window is chosen as 100 milliseconds, which is sufficient to cover one complete cycle of oscillation frequency of 10Hz. For oscillation frequency of 25Hz, 100 millisecond covers 2.5 cycles of oscillation that is sufficient to calculate the magnitude of the oscillation. To overcome the limitation of having a fixed window size that may delay the SSO detection speed, the Continuous RMS (CRMS) calculation was implemented. The traditional RMS method calculated the result after collecting *n* new samples. The CRMS method updates the RMS value for every new sample as shown in Equation 2. It is an iterative process that can be efficiently implemented on the selected hardware platform.

$$X_{rms_i} = \sqrt{X_{rms_{i-1}}^2 + \frac{1}{n}(x_i^2 - x_{i-n}^2)} \quad (2)$$

Another advantage of using CRMS is that CRMS has a built-in time inverse characteristic. Figure 10 illustrates how CRMS value increases as oscillation progress. If the CRMS calculation time window is 100 milliseconds and the pickup threshold set as 60, it will take about 30 milliseconds instead of 100 milliseconds to detect the SSO with a frequency of 10Hz and an amplitude of 141.4($100\sqrt{2}$).

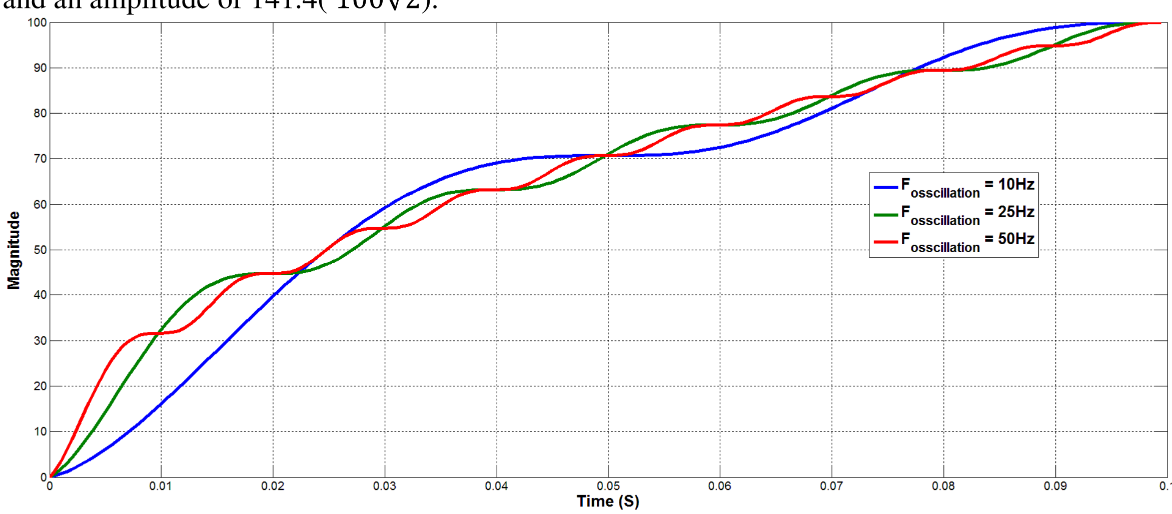

Figure 10 Time inverse characteristics of Continuous RMS (CRMS)

The overall protection logic is illustrated in Figure 11. The *fundamental component minimum threshold value* setting ensures the SSO protection is enabled only under minimum load conditions. The *SSO minimum pickup threshold* is set as a percentage. For current-based SSO protection, the recommended default setting is 50%. For voltage-based SSO protection, the recommended default setting is 20%. These default settings will provide enough security and detection speed for the SSO event that is analyzed in the previous sections. Since SSO is a 3-phase phenomenon, oscillation has to be detected in all three phases before *SSO Detected* is asserted and misoperation from an unbalanced system fault can be prevented. Additional finite time delay can be added after SSO detection to add additional security under the discretion of the specific application.

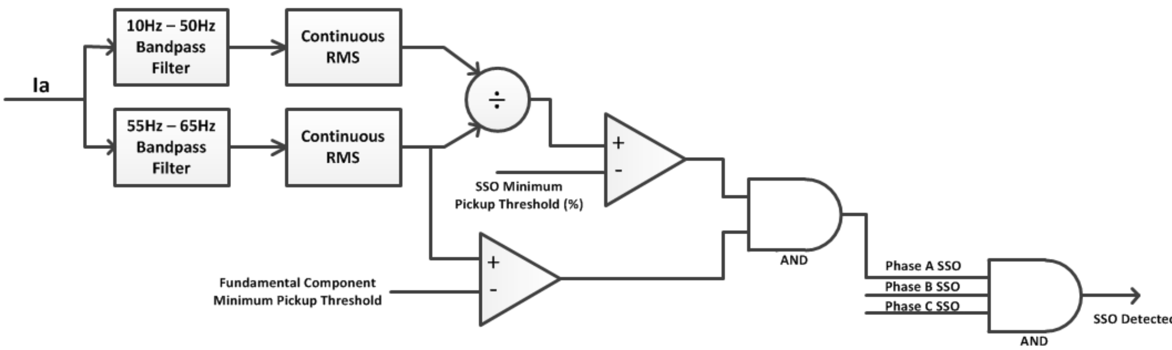

Figure 11 SSO Protection Logic

Protection Performance Verification

Performance Validation through Simulation

The recorded current signals as shown in Figure 8 are used to verify the performance of the presented SSO protection logic. The upper plot in Figure 12 shows the CRMS value of the SSO component and the 60Hz component. The SSO component value increases much faster than the 60Hz component after the system entered into the oscillation mode. The lower plot in Figure 12 shows the ratio of two RMS values in percentage with the indication of *minimum pickup threshold* set as 100%. For this case, the SSO protection logic will detect the SSO condition within 50 milliseconds.

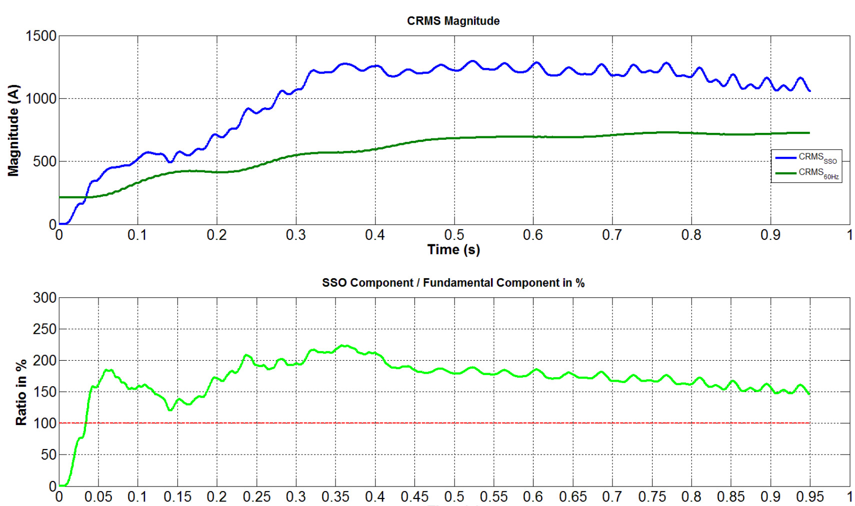

Figure 12 Performance Validation of SSO Protection Logic

RTDS Testing Validation

The presented algorithm is implemented in a powerful programmable control device and we call it SSO relay. All the filtering and CRMS calculations are executed in field-programmable gate array (FPGA) with 40 MHz clock speed built in the SSO relay. The FPGA implementation provides deterministic speed of execution. The relay has been tested in a hardware-in-the-loop (HITL) test environment by using real time digital simulator (RTDS). In the test case shown in Figure 13, the *SSO minimum pickup threshold* setting in the relay is 30% and the time delay is set as 100 milliseconds to increase the security. Figure 13 shows that the relay detected the initiation of oscillation within 10 milliseconds and correctly asserted the SSO detection after 100 milliseconds intentional delay. Intensive HITL testing in the lab proves the performance of the SSO relay is satisfactory to the design specifications.

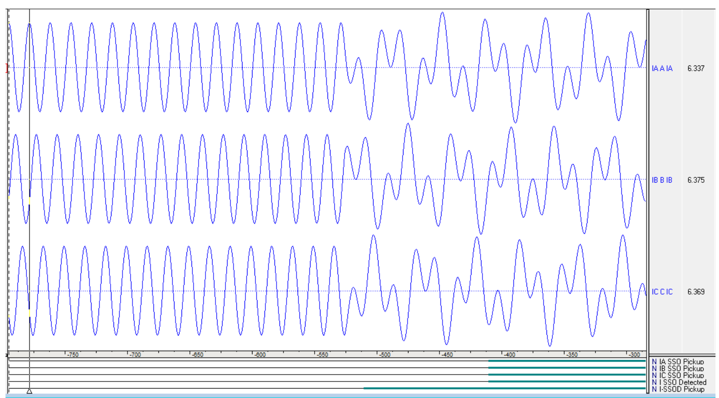

Figure 13 Hardware-in-the-loop test of the SSO relay

Summary

The subsynchronous oscillation (SSO) caused by the control interaction between wind generators and series compensated transmission networks requires new protective relays to prevent damage to system equipment. By carefully examining the characteristics of the SSCI phenomena, we present a relay design that applies signal processing techniques tailored to extract the subsynchronous signals and special protection logics to securely detect the SSO. The algorithms have been implemented in a powerful hardware platform that provides deterministic speed of execution. The RTDS-based lab test results verify the performance of the SSO relay. Depending on the application requirements, the relay may be deployed at series capacitor bank location or the interconnection point of power generation such as wind farms.

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