Protection Against Sub-Synchronous Oscillations, A Relay Model

Dinesh Rangana Gurusinghe, Sachintha Kariyawasam, and Dean S. Ouellette

***Abstract*—With increased integration of renewable energy resources, FACTs devices and series compensation, sub-synchronous oscillations (SSO) have become more common in electrical power systems in recent years. Specially designed relaying devices are often employed to detect and isolate harmful SSO conditions as when unconstrained, they can lead to widespread equipment damage and system instability. This paper presents design and implementation of a SSO relay model that can effectively extract sub-synchronous components in system measurements to quickly detect SSO conditions. Dependability and security of the developed relay model are validated using electro-magnetic transient (EMT) type simulations. In addition, performance of the developed relay model is compared against a commercial (physical) SSO relay. Obtained results demonstrate the effectiveness of the implemented relay model in detecting SSO and protecting electrical power systems against SSO conditions.**

***Keywords*: Sub-synchronous oscillations, sub-harmonics, SSO protection relay, power system protection.**

I. INTRODUCTION

SUB-SYNCHRONOUS Oscillations (SSO) are a form of interactions between an electrical energy source and a transmission system, which cause an energy exchange between the two entities at a frequency below the nominal system frequency (60 or 50 Hz) [1]. There are several types of SSO phenomena depending on what segments of the power system get involved in the interactions. The most prominent types of SSO are Sub-Synchronous Resonance (SSR), Sub-Synchronous Torsional Interactions (SSTI), and Sub-synchronous Control Interactions (SSCI) [2], [3].

In some conditions, SSO can cause fatigue or failure of mechanical systems (i.e., turbine-generator shaft) as well as electrical instability [2]. In addition, certain types of SSO such as SSCI conditions can quickly escalate to create damagingly high currents and voltages in the system [4], [5]. Undesirable power system issues including equipment damage caused by real-world SSO events associated with inverter-based resources are reported in [6]. Since regular power system protection relays are designed to operate based only on fundamental frequency components, they are generally oblivious to SSO conditions. Specially designed relaying devices are therefore required to detect and counter SSO conditions in power systems.

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Details about various efforts made to develop SSO relay models can be found in literature. SSO protection relays in [1], [7] are based on the standard Discrete Fourier Transform (DFT) techniques with a resolution of 1 Hz. In [8], the envelope of signal (containing SSO) is utilized to separate the SSO from the synchronous power signal. A combination of an artificial neural network and wavelet transform based method is proposed in [9]. In [4], a special signal processing technique is used to extract sub-synchronous components from input signals. Another approach employs a ringdown analysis-based algorithm to estimate the frequency and damping of torsional SSR signals in conventional generation [10]. An SSO detection technique based on the Fast Fourier Transform (FFT) and Discrete Time Fourier Transform (DTFT) is provided in [11]. Prony, Eigensystem Realization Algorithm (ERA) and moving FFT techniques are proposed in [12]. Standard DFT based techniques require a data window of at least 1 s to obtain a resolution of 1 Hz, therefore it is not suitable to detect fast SSO phenomena (such as SSCI). In addition, most of relay models mentioned in literature have only been tested for a few operating conditions. Furthermore, most of the above-mentioned work does not disclose details about detection algorithm(s) and relay operation times.

This paper presents development of a SSO detection technique and its implementation as a relay model in a real-time simulation environment. The developed relay model can effectively detect SSO conditions including oscillations with multiple SSO frequency modes. Implementation details of the developed model are provided to facilitate further research and analysis. Since SSO studies are commonly carried out in Electro-Magnetic Transient (EMT) simulation tools, benefits of having a SSO relay model available in them are multiple. The developed relay model can be used as a tool to identify and analyze possible occurrences of SSO in simulation studies. It can also be used to evaluate the requirement of deploying SSO relays in a power system, evaluate their effectiveness and determine robust settings. Additionally, data provided by the relay model may also be useful to verify results obtained by other means such as analytical calculations and other types of simulations.

The objective of this work is to implement an SSO relay model and evaluate its performance. Extensive simulations are carried out to validate dependability and security of the developed SSO relay model. The relay model is also used in a realistic simulated power system to identify and mitigate the effects of SSO. In addition, performance of the developed relay is compared against a commercial (physical) SSO relay using real-time hardware-in-the-loop simulations.

II. Technical Challenges of Detecting SSO

Even though there are several methods to avoid SSO, specially designed relaying devices are often deployed to detect and counteract their effect as a safeguard [12].

However, there are several technical challenges when developing a SSO protection relay. Conventional numerical protection relays are designed to operate on fundamental frequency components and, therefore, often apply various filtering techniques to remove off-nominal frequencies from measurements. In contrast, SSO protection relays are specially designed to detect frequency components in system currents (and voltages) below the system synchronous frequency (i.e., sub-synchronous frequencies). It is important to understand that accurate phasor estimation of a sinusoidal signal of given frequency requires a finite amount of data. Therefore, the time required for calculations grows larger as the frequency of interest becomes lower. Most SSO conditions are slow-developing phenomena by nature [7], [13], [14], as opposed to most other types of system faults. As a result, SSO relays generally have longer operating times that can go up to 1 second with added time delays. However, quicker operation is required from relays to be effective against fast-developing SSO phenomena such as SSCI.

In a complex power system (particularly with series compensation), phenomena unrelated to SSO can also generate sub-harmonics. These events, however, are transient in nature and tend to be well-damped, hence SSO protection relays should not respond to them. In addition, lower order harmonics resulting from inrush, saturation, instrumental voltage and current transformers and faults in a power system can adversely affect calculations in a relay [5]. Moreover, modern power systems containing various entities that interact with each other can potentially generate SSO conditions with more than one genuine sub-synchronous frequency component, further complicating their detection. The relay model presented in this work has been designed and developed to effectively address all the above-mentioned challenges.

It is worth noticing that behavior of SSO events (such as SSCI) depends heavily on control systems of energy sources, network topology and other power system parameters and operational conditions [14]. Furthermore, determining robust settings (pickups and operating time delays) for SSO protection elements is also vitally important for successful operation of a SSO relay [5]. Therefore, this often demands detailed EMT type simulation studies with accurate modelling of the entire power system and its control systems.

III. SSO Relay Model

The SSO relay model proposed in this paper is capable of detecting the presence of SSO in current or voltage waveforms. Fig. 1 illustrates the functional overview of the SSO relay model implemented in an EMT type digital real-time simulator (DRTS) platform.

A. *SSO Protection Algorithm*

A set of 3-phase inputs from the DRTS simulation, chosen as the SSO detector (either voltage or current), is firstly fed to

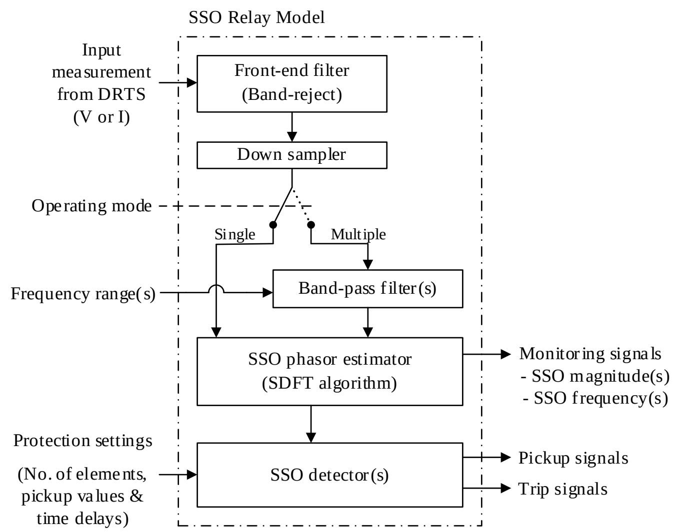


Fig. 1. Schematic of the SSO relay model developed in DRTS

a 2nd order band-reject filter (also known as a notch filter) to eliminate the nominal frequency component (50 or 60 Hz). The transfer function of the front-end band-reject filter used in this work is provided in (1) in discrete frequency-domain (z-domain) representation [15].

$$H(z) = \frac{z^2 - 2cos(2\pi.f_0.dt).z + 1}{z^2 - 2r.cos(2\pi.f_0.dt).z + r^2} \quad (1)$$

Here, $r = 0.999$, dt is simulation time-step (typically 50 μs) and f_0 is the nominal frequency. Magnitude errors introduced by the band-reject filter are appropriately compensated and signals are then passed to a down-sampler.

The proposed SSO protection algorithm has two main modes of operation based on number of expected sub-synchronous frequency components in system inputs. The operating mode '*Single*' is to protect against SSO conditions where there is only one sub-synchronous frequency component in the oscillation. The operating mode '*Multiple*' is used when there are more than one possible sub-synchronous frequency components in the oscillation. In this mode, the output signals of the down-sampler are fed to a set of 12th order Butterworth band-pass filters where user defined frequency ranges can be set for each potentially possible sub-synchronous frequency mode. When there are multiple SSO frequency modes in close proximity, quick filter roll-offs around cut-off frequencies are required to separate them. This demands higher-order filters. Choosing a filter order is a compromise between filter roll-offs (reliability) and time delay (performance). Authors investigated numerous filtering techniques and based on results obtained, selected a 12th order Butterworth band-pass filter, which produced the best overall performance. This additional filtering results in an added time delay of about 80-120 ms in the multiple mode operation.

The filtered signals are then passed to a SSO phasor estimator where a Smart Discrete Fourier Transform (SDFT) algorithm, an extension to the standard DFT, is deployed to estimate the SSO frequency(s) using (2). Details of the SDFT algorithm can be found in [16]-[18]. The SDFT algorithm is well-suited for fast and accurate estimation of SSO magnitude and frequency. It is effective for a wider off-nominal frequency range and immune to noise and harmonics, therefore dedicated ani-aliasing is not necessary [16].

$$f_{SSO} = \frac{Nf}{2\pi} cos^{-1}\left(\frac{w}{2}\right) \quad \text{where,} \quad w = \text{Re}\left(\frac{\hat{x}_n - \hat{x}_{n-2}}{\hat{x}_{n-1}}\right) \qquad (2)$$

In the single frequency operation, N = 16 and the base frequency, f for the SDFT algorithm is chosen as the middle value of the SSO frequency range (30 Hz for 60 Hz systems and 25 Hz for 50 Hz systems). For the multiple frequency operation, N = 8 and f values are taken as the middle of passband frequency for each frequency mode. Re( ) denotes the real-part of a complex number and $\hat{\boldsymbol{x}}_{\boldsymbol{n}}$, $\hat{\boldsymbol{x}}_{\boldsymbol{n-1}}$ and $\hat{\boldsymbol{x}}_{\boldsymbol{n-2}}$ are three consecutive phasors estimated from the standard DFT algorithm at the base frequency (i.e., 30 or 25 Hz). Next, the SSO magnitude(s) is estimated using (3).

$$X_{SSO} = |\boldsymbol{A_r}| \frac{N \cdot \sin\left(\frac{\pi\Delta f}{Nf}\right)}{\sin\left(\frac{\pi\Delta f}{f}\right)} \qquad (3)$$

$$\text{where, } \boldsymbol{A_r} = \frac{\boldsymbol{a}^2\hat{\boldsymbol{x}}_{\boldsymbol{n}} - \boldsymbol{a}\hat{\boldsymbol{x}}_{\boldsymbol{n-1}}}{\boldsymbol{a}^2 - 1}, \ \boldsymbol{a} = \frac{w}{2} \pm \mathbf{j}\frac{\sqrt{4 - w^2}}{2}, \ \Delta f = (f_{\text{SSO}} - f)$$

As a basic security measure, the estimated SSO frequency(s) is validated to make sure that the relay does not misoperate for frequencies outside the SSO frequency range. For single frequency operation, this frequency range is 5-55 Hz (5-45 Hz for 50 Hz systems), while user-defined SSO frequency ranges are used in multiple mode operation. Subsequently, the estimated SSO magnitude(s) is compared against user specified SSO magnitude threshold level(s) and output pickup and trip signals are asserted if the threshold(s) is exceeded.

B. *Optional Security Features*

The SSO relay model comprises of an optional security feature to have the SSO detection logic supervised by system line-to-neutral voltage and/or the rate of change of frequency (ROCOF) of estimated SSO frequencies. These two security elements operate independently, and it can be enabled individually as necessary.

The undervoltage supervisory element guards against misoperation of the relay for fault-induced behaviours of the system. If this option is enabled, the 3-phase voltage input is passed through a 2nd order band-pass filter with a bandwidth of 3 Hz to extract voltage measurements at the nominal frequency. The transfer function of this band-pass filter is provided in (4) (z-domain).

$$H(z) = \frac{(1-k)z^2 + 2(k-r)cos(2\pi f_0 dt).z + (r^2 - k)}{z^2 - 2r.cos(2\pi f_0 dt).z + r^2} \qquad (4)$$

$$\text{where } k = \frac{1 - 2rcos(2\pi f_0 dt) + r^2}{2 - 2\cos(2\pi f_0 dt)} \text{ and } r = (1 - 9dt)$$

Here, the band-pass filter output signals are used to estimate voltage magnitudes at the nominal frequency. If any one of the line-to-neutral voltages drops below the supervision setting(s), the SSO detection logic will be blocked.

SSO ROCOF supervision would be helpful to prevent misoperation of the relay due to any inaccuracies or fluctuations in SSO frequency estimation during transients and sub-synchronous frequencies that are not related to any SSO conditions. Here, if the estimated ROCOF (absolute value) for SSO frequency upswings above the supervision setting, SSO trip signal will be blocked.

C. *SSO Relay Settings*

Since the magnitude and the rate of growth of SSO conditions are unpredictable, in order to enhance dependability of protection, SSO detector shown in Fig. 2 comprises of multiple (up to 3) SSO elements that can be setup in parallel with different pickup settings and time delays. This forms a definite-time characteristic that provides a faster operation for rapidly growing SSO conditions and slower operation for low levels of SSO conditions as shown in Fig. 2.

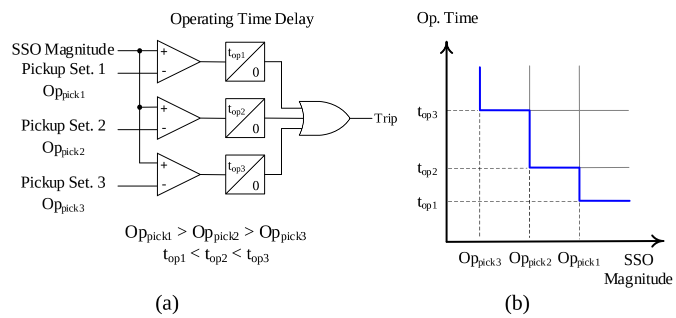


Fig. 2. (a) Multiple SSO elements, (b) corresponding operating characteristics

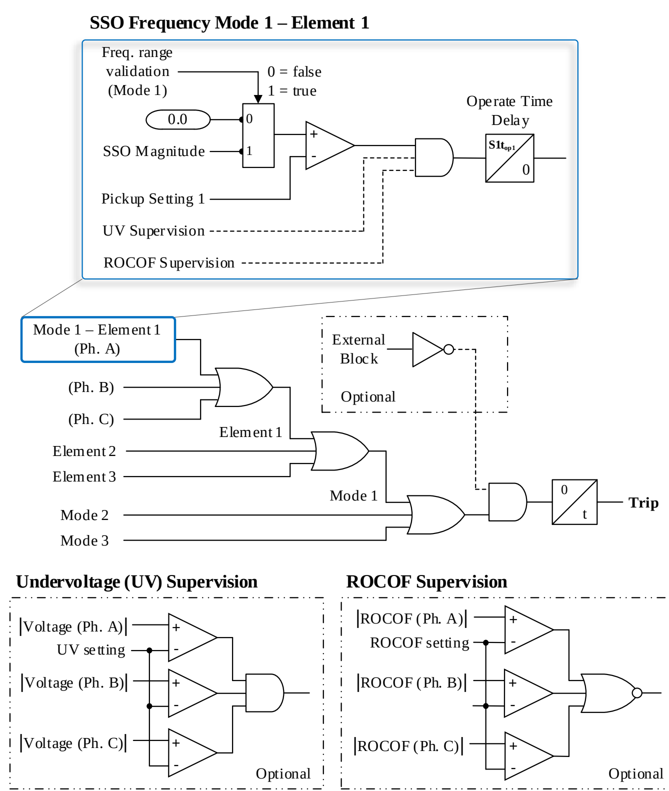


Fig. 3. Operation logic of the SSO relay model

Pickup settings can be provided with respect to system base values (so-called normalized form) or as absolute secondary values. The SSO elements can also be used as instantaneous elements by setting the operate time delay to zero (not recommended). The time delay settings should be sufficiently long to ride-through any transient dips in voltage/current and to provide time for power system controls to respond. This should be balanced against the system survival requirement as excessive time delays may cause the system stability to be in jeopardy.

The operation logic of the developed SSO relay model is shown in Fig. 3. Here, the SSO relay firstly validates estimated SSO frequency to make sure the relay does not pickup for frequencies outside the desired SSO frequency range(s). Next, the relay checks the estimated SSO magnitude against pickup settings and asserts the relay after a pre-set time delay. Notice that undervoltage and SSO ROCOF blockings discussed in Section B are optional. The optional external block signal prevents the tripping operation of the SSO relay model. This feature helps users to disable protection functions as necessary using an external logic.

IV. Model Validation

All the features of the developed SSO relay model are evaluated in an EMT type real-time simulation environment. Here, test signals and relay settings are specifically generated to verify expected performances of the relay model. Operation of the relay model is tested for different SSO frequency ranges, SSO pickup settings and time delays. In addition, two optional security features discussed in Section III-B are also tested.

In order to evaluate the functionality of the SSO relay model, synthesized waveforms with known sub-synchronous frequencies and magnitudes are superimposed to a nominal system frequency signal and fed to the SSO relay model. Then, the relay response is captured and recorded. All tests are carried out in the DRTS simulation environment itself.

A. *Single Frequency Mode*

For single frequency mode testing, test signals comprise of one SSO frequency component only. Here, all three SSO elements are enabled, and relay settings are provided in Table I. An extensive number of scenarios are tested including optional security features with the aid of scripting capability of the DRTS. The SSO relay model demonstrates excellent performance and chosen test results are given in Table II.

B. *Multiple Frequency Mode*

In multiple frequency operation, the relay model expects more than one sub-synchronous frequency components. Here, all three frequency modes and all three SSO elements for each mode are enabled, and relay settings are provided in Table III. A large number of test scenarios are carried out including optional security features. A chosen set of test results are shown in Table IV.

TABLE I
Relay Settings (Single Mode)

Element	Pickup value (normalized)	Time delay (ms)
Element 1	10%	400.0
Element 2	20%	300.0
Element 3	50%	200.0

TABLE II
Selected Test Results (Single Mode)

SSO frequency (Hz)	SSO magnitude (%)	Relay response	
		Operated element	Operating time (ms)
4.5	100.0	Did not operate	
21.3	7.5	Did not operate	
21.3	15.0	Element 1	470.9
21.3	25.0	Element 2	371.8
21.3	60.0	Element 3	271.8
41.7	7.5	Did not operate	
41.7	15.0	Element 1	471.5
41.7	25.0	Element 2	371.1
41.7	60.0	Element 3	271.2
55.5	100.0	Did not operate	

TABLE III
Relay Settings (Multiple Mode)

Mode	Element	Pickup value (normalized)	Time delay (ms)
Mode 1 (5-15 Hz)	Element 1	10%	400.0
	Element 2	20%	300.0
	Element 3	50%	200.0
Mode 2 (25-30 Hz)	Element 1	10%	400.0
	Element 2	20%	300.0
	Element 3	50%	200.0
Mode 3 (40-50 Hz)	Element 1	10%	400.0
	Element 2	20%	300.0
	Element 3	50%	200.0

TABLE IV
Selected Test Results (Multiple Mode)

SSO frequency (Hz)	SSO magnitude (%)	Relay response		
		Operated mode	Operated element	Operating time (ms)
10.7	25.0	Mode 1	Element 2	489.7
27.5	25.0	Mode 2	Element 2	461.2
43.2	25.0	Mode 3	Element 2	419.1
10.7, 27.5	18.0, 18.0	Mode 2*	Element 1	546.4
10.7, 27.5	40.0, 18.0	Mode 1*	Element 2	466.0
10.7, 27.5	18.0, 60.0	Mode 1*	Element 2	466.0
27.5, 43.2	18.0, 18.0	Mode 3*	Element 1	495.5
27.5, 43.2	40.0, 18.0	Mode 2*	Element 2	428.3
27.5, 43.2	18.0, 60.0	Mode 3*	Element 3	314.6
10.7, 27.5, 43.2	18.0, 18.0, 18.0	Mode 3*	Element 1	516.7
10.7, 27.5, 43.2	40.0, 18.0, 18.0	Mode 1*	Element 2	462.4
10.7, 27.5, 43.2	18.0, 40.0, 18.0	Mode 2*	Element 2	433.8
10.7, 27.5, 43.2	18.0, 60.0, 18.0	Mode 2*	Element 3	365.1
10.7, 27.5, 43.2	18.0, 18.0, 60.0	Mode 3*	Element 3	312.9

* Only the mode operated first is indicated. Other modes also operated in due course.

As seen in Table II, the developed SSO relay model takes about 70 ms to detect SSO conditions in the single frequency mode whereas it requires 150-200 ms in the multiple frequency mode (as seen in Table IV). Additional time requirement in the multiple frequency mode is due to Butterworth band-pass filters utilized in this mode.

V. Case Study

The developed SSO relay model is further validated under realistic conditions using a detailed EMT simulation case study.

A. Simulated Power System

Power system simulated in this work consists of a Type III wind plant and a series compensated transmission line, which as a result, is prone to produce SSCI. As shown in Fig. 4, two transmission lines (Line 1 and Line 2) connect two remote power systems represented by their equivalent Thevenin's voltage sources. A Type III wind plant, rated at 250 MW, is connected to the transmission system at Bus 1. Series capacitor banks are installed on Line 1 (at Bus 1 end), which compensates 50% of the line's inductive impedance. The series capacitor model used in the simulation incorporates a Metal-Oxide Varistor (MOV), a bypass gap and a bypass breaker. The two 60 Hz, 345 kV equivalent systems are represented as voltage sources behind an impedance with given impedances. The type III wind turbine-generator (WTG) system is interfaced to the AC grid using a back-to-back two-level converter that uses generic DQ decoupled controls. The WTG system is simulated with a time-step of 2.5 μs while the rest of the power system is simulated with a standard 50 μs time-step.

A SSO relay is deployed at Bus 1 as shown in Fig. 4. The relay is configured to operate in '*Single*' frequency mode since only one sub-synchronous oscillation frequency is expected. Three SSO elements are enabled, and relay settings are provided in Table V. Note that in this case, trip signal from the relay is used to bypass the series capacitor, thus eliminating one of the two main constituents of SSCI from the system. This allows to keep power from the wind plant flowing into remote system 1. It may also be used to disconnect the wind plant or the entire transmission line from the system.

B. SSCI Event without SSO Relay Operation

The sequence of events that precedes the SSCI condition is as follows. The Type III wind plant is connected to the power

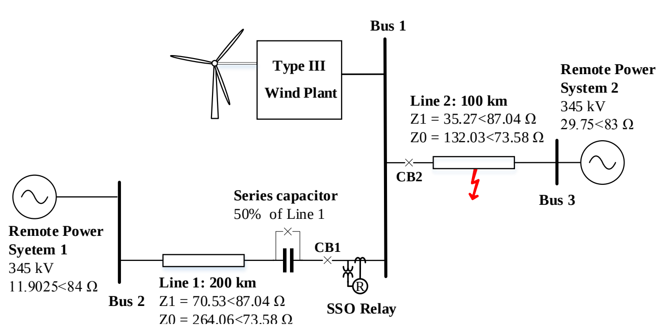


Fig. 4. Single line diagram of the simulated power system

TABLE V
RELAY SETTINGS FOR SIMULATED POWER SYSTEM

Element	Pickup value (normalized)	Time delay (ms)
Element 1	10%	400.0
Element 2	20%	250.0
Element 3	40%	200.0

system and generates its rated output of 250 MW (wind speed 12 m/s). Then, a single-line-to-ground fault occurs on Line 2, 20 km away from Bus 1. Line protection at Bus 1 trips breaker 'CB2' and disconnects Line 2 from the rest of the power system 70 ms after the inception of the fault (20 ms: protection operation + 50 ms: breaker operation). Once Line 2 is disconnected from the system, the wind plant becomes radially connected to the rest of the system, which contains a series compensated transmission line. Entering into this type of a network topology, which is conducive to SSCI, triggers a SSCI condition in the system.

Fig. 5a presents line current (measured at 'CB1') and Bus 1 voltage waveforms during the SSCI event. At first, operation of the SSO relay is blocked in order to observe the unchallenged behavior of the SSCI event. Appearance of SSO is noticeable in both current and voltage waveforms following the opening of 'CB2' (signal 'CB2 Status' → 0), which disconnects Line 2 from the system. Given in Fig. 5b is the magnitude spectrum of sub-harmonic frequency components of Phase-A line current during the same SSCI event. The sub-harmonic magnitude spectrum indicates that the dominant sub-synchronous frequency component of this SSO condition

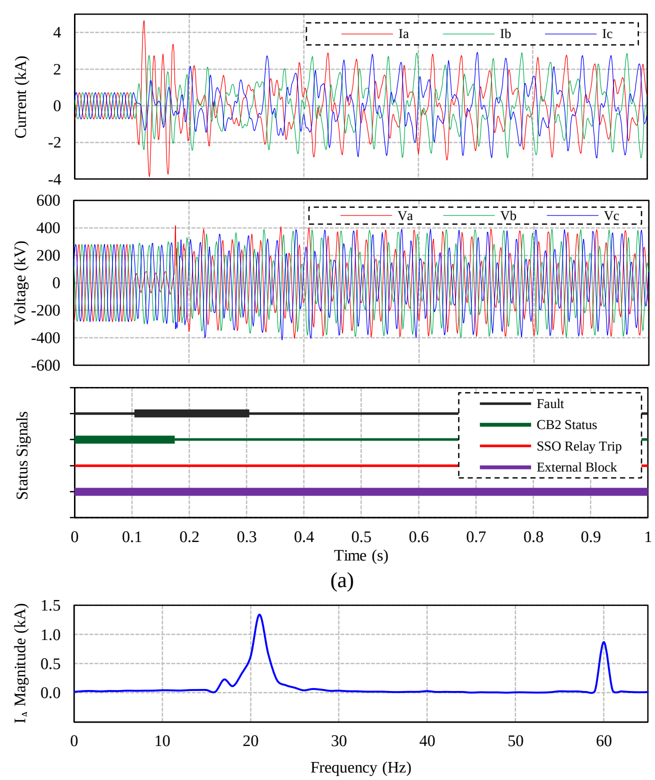


Fig. 5. (a) Line currents, Bus 1 voltages and digital statuses, (b) Sub-harmonic magnitude spectrum of Phase-A line current, during the SSCI condition

is around 21 Hz, with a magnitude well above that of the fundamental frequency (60 Hz) component. Looking at the time-domain current waveforms, one can observe that the instantaneous line currents during the SSCI event reach values that are significantly higher than the pre-fault values and are even comparable with fault current levels. In addition, voltage waveforms also exhibit the presence of sub harmonics and increased amplitudes. These abnormal currents and voltages generally are undetectable to conventional protection and control schemes; as a result, they can persist for extended periods of time causing equipment damage and system instability. Moreover, notice that the oscillations have grown to dangerously high values within a few hundred milliseconds, which is a faster rate of growth in comparison to other types of SSO phenomena and a characteristic feature of SSCI.

Fig. 6 presents the secondary line currents (A_{sec}), estimated SSO magnitude (A_{sec}), estimated frequency (Hz) and relay pickup and trip output signals during the same event. As mentioned earlier, opening of ‘CB2’ creates a radial connection between the WTG system and the series capacitor and therefore, it is considered as the inception point of the SSCI event in this study. Accordingly, time taken for relay operation is calculated in the simulation as time elapsed from opening of ‘CB2’ (CB2 Status → 0) to assertion of the trip signal (SSO Trip → 1). In this scenario, the relay does not issue a trip despite detecting the SSCI event (as indicated by ‘SSO pickup’ signal), since the external block signal is turned on.

Looking at Fig. 6, one can appreciate the fact that the estimated frequency and magnitude of the dominant sub-harmonic component match with the sub-harmonic magnitude spectrum given in Fig. 5. However, notice that the SSO magnitude and frequency calculations yield non-zero values starting from the initial fault inception on Line 2. This

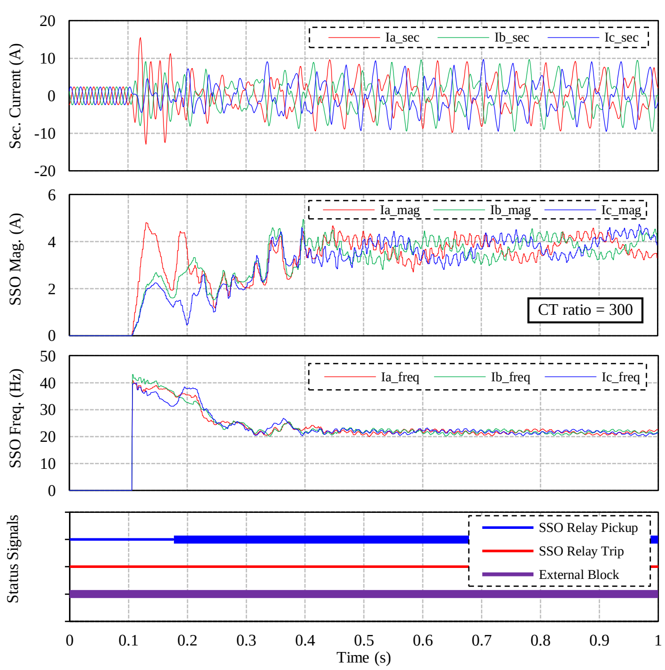


Fig. 6. Secondary line currents (A), estimated SSO magnitude (A_{sec}), estimated SSO frequency (Hz) and SSO relay pickup/trip signals

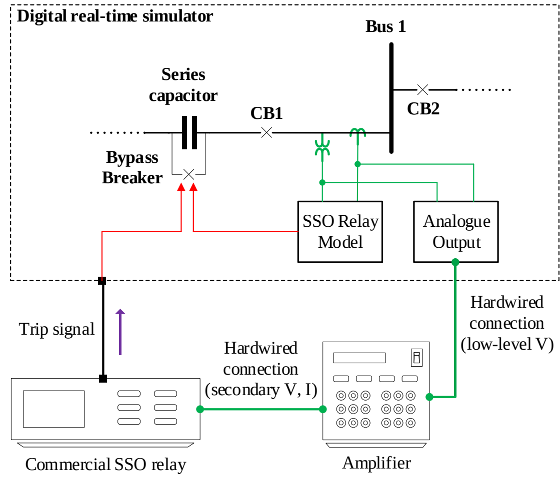


Fig. 7. Connections of SSO relay model and commercial SSO relay with the digital real-time simulator

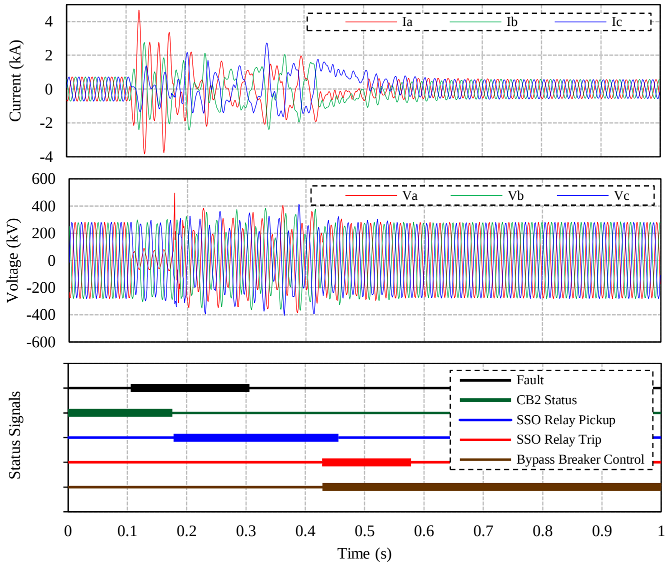
is primarily due to two reasons. Firstly, large transients (such as faults) in a system with series capacitors inherently generate a certain amount of sub-harmonics even without an active SSO condition (these usually damp out). Secondly, the values produced by the phasor estimation algorithms used in the relay model for SSO magnitude and frequency calculations can be erroneous during transitions between different operational states. Security of the SSO protection elements can be compromised as a result. However, a SSO relay should be able to overcome this deficiency in phasor estimation methods with appropriately set pickup time delays.

C. SSCI Event with SSO Relay Operation

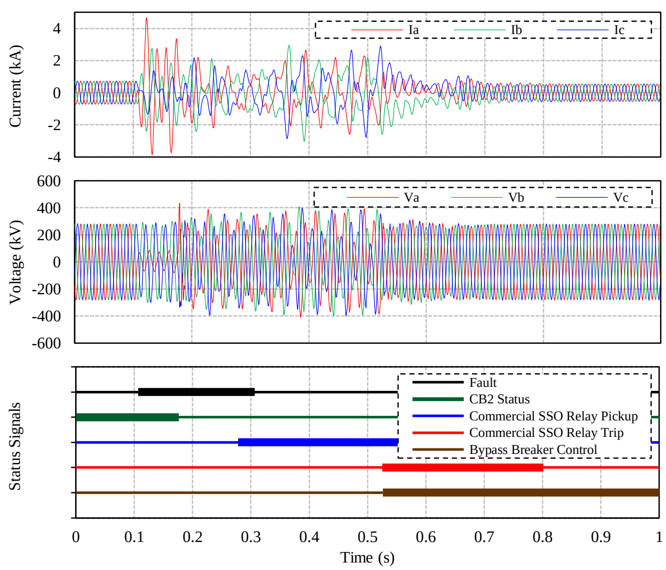
In order to benchmark performances of the developed SSO relay model, a commercial SSO relay (physical) is connected and tested in parallel as shown in Fig. 7 with identical settings (as the developed relay model). Here, low-level analog signals produced by the DRTS are sent out to a secondary injection amplifier to produce secondary voltage and current signals that are in turn fed to the commercial relay. Once the relay detects the SSCI condition and issues a trip signal, it is sent back to the DRTS to close the loop. Although the two relays (model relay in DRTS and commercial relay) are connected in parallel, the setup is configured in such a way that only one is active at a given instant. This arrangement helps to observe performances of the two SSO relays independently.

Fig. 8a presents the current and voltage waveforms observed for the same SSCI event described in Section V-B with operation of the developed SSO relay model enabled.

The relay model detects the SSCI condition and issues a trip signal in approximately 252 ms (operating element 2) after the opening of ‘CB2’ (CB2 Status → 0). The commercial SSO relay detects and issues a trip signal for the same SSCI condition in approximately 345 ms (operating element 2) as shown in Fig. 8b. In these tests, the trip signal issued by the SSO relays are used to bypass the series capacitor from the circuit. As can be seen in Fig. 8, bypass breaker of the series capacitor (signal ‘Bypass Breaker Control’) is closed as soon as the SSO relays issue a trip command. Following the removal of the series capacitor, one can observe how the SSO



(a)

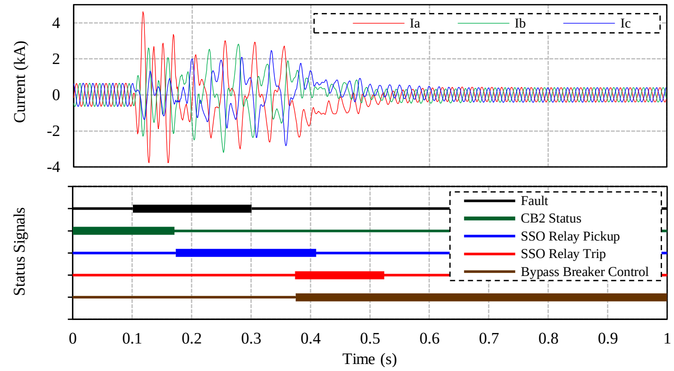


(b)

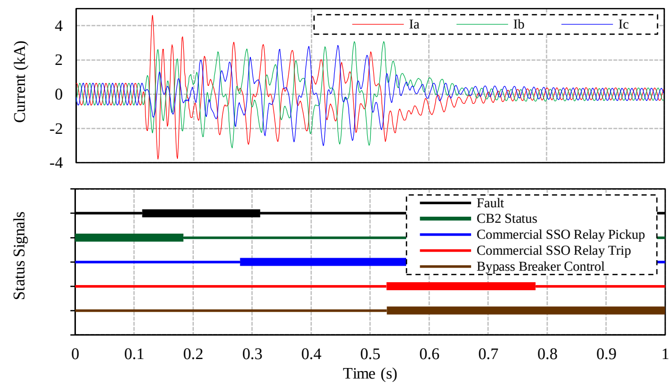
Fig. 8. Line currents, Bus 1 voltages and digital statuses including SSO relay pickup/trip signals during the SSCI condition with SSO protection enabled at wind speed: 12 m/s: (a) SSO relay model, (b) Commercial SSO relay.

diminish from the system as it recovers back to a stable operating condition.

Then, a fault is applied while the system is at a slightly different operating point by setting the wind speed input of the wind plant to 11 m/s, which reduces its power output to around 190 MW. Observe that the SSO grow faster in magnitude compared to the previous case and in response, the SSO relay model too operates quicker in approximately 203 ms (operating element 3) as shown in Fig. 9a. These results underline the importance of having multiple relay elements operating in parallel to detect and counter SSO events with different characteristics resulting from varying operating conditions. However, there is no discernable difference in the operation of the commercial SSO relay in this scenario. It detects the SSCI event and issues a trip signal in approximately 344 ms (operating element 2) as can be seen in Fig. 9b. In both scenarios, the developed SSO relay model yields faster responses compared to the commercial SSO relay, yet the latter's operating times are also well-within acceptable limits for this application.



(a)



(b)

Fig. 9. Line currents and digital statuses including SSO relay pickup/trip signals during the SSCI condition with SSO protection enabled at wind speed: 11 m/s: (a) SSO relay model, (b) Commercial SSO relay.

VI. Discussion

In a real-world power system study, detailed EMT studies are carried out to identify potential SSO conditions in the system of interest. In general, deployment of SSO relays is not the first level of mitigation for potential SSO conditions. However, while other control and operational level countermeasures are generally applied before providing protection using SSO relays, they are a dependable safeguard and an important aspect of defense against SSO in power systems. Accurate simulation studies can reveal potential sub-synchronous frequency modes in the system, their locality and scale, which help determining appropriate relaying locations and settings. For example, SSO relay settings used in the case study (Section V-C) are determined based on information gathered from prior simulations (Section V-B) and recommendations provided in related literature [5], [13].

Accurately representing the elements of the power system of interest is also vitally important in SSO simulation studies. Particularly significant in this context is accurate modeling of series capacitors and their protection (MOV, air gap, etc.), controls of the energy source (wind plant controls) and the transmission network.

The developed relay model has many features and workings of a real protection relay. It outputs a multitude of analog and digital monitoring signals including frequencies and magnitudes of detected SSO, relay pickup, trip signals for each element etc. Input signals to the relay model in the DRTS environment are digital and produced with high fidelity for each simulation time-step (typically, 20 kHz at 50 µs). The SSO relay model down-samples these inputs to 16 and 8 samples/cycle for the single and multiple mode operations, respectively, using linear interpolation. The developed relay model executes several computationally expensive processes such as filtering and phasor estimation while supporting multiple protection elements simultaneously. Hence, it adopts a multi-thread strategy to prioritize the workflow and to lower processing requirements of the component on a given simulation time-step. It has 4 threads that are run sequentially in consecutive time-steps of the simulation (i.e., each thread is executed every 200 µs with a simulation time-step of 50 µs, for instance).

As can be seen from the results presented in the paper, the proposed relay model performed very well in detecting SSO and the results it produced are comparable to those of a commercial SSO protection relay. In particular, the proposed relay model produced excellent results in single frequency mode operation, which is applicable for a majority of real-world SSO events. Hence, the authors believe that it can be used in EMT simulation studies to evaluate the necessity and the effectiveness of deploying SSO relays in a real system before acquiring commercial relays. One limitation of the proposed technique is that it can perform poorly if there are two simultaneously active frequency modes of comparable magnitude in very close proximity (that are within 1-3 Hz of one another). This, however, is a very rare occurrence in a real-world power system.

VII. Conclusions

Application of SSO relays is an effective countermeasure used to avoid or minimize damage caused by SSO conditions. This paper presented a SSO relay model that can promptly detect and respond to harmful SSO conditions. In this work, information about the SSO detection technique, operation of the relay model and its features were explained in detail. The SSO relay model was implemented in an EMT type real-time simulation environment. Performance of the developed relay model was assessed extensively by using synthesized SSO inputs. In addition, the relay model was deployed to detect SSO conditions in a simulated power system under realistic conditions and its performance was compared against a commercial SSO relay. Test results presented verified the robustness of the developed SSO relay model and its effectiveness in mitigating harmful SSO conditions.

VIII. References

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