Sub-harmonic protection application for interconnections of series compensated lines and wind farms

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Abstract

With the increased use of renewable wind energy, wind farms are being built in remote areas, often far from load centers. The required long transmission lines are often constructed with series capacitive compensation to electrically shorten the lines. Events in the transmission system can cause interactions between the series capacitors and the system's inherent impedance which can result in sub-synchronous resonance frequencies.

Modern wind turbine systems use advanced electronic control and converter systems which can generate harmonics and inter harmonics. Mechanical system interactions (tower-to-blade) can also generate sub-harmonics. Wind generator speeds vary continuously depending on the availability of wind at any particular time. This particular operating characteristic of wind farms introduces the challenge of predicting when and how much harmonics and sub-harmonics are being introduced to the power system.

Synchronous generators are often built with shaft torsional modes that are in the same range as system sub-synchronous resonance frequencies. These torsional modes can interact with transmission network resonances to produce damaging oscillations that can damage generators and transformers, and cause damage at points of common coupling in the electrical grid.

This paper discusses an engineering process that can be followed for the application of a new sub-synchronous relay that provides protection for transmission lines, particularly those with serial compensation and wind farm interconnections, and how it can be used together with digital fault recorders to monitor the power system to determine the existence of sub-synchronous resonance phenomenon. Moreover, it gives the reader criteria to determine if the levels of SSR obtained by means of DFRs are considered critical. The paper goes further, providing possible settings for the sub-harmonic protection relay including the protection elements associated to sub-harmonics as well as providing overcurrent and other protection functions.

1 Introduction

Sub-harmonic currents, i.e. components with frequencies lower than 60 or 50 Hz, are injected by a many modern loads. A brief list of the most significant contributors follows:

- Arc Furnaces
- Cyclo Converters
- Automated spot-welders
- Integral-cycle-controlled furnaces or any type of pulse burst-modulation power conditioned load
- Rectifiers supplying fluctuating or cyclic loads
- Motor driving cyclic loads, such as forges, drop hammers, stamping tools, saws, compressors and reciprocating pumps
- Wind generators; interaction tower-to-blade causes the modulation of the driving torque

The direct consequence of this low frequency current injection is voltage modulation and visual flicker. Saturation of power and measurement transformers is possible and the accuracy of instrumentation that includes current transformers may be diminished.[1]

This paper focuses on sub-synchronous events caused by the interaction phenomena found when wind farms are interconnected with series compensated lines.

Sub-synchronous events are not new to the industry; the following is an overview of relevant terminology:

- *Sub-Synchronous Frequency (SSF)*: The frequency of an oscillation that is less than the nominal frequency of the power system, not be confused with power system fundamental frequency that becomes slightly lower than nominal that may temporarily occur under normal conditions.

- *Harmonics:* Frequencies that are multiples of the fundamental frequency (i.e. 2nd - 120Hz, 3rd - 180 Hz for a 60 Hz fundamental).
- *Sub-Harmonics:* Frequencies that are less than the fundamental but at reflections of the harmonics (i.e. 1/2 - 30 Hz, 1/3rd - 20 Hz for a 60 Hz fundamental).
- *Sub-Synchronous Interactions (SSI):* Defines two parts of an electric system exchanging energy with each other at one or more of the natural frequencies of the combined system below the fundamental frequency of the system.
- *Sub-Synchronous Oscillations (SSO):* Defines the result of SSI described above.
- *Sub-Synchronous Resonance (SSR):* Defines the known problem of synchronous generators near a series capacitor when the mechanical mass resonates with the effective impedance of the system, known to cause damage in generators.
- *Sub-Synchronous Tortional Interactions (SSTI):* Defines the known problem of a synchronous generator near a power electronic controller when the mechanical mass resonates with the negative damping at of the controller at sub-synchronous frequencies, known to cause damage in generators.
- *Induction Generator Effect (IGE):* Defines the known problem of the electrical properties of the machine resonating with the system at sub-synchronous frequencies. The rotor resistance of the machine presents itself as a negative resistance with respect to sub-synchronous frequencies. The system presents itself as a positive resistance at the system natural frequencies, but if the negative resistance is greater than the positive resistance then sub-synchronous currents will be sustained.
- *Sub-Synchronous Control Instability (SSCI):* Defines a relatively new problem of “Interactions between a power electronic device (such as an HVDC link, SVC, wind turbine etc…) and a series compensated system.”[2]

From the above list of sub-synchronous events, sub-synchronous interactions (SSI) is a family of physical interactions which involve exchange of energy between a generator and a transmission system at AC frequencies below the system nominal frequency. They include SSR, SSTI, and SSCI. SSR tends to involve an interaction between a series compensated transmission system and a generator. SSTI involves an interaction between a generator and a power electronic controller such as would be found in an HVDC transmission system. SSCI involves an interaction between a series compensated transmission system and a power electronic control system such as would be found in a Type 3 wind turbine generator. SSR and SSTI in particular are well documented and well understood phenomena. SSCI can present a very serious threat to the safe and reliable operation of a wind plant, introducing the potential for severe equipment damage. It is also evident that most manufacturers of Type 3 wind plants are vulnerable to SSCI.[3]

2 Sub-Synchronous Resonance Case

2.1 Background

The wind energy industry is growing rapidly. More and more utilities are connecting wind generation throughout their system. This includes some generation near series compensated lines, and in some cases, radially connected through series compensated lines.

The normal interaction of the power system components may create the conditions that will cause the appearance of non-characteristic sub-harmonic frequencies. This effect is particularly prevalent on the power system where wind farms are interconnected with the rest of the power grid via series compensated lines. The wind turbine mechanical system interactions (tower-to-blade) can also generate sub-harmonics, and may cause resonance at the point of common coupling (PCC) in the electrical grid.

2.2 Power System

The Minnesota and South Dakota areas of Xcel Energy experienced significant improvements on their transmission systems in order to accommodate a large growth in power demand for wind generation. One of the improvements included the addition of a series line capacitor on a 54 mile long 345kV transmission line located in southwestern Minnesota.

The degree of compensation was decided to be 60%, based on planning studies and with the use of parametric analysis to determine the effect on constrained interface loading. A 240 MVAR series capacitor was installed in the middle of the line. One end of this series compensated line has 150 MW of installed wind generation and six combustion turbine generation (CTG) totalling 639 MW, as shown in Figure 1.[4]

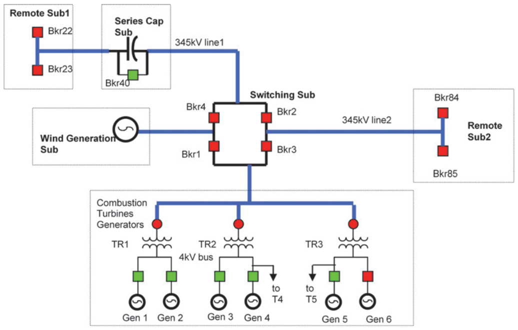


Fig.1 System one line showing generation and series compensated line.

During the commissioning process of the series capacitor and associated controls, 345 kV Line -1 was taken out of service before bypassing the capacitor. At the time of the event, the total wind generation was 15 MW and one of the six CTG units was generating 46 MW. No other units were not on-line. This switching operation resulted in radial connection of generation to the system through the series compensated line. The system tripped due to a flashover in the generator bus duct, resulting in a bypass of the series capacitor bank. The oscillation started by the switching event continued in the wind generators even after the series capacitor was bypassed.[4]

The generator current waveforms captured are as shown in Figure 2. Analyses of the captured waveforms indicated the presence of DC and low frequencies between 9-13 Hz, indicating different oscillatory interactions between wind machines and the system.

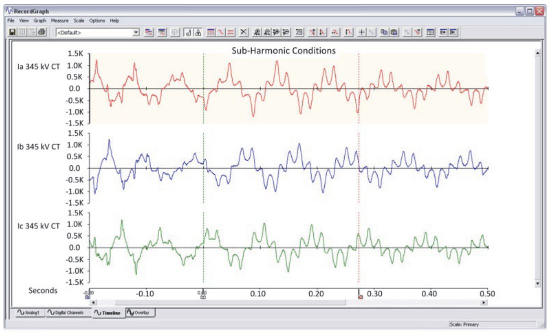


Fig. 2 Sub-harmonic oscillations at wind farm interconnections.

2.3 Sub-harmonic Protection Relay

At the moment, this series compensated line is being protected by the first generation sub-harmonic microprocessor based relay. The relay protects against sub-harmonic oscillations by measuring the voltages and currents with frequencies in the range of 5-40Hz. The relay not only initiates protective actions, it can also record individual sub-harmonic currents and voltages that can be used for future system studies.

The new sub-harmonic relay is composed of four sets of currents and two sets of 3-phase voltage inputs. Each input can be set to detect individual frequencies from 5-40Hz with two levels of detection. The device also has the ability to sum quantities from two of the current inputs, a useful feature that allows the monitoring of currents in lines that are associated to two breakers, applying the level detectors to these summated quantities. Furthermore, the device also has triggered-recording capability to alarm or take action for cyclical sub-harmonic quantities that may be oscillating just below the tripping levels.

The intention here is to collect sub-harmonic data as it occurs, even if it is on the verge of being a problem. The pickup levels and time delays of the detectors, and resulting action, is fully user selectable.

The theory behind the sub-harmonic detection is to compare the magnitude of each of the sub-harmonic currents and voltages that are observed between the user-defined minimum (F_{min}) and maximum (F_{max}) frequency range, with the settings specified by the user (Lset) magnitude. This can be done as shown in Figure 3.

$$\text{Trip or Alarm: } = \max(f2, f3, f4, f5, f6, f7) > Lset \quad (1)$$

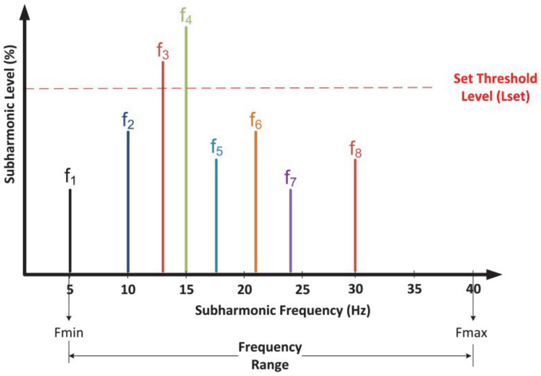


Fig. 3 Sub-harmonic Detection Principle.

Figure 4 shows the logic behind the sub-harmonic principle. As can be observed, there are three level detectors available for each voltage, current, or virtual input.

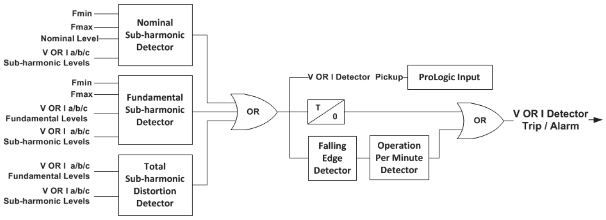


Fig. 4 Sub-harmonic Detection Logic Diagram.

The nominal sub-harmonic detector compares the level by estimating the ratio of sub-harmonic magnitude to the nominal CT/PT ratio. To emphasize this, let’s take a nominal CT ratio of 5A and an estimated sub-harmonic magnitude of 2.5 A at 5 Hz. The nominal sub-harmonic level is then compared as follows:

$$f1_{5Hz}\,(\%) = (2.5/5) * 100 \quad (2)$$

In a similar manner, the fundamental sub-harmonic detector logic is compares sub-harmonic magnitude with respect to the fundamental voltage or current quantities.

The Total Sub-Harmonic Distortion (TSHD) detector calculates the distortion level as follows:

$$TSHD(\%) = \left(\frac{\sqrt{f_{5\,Hz}^2+f_{6\,Hz}^2+f_{7\,Hz}^2+\cdots+f_{40\,Hz}^2}}{f_{60\,Hz}}\right)x100 \quad (3)$$

Equation 3 demonstrates that all the sub-harmonic magnitudes from 5-40 Hz are taken into consideration for the TSHD evaluation (with respect to 60 Hz fundamental voltage, current, or virtual derived channel). The same definition is applicable for a 50 Hz system.

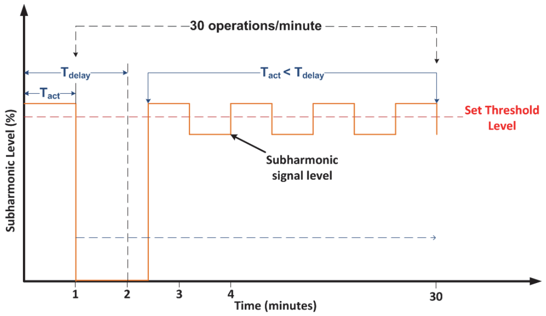


Fig. 5 Operations/Minute Detector Functionality.

The statistical nature of wind generation and its interactions with the rest of the system may produce sub-harmonic oscillations above threshold set limit for a lesser time period than the configured time delay. These conditions may be unnoticeable by the conventional detectors mentioned in the above section. Periodic occurrence of such events, even though for a shorter duration than the configured time, can have a negative impact in the power system network and its components if sustained for longer periods of time. To capture such events, a special operations/minute detector is designed, which functions as shown in Figure 5.

In the example above, an event with 30 operations per minute is depicted (not to scale). The time T_{act} corresponds to the actual duration of the sub-harmonic signal which is asserted. This event is not captured by the conventional detectors mentioned in the previous section, as the pickup delay T_{delay} has not been exceeded so the event is not noticeable. However, with the special detector, the 30 operations (assertion above set limit) will be internally counted and monitored. If the set operations per minute count exceeds the calculated count, then this special detector will issue a trip or an alarm as per the configuration. In this way, periodic disturbances with durations shorter than the configured limit can be captured.

2.3 Lessons Learned

Even with simulation studies, sub-harmonic disturbances are difficult to predict. Modern wind turbine systems use advanced electronic devices such as AC/DC convertors which can generate their own harmonics and inter-harmonics. Due to lack of accurate wind generator models from the manufacturers, it is important to capture and analyze the data for protective action.

The event captured at the Xcel Energy led to the development of a new microprocessor based sub-harmonic protection relay. It also identified several new challenges for protection and control engineers:

- Under what operating conditions will sub-harmonics appear in the system?
- What tools are available that can be utilized to capture data for subsequent analysis?
- What are the appropriate relay settings for the proper monitoring of a power system subject to potential sub-synchronous resonance phenomena?

The analysis of the sub-harmonic events would have been much more difficult if high precision digital fault records would not have been captured. For the event described above, a high precision digital fault recording device was located at the point of interconnection between the power grid and the wind farm.

3 Tools for Sub-Synchronous Resonance Monitoring

With the increased use of wind generators feeding HV and EHV utility networks with series compensated lines in the near vicinity, it is necessary to ensure that sub-harmonic oscillations are monitored, and that the electrical grid is protected from any resulting detrimental effects. Monitoring voltage and current signals for sub-harmonics becomes a critical factor.

At Xcel Energy, a digital fault recording device, located at the point of interconnection between the wind farm and the series compensated line, captured the system event which was the main evidence that revealed the sub-harmonics currents and voltages were involved in the event.

Due to their ability to sample at a higher rate, digital fault recorders (DFRs) provide better quality recording when compared to oscillographic records captured by digital relays. DFRs do not filter any frequencies and provide the true signal observed during the event. Furthermore, due to their storage capacity, DFRs can capture records of longer duration, with sufficient data before and after the event.

For the proper collection of data, a DFR capable of capturing records longer that one second and graphing sub-harmonic spectrums is recommended. It should be installed at the substation that serves as the point of interconnection between the wind farm and the series compensated station. At Xcel Energy, the DFR that captured the information presented in Figure 6 was located at the Lakefield Generation Substation, shown with a ring bus arrangement in Figure 1.

This will allow engineers to perform event analysis and to easily determine the magnitude of the currents and voltages for the different sub-harmonic frequencies present in the system due to the series compensated circuit.

Figure 6 below shows the current oscillography record captured during the event. As can be observed, the currents are not sinusoidal, but rather are quite distorted. An oscillographic record of this nature suggests that the waveform is rich with multiple frequencies.

Using a sub-harmonic analysis tool, the sub-harmonic currents were extracted from the record, as shown in Figure 7. From Figure 7 (b) we can see that the 11th sub-harmonic current, with a value of 172 primary amps, was the highest harmonic observed during the event. The presence of sub-harmonics with high magnitudes indicates the presence of a sub-synchronous resonance or exchange of energy between the wind generator controls and the series compensated system [3].

Different studies indicate that wind farms that are interconnected with a series compensated lines may experience SSR conditions [2]. For this case, it is unclear what type of sub-synchronous resonance the system experienced, but we know high sub-harmonic values were observed. The following section describes the steps for the proper setting of a sub-harmonic protection IED based on data captured by a high precision DFR and the sub-harmonic analysis performed by the appropriate tool.

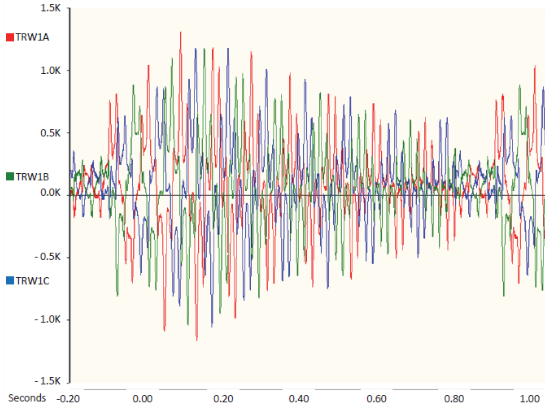
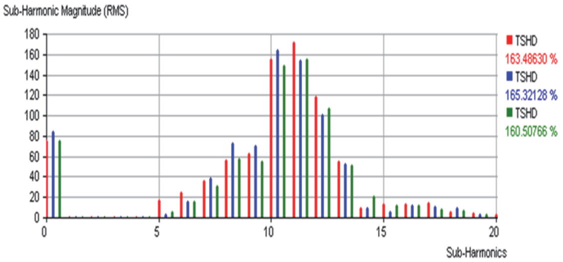
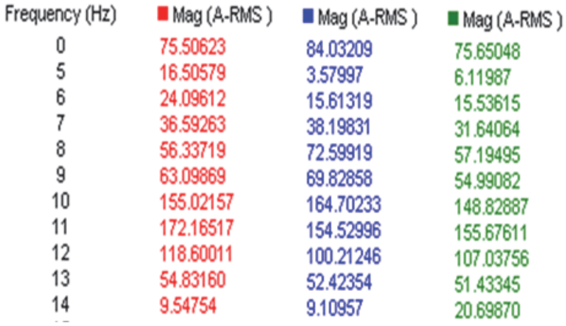


Fig. 6 Current response to sub-synchonous resonance.



a) Sub-harmonic magnitudes (RMS).



Frequency (Hz)	🟥 Mag (A-RMS)	🟦 Mag (A-RMS)	🟩 Mag (A-RMS)
0	75.50623	84.03209	75.65048
5	16.50579	3.57997	6.11987
6	24.09612	15.61319	15.53615
7	36.59263	38.19831	31.64064
8	56.33719	72.59919	57.19495
9	63.09869	69.82858	54.99082
10	155.02157	164.70233	148.82887
11	172.16517	154.52996	155.67611
12	118.60011	100.21246	107.03756
13	54.83160	52.42354	51.43345
14	9.54754	9.10957	20.69870

b) Sub-harmonic magnitude valus per phase.

Fig. 7 Sub-harmonic current magnitudes from event.

4 Sub-Harmonic Relay Settings

Detailed data shown in Figure 7 provided important information about each of the sub-harmonic frequencies present in the system during the original event.

The sub-harmonic relay was set to capture a range of sub-harmonic current and voltages frequencies from 5Hz-40Hz. The settings functions applied to the relay are shown below:

Sub-Harmonic Current Nominal Ratio: This ratio is calculated by taking the highest sub-harmonic current observed for the 5Hz - 40Hz range and dividing it by the nominal input current setting (1A or 5A). In order to set this ratio, one would need to run a sub-harmonic study that reveals the highest sub-harmonic currents magnitudes observed during sub-harmonic system study. This can be done by performing a frequency scan analysis. Because the sub-harmonic current levels can vary depending on the type of event, it is recommended that different contingencies be considered. These contingencies would simulate fault and switching contingencies with one or more power system elements being out of service.

In the case under consideration, the highest sub-harmonic current observed during the event was the 11th harmonic with a magnitude of 172 primary amps with a current transformer ratio of 400:1. The relay current inputs were 5A inputs. Applying the nominal ratio setting, we have the following:

$$Nominal\ Ratio = \frac{Highest\ Subharmonic\ Current}{Nominal\ Current\ 1A\ or\ 5A}$$

$$Nominal\ Ratio = \frac{172/400}{5A}$$

$$Nominal\ Ratio = 8\%$$

Set nominal ratio > 6%

Sub-Harmonic Current Fundamental Ratio:

This ratio is calculated be taking the highest sub-harmonic current between 5Hz - 40Hz divided by the fundamental current value (50Hz or 60 Hz). This ratio is calculated as follows:

$$Fundamental\ Ratio = \frac{Highest\ Subharmonic\ Current}{Fundamental\ current}$$

The fundamental current observed in the record was 1300 primary amps with a current transformer ratio of 400:1. The fundamental ratio then becomes:

$$Fundamental\ Ratio = \frac{172/400}{1300/400}$$

$$Fundamental\ Ratio = 13.5\%$$

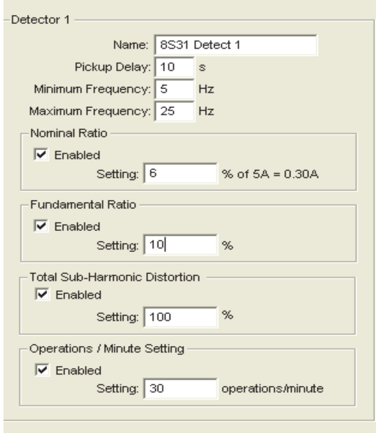
Set fundamental ratio > 10%

Total Sub-Harmonic Distortion: This setting takes into account every sub-harmonic from 5Hz - 40Hz by taking the square root of the sub-harmonics currents squared.

$$TSHD = \sqrt{\frac{(I(5Hz))^2 + (I(6Hz))^2 + \cdots (I(40Hz))^2}{I(60Hz)}}$$

The record in Figure 7 (b) shows a captured value of total sub-harmonic distortion (TSHD) between 160% and 165%. A TSHD setting greater than 100% would be appropriate.

Operations per Minute: Due to nuisance cases, an operations per minute setting should be applied. For this case, a minimum of 30 op/min is required for any of the other sub-harmonic settings to take effect.



Detector 1

Name: 8S31 Detect 1

Pickup Delay: 10 s

Minimum Frequency: 5 Hz

Maximum Frequency: 25 Hz

Nominal Ratio

☑ Enabled

Setting: 6 % of 5A = 0.30A

Fundamental Ratio

☑ Enabled

Setting: 10 %

Total Sub-Harmonic Distortion

☑ Enabled

Setting: 100 %

Operations / Minute Setting

☑ Enabled

Setting: 30 operations/minute

Fig. 8: Sub-harmonic current relay setting.

Sub-Harmonic Voltage Nominal Ratio: In a similar way to the current nominal ratio, the voltage nominal ratio is calculated by taking the highest sub-harmonic voltage value seen in the 5Hz – 40Hz frequency range; then, this value is divided by the secondary nominal voltage level 69V. For this case, the 11th sub-harmonic had the highest magnitude. Using the PT ratio of 3000:1, the nominal ratio is:

$$Nominal\ Ratio = \frac{Highest\ Subharmonic\ Voltage}{Nominal\ Voltage\ Level\ 69V}$$

$$Nominal\ Ratio = \frac{7600/3000\ V}{69V}$$

$$Nominal\ Ratio = 3\%$$

Setting > 2%

Sub-Harmonic Voltage Fundamental Ratio: The ratio is calculated by taking the highest sub-harmonic voltage value and dividing it by the fundamental voltage value.

$$Fundamental\ Ratio = \frac{Highest\ Subharmonic\ Voltage}{Fundamental\ Voltage}$$

$$Fundamental\ Ratio = \frac{7600/3000}{214000/3000\ Voltage}$$

$$Fundamental\ Ratio = 3\%$$

Setting > 2%

Overcurrent and Overvoltage Setting: A sub-harmonic study should also reveal the current and voltage levels during the simulations performed. The overcurrent settings shall be coordinated with the other overcurrent relays being used to protect the transmission line. The overvoltage settings shall be coordinated with the regional reliability center requirements and the minimum insulation requirements for the equipment.

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