A Microprocessor-Based Sub-Harmonic Protection Technique for Wind Farms

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Abstract:

Wind farms are generally located far away from load centers and, to increase the power flow, series capacitors are normally installed to compensate the transmission line reactance. The interaction of the series capacitor with the wind system can cause undamped sub-harmonic (below 60 Hz or 50Hz system frequency) current and voltage oscillations, which can cause serious damage to wind turbine controllers and also to conventional generators. A routine switching event in the Xcel Energy transmission system resulted in sustained oscillations between wind generators and the system connected through a series compensated line. This is the motivation behind the development of a new microprocessor-based sub-harmonic protection relay.

Key Words: sub-harmonic oscillations, series compensated wind farms, sub-harmonic protection, recursive Fourier transform

1. Introduction

The goal of a power system is to provide reliable power, from sources of generation to customer loads. In the process of providing this power, the operation of the power system can be affected by the interaction of various components of the power system that can excite non-characteristic sub-harmonic frequency (below 60Hz or 50Hz system frequency) voltages and currents [1]. This effect is particularly prevalent on the power system where wind generation farms, typically located far away from load centers, are often interconnected with the rest of the power grid via transmission lines with series capacitor compensation [2-4]. The wind turbine mechanical system interactions (tower-to-blade) can also generate sub-harmonics, which are detrimental to induction generators and transformers, and may cause resonance at the point of common coupling in the electrical grid [5].

The desire to have renewable energy has triggered a tremendous growth in the renewable energy market sector, consequently the number of wind farms is increasing dramatically throughout North America, and the same trend is manifesting around the world. This sub-synchronous effect takes place when the sources of sub-harmonics excite the sub-harmonic frequencies of the L-C circuit. This in turn can also cause low frequency mechanical resonant forces within the rotor shafts of electrical generators. If it allowed to persist, extreme mechanical damage to these generator shafts will occur.

1.1 System Event

Figure 1 shows a single line diagram of Xcel Energy's 345 kV system around the substation connected to the wind farm, a series compensated line and combustion generators. The wind farm is represented by a single unit in the diagram.

The switching of line 1 started by opening breakers 1 and 2 at the remote substation. After nearly six seconds, breakers 4 and 6 opened by protective relays, indicating fault on the low side of combustion turbine 1 (CT1) transformer. At this time, only one generator CT1 was in service and the wind was generating at about 20% of the installed capacity.

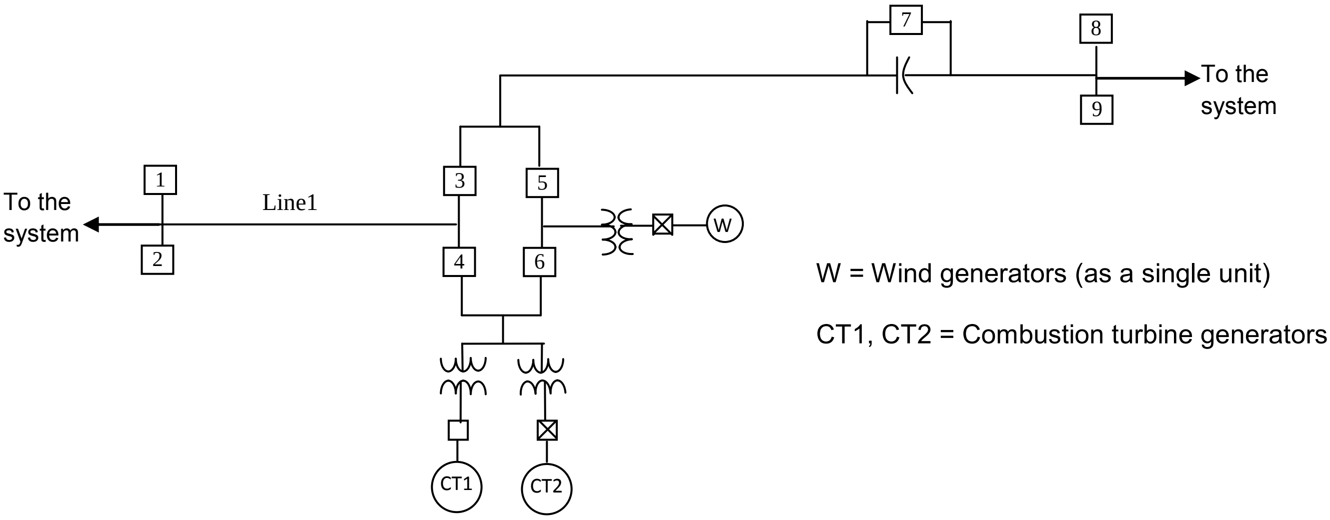

Figure 1: System one line diagram – All breakers were closed except CT1 breaker and Breaker-7.

1.2 Event Analysis

The generator current waveforms captured are shown in Figure 2. Initial investigation of the captured waveforms indicated the presence of D.C. and low frequencies from 9 to 13 Hz, indicating different oscillatory interactions between wind machines and the system. These frequencies were below the sub-synchronous resonance mode 1 frequencies of combustion turbine generator (CTs).

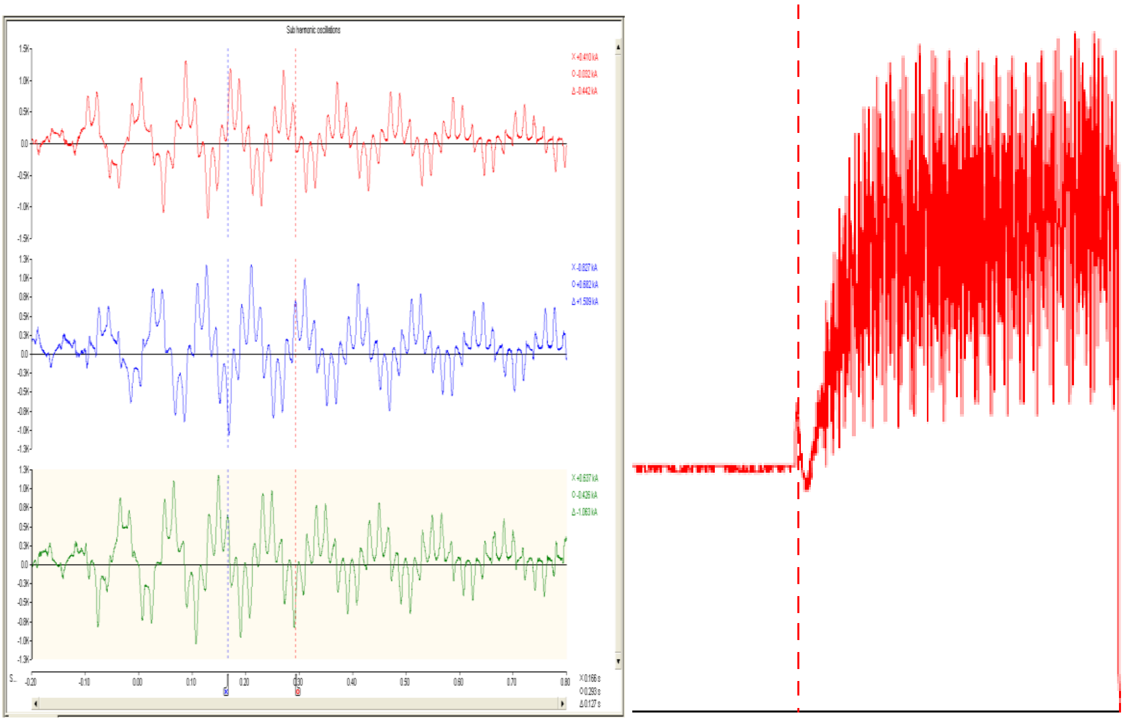

Figure 2: Real event capture of the generator currents with wind farm sub-harmonic interaction.

This was the motivation for designing a microprocessor-based sub-harmonic protection scheme to detect and isolate the wind generation in the event of sustained sub-harmonic oscillations. The new device monitors system voltages and currents on the power system that may be present in the 5Hz to 25Hz frequency window. There are provisions to set the sub-harmonic frequency bandwidth or the specific sub-harmonic frequency components of the collected system's voltages and currents. The device can be programmed to either detect only the sub-harmonic quantities or record them for future use in simulations. It an also initiate protective action by closing output contacts that can be used to shut down equipment or to initiate corrective actions to prevent damage. The high-level hardware architecture for the protection scheme is described in the next section.

2. Microprocessor-Based Hardware Architecture

The microprocessor based device can accept four sets of three phase currents and two sets of three phase voltages from instrument transformers. Two sets of level detectors can be set for each input quantity to detect specific frequency components in the 5 to 25 Hz range, or to detect all frequencies over this range. The device also has the ability to sum quantities from two current transformers on a ring or breaker-and-a-half bus arrangement that might represent the total current on a particular line, and then apply the level detectors to these summated quantities. 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 device has the ability to collect and store fault and harmonic voltage and current quantities. The device samples the input signals at 96 samples per cycle (60Hz or 50 Hz system), so with its anti-aliasing filtering, up to the 25^{th} harmonic is available. Following this process, a complete synopsis of power system data is collected for further studies by the user. All detector and event operations are time tagged and presented in an event log. IRIG-B time synchronization is possible by connecting this device to a GPS clock. All information and data collected can be retrieved remotely via the local area network (LAN) through Ethernet ports, or locally via the USB port located on the front of the device.

Figure 3 shows the block diagram of the microprocessor based hardware architecture used to detect the sub-harmonic oscillations.

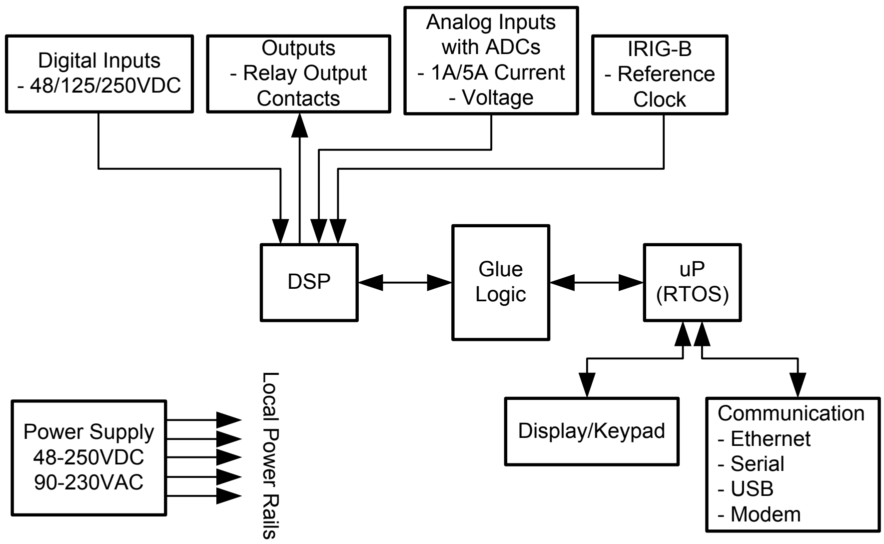

Figure 3: Block diagram of the microprocessor-based hardware architecture to detect sub-harmonic oscillation.

3. Sub-Harmonic Detection Process

The analog signals from the CTs and PTs are fed to the low pass analog filter to eliminate aliasing effects, and then passed to the A/D convertor where the signals are converted to digital samples at a rate of 5760 Hz (96 samples/cycle). The digital samples of each analog channel and the derived virtual channels are evaluated for the sub-harmonic frequencies from 5 Hz to 25 Hz with a resolution of 1Hz, using Recursive Fourier Transform (RFT). The extracted sub-harmonic signals pass onto the sub-harmonic detection logic module for comparison, and based on the detector level, the output contacts will be actuated for alarm and/or trip conditions. The simplified process is illustrated in Figure 4.

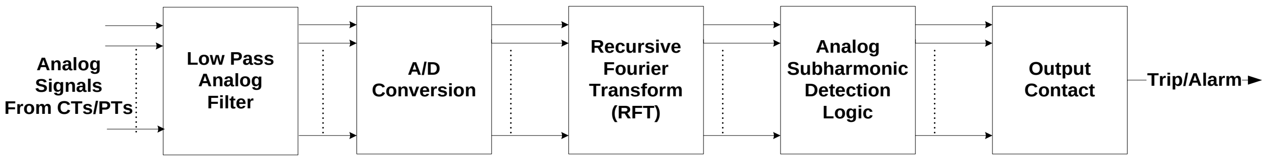

Figure 4: Illustration of the sub-harmonic detection process.

4. Principle of Sub-Harmonic Detection

The basic principle used in detecting the presence of the sub-harmonic is to compare the magnitude of each sub-harmonic between the Fmin and Fmax of the user-defined frequency range, and then compare it with the user-defined (Lset) magnitude threshold level using the following logic (see Figure 5):

Trip or Alarm: = max (f2, f3, f4, f5, f6, f7) > Lset

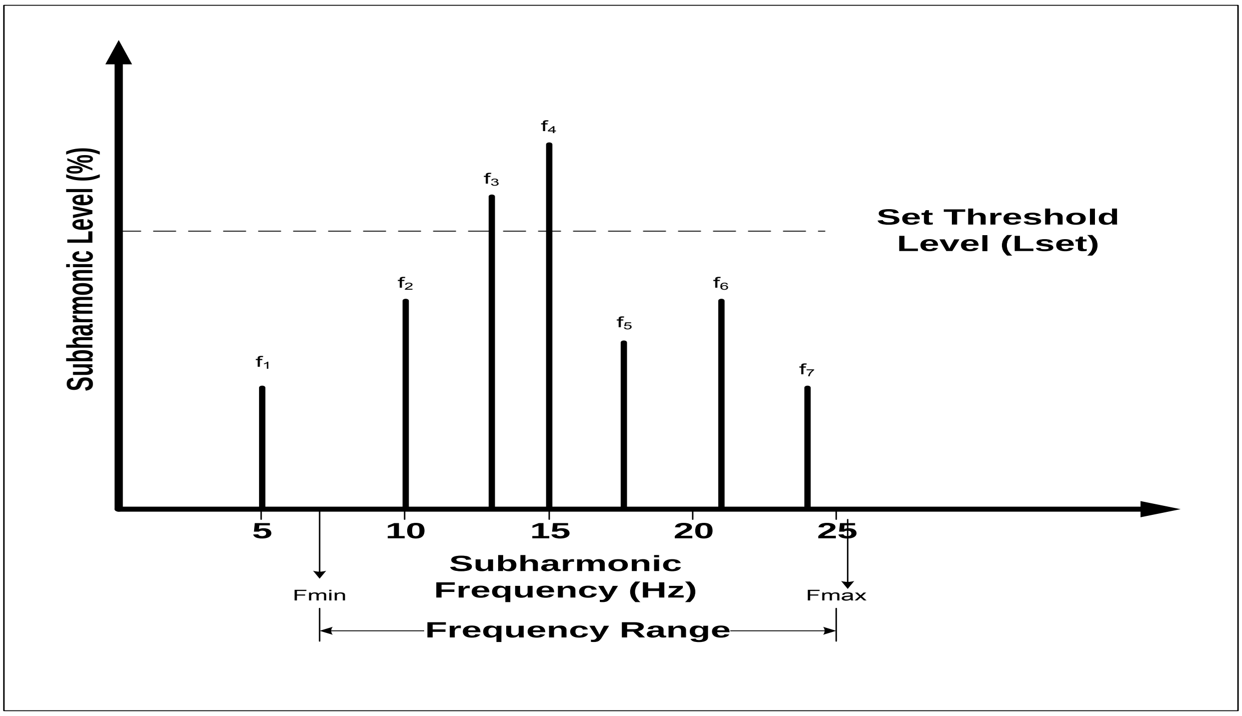

Figure 5: Sub-harmonic detection principle.

The functional logic diagram corresponding to the above principle is illustrated in Figure 6. As described in the figure, there are three level detectors available for each voltage, current, or virtual input.

The nominal sub-harmonic detector compares the level by estimating the ratio of sub-harmonic magnitude to the nominal CT/PT ratio. For example, if the nominal CT ratio is 5A and the estimated sub-harmonic magnitude is 2.5 A at 5Hz, then the nominal sub-harmonic level is compared as follows:

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

Similarly, the fundamental sub-harmonic detector logic is compared with respect to the fundamental voltage or current quantities.

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

$$\text{TSHD (\%)} = \left(\frac{\sqrt{f_{5Hz}^2 + f_{6Hz}^2 + f_{7Hz}^2 \dots\dots\dots\dots\dots + f_{25Hz}^2}}{f_{60Hz}} \right) x\,100$$

Note, as shown in the above equation, that all the sub-harmonic magnitudes from 5Hz to 25 Hz will be taken into consideration for the TSHD evaluation, with respect to 60Hz fundamental voltage, current, or virtual derived channel. The same definition is applicable for a 50Hz system.

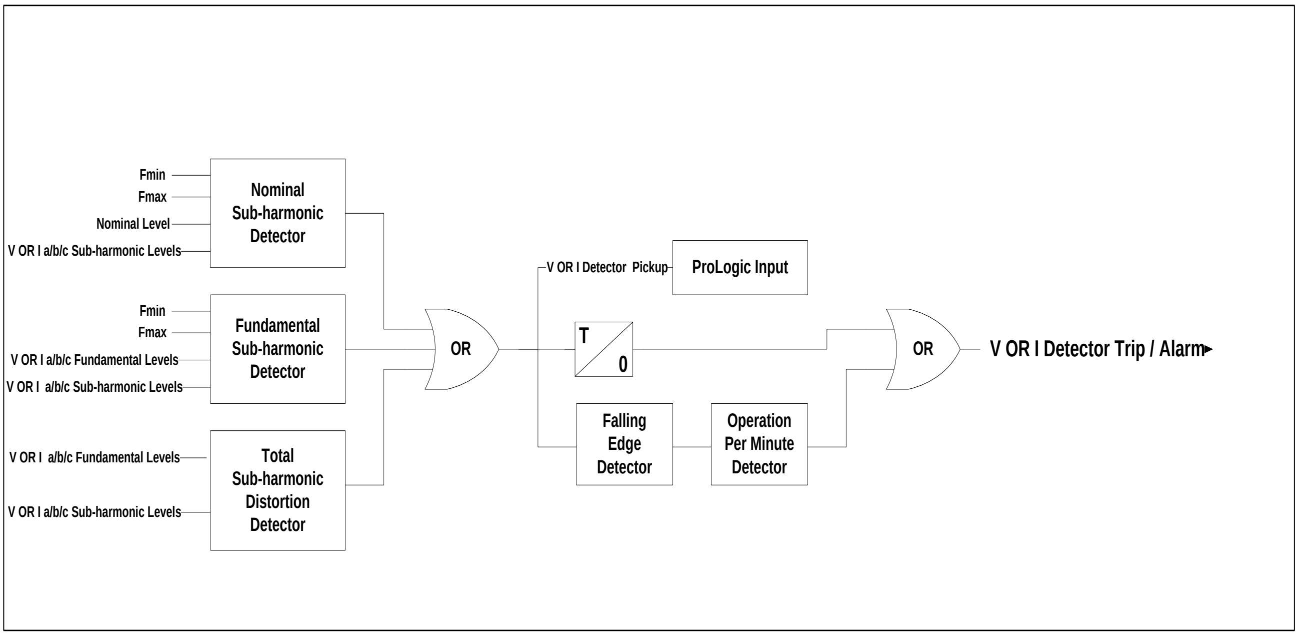

Figure 6: Functional logic diagram for sub-harmonic detection using various detectors for trip/alarm indication.

5. Operations/Minute Detector

There are occasions when the statistical nature of the 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, and will never be noticeable by the conventional detectors mentioned in the above section. Periodic occurrence of this event, even though for a shorter duration than the configured time, can cause detrimental effects to the power system network and its components. To capture such events, a special operations/minute detector is designed, which functions as shown in Figure 7.

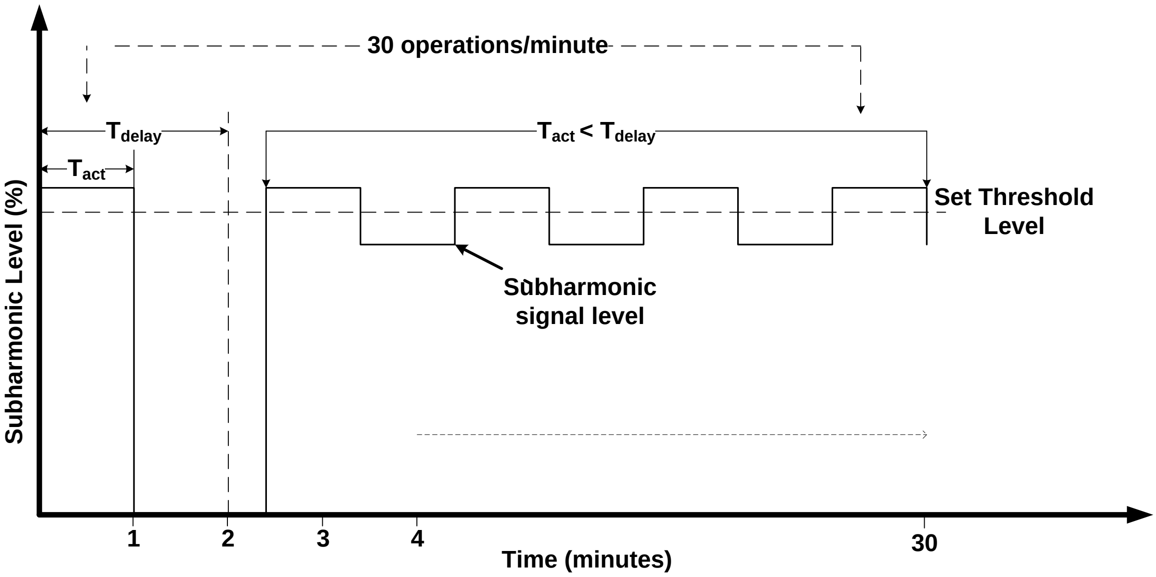

Figure 7: Special operations/minute detector to capture periodic events not captured by conventional detectors.

In the above example, 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.

6. Results and Discussions

Several test cases have been carried out to verify the sub-harmonic protection technique, using an RTDS simulator.

1. Nominal sub-harmonic detector
2. Fundamental sub-harmonic detector
3. Total sub-harmonic detector
4. Operations/minute detector

The settings screen shown in the Figure 8 is used to set the various detector levels. As explained in the previous section, each current, voltage, or virtual derived channel can be configured to have two detectors, and each can be used for an alarm and/or trip output.

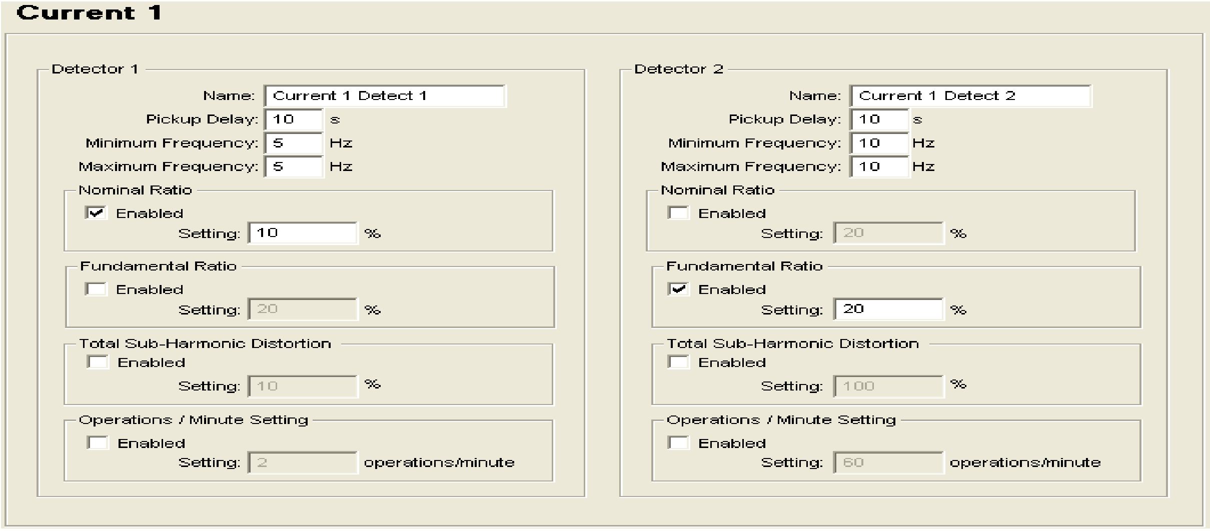

Figure 8: Settings screen for configuring various sub-harmonic detector levels.

As shown in Figures 9a-9d, the nominal, the fundamental, the TSHD, and the operations-per-minute detectors have been verified using simulated COMTRADE files. These files are then played back using the RTDS simulator, and the detectors have operated correctly, as per their configurations.

In Figure 10, a sequence of event for the operations-per-minute detector is depicted.

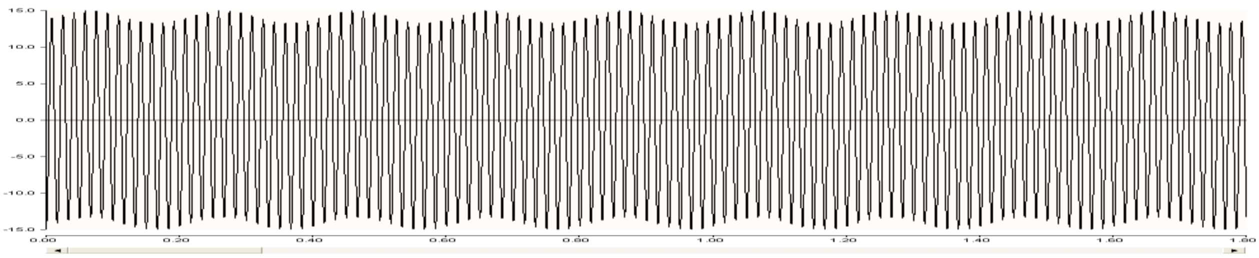

Figure 9(a): Nominal sub-harmonic detector – 5Hz (X axis – time in seconds), (Y axis – current in amps).

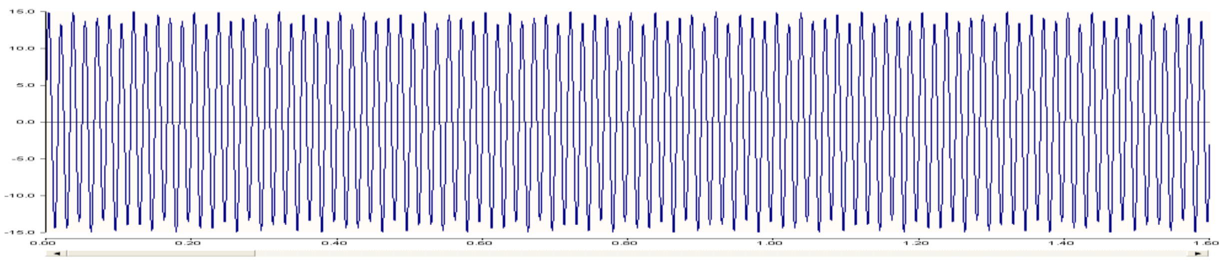

Figure 9(b): Fundamental sub-harmonic detector – 25 Hz (X axis – time in seconds), (Y axis – current in amps).

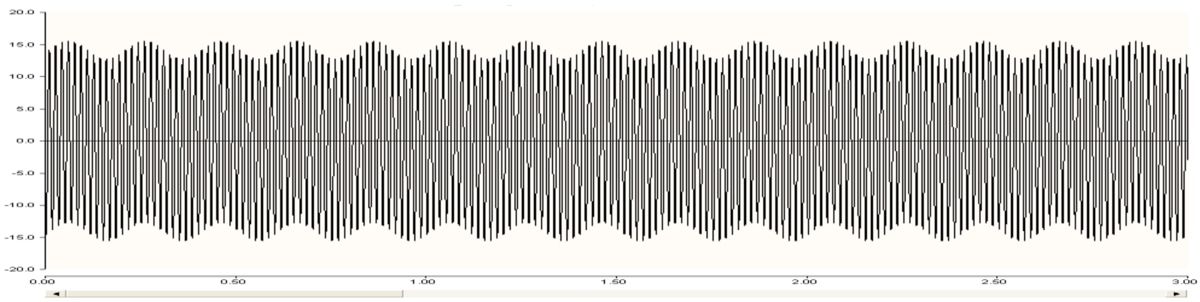

Figure 9(c): TSHD detector – 5Hz (X axis – time in seconds), (Y axis – current in amps).

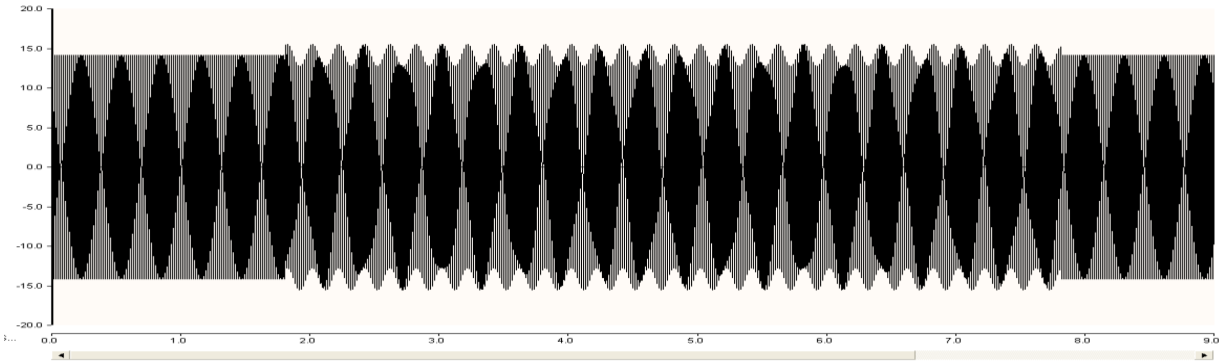

Figure 9(d): Operation/minute detector – 5Hz and 5 operations/minute.

Figure 9: Input COMTRADE file current channels for testing various sub-harmonic detectors.

```
2010Sep23 21:55:47.916  Spare 1:OUT1 : Open
2010Sep23 21:55:47.814  Current 1 Detect 1:SHD1: Low
2010Sep23 21:55:47.811  ProLogic 1:PL1 : Low
2010Sep23 21:55:47.811  Current 1 Detect 1:SHD1: High (R)
2010Sep23 21:55:47.811  Spare 1:OUT1 : Closed
2010Sep23 21:55:39.811  ProLogic 1:PL1 : High
2010Sep23 21:55:37.811  ProLogic 1:PL1 : Low
2010Sep23 21:55:29.811  ProLogic 1:PL1 : High
2010Sep23 21:55:27.811  ProLogic 1:PL1 : Low
2010Sep23 21:55:19.811  ProLogic 1:PL1 : High
2010Sep23 21:55:17.811  ProLogic 1:PL1 : Low
2010Sep23 21:55:09.811  ProLogic 1:PL1 : High
2010Sep23 21:55:07.811  ProLogic 1:PL1 : Low
2010Sep23 21:54:59.811  ProLogic 1:PL1 : High
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Figure 10: Operations/minute event log display, showing the trip after detecting 5 operations.

7. Conclusions

The new event captured at the Xcel Energy utility lead to the development of a microprocessor-based sub-harmonic protection technique. With the increased use of wind generators feeding HV and EHV utility networks, it is necessary to ensure that sub-harmonic oscillations are monitored, and that the electrical grid is protected from any resulting detrimental effects.

8. References

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