Commissioning Process and Acceptance Test of a Sub-harmonic Protection Relay

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Abstract

Numerous technical papers have been published discussing the topic of Sub-Synchronous Resonance (SSR) and more recently about new protection devices capable of detecting and protecting against the detrimental effects of SSR. The advent of such protection devices has created the new challenge of testing and commissioning such devices. Commissioning sub-harmonic protection devices require following a process that differs from the traditional testing and commissioning process of microprocessor devices. This paper presents the experiences of the authors during the commissioning of Sub-harmonic Protection Relays and describes the process that was followed prior to the site visit and then during the actual commissioning of the relay.

The paper will review the following topics:

- The characteristics of a Sub-Harmonic Protection Relay
- The engineering process for the determination of settings
- The determination of test cases to make sure all the features of the relay are properly tested
- The use of a real time digital simulator for the preparation of COMTRADE files to be used during the relay testing
- The process followed at site to commission the relay by using advanced relay test equipment capable of playing back COMTRADE files.

During the commissioning process of sub-harmonic protection relays the authors discovered that there is very little understanding on SSR and SSCI phenomena, on the engineering behind the selection of settings for sub-harmonic protection IEDs and on the process of testing and commissioning such IEDs, hence the need to educate the Protection & Control community.

The paper describes the use of software capable of simulating and modeling power systems, similar to PSCAD™/EMTDC™ or RTDS™ for the creation of test cases in COMTRADE format that will be used to test de relay. Prior to the creation of test cases, the process requires the review of power system simulation cases that were used to determine the relay settings in order to create COMTRADE test cases that will confirm that the relay responds as expected. The process requires testing for:

- Sub-harmonic frequency ranges – making sure the relay does not misoperate for frequencies outside the desire frequency range
- Sub-harmonic magnitudes – making sure the relay does not misoperate for sub-harmonics with magnitudes below the set thresholds
- Protection features at the fundamental frequency

Keywords: Sub-synchronous resonance (SSR), sub-synchronous interactions, transmission lines, series capacitors, sub-harmonics, Real Time Digital Simulator

1. Introduction

A few papers have been written in the last few years discussing the different type of sub-synchronous Interactions between elements of the power system particularly those involving large steam generators, wind farms, HVDC and series compensated transmission lines.

Sub-synchronous Interactions (SSI) are 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. Several types of sub-synchronous interactions are possible, including Sub-Synchronous Resonance (SSR), Sub-Synchronous Torsional Interactions (SSTI), and Sub-Synchronous Control Interactions (SSCI). SSR and SSTI in particular are well document and well understood and explained with some detail by Andrew L. Isaacs, Garth D. Irwin, and Amit K. Jindal in [1].

The IEEE published a guide for sub-synchronous resonance [2] reviewing the most basic aspects of SSR and device dependent sub-synchronous oscillations and cites pertinent references that support the reviews.

NERC published a Lesson Learned - Sub-Synchronous Interaction between Series-Compensated Transmission Lines and Generation in July 26, 2011. The Lessons Learned where indicating that recent events of sub-synchronous oscillations between wind turbines and a series capacitor in the transmission network resulted in significant damage to the wind turbines. A normally cleared fault on a 345 kV transmission line resulted in a post-contingency system configuration in which two wind farms were radially connected to a series compensated 345 kV transmission line. This configuration produced sub-synchronous control instability (SSCI) between the wind turbines and the series compensated transmission line, resulting in severe over-voltages, current distortion, tripping of additional transmission facilities, and damage to the wind farm control circuits. The document concludes that appropriate transmission system design enhancements need to be considered when studying integration of large scale wind farms. Some measures that may be considered include installing additional protection systems to detect SSR and take corrective action and also installing additional protection systems to avoid SSR based on system topology.

The recommendations by NERC lead protection relay vendors to develop a Sub-harmonic Protection Relay capable of detecting sub-synchronous interactions to take corrective or even preventive actions.

K. Narendra et al., provide in [3] a detailed description of a microprocessor based relay designed specifically to detect and protect against sub-synchronous interactions. [4][5][6] provide details on the application of a sub-harmonic protection relay, the engineering process to calculate settings, and also propose a process to validate the performance of the relay.

This paper focuses on the process for site acceptance testing of a sub-harmonic protection relay for both the sub-harmonic detection features as well as for the fundamental frequency protection features.

2. Sub-Harmonic Protection Settings Description

[6] A sub-harmonic protection relay protects against sub-harmonic oscillations by measuring the voltages and currents magnitudes of sub-harmonics with frequencies in the range of 5-45Hz for 50Hz systems or 5-55Hz for 60Hz systems. The 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 5-45Hz for 50Hz systems or 5-55Hz for 60Hz systems, with two levels of detection. The device also has the ability to sum quantities from any 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.

Each current or voltage detectors have the following sub-harmonic detection settings:

- Frequency Range selectable between 5 and 45 Hz for 50Hz systems or 5 and 55Hz for 60Hz systems
- Sub-harmonic level pick up value
  - Nominal Ratio
  - Fundamental Ratio
- Time delay
- Total Sub-harmonic Distortion
- Operations / Minute Setting

- 2^{nd} Harmonic Blocking – only for current detectors
- 5^{th} Harmonic Blocking – only for current detectors

The setting format is shown in Figures 1 and 2 below.

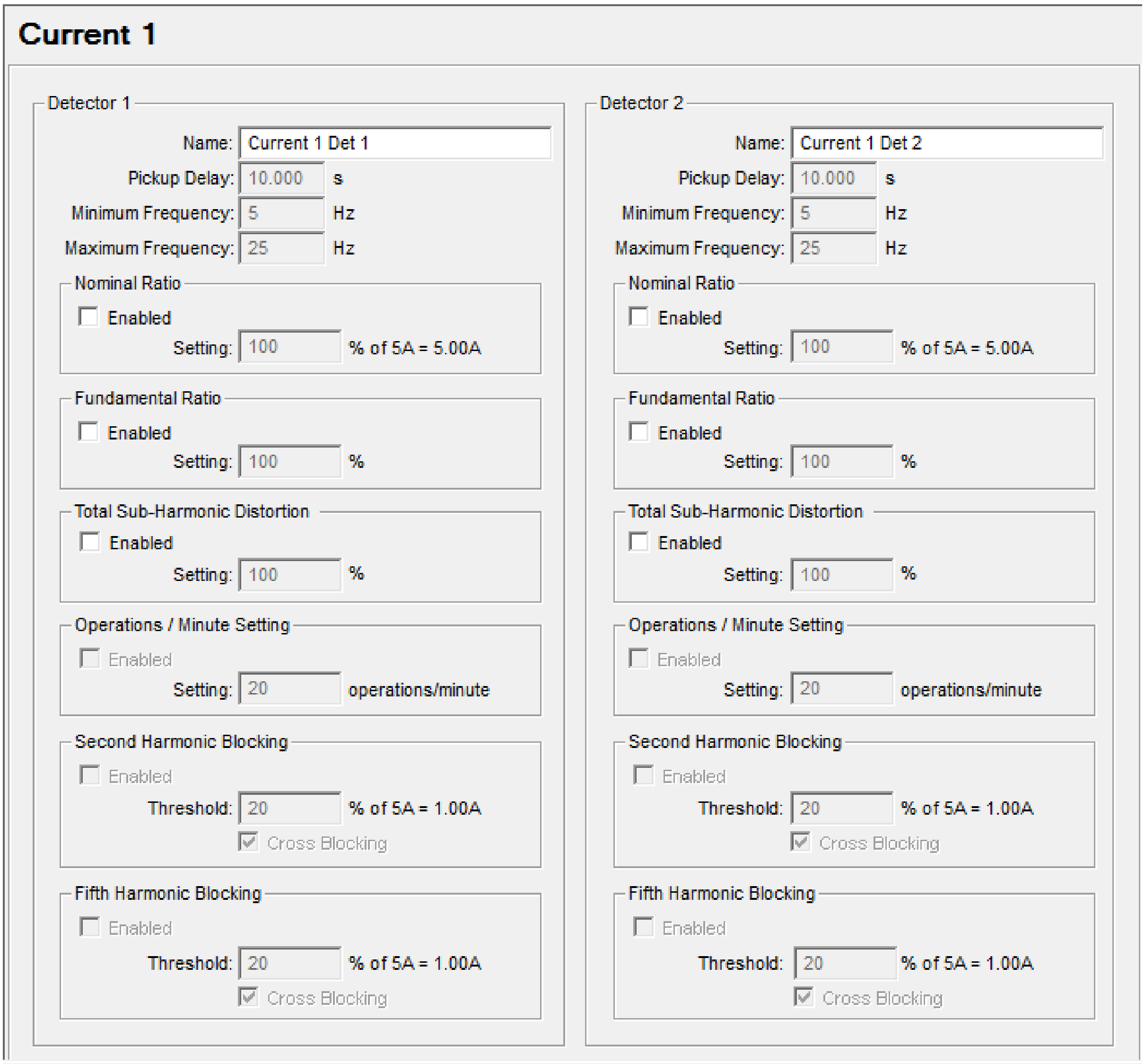

Figure 1 - Current Detector Settings

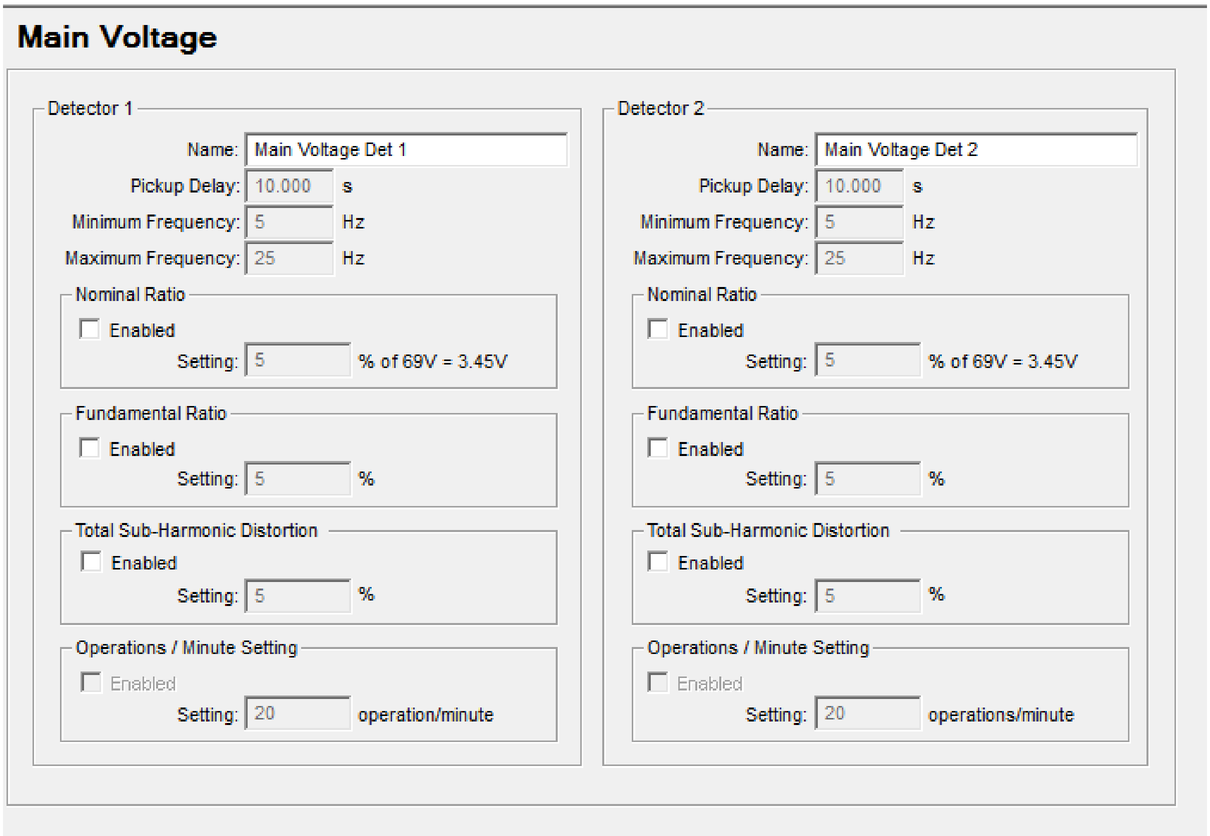

Figure 2 - Voltage Detector Settings

The following sections provide a description of protection features shown in Figures 1 and 2.

2.1. Frequency Range

The Frequency Range is the range of frequencies of the sub-harmonics that the relay will monitor. The boundaries of the frequency range are defined by Minimum Frequency and Maximum Frequency as shown in Figure 1 and 2. Any sub-harmonic with a frequency outside the frequency range will not be considered for the application of settings, except for TSHD.

[3] The basic principle used in detecting the sub-harmonic is to compare the magnitude of each sub-harmonic between the minimum and maximum frequencies of the user defined frequency range, and then compare it with the user defined magnitude threshold level.

For the purpose of testing the relay, it is necessary to demonstrate that the relay discriminates between sub-harmonic frequencies within and outside the frequency range.

2.2. Sub-harmonic Level Pickup Value

The sub-harmonic level pickup can be associated to the Nominal and Fundamental ratio settings.

[3]The nominal sub-harmonic function compares the pickup level setting with the ratio of sub-harmonic magnitude over the relay's nominal current or voltage inputs. Similarly, the fundamental sub-harmonic detector compares the pickup level setting with the ratio of sub-harmonic magnitude over the fundamental quantity. The relay will declare a pickup when the nominal or fundamental ratio of any sub-harmonic within the frequency range exceeds the pickup level setting. [3]Figure 3 provides a graphical interpretation.

During testing it is necessary to demonstrate that the relay is able to accurately calculate the Nominal and Fundamental ratio magnitudes and that it picks up at the corresponding setting within the specified accuracy.

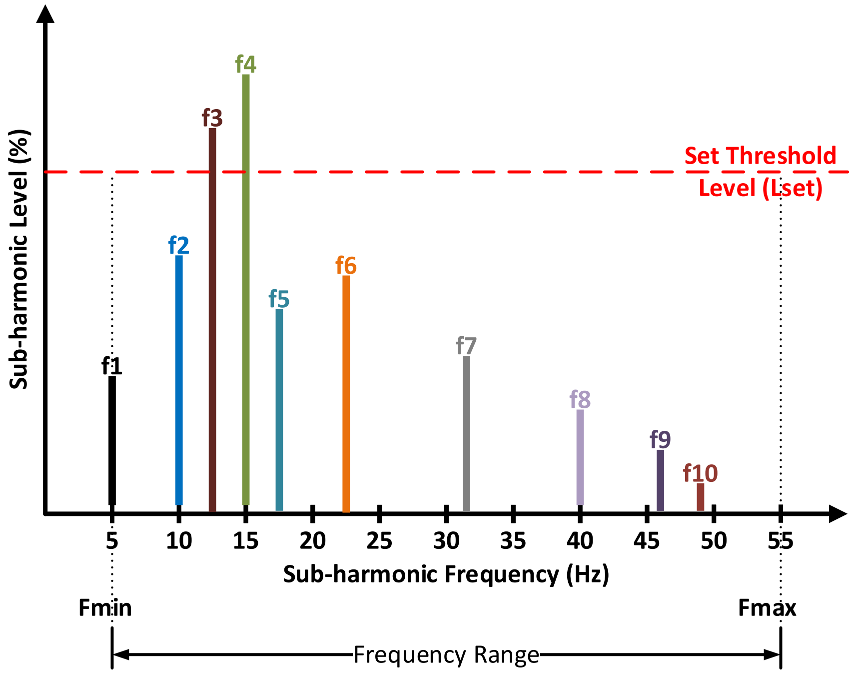

Figure 3 - Sub-harmonic levels for Nominal and Fundamental Ratio for a 60Hz system

2.3. Total Sub-harmonic Distortion

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

$$\mathrm{TSHD}(\%) = \frac{\sqrt{f_{5Hz}^2 + f_{6Hz}^2 + f_{7Hz}^2 + \cdots + f_{55Hz}^2}}{f_{60Hz}^3} \qquad (1)$$

[3] Note that, as shown in the above equation, all the sub-harmonic magnitudes from 5-45 Hz for 50Hz systems or 5-55Hz for 60Hz systems will be 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.

Testing this function will verify that the relay properly calculates the TSHD and that it picks up at the set value within the specified accuracy.

2.4. Operations per Minute

[3] This function has the purpose of counting sub-harmonic oscillations above threshold set limit with a duration shorter than the configured time delay, that may take place unnoticed by the conventional detectors as described above. Periodic occurrence of this event, even though for a shorter duration than the configured time, can have a negative impact in the power system network and its components, particularly in large thermal generators or wind turbine generators. To capture such events, a special operations/minutes detector is designed, which functions as shown in Figure 4.

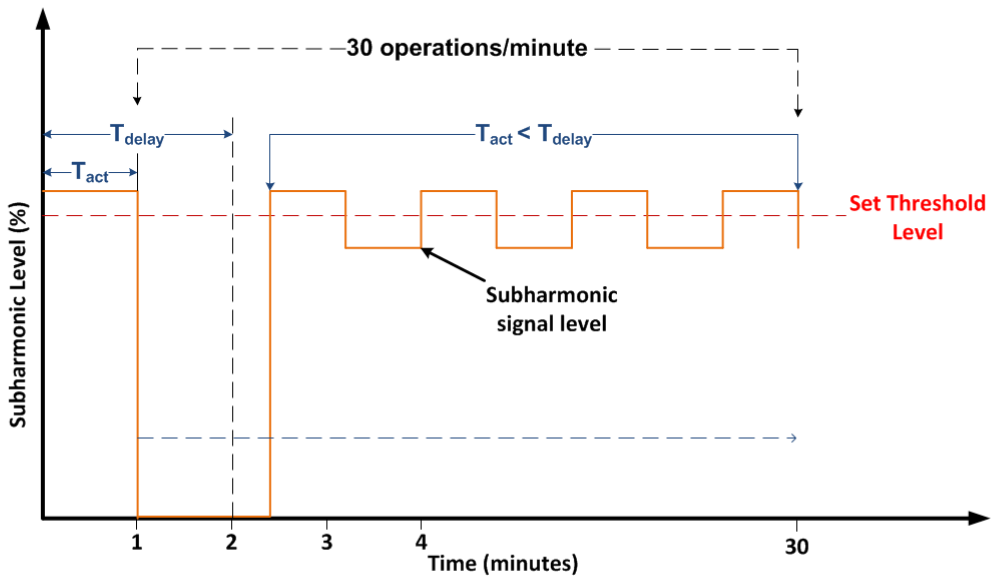

Figure 4 - Operations per minute principle

[3] 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. The 30 operations (assertion above set limit) will be internally counted and monitored. If the set operations per minute count exceed 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.

Testing this feature confirms that the relay accurately measures the time duration of each event, that the relay properly identifies the number of incidents with shorter duration than T_{delay}, and that it accurately counts the number of short duration incidents.

2.5. 2nd and 5th Harmonic Blocking

Since the relay will be exposed to transients including transformer or feeder pickup inrush, or over-fluxing the primary winding of the transformer, by harmonic blocking, the relay measures the 2nd and 5th harmonic content of the current wave and blocks the relay operation thereby eliminating false tripping (inrush current may be rich in 2nd harmonic component and 5th harmonic for over-fluxing).

Testing these features confirm that the relay properly extracts the 2nd and 5th harmonic from the current wave, which also may contain sub-harmonics, and properly blocks tripping outputs when the 2nd and 5th harmonic content exceeds the threshold setting.

3. Testing the Relay Functions

3.1. Test Setup

Figure 5 shows the equipment setup for testing.

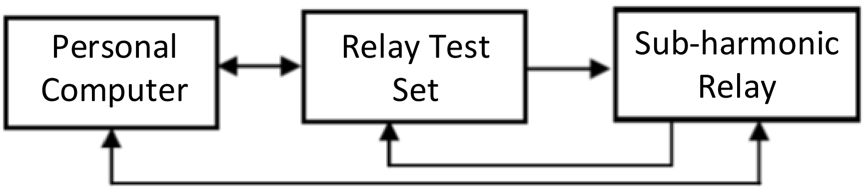

Figure 5 - Equipment Setup for Testing

The COMTRADE files needed to test each one of the features discussed in this paper are generated by means of software capable of simulating and modeling power systems, similar to PSCAD™/EMTDC™ or RTDS™. The COMTRADE waveforms are played back using a compatible relay test set with capabilities for transient playback.

3.2. Testing the Boundaries

For the settings of the Sub-Harmonic Detectors, voltage and current, a sub-harmonic frequency range can be set by choosing a ‘Minimum Frequency’ and a ‘Maximum Frequency’ within S-PRO’s frequency range of 5Hz to 45Hz for 50Hz systems or 5Hz to 55Hz for 60Hz systems.

The settings of minimum and maximum frequency are used by the ‘Nominal Ratio’ and ‘Fundamental Ratio’ only and the elements associated to them, ‘Operations/Minute’ and ‘Harmonic Blocking’ (for current only).

For ‘Nominal Ratio’ and “Fundamental Ratio’ elements to pick up, two conditions must be met: the magnitude of the sub-harmonic components result in ratios greater than the elements’ settings’ threshold, respectively, and the frequency of the sub-harmonic components falls within the frequency range settings.

Testing the boundaries of the frequency range is performed by injecting voltage and current signals by means of a customized COMTRADE files that contain signals with specific sub-harmonic content.

COMTRADE files are used to test the frequency boundaries of the frequency range of the ‘Nominal Ratio’ of the voltage detectors. For the lower boundary, the COMTRADE file contains a fixed fundamental voltage with a magnitude equal to the relay nominal voltage component plus a sub-harmonic component with a magnitude which results in a nominal ratio greater than the voltage detector’s ‘Nominal Ratio’ threshold setting. The sub-harmonic frequency in the COMTRADE file is ramped up starting from a value lower than the ‘Minimum Frequency’ setting to a value greater than the ‘Minimum Frequency’ setting. It is expected that the relay will respond only when the frequency of the sub-harmonic content matches or it is greater than the frequency of the lower boundary setting of the sub-harmonic frequency range.

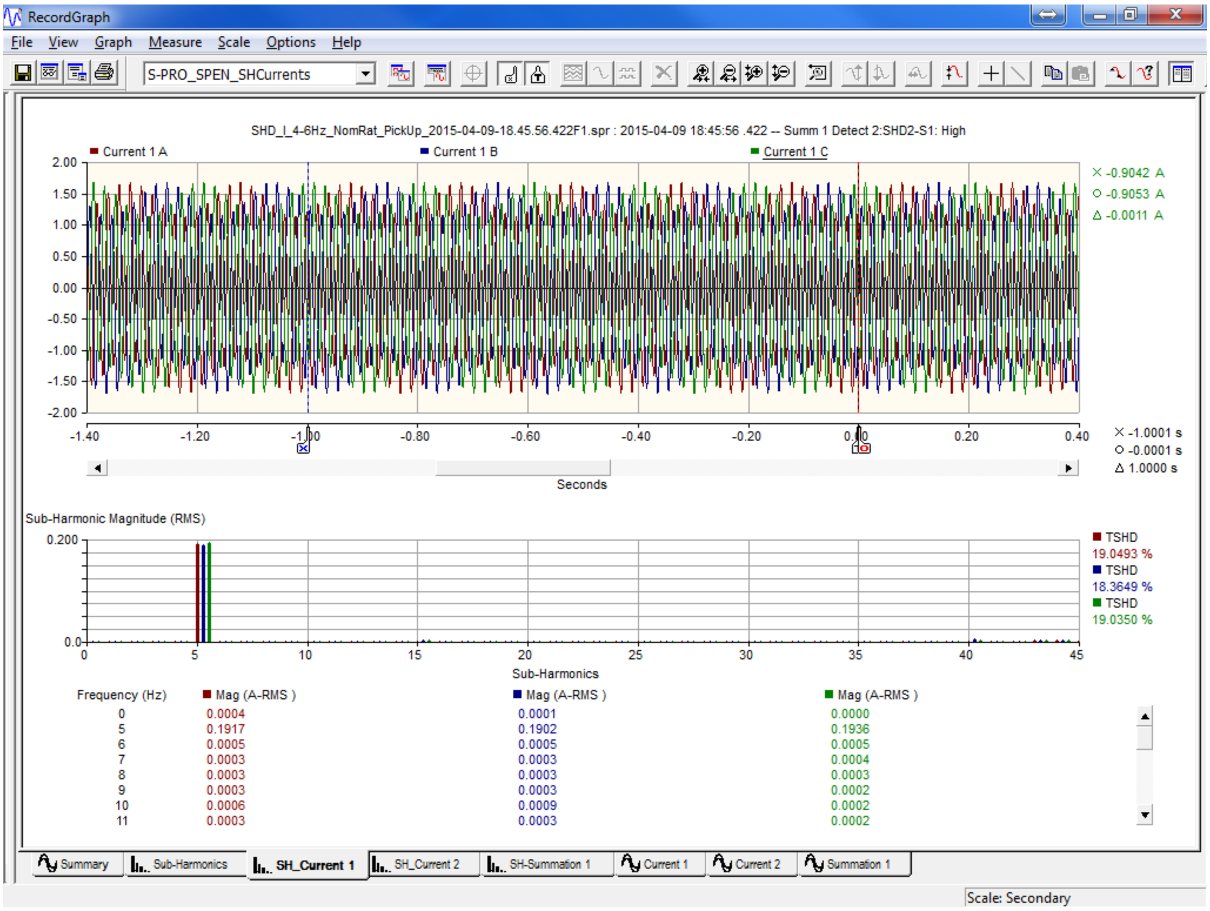

Figure 6 - Current Waveform used to test Minimum Frequency

Another COMTRADE file is used to test the upper boundary setting of the sub-harmonic frequency range for voltage. As for the lower boundary, it contains a fixed fundamental voltage component with a magnitude equal to the relay nominal voltage plus a sub-harmonic component with a magnitude which results in a nominal ratio greater than the voltage detector's 'Nominal Ratio' threshold setting. The sub-harmonic frequency in the COMTRADE file is ramped down starting from a value higher than the 'Maximum Frequency' setting to a value lower than the 'Maximum Frequency' setting. It is expected that the relay will respond only when the frequency of the sub-harmonic content matches or it is lower than the frequency of the higher boundary setting of the sub-harmonic frequency range.

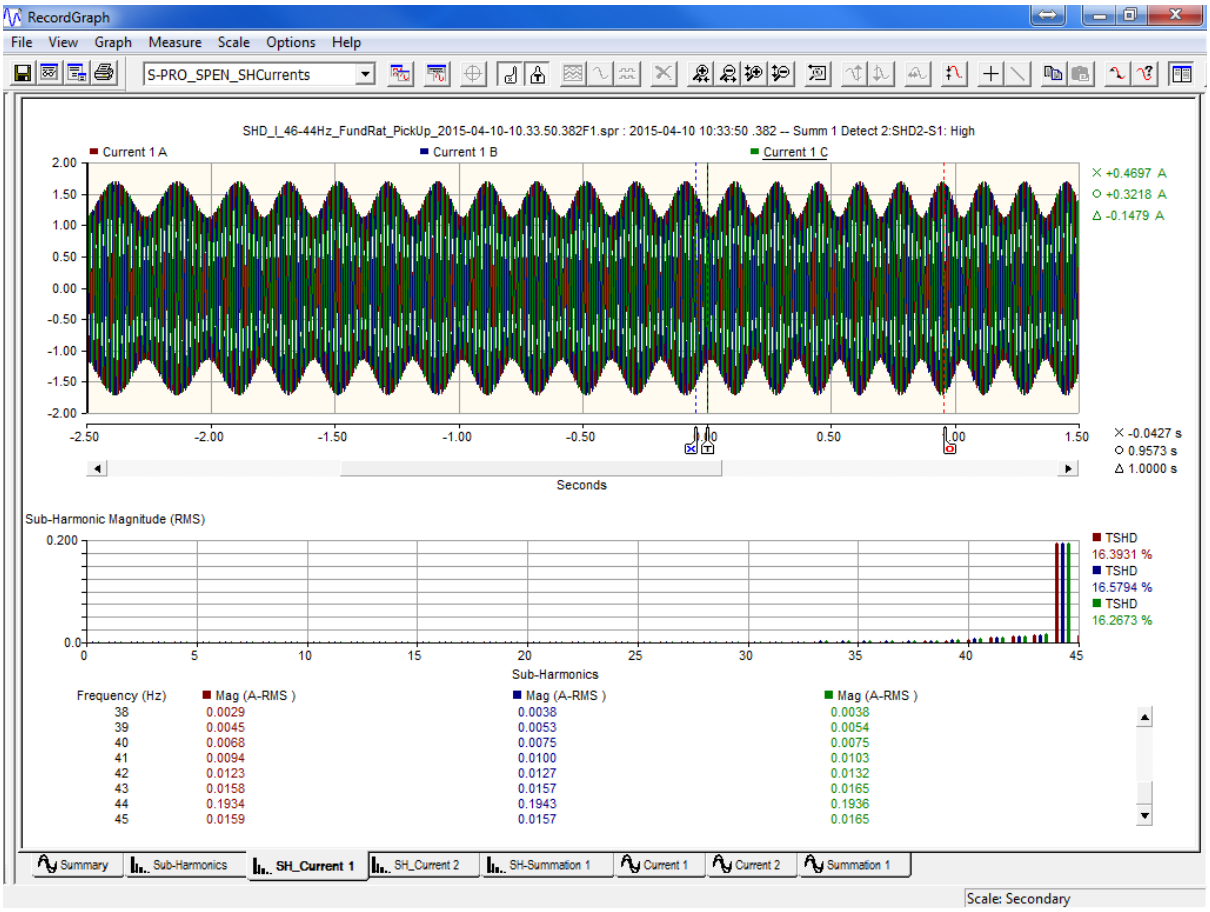

Figure 7 - Current Waveform used to test Maximum Frequency

The same procedure is repeated to test the frequency boundaries for voltage 'Fundamental Ratio' element. However, this time the magnitude of the fundamental voltage is not equal to the nominal voltage and the sub-harmonic content is selected such that 'Fundamental Ratio' is greater than the settings' threshold for the voltage detector.

The current detector elements are tested in the same fashion as the voltage ones.

3.3. Testing for Pickup Values

For the settings of the Sub-Harmonic Detectors, voltage and current, thresholds can be set individually for each element.

For the 'Nominal Ratio', the elements' threshold are defined by the ratio of the sub-harmonic component magnitude and the nominal quantity magnitude, i.e. 69V for the voltage element and either 5A or 1A for the current element.

For the 'Fundamental Ratio', the elements' threshold is defined by the ratio of the sub-harmonic component magnitude and the fundamental component magnitude for voltage and current.

For 'Nominal Ratio' and "Fundamental Ratio' elements to pick up, two conditions must be met: their ratios greater than the respective elements' settings' threshold and the frequency of the sub-harmonic components fall within the frequency range settings.

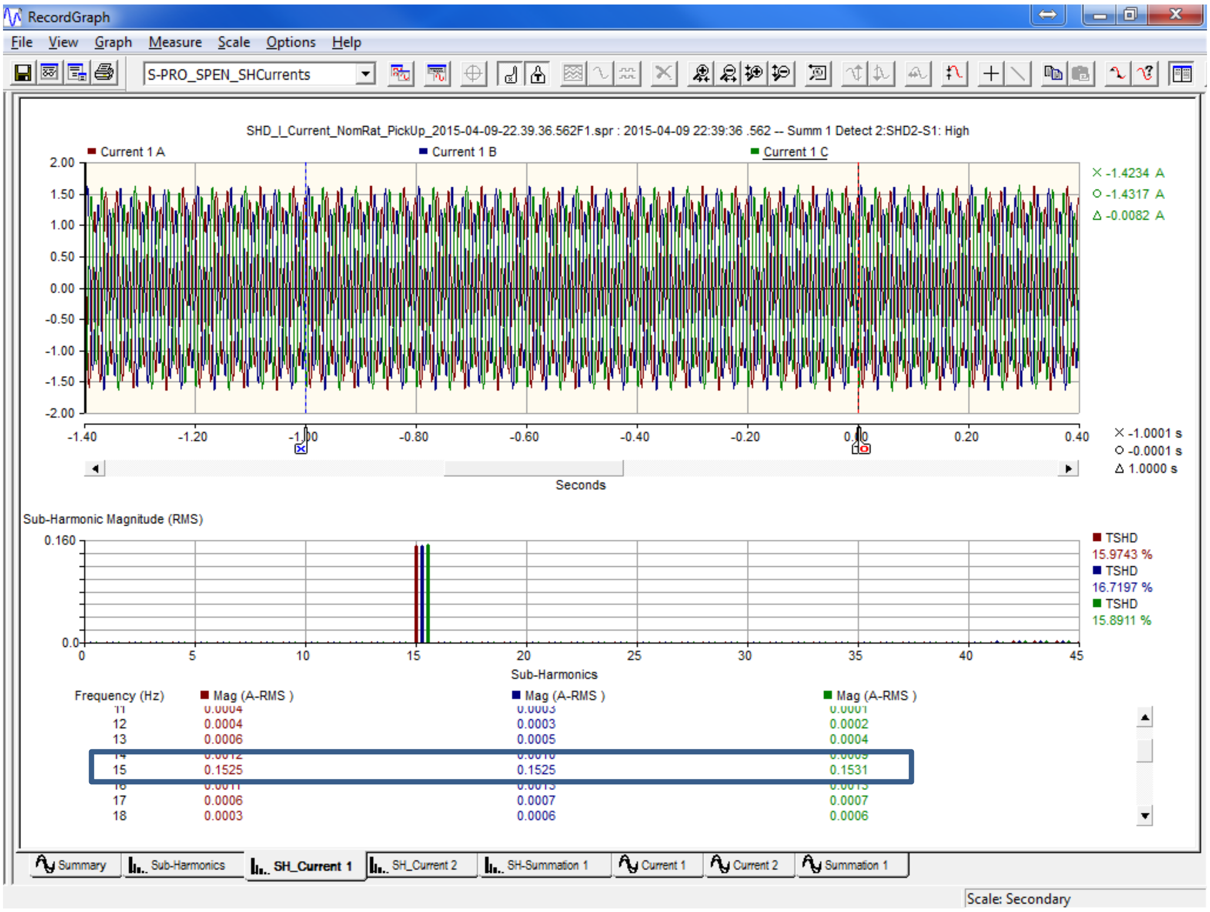

Figure 8 - Current Waveform used to test Nominal or Fundamental Ratio Pickup

For the 'Total Sub-Harmonic Distortion (TSHD)', the elements' threshold are defined by the ratio of the summation of all magnitudes of the quantities within either 5Hz-45Hz, for 50Hz systems, or 5Hz-55Hz, for 60Hz systems, and the fundamental quantity magnitude.

For the 'TSHD' elements to pick up, the summation of all sub-harmonic magnitudes of the quantities must be greater than the TSHD elements' thresholds.

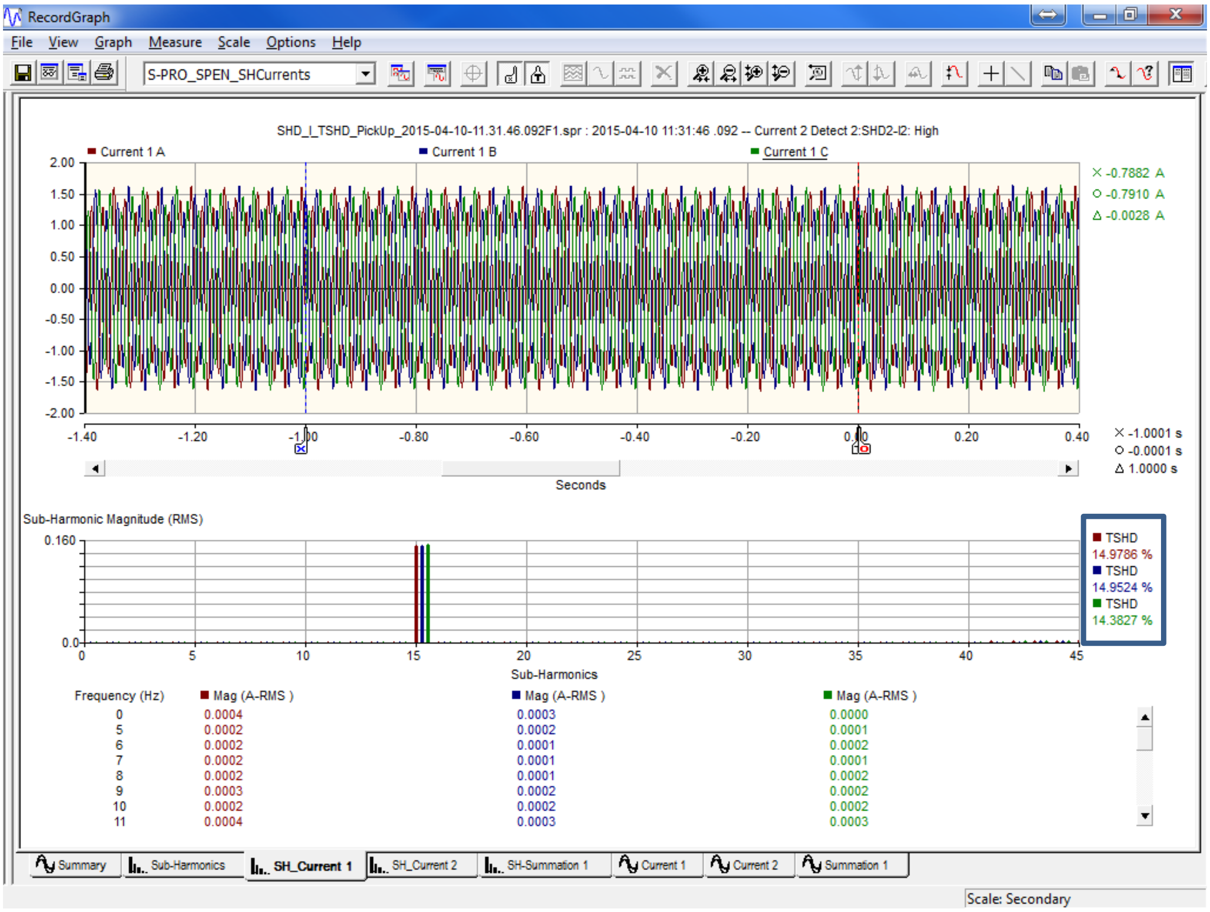

Figure 9 - Current Waveform used to test Total Sub-harmonic Distortion (TSHD)

The pickup for all sub-harmonic detectors, voltage and current, are tested.

The testing is performed by injecting voltage and current signals as a customized COMTRADE files.

A COMTRADE file is used to test the pickup of the 'Nominal Ratio' for voltage with a fixed fundamental voltage component. The COMTRADE also has a sub-harmonic component at a fixed sub-harmonic frequency and their magnitude varying in a way where the 'Nominal Ratio' also varies from a value smaller to greater than its threshold.

A second COMTRADE file is used to test the pickup of the 'Fundamental Ratio' for voltage. However, this time the fixed fundamental voltage component magnitude of the COMTRADE file is considered, besides the sub-harmonic component, to have a 'Fundamental Ratio' varying from a value smaller to greater than its threshold.

The current detectors' elements are tested in the same fashion as the voltage ones for 'Nominal Ratio' and 'Fundamental Ratio' pickup tests.

Another customized COMTRADE file is used to test the pickup of the TSHD for voltage with a fixed fundamental component and increasing the sub-harmonic component magnitude to vary the TSHD from a value smaller to greater than its threshold at a fixed sub-harmonic frequency.

The current detectors' elements are tested in the same fashion as the voltage ones for 'TSHD' pickup tests.

3.4. Testing for Operating Time

To verify the response time of the S-PRO, the 'Nominal Ratio', 'Fundamental Ratio' and 'TSHD' elements, for voltage and current, of the Sub-Harmonic detectors are tested.

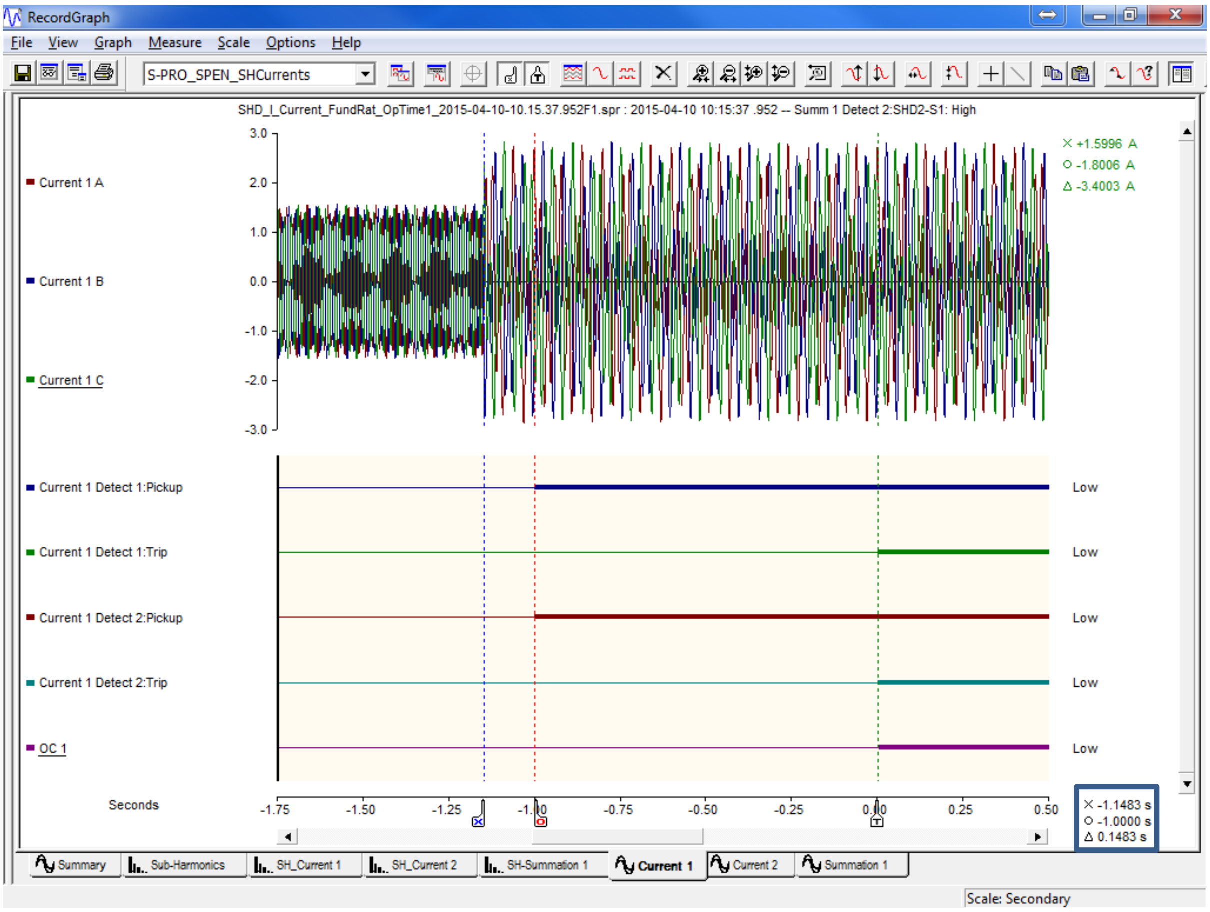

Figure 10 – Relay Operating Time

COMTRADE files are customized with the fundamental quantity component magnitudes and Sub-Harmonic component frequency fixed and the Sub-Harmonic quantity component magnitudes varying in a single step.

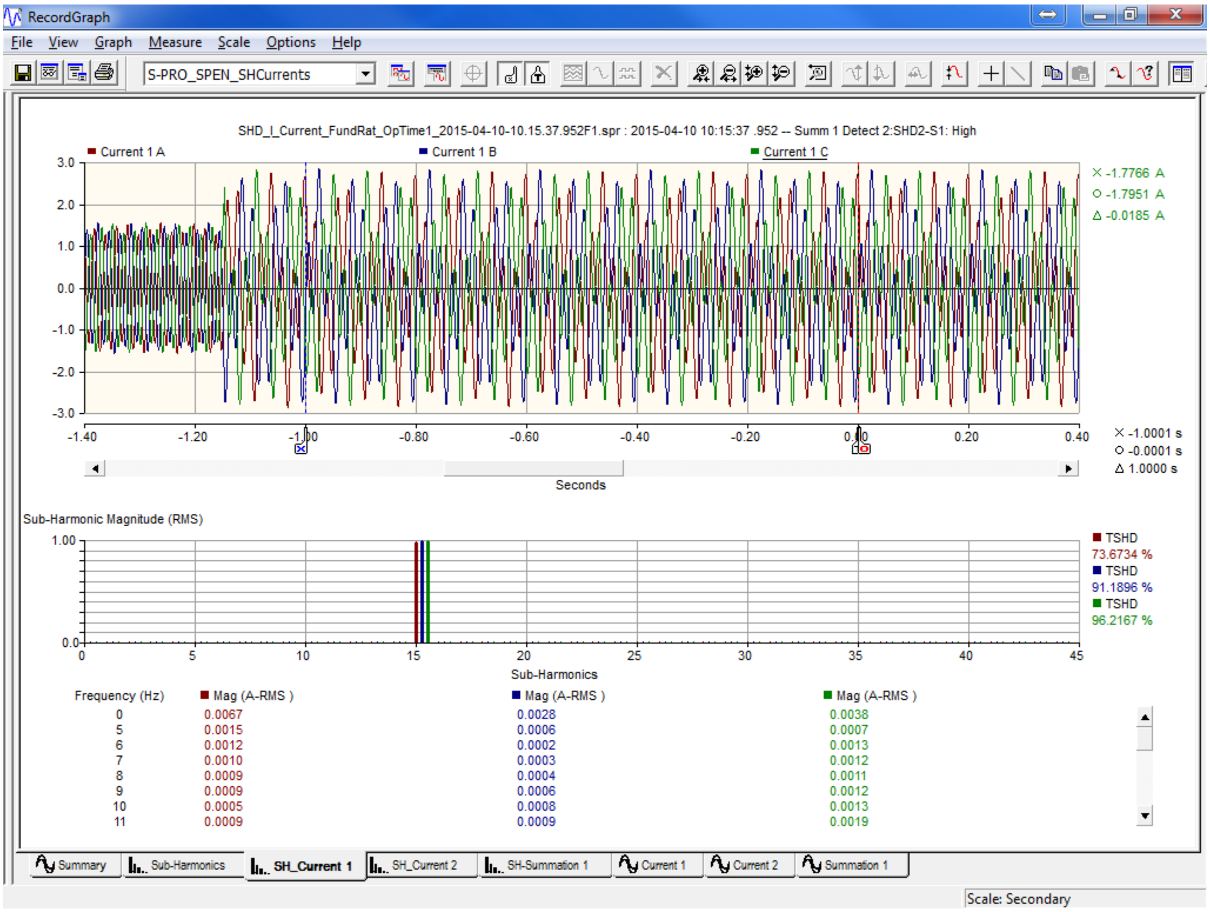

Figure 11 - Waveform used to test Relay Operating Time

3.5. Testing for Operations/Minute

For the settings of the ‘Operations/Minute’ elements, voltage and current, a number of occurrences in a minute can be set. An occurrence is an event where either the ‘Nominal Ratio’, ‘Fundamental Ratio’ or ‘TSHD’ element picks up but it does not last longer than the ‘Pickup Delay’ to prompt the S-PRO to trip. The ‘Operations/Minute’ element is only available once one of the Sub-Harmonic elements associated to it is already enabled.

For the ‘Operations/Minute’ elements to pick up, the number of occurrences in a minute must be greater than their threshold.

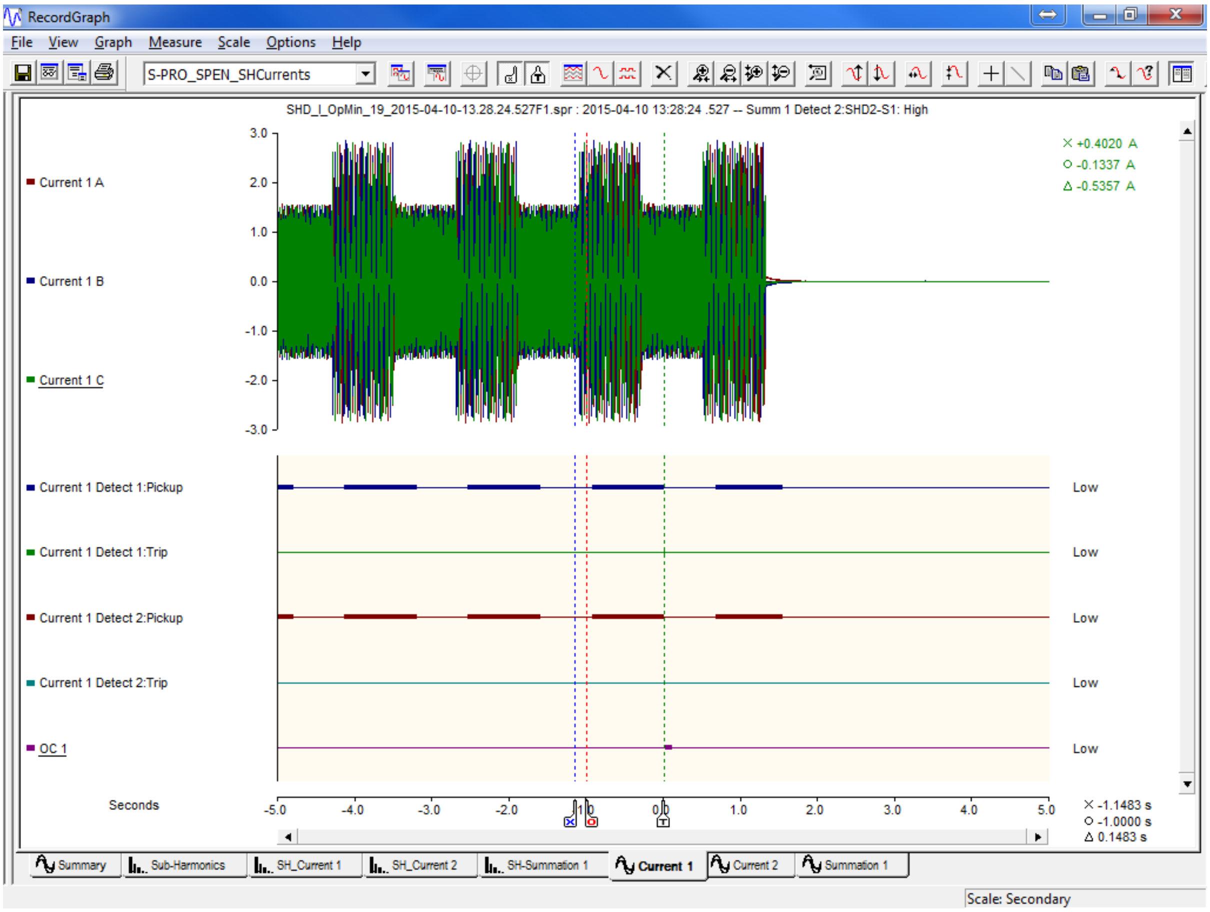

Figure 12 - Relay Response for Operations per Minute

COMTRADE files are customized with the number of occurrences smaller and greater than 'Operations/Minute' element's threshold.

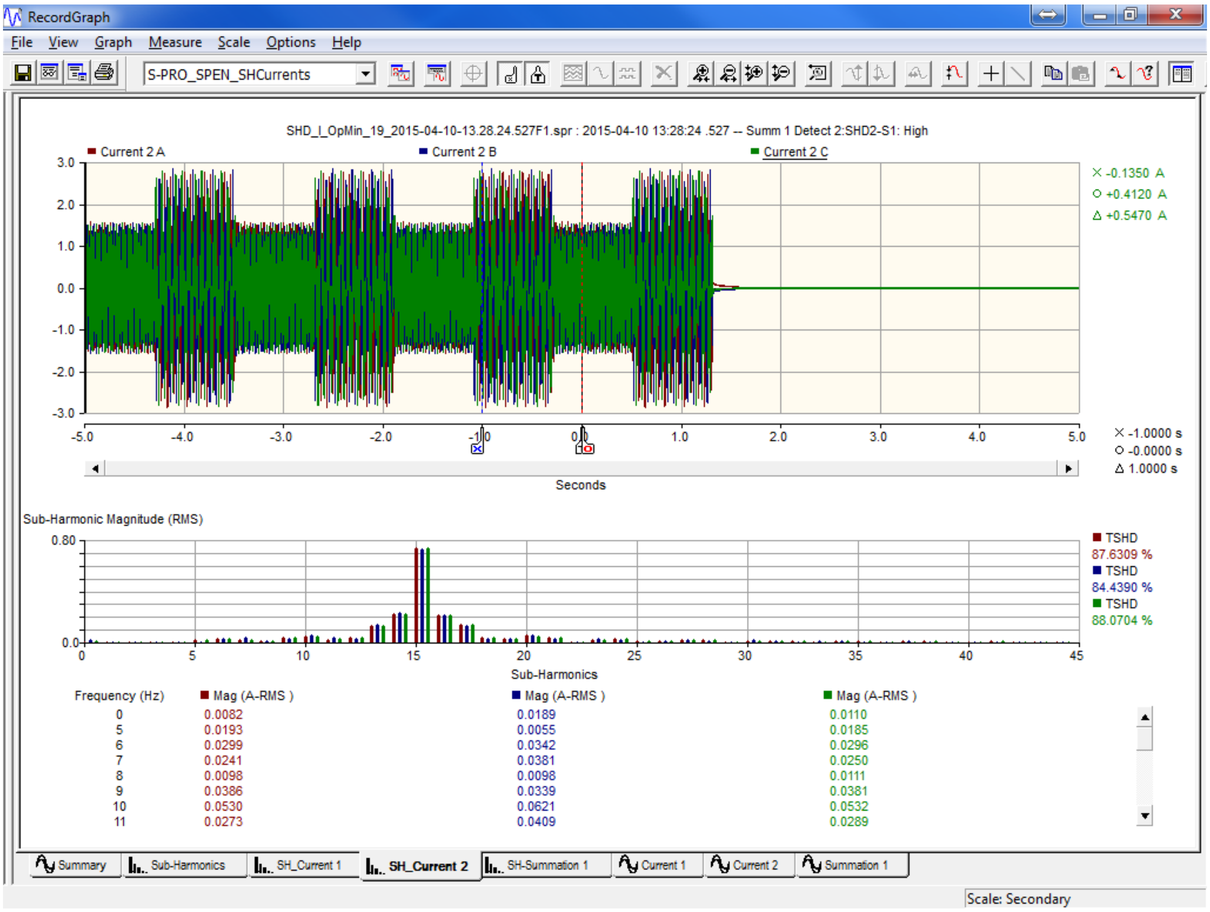

Figure 13 - Waveform used to test Operations per Minute

3.6. Testing for 2nd and 5th Harmonic Blocking

For the settings of the ‘2nd and 5th Harmonic Blocking’ elements, current only, the elements’ thresholds are individually defined by the ratio of either the second harmonic component magnitude or fifth harmonic component magnitude and the nominal current magnitude of 5A or 1A.

For the ‘2nd Harmonic Blocking’ and ‘5th Harmonic Blocking’ elements to block the Sub-Harmonic Detectors, the ratio of the component magnitude of 2nd harmonic and / or 5th harmonic and nominal current must be greater than their respective thresholds.

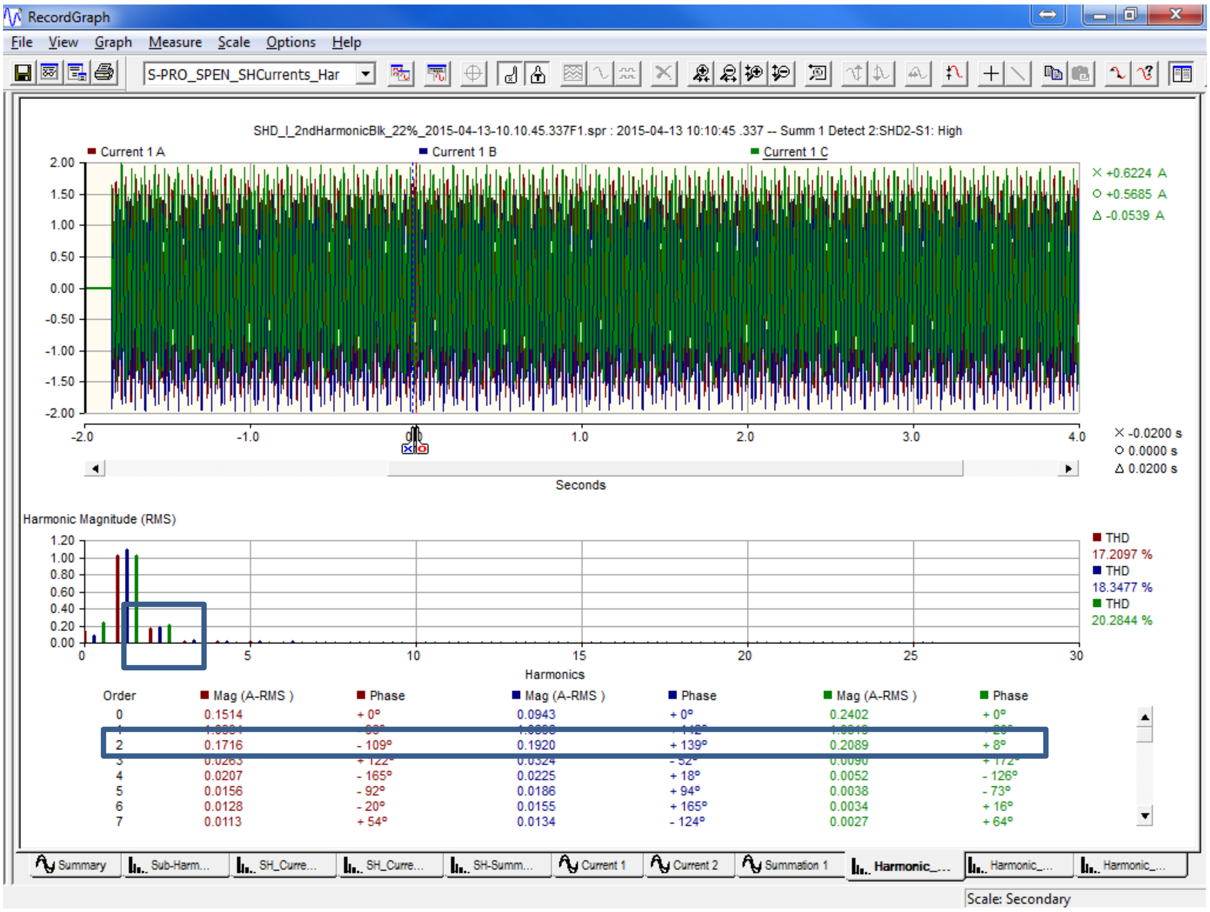

Figure 14 - Waveform used to test 2nd Harmonic Blocking

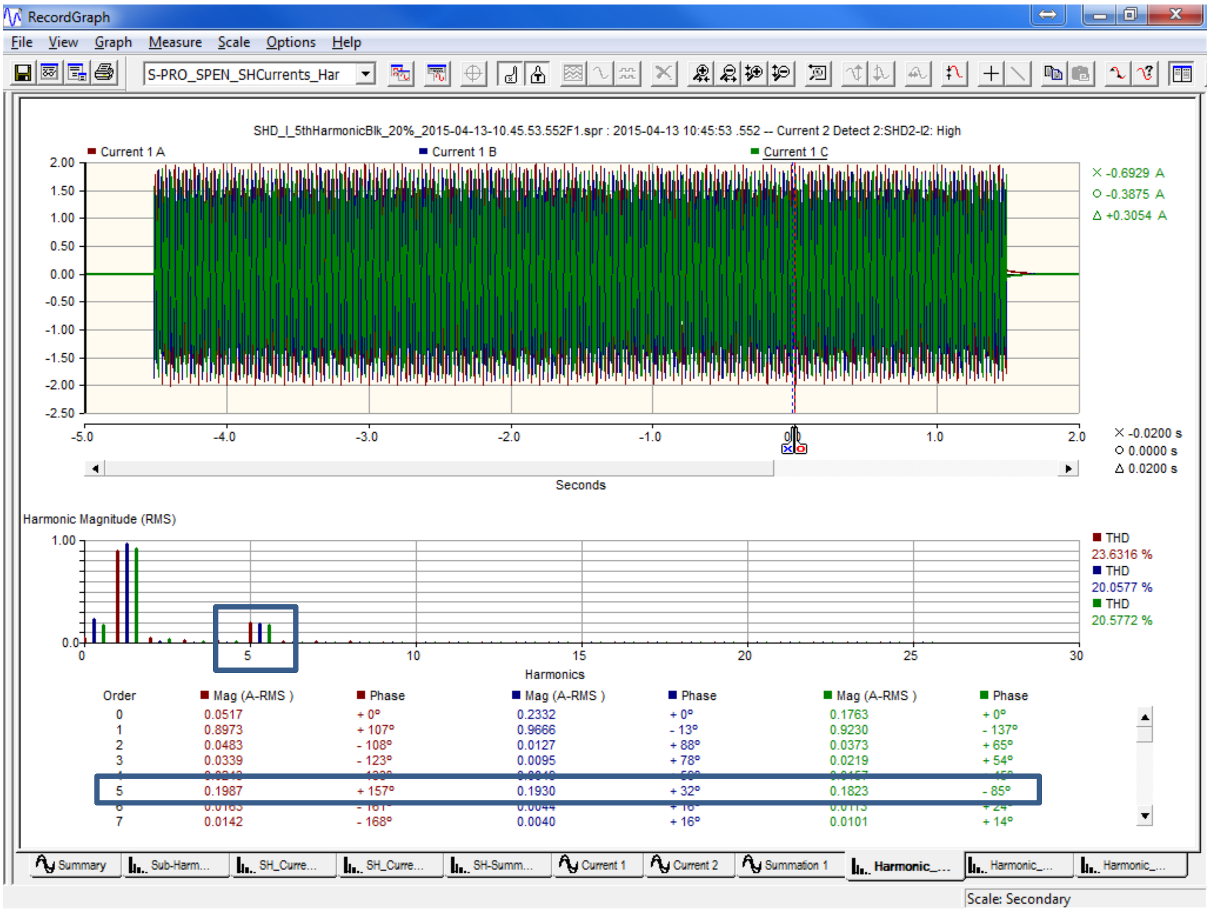

Figure 15 - Waveform used to test 5th Harmonic Blocking

COMTRADE files are customized with fundamental component, 2nd harmonic component and sub-harmonic component. The fundamental and sub-harmonic current components are fixed and their magnitudes are enough to prompt S-PRO Sub-Harmonic Detectors to pick up. The magnitude of the 2nd harmonic are decreased to make the ratio between the 2nd harmonic component and the nominal component vary from a value greater to smaller than the '2nd Harmonic Blocking' element. Doing so, the element goes from a blocking condition to an allowing condition, thus the Sub-Harmonic elements pick up.

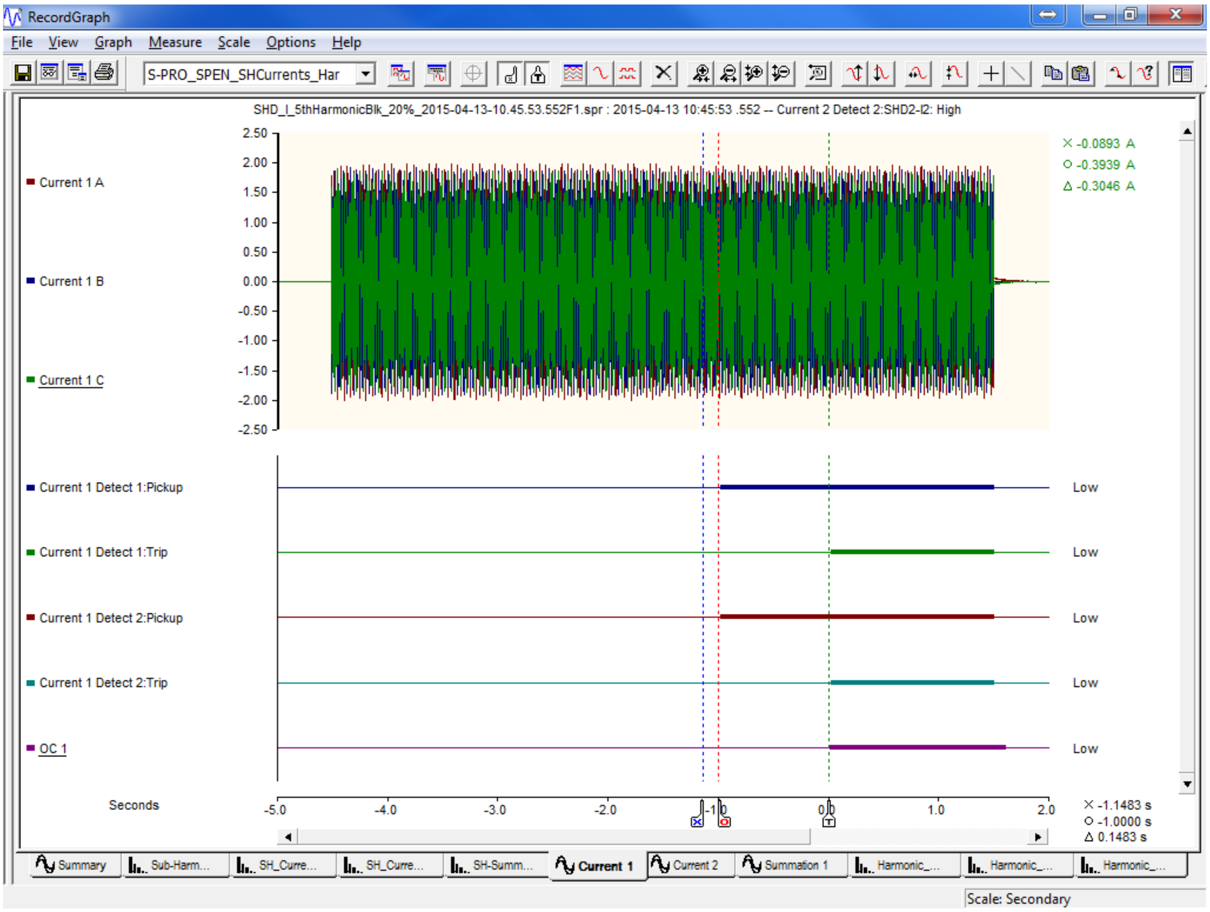

Figure 16 - Relay Operation in response to 2nd or 5th Harmonics

The '5th Harmonic Blocking' elements are tested in the same fashion as the '2nd Harmonic Blocking' ones.

4. Conclusion

The intention of this paper is to describe the use of COMTRADE files generated by means of software capable of simulating and modeling power systems, similar to PSCAD™/EMTDC™ or RTDS™, tailored for the testing of the protection and control features of a sub-harmonic protection relay.

A full description of the testing process is provided as well as examples showing typical waveforms used for testing each feature.

It is important to remark that sub-harmonic protection relays cannot be tested following a simple current and voltage injection either manually of by means of pre-defined relay tester scripts, because each test requires a specific combination of fundamental signal as well as sub-harmonic content.

The paper demonstrates the process to test current or voltage detectors for the following sub-harmonic detection settings:

- Frequency Range selectable between 5 and 45 Hz
- Sub-harmonic level pick up value
    - Nominal Ratio
    - Fundamental Ratio
- Time delay
- Total Sub-harmonic Distortion
- Operations / Minute Setting
- 2nd Harmonic Blocking

- 5^{th} Harmonic Blocking

5. REFERENCES

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