Commissioning a Sub-Harmonic Protection IED Using Advanced Testing Tools

R. Midence, A. Oliveira, N. Perera - ERLPhase Power Technologies Ltd

E. Carvalheira, K. Donaldson - OMICRON electronics

Abstract

Applicability of protection devices capable of detection Sub-Synchronous Resonance (SSR) conditions has become more common in during recent years. The advent of such protection devices has created the new challenge of testing and commissioning these 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 using an advanced relay test system (OMICRON CMC 356, the Test Universe modules Ramping and PQ Signal Generator as well as an OCC template) and the recommended process to be 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 an advanced relay testing system for the preparation of testing plans to be used during the relay testing
- The process followed at site to commission the relay by using advanced relay testing software and equipment.

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 an advanced relay testing system which includes software capable of creating the scripts that will be used to test all the relay features and validation of settings. Prior to the creation of test scripts, the process requires the review of power system simulation cases that were used to determine the relay settings in order to create 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
- Testing all the associated features such as operation per duration, total subharmonic distortion, 2^{nd} and 5^{th} harmonic blocking, etc.
- Protection features at the fundamental frequency

Keywords: Sub-synchronous resonance (SSR), sub-synchronous interactions, transmission lines, series capacitors, sub-harmonics, advanced relay testing systems

Introduction

During recent years a few papers have been presented 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 whi ch involve exchange of energy between a generator and a transmission system at AC frequencies below the system nomin al frequency. They include SSR, SSTI, a nd 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.

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

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

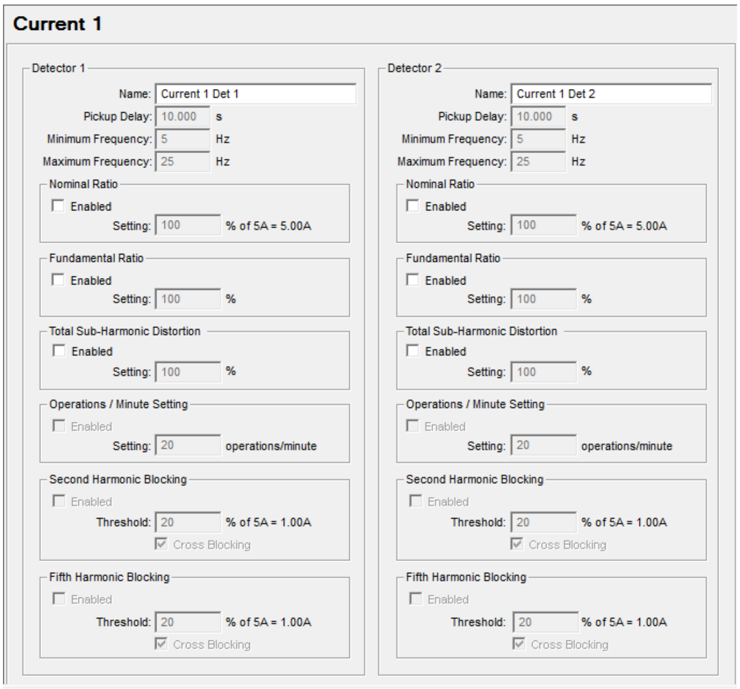

Figure 1 - Current Detector Settings

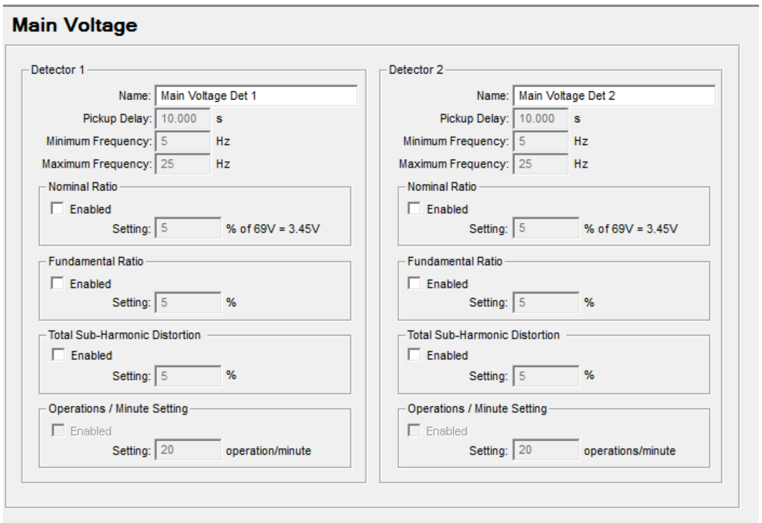

Figure 2 - Voltage Detector Settings

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

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.

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.

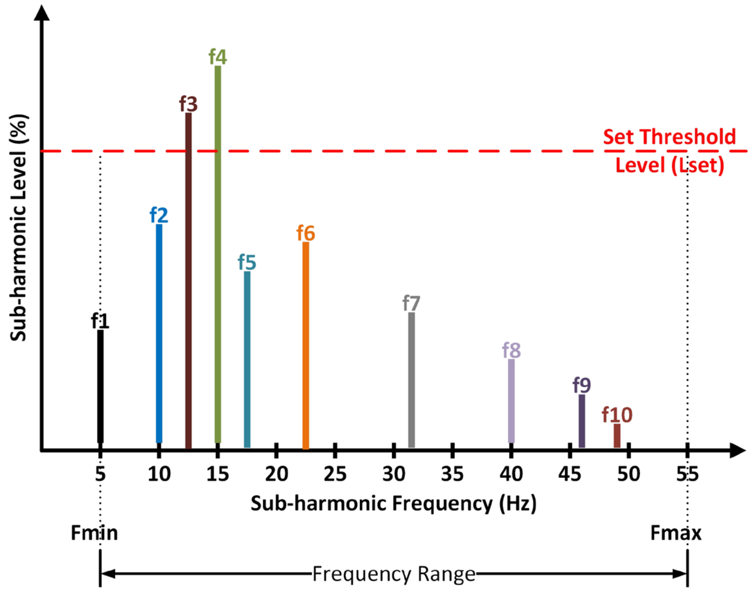

Figure 3 - Sub-harmonic levels for Nominal and Fundamental Ratio for a 60Hz system

Total sub-harmonic distortion

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

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

[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.

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.

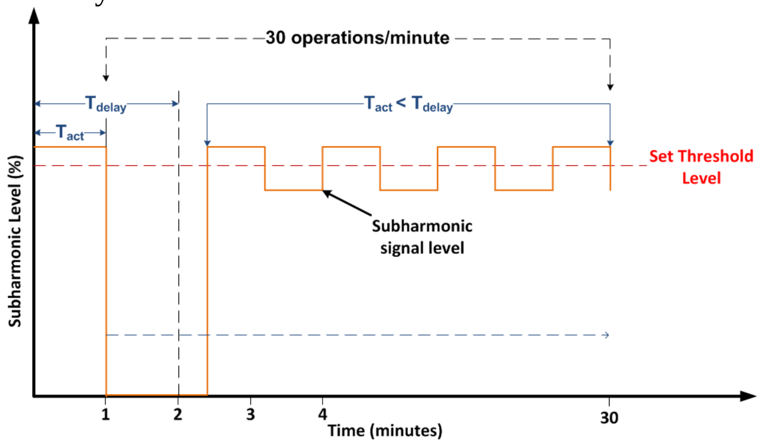

Figure 4 - Operations per minute principle

[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.

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.

Testing the Relay Functions

Test setup

Figure 5 shows the equipment setup for testing.

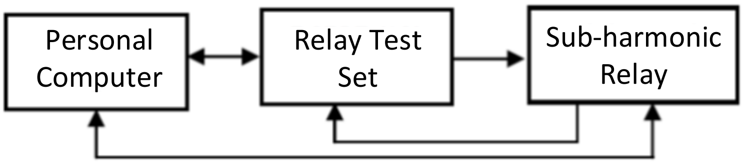

Figure 5 - Equipment Setup for Testing

The relay test system should be able to generate different content of sub-harmonic signals, superimposed to the fundamental frequency, in order to test the functionality of the relay and validate the relay settings.

Testing the boundaries and pickup values

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. The settings of minimum and maximum frequency are used by the ‘Nominal Ratio’, ‘Fundamental Ratio’ and the elements associated to them. Thresholds can be set individually for each element in two different ways: (a) ‘Nominal Ratio’, the elements’ threshold are defined by the ratio of the sub-harmonic component magnitude and the nominal quantity magnitude; (b) ‘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: 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 and pickup threshold values is performed by using a software tool which is capable of ramping voltage and current magnitudes at specific sub-harmonic frequencies. For the test described below, the frequency range was set to 5 Hz and 45 Hz and the current pickup threshold set to 100 mA.

Figure 6 shows a screenshot of the test module configured for this test. The whole test sequence was performed by applying nominal voltage and a load current of 2.5 A on each phase at nominal frequency (see {1} in Figure 6). Five ramp segments were created for simulating the following conditions we want to test:

- Ramp 1: this state was introduced to verify that the relay will not misoperate for sub-harmonic frequencies lower than the minimum frequency range. A constant current at a sub-harmonic frequency of 4 Hz and magnitude higher than the pickup value is superimposed to the signal (see {2}). It can be verified in the time signal view (see {3}) that there is no trip from the relay.
- Ramp 2: verify the relay trips when sufficient content of sub-harmonic is measured for sub-harmonics within the range. The current magnitude at 5 Hz is ramped up until the relay trips. Each step of the ramp has a duration of 5 seconds which is higher than the element trip delay time. The assessment window (see {4}) shows the relay trips at a measured pickup value of 102 mA.
- Ramp 3: same as ramp 1, but this time with a sub-harmonic of 46 Hz. No trip is recorded since the frequency range criteria is not met.
- Ramp 4: same as ramp 2, but this time for a sub-harmonic of 45 Hz. The assessment window (see {4}) shows the relay trips when the current magnitude reaches 102 mA.
- Ramp 5: apply signals only at nominal frequency. Relay resets.

The same procedure can be repeated

to test the frequency boundaries and pickup values for the voltage detector elements, in case they are enabled.

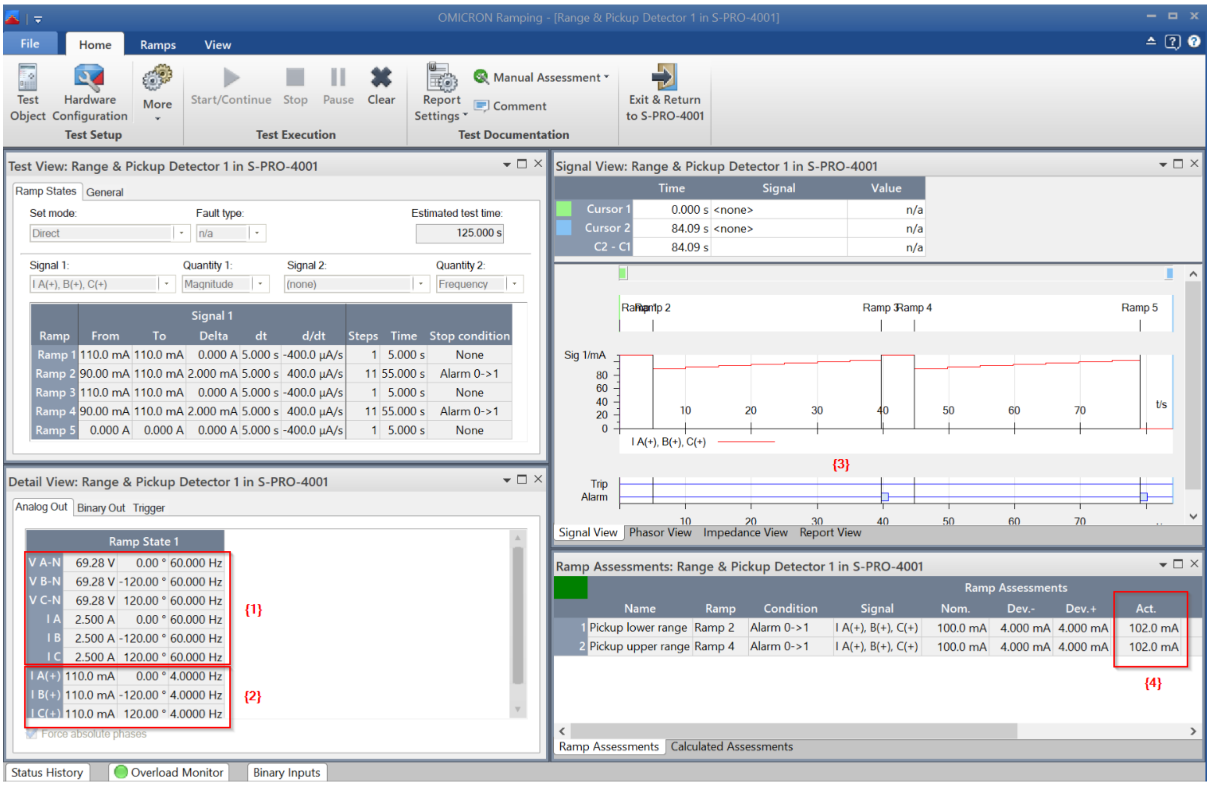

Figure 6 - Test configuration for frequency boundaries and pickup values

Testing the Total Sub-Harmonic Distortion (TSHD) element

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 (set to 5 % during this test).

For performing this test, nominal voltage and 1 A current at nominal frequency were applied. Sub-harmonic frequencies of 5, 25 and 45 Hz were added to the current signals. Two signals were simulated with sub-harmonic contents of:

- THD of 6.93 % to prove trip for values higher than the set threshold (Figure 7).
- THD of 4.92 % to prove the relay does not misoperate for values below the set threshold.

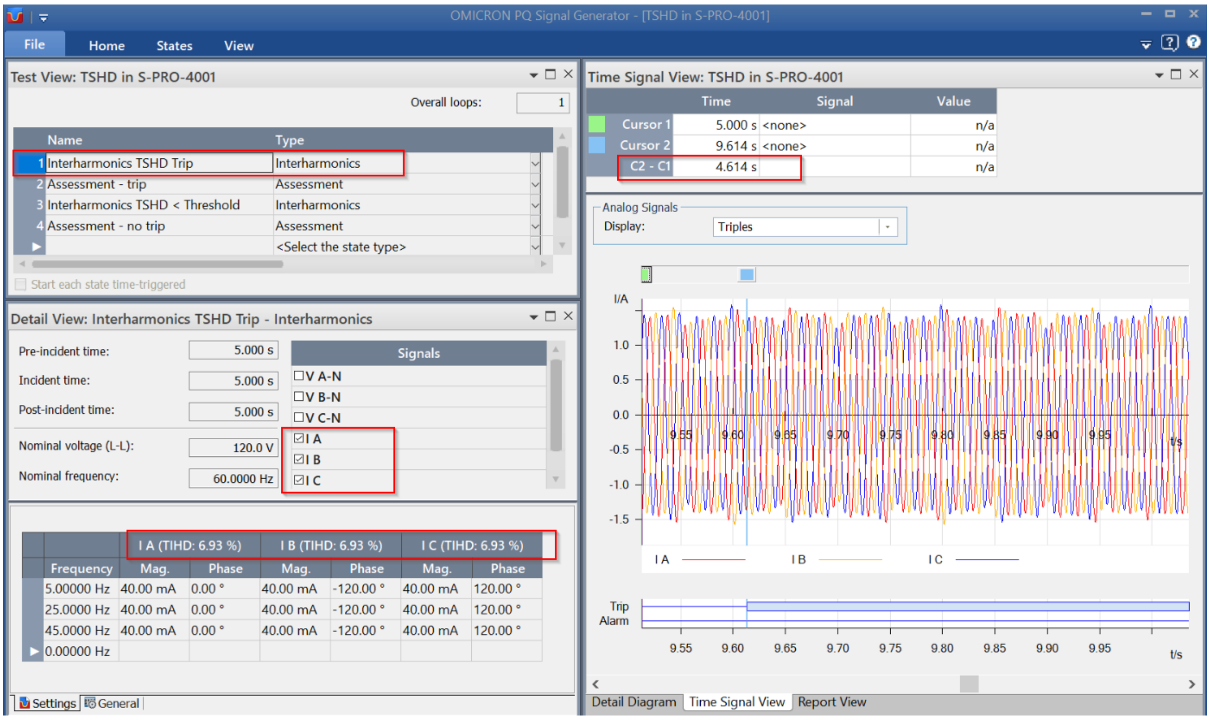

Figure 7 - Current Waveform used to test Total Sub-harmonic Distortion (TSHD) Trip

Testing for operations/duration

For the settings of the ‘Operations/Duration’ elements, voltage and current, a number of occurrences in a certain duration (defined in minutes) 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/Duration’ element is only available once one of the Sub-Harmonic elements associated to it is already enabled.

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

Figure 8 shows the configuration for this test. A signal was customized with the magnitude of a sub-harmonic frequency of 25 Hz higher than the pickup value but with a duration of only 3 sec, which is shorter than the set pickup delay of 4 sec.

The test tool allows the repetition of the same signal by defining the parameter “No. of loops” as shown in Figure 8. The element was set for 25 operations per 2 minutes, therefore the signal was configured for 25 repetitions. As each repetition has the duration of 4 sec (1 sec of pre-incident plus 3 sec of incident time), the overall test time is of approximately 1 minute and 40 seconds. At the end of the 25th repetition a trip of the relay could be observed. Figure 9 shows the report of the test with proof that the operation of the element was sensed by the test set after the end of the 25th operation and within the 2 minutes interval.

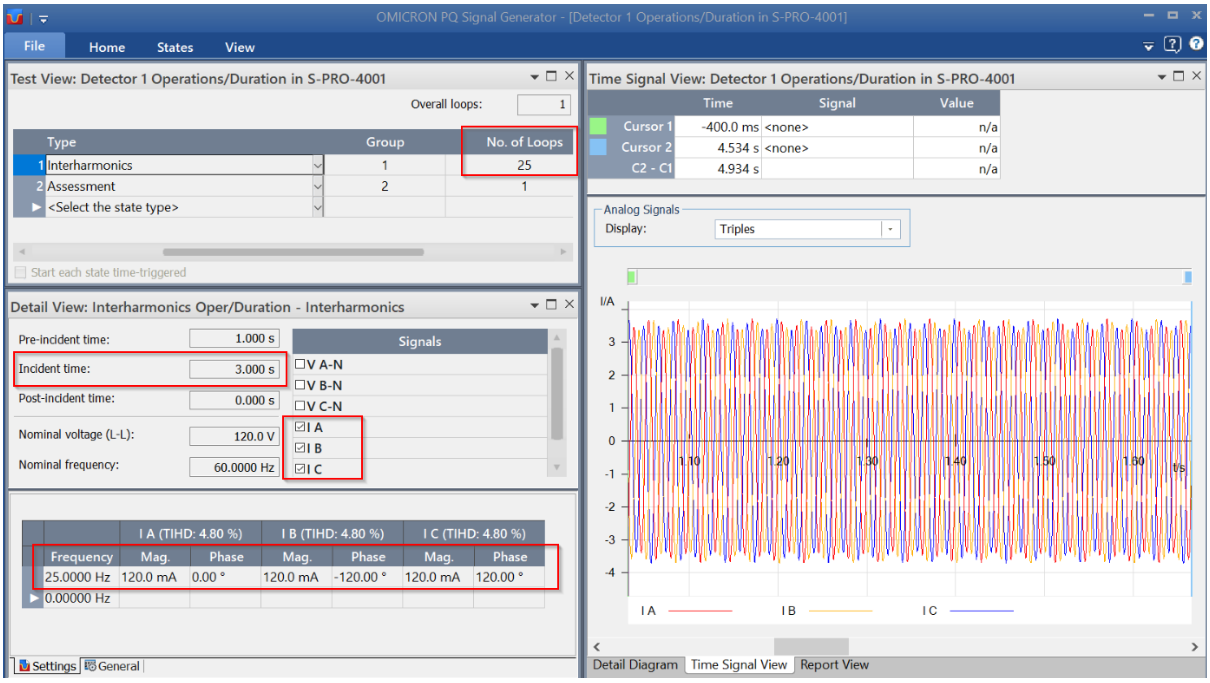

Figure 8 - Waveform used to test Operations per Minute

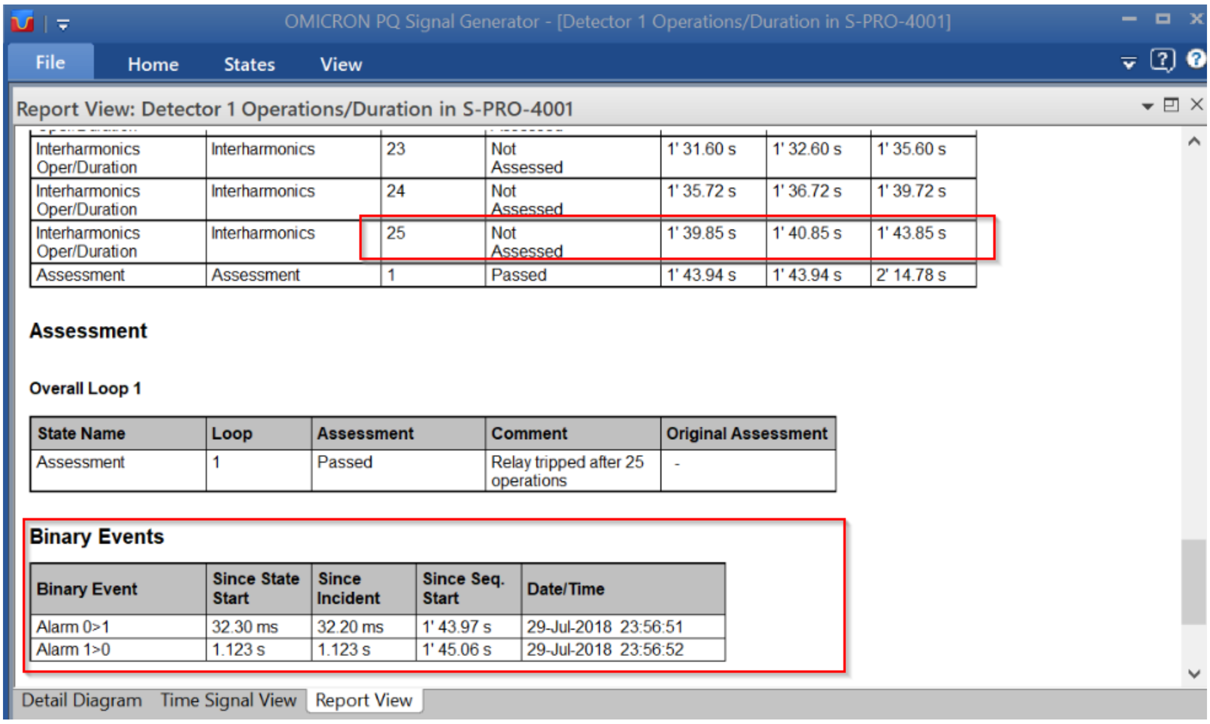

Figure 9 - Report of test Operations per Minute with Recording of Binary Event

Testing the Operating Time

For verifying the pickup delay time of the relay, a signal is created with fundamental component and a sub-harmonic component of 25 Hz. 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 delay time of the relay can be observed from the time signal oscillography view by tracking the binary event, as shown in Figure 10.

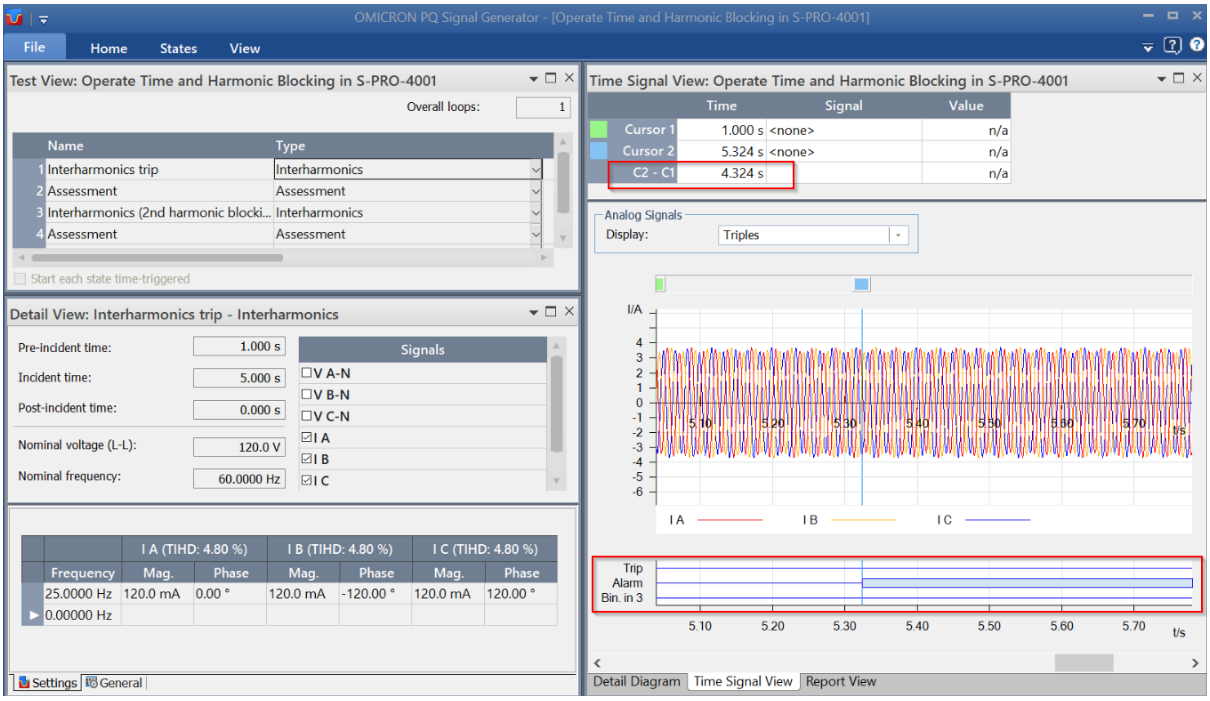

Figure 10 - Test of the Pickup Delay Time

Testing for 2nd 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.

This test is performed the same way as in Figure 10 for the operating time, but now by also adding a second harmonic component to the signal as shown in Figure 11. The magnitude of the 2nd harmonic is set greater than the '2nd Harmonic Blocking' element threshold, blocking the operation of the Sub-Harmonic elements.

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

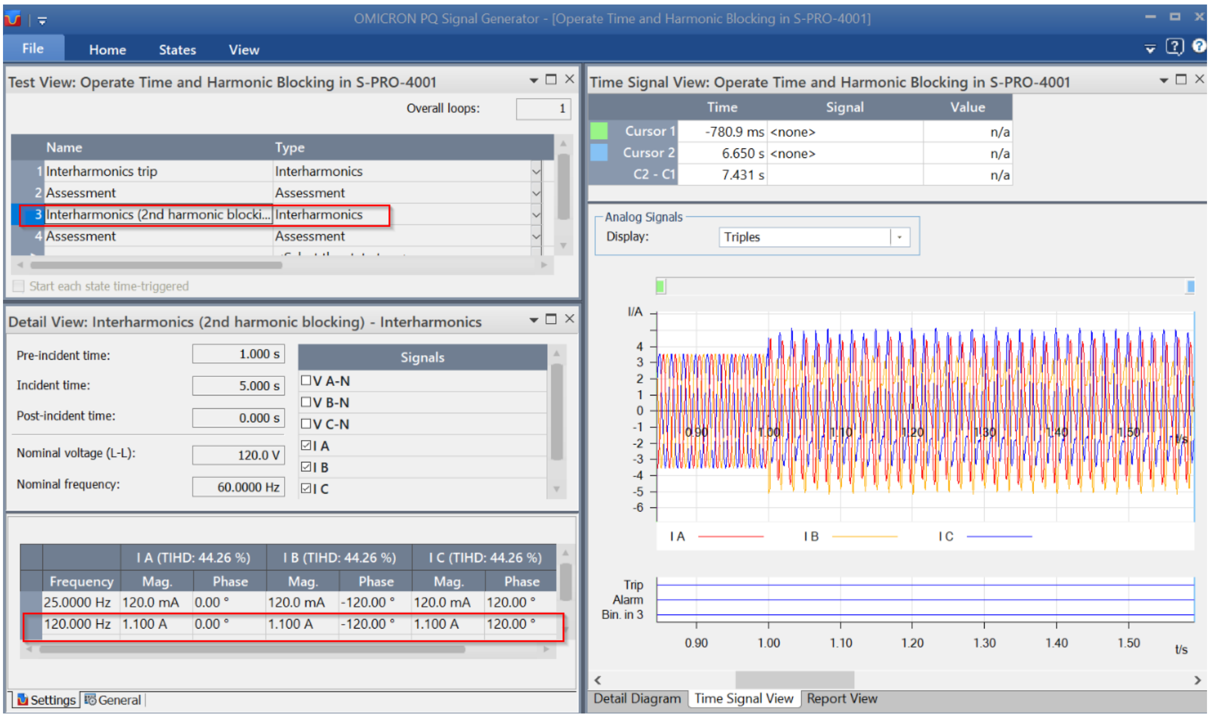

Figure 11 - Waveform for the 2nd Harmonic Blocking Test

Conclusion

The intention of this paper is to describe the test procedure for the commissioning of a sub-harmonic protection relay by means of an advanced relay test system capable of generating the waveforms needed for the simulation of suitable test cases.

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, 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 55 Hz
- Sub-harmonic level pick up value
  - Nominal Ratio
  - Fundamental Ratio
- Time delay
- Total Sub-harmonic Distortion
- Operations / Minute Setting
- 2nd Harmonic Blocking
- 5th Harmonic Blocking

1. REFERENCES

[1] "Sub-Synchronous Control Interactions between Type 3 Wind Turbines and Series Compensated AC Transmission Systems", Andrew L. Isaacs, *Member, IEEE*, Garth D. Irwin, *Member, IEEE* and Amit K. Jindal, *Member, IEEE*

[2] "Reader's Guide to Sub-Synchronous Resonance" and IEEE Committee Report by Sub-Synchronous Resonance Working Group of the System Dynamic Performance Subcommittee, Transactions on Power Systems, Vol. 7, No. 1, February 1992

[3] “A Microprocessor-Based Sub-Harmonic Protection Technique for Wind Farms”, Krish Narendra, Dave Fedirchuk, Adi Mulawarman, Pratap Mysore, IEEE EPEC Conference 2011

[4] “New Microprocessor Based Relay to Monitor and Protect Power Systems against Sub-Harmonics”, K. Narendra, D. Fedirchuk, R. Midence, N. Zhang, A. Mulawarman, P. Mysore, V. Sood., IEEE EPEC Conference 2011

[5] “Performance Evaluation of a Sub-Harmonic Protection Relay Using Practical Waveforms” N. Perera, K. Narendra, D. Fedirchuk, R. Midence, V. Sood, IEEE EPEC Conference 2012

[6] “Sub-harmonic protection application for interconnections of series compensated lines and wind farms”, René Midence, Joe Perez, P.E., Adi Mulawarman, Western Protection Relay Conference 2012, Pullman, Washington.

OMICRON is an international company serving the electrical power industry with innovative testing and diagnostic solutions. The application of OMICRON products allows users to assess the condition of the primary and secondary equipment on their systems with complete confidence. Services offered in the area of consulting, commissioning, testing, diagnosis and training make the product range complete.

Customers in more than 160 countries rely on the company's ability to supply leading-edge technology of excellent quality. Service centers on all continents provide a broad base of knowledge and extraordinary customer support. All of this together with our strong network of sales partners is what has made our company a market leader in the electrical power industry.

For more information, additional literature, and detailed contact information of our worldwide offices please visit our website.

www.omicronenergy.com

© OMICRON