Protection for Sub Synchronous Torsional Interaction Conditions Using an Industrial Sub-harmonic Relay

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***Abstract*— The Sub Synchronous Torsional Interaction (SSTI) conditions occurred due to the interactions of the generator-turbine systems and devices such as series compensated systems and HVDC systems has identified as harmful condition to avoid. Although it is a common practice to study and mitigate possibilities of SSTI conditions at system level designs, the power systems are not fully immune to SSTI conditions. This paper investigates the applicability of a numerical sub-harmonic relay for providing the protection against such SSTI conditions. Performance (accuracy and speed) of the proposed solution is investigated using various SSTI conditions injected into the relay.**

***Keywords*—SSTI, protection relaying, synchronous generators, HVDC, series compensated lines**

I. Introduction

Use of series capacitors, HVDC systems and different FACTS devices has become more common in the modern power networks. The Sub Synchronous Torsional Interaction (SSTI) conditions occurred in the generator-turbine systems associated with aforementioned devices is considered as one of the harmful situations to avoid which (i) creates damages to the equipment and (ii) reduces the stability of the power network. The conventional method to provide protection against such conditions is the use of mechanical type torsional relays that measure torsional oscillations in the generator turbines. Alternative to these conventional mechanical type torsional relays, the sub-harmonic protection relays that measure electrical oscillations (complementary of the mechanical frequency) can also be used. The use of electrical measurements will provide inherent benefits such as lower cost and higher reliability [1-3].

The phenomena of Sub Synchronous Torsional Interactions (SSTI) in the turbine-generator shafts can be categorized into three main areas [4-5].

- <u>Sub-synchronous torsional interactions</u>
  - Interaction with power system controllers such as the excitation/ prime mover controls of generators and the controls of nearby HVDC systems, and FACTS devices.
- <u>Sub-synchronous resonance</u>
  - Interactions between series capacitor-compensated transmission systems with the torsional dynamics of turbine-generators.
- <u>Torsional fatigue</u>
  - Operations of maneuver in the network

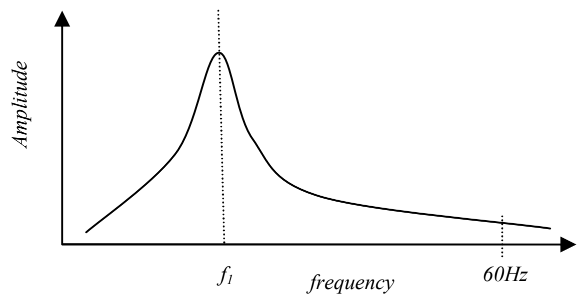

Fig. 1. Mechanical response of a turbine with a single frequency mode

Fig.1 shows an example case of mechanical characteristics, showing a single mechanical mode at a frequency of f_1 Hz. Presence of a system condition leading to SSTI may results in exciting the above mechanical mode on the turbine side. As a result, the resonance is propagated to the electrical network at the complementary frequency of f_1 Hz which is equal to (60-f_1) Hz.

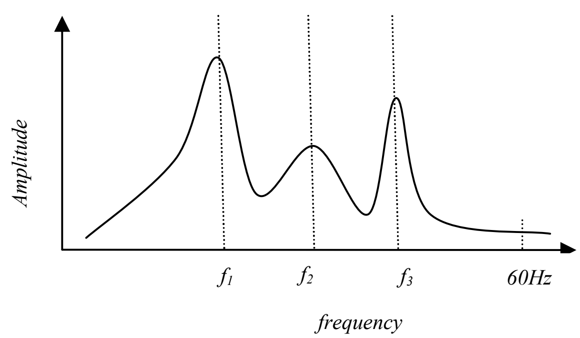

Fig. 2. Mechanical response of a turbine with multiple frequency mode

Fig.2 shows mechanical characteristics with three frequency modes at f_1, f_2 and $f3$ Hz. Depending on the network characteristics, one or more of these modes can be excited. The network side measurements (voltage and current) will show the resultant complement frequencies (i.e. 60-f1, 60-f2 and 60-f3). It should be noted that the phase responses corresponding to different modes are also non-liner in nature. Excitation of multiple modes at the same time may result complex conditions. In this paper, an industrial microprocessor based sub harmonic protection relay widely used to protect against various Sub Synchronous Oscillation (SSO) conditions is investigated for

SSTI protection applications. The performance of the relay was evaluated using different cases studies covering various SSTI conditions with single mode and multiple modes. Rest of the paper is organized as following. Section II provides a brief introduction to SSTI and its nature. Section III provides the proposed protection concepts/philosophy. Cases studies are presented in Section IV. Finally, conclusions are given in Section V.

II. UNDERSANDING OF SUB-HARMONICS

This paper investigates the applicability of a numerical sub-harmonic protection relay to provide the protection against SSTI conditions measured from voltage and current quantities. Therefore, the understanding of sub harmonics is essential in developing protection settings. This section provides a brief overview on the nature of sub-harmonics and practical aspects related to sub-harmonics.

A. Nature of Sub-harmnics

The sub-harmonics have a wider range of frequency, typically from few Hz up to the system frequency. The accurate magnitude estimation of a particular frequency component requires a minimum time delay proportional to the inverse of that frequency. In addition, energies carried at different frequencies have different effects on the performance of different power components in the system.

B. Other Sources of Sub-harmnics

The normal faults occur in transmission line or associated component may generate sub-harmonics. The series compensated transmission lines is one example. Typically, the nature of these sub-harmonics is temporary and well damped. The pickup time delays used in the protection logic plays a major role in differentiating stable SSO verses unstable SSO. Apart from the faults, the normal non faulty transients such as transformer inrush, normal faults, current transformer saturation etc. could mislead the sub-harmonic calculations. In addition, presence of lower order harmonics may also mislead the sub-harmonic calculations. Therefore, in selecting a sub-harmonic relay, it is essential to ensure that the relay is capable of handling these scenarios to ensure correct and secure operation. If voltage sub-harmonics measurements are used for decision making, special attention shall be given to differentiate capacitive voltage transformer (CVT) generated sub-harmonics versus unstable SSO generated from the system or controller interactions. In such application, appropriate pickup time delays should be used to cope up with the physical phenomena.

C. Sources of Errors

In using microprocessor based sub-harmonic protection to estimate SSTI, there are a number of sources of errors. These errors include those introduced by analog sensors (CTs, PTs and CVTs), analog to digital convertor (ADC) resolutions and computation errors. It should be noted that analog sensors are designed to provide accurate phase angle/magnitude responses near nominal frequency components and accuracies below nominal frequency (sub-harmonic range) will be different. In addition, in digital protection relays, the ADC resolutions are set based on the maximum voltage and current magnitude limits at nominal frequencies. The magnitudes of sub-harmonics that need to be detected could be significantly lower compared to those maximum limits and therefore special attention shall be given in selecting the ratings. Furthermore, depending on the estimation technique used by the relay, the computational errors could be higher in estimating decimal frequencies. In selecting a suitable protection relay, all these factors shall be carefully evaluated and appropriate margins shall be provided in the protection settings. Decimal sub harmonic estimation helps to accurately estimate the possible resonance frequencies between the mechanical and electrical systems.

D. Current Sub-harmonics and Voltage Sub-harmonics

One of the common queries related to the SSTI conditions associated with most of the typical applications is the selection of most suitable input signal for successful detection of unstable subharmonics. The field recorded investigations confirmed that sub-harmonics on current measurements are more dominant compared to those of the terminal voltage measurements compared with relative fundamental values. In addition, the sub-harmonics on terminal voltage measurements are dependent on the source-side impedance. Therefore, it is a common practice to use current signals as the primary (fast) protection method and the voltage signals as the back-up (slow) protection method.

III. PROTECTION USING NUMERICAL RELAYS

This section provides key features of the sub-harmonic protection relay under consideration and general guidelines for development of protection settings considering the nature of the SSTI conditions.

A. Sub-harmonic Relay

The sub-harmonic protection relay evaluated in this paper provides the protection against sub-harmonic oscillation conditions 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 3-phase current inputs 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 summate current quantities from any two of the current inputs. This is 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 basic sub-harmonic detection functions with pick-up time delays.

1. Nominal Ratio (NR)
   - Operates based on the measured sub-harmonic levels specified as a percentage of the secondary nominal (1/5A, 69 V)
   - Frequency range selectable between 5 and 45 Hz for 50Hz power system or 5 and 55Hz for 60Hz power system
2. Fundamental Ratio (FR)
   - Operates based on measured sub-harmonic levels as a percentage of the measured fundamental component.

- Frequency range selectable between 5 and 45 Hz for 50Hz power system or 5 and 55Hz for 60Hz power system

3. Total Sub-harmonic Distortion (TSHD)

   - Operates based on measured equivalent-sum of all sub-harmonics as a percentage of the measured fundamental.

Each of these detection functions can be enabled or disabled individually. Each detector uses the OR combination of NR, FR and TSH.

In addition, the special protection function/feature "**Operations per Duration**" provides the back-up protection during the situations where SSTI events can show up momentary during a specified period of time. The number of event counts and the duration of interest is user programmable. Furthermore, the 2nd and 5th harmonic blocking has been provided for current signals to ensure secured operations during energization transients. More details about this relay can be found in [6]. Considering the nature of SSTI events and protection features available in sub-harmonic protection relay, following setting criterions are proposed.

B. Protection Criterion for Turbines with Single Mode

When there is only one mode of frequency, users prefer better selectivity for the specific sub-harmonic frequency. Use of the combination Nominal Ratio (NR) settings and Fundamental Ratio (FR) Settings gives proper selectivity. Fig.3 shows basic protection log proposed using NR and FR settings. The NR ratio provides secured operation if there in insignificant fundamental measurements available whereas, the FR setting provides the secured operation if the percentage of sub-harmonics is above the fundamental measurement. Frequency range settings (f1min-f1max) shall be selected such that, complement frequency (aforementioned 60- f_1) is covered with a reasonable error margin.

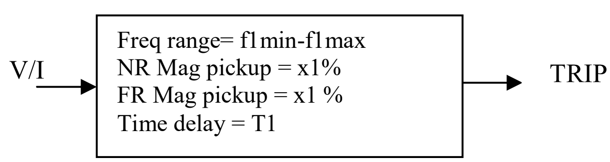

Fig. 3. Basic logic for single mode of frequency

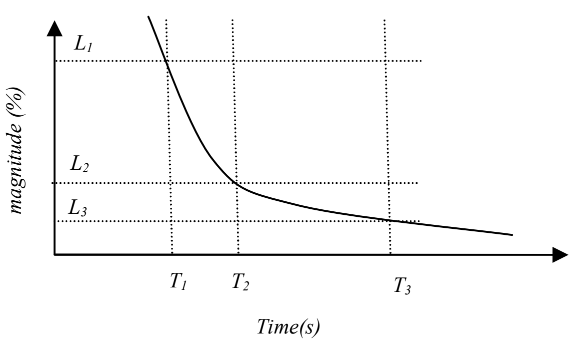

Fig. 4. Formation of inverse characteristics

The selection of multiple pick-up levels with multiple time delays in a way that it forms an inverse time characteristics will give a faster operation for rapidly growing SSTI and slower operation for low level of SSTI. Fig.4 shows the formation of inverse time characteristics using multiple pickup levels settings (L1, L2 and L3) and time delay settings (T1, T2 and T3). Fig.5 shows the development of inverse SSTI protection logic using multiple level detectors and time delays.

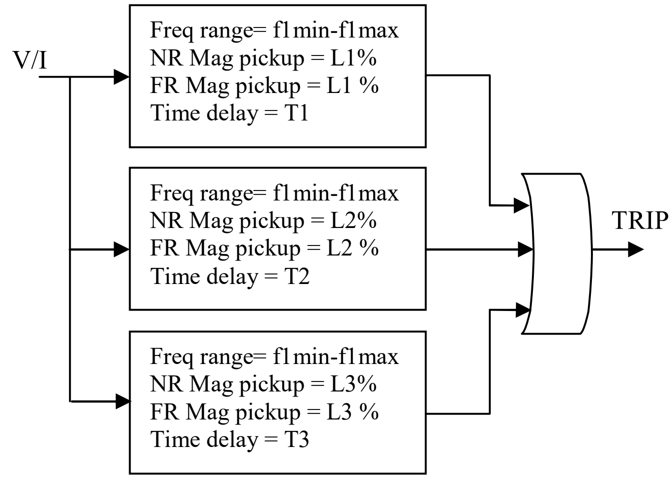

Fig. 5. Combined logic to achieve inverse characteristics

C. Protection Criterion for Turbines with Muliple Modes

When there are multiple modes of frequencies involve, same logic can be applied by appropriately adjusting the frequency settings. However, the inclusion of Total Sub-harmonic Distortion (TSHD) Settings will provide better security considering the uncertainties involve in summated sub-harmonics. Fig.6 shows the extended logic with the THSD functions.

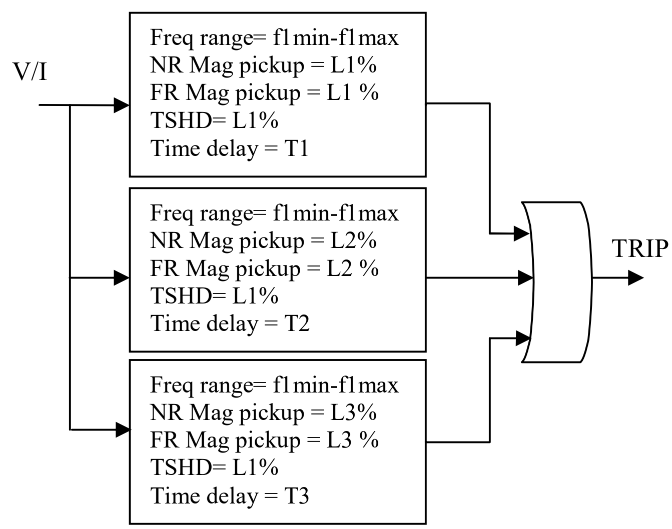

Fig. 6. Extended SSTI logic with TSHD

D. Protection for Momentroy Picking up

One of the main protection issues associated with SSTI is the momentary picking up (with no tripping) of sub-harmonics. This may also lead to severe damages to the turbines. As explained above, the **Operation per Duration** function available in the selected relay provides an ideal solution. This function counts number of alarm events during the user specified time duration. When the counted number if events during the specified period is higher that the specified number, relay will trip.

E. Standard Settings

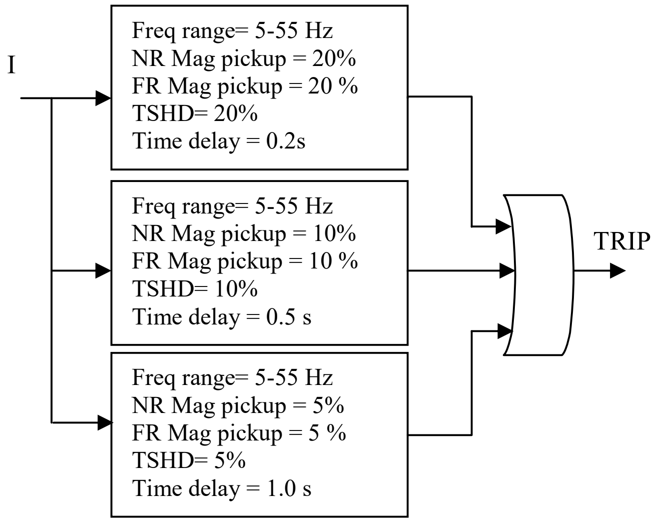

Fig. 7. Standard settings for current detection

When setting up a sub-harmonic relay, frequencies corresponding to the undamped modes available from the system studies are incorporated. There are some practical situations where use may not be able to identify the details due to lack of resources available to carry out the system studies or lack of accurate information from the actual turbines and power systems. In such situations, following settings (shown in Fig.7 and Fig.8) are recommended for a 60 Hz power system.

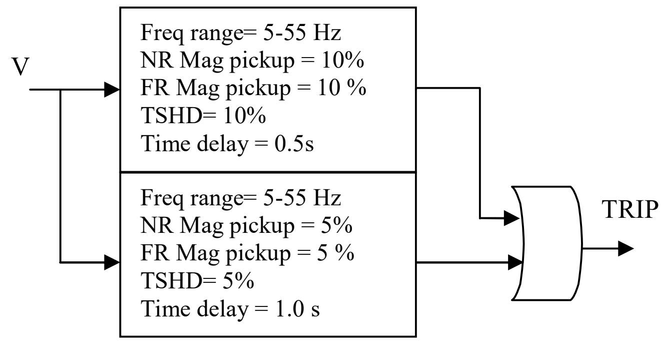

Fig. 8. Standard settings for voltage detection

As explained in Section-II, considering the nature of the voltage sub-harmonics two levels are adequate. In order to ensure proper selectivity between SSTI events and possible low frequency transients (non-SSTI) generated from CVT, longer time delays are provided for voltage detectors compared to those of the current detectors.

IV. Cases Studies

In order to demonstrate the applicability of the proposed solution, consider the following SSTI case studies. Results were presented based on the simulations carried out using the PSCAD simulation program. The simulated waveforms (COMTRADES) were played back into the relay using a real time signal generator. Standard settings are used assuming that results from system studies are not available.

A. SSTI with Single Mode

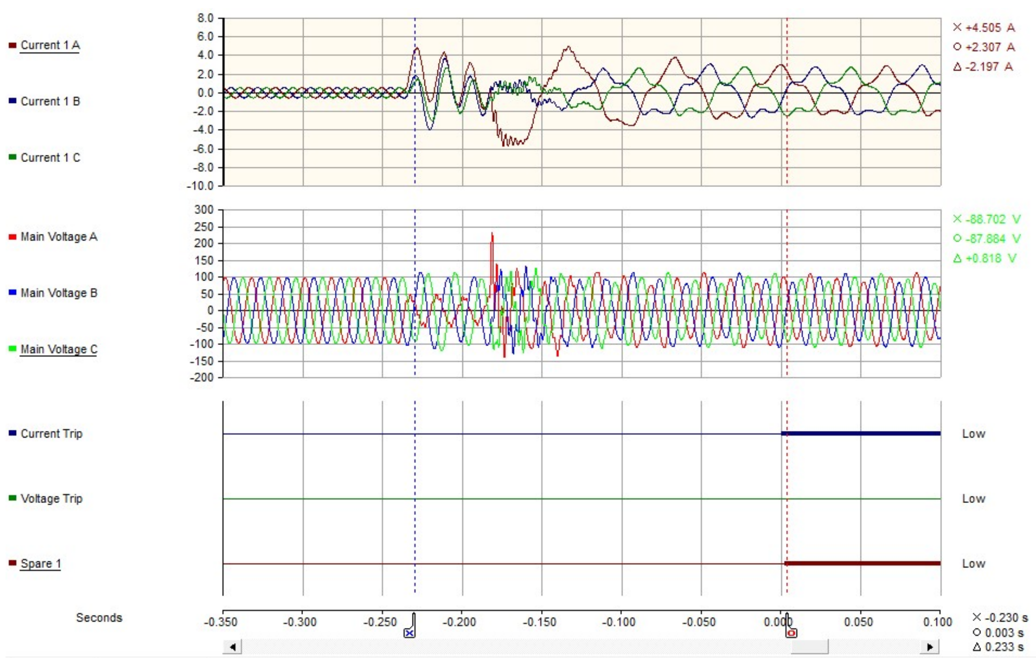

Fig. 9. Operation of the relay during SSTI event with a sigle frequency.

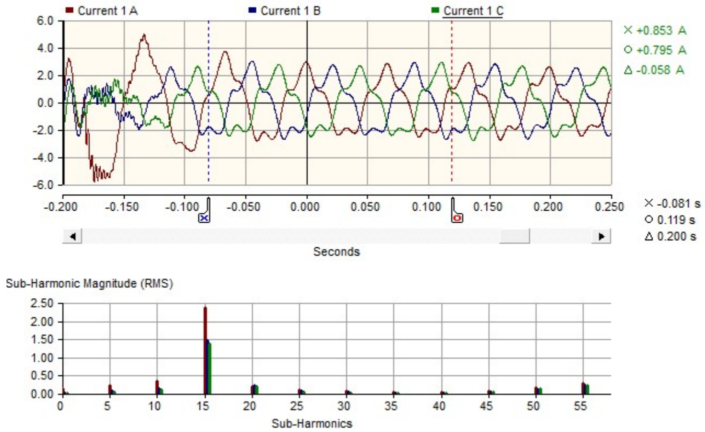

Fig. 10. Sub-harmonic Spectrum

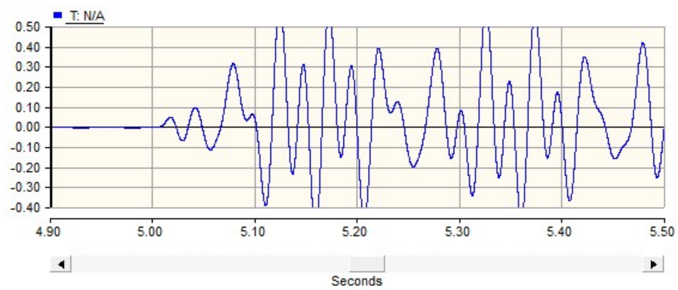

Fig. 11. Generator Oscillations (dc removed)

Fig. 9 show the repose of the relay for a SSTI simulated with a single mode of frequency. As it can be seen from Fig.9, response of the relay is ~230 ms. Sub harmonic frequency response of the network signals is shown in Fig. 10. The most dominant sub-harmonic frequency is ported as ~15 Hz. The generator side mechanical oscillation reported during the simulation is in the range of 40-45 Hz is shown in Fig. 11 which is corresponding to the complementary frequency of the sub-harmonic measurements observed on the network side. Results observed during this case study showed correct operation of the relay.

B. SSTI with Muliple Frequency Modes

Performance of the relay was also evaluated for SSTI events simulated with multiple modes of frequencies. Fig. 12 shows the response of the relay for a sub-harmonic event simulated with three frequency modes. Sub-harmonic spectrum observed on the current measurements is shown in Fig.13. As it can be seen from Fig.13, modes of frequencies observed are 11.2 Hz, 32.5 Hz and 48.2 Hz. The sub-harmonic level of the simulated event was in the range of 5-10%. As anticipated from the protection settings, operating time of the relay is reported as ~1.1s. Additional simulations and testing carried out with multiple oscillatory modes with frequency in nearly equal (e.g. 11.2 Hz, 13.5 Hz and 14.8Hz) ranges showed correct operations. It should be noted that this part of the simulation is carried out without a system model (i.e. theoretical waveforms are used).

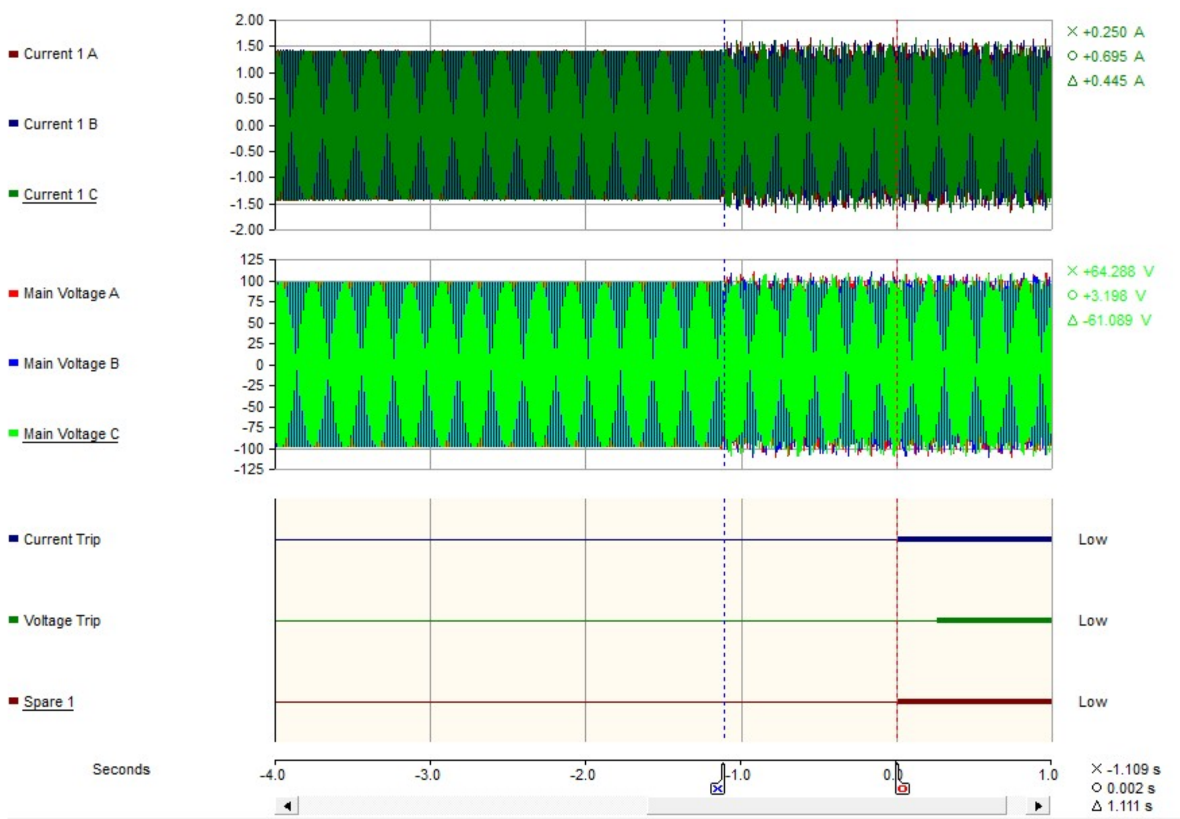

Fig. 12. Operation of the relay for SSTI with multiple frequecnies.

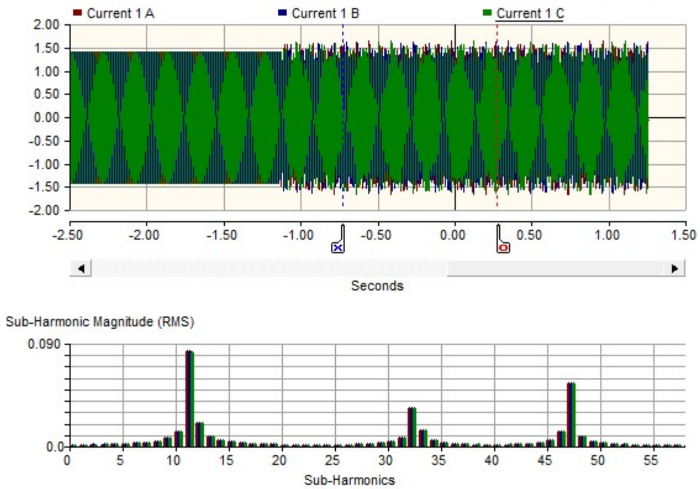

Fig. 13. Sub-harmonic Spectrum

C. *Momentory/Temporary SSTI Events*

As explained in Section-II and III, the "Operations per Duration" function provide enhanced protection for situations where SSTI events are generated momentary without lasting for sufficient duration to trip the relay. In order to investigate the behavior of the relay during such conditions, a sub-harmonic event was simulated with momentary in nature. For functional settings, a duration setting of 1 minute and an event count of 3 was used. Events were repeated ~5s apart and Fig.14 shows the operation of the relay showing the correct tripping for the third event observed during the one minute period..

V. Conclusions

In this paper, applicability of a numerical sub-harmonic protection relay to provide the protection against SSTI conditions associated with interactions of various power system components in the system was investigated. A brief overview on the nature of sub-harmonics and the key challenges in using numerical relay to provide the protection against SSTI were discussed. A protection setting structure that provides the flexibility for user to select basic setting, even during the situations where limited information or no information is available from system studies was proposed. Applicability of the proposed setting structure was verified using various SSTI conditions simulated in PSCAD/EMTDC simulation program. Results presented in this paper demonstrate the capability of the relay in providing adequate protection against SSTI conditions.

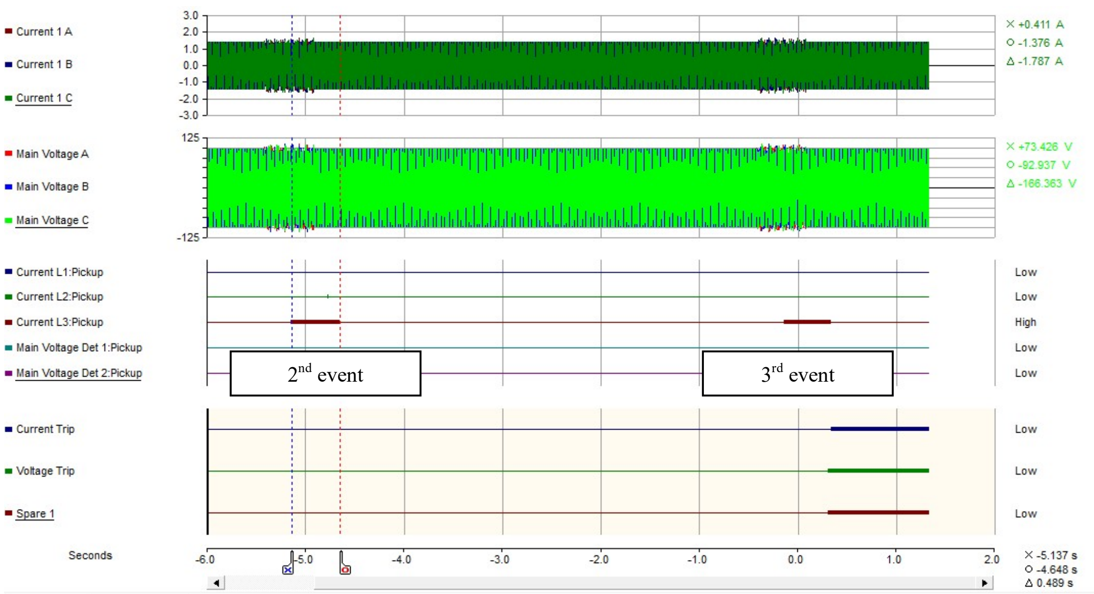

Fig. 14. Behaviour of operarations per duration function

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