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Use of a Sub Harmonic Protection Relay to Detect SSO Conditions Associated with Type-III Windfarms and Series Compensated Transmission Systems

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SUMMARY

With the increased use of renewable wind energy, wind farms are being built in remote areas, often far from load centres. 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 natural frequencies of the series capacitors and the system's inherent impedance, which can result in sub-synchronous resonance (SSR). 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. Therefore wind farms now face a challenge to predict when (and to what extent) harmonics and sub-harmonics are being introduced to the power system. Although the electromagnetic transient type simulation based studies are being carried out to estimate aforementioned quantities and the sub harmonic protection relays are available in the market, usability of the simulation results for setting up a protection relay for protecting an actual system has become a challenge. In literature, limited work has been presented associated with developing adequate settings for sub harmonic relays. This paper investigates the use of a sub harmonic protection relay for detecting the sub synchronous oscillation (SSO) conditions generated due to the interaction of series compensated transmission systems.

KEYWORDS

Sub-harmonics, Protection, Series Compensation, Wind farms, Sub Synchronous Oscillation

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INTRODUCTION

Worldwide expeditious installation of renewable and distributed energy resources (DERs) is occurring. To achieve faster execution of these projects, most of the existing transmission systems are being upgraded with the addition of various compensating devices such as SVCs, series capacitors, shunt compensators to support wind farms, large PV systems, and other DERs. In this context, the operation of the power grid due to the additional energy resources is posing new challenges in the field of power system protection, monitoring, and control. One of the major issues faced by the utilities with regards to interconnection of DERs into the grid is SSO generated due to the interaction of various elements in the power system [1].

In recent literature, several SSO events have been reported in the existing installations with wind turbine and series compensated systems [2]. System studies carried out using simulation models of the windfarms has confirmed that controllers of Type-III windfarms are more susceptible to interact with series compensated systems to generate unstable SSO conditions [3-5]. Lack of knowledge and availability of suitable protection methodology have led some of these events to damage the hardware components associated with windfarms and series compensating system. Figure-1 shows the oscillography captured during a real SSO event captured by a digital fault recorder. As it can be observed from the sub-harmonic spectrum, sub-harmonics in the range of 9-13 Hz were reported as dominant. As most of the conventional protection relays operate based on the power frequency (50/60Hz) components, such resonance conditions was not detected by those relays in the system.

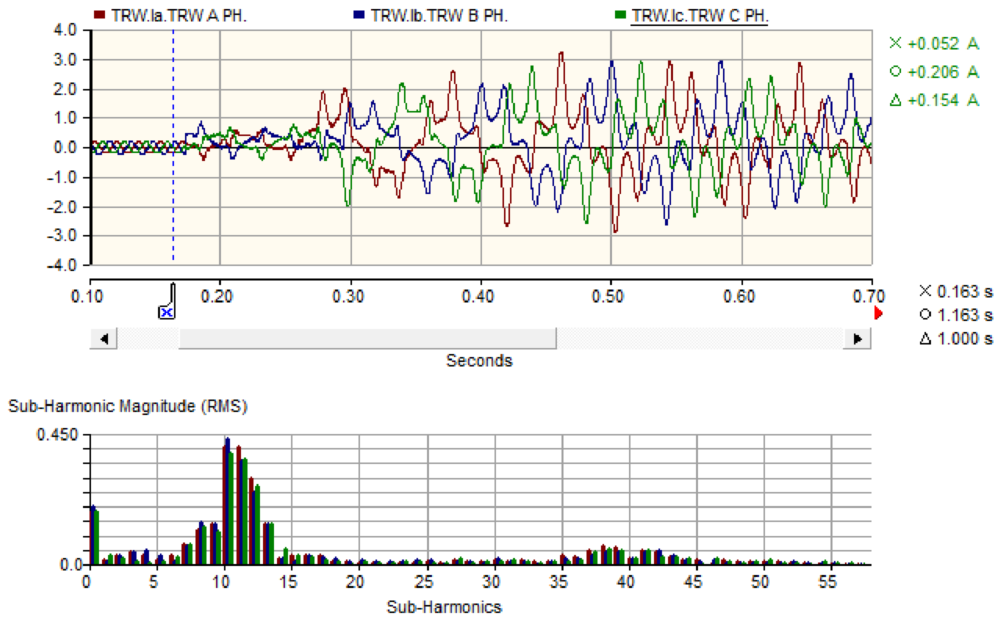

Fig. 1. Field recorded waveform during a SSO condition

In order to overcome the SSO issues associated with Type-III windfarms, research has been carried out to change the controller designs to eliminate the possibility of generating sub-harmonics [6-7]. Although the modern Type-III windfarm controllers have been developed with the capability of mitigating the SSO conditions associated with series compensated lines, it is not possible to eliminate the SSO phenomena due the nature of continuously changing topological network conditions. Also, there are several existing installations that are equipped with older Type-III windfarm controller designs which are susceptible to aforementioned SSO conditions. Therefore, the use an appropriate SSO protection method to prevent system damages against such SSO conditions has been identified as essential. In addition, international regulatory authorities such as the North American Electric Reliability Corporation (NERC) have mandated the use of SSO protection for such applications [8]. This paper discusses the key considerations in developing such a protection methodology using a microprocessor based numerical sub-harmonic protection relay.

PROTECTION USING A SUB-HARMONIC RELAY

During recent years, the use of a sub harmonic relay to provide the protection against such conditions has become attractive. Based on the reported practical application case studies, SSO protection applications used by different utilities can be broadly categorized into two main types (i) use of a sub harmonic relay to by-pass the series capacitors and (ii) use of a sub harmonic relay to trip the windfarms at collector locations. Brief explanations on these applications are provided below.

By-pass Series Capacitors

Figure 2 shows the arrangement of a sub-harmonic protection relay configured to by-pass the series capacitors. In this arrangement, the sub-harmonic relay takes the measurements from the transmission line for analysis. For this application, measurements can be taken from any point on the transmission line and provide more economical use for users compared to the other approach explained below. However, determination of protection settings for this application may require the analysis of multiple contingencies as decisions are made based on the full current flow on the line. It should be noted that in this arrangement, relay can also be used to trip the transmission line instead of by-passing the capacitors.

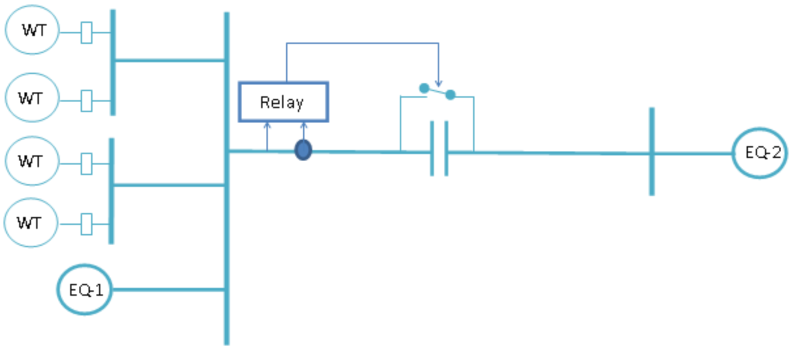

Fig. 2. Relay arrangement for by-passing the series capactior

Trip Wind Farms

Figure 3 shows the arrangement of the protection relays configured to trip the windfarms. In this arrangement, the relays are installed at wind farm collector locations. Depending on the arrangement of the collector feeders, measurements from multiple or single points may be required. Such requirements have to be accessed and selected appropriately. However, the use of local measurements provides more flexibility and selectivity for settings compared to the approach explained above. It should be noted that in this arrangement, decisions from relays can also be used to by-pass the series capacitors or trip the transmission line completely.

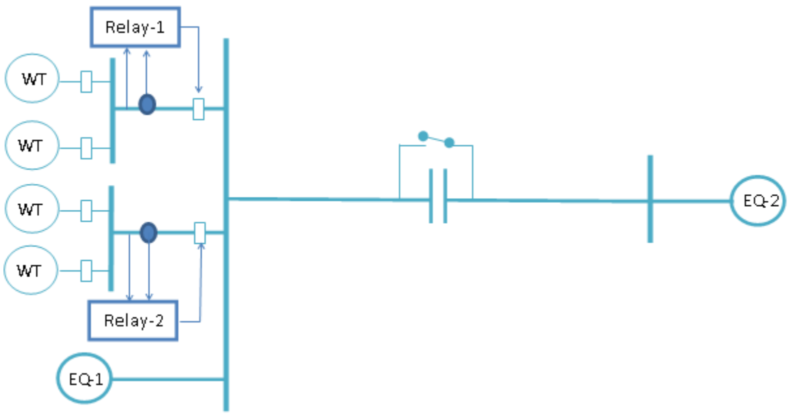

Fig. 3. Relay arrangement for tripping the windfarm

UNDERSTANING OF SUB-HARMONICS AND PRACTICAL CHALANGES ASSOCIATED WITH SUB-HARMONICS

As described in above section, the relays could be installed at transmission line substation or collector substation. For both application considerations, objective of the relay is to determine unstable sub-harmonic conditions generated by the interaction of windfarm and series compensated lines to perform required control actions.

In the process of developing the protection settings, special attention should be given to several practical considerations as described below.

Nature of Sub-harmonics

Sub-harmonics have a wider range of frequency, typically around 5-45 Hz for 50Hz power system and around 5-55Hz for 60Hz power system. Therefore, 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 effect on the performance of different power components in the system.

Effect of Normal Faults

Normal transmission line or associated component faults may generate sub-harmonics depending on the location of the faults and location of the series capacitor installations. Usually, the nature of these sub-harmonics is temporary and well damped. However, if the power system is in a state/contingency where unstable SSO can be generated due to the interaction of windfarm controller and a series capacitor, normal faults can initiate the unstable SSO. The pickup time delays used in the protection logic plays a major role in differentiating stable SSO verses unstable SSO.

Effect of Non-faulty Trainsets

The normal 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.

Sources of Errors

In using digital sub-harmonic protection to estimate SSO, 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. 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 (e.g. 22.3 Hz) helps to accurately estimate the possible resonance frequencies between the mechanical and electrical systems.

Limitations in Modelling and Simulation

Use of electromagnetic transient (EMT) type simulation programs for protection setting validation is recommended by the common standards such as CIGRE, IEEE, IET, etc. Although the SSO conditions associated with windfarms and series compensated system can be simulated and modelled using simulation programs, there several practical limitations involved.

- Unavailability of accurate system models
- Limitation with simulation bandwidth
- Limitation with simulation of multiple contingencies
- Modelling limitations with instrument transformers, etc.

Therefore, in most of the practical scenarios, protection settings have to be determined based on the limited information available from the simulation studies. Some applications may not have the results from all contingencies of the system.

Current Sub-harmonics and Voltage Sub-harmonics

One of the common queries related to the SSO conditions associated with windfarm/series capacitor application is the selection of most suitable input signal for successful detection of unstable sub-harmonics. The field recorded waveforms and EMT-type simulation based 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.

DEVELOPMENT OF PROTECTION SETTINGS

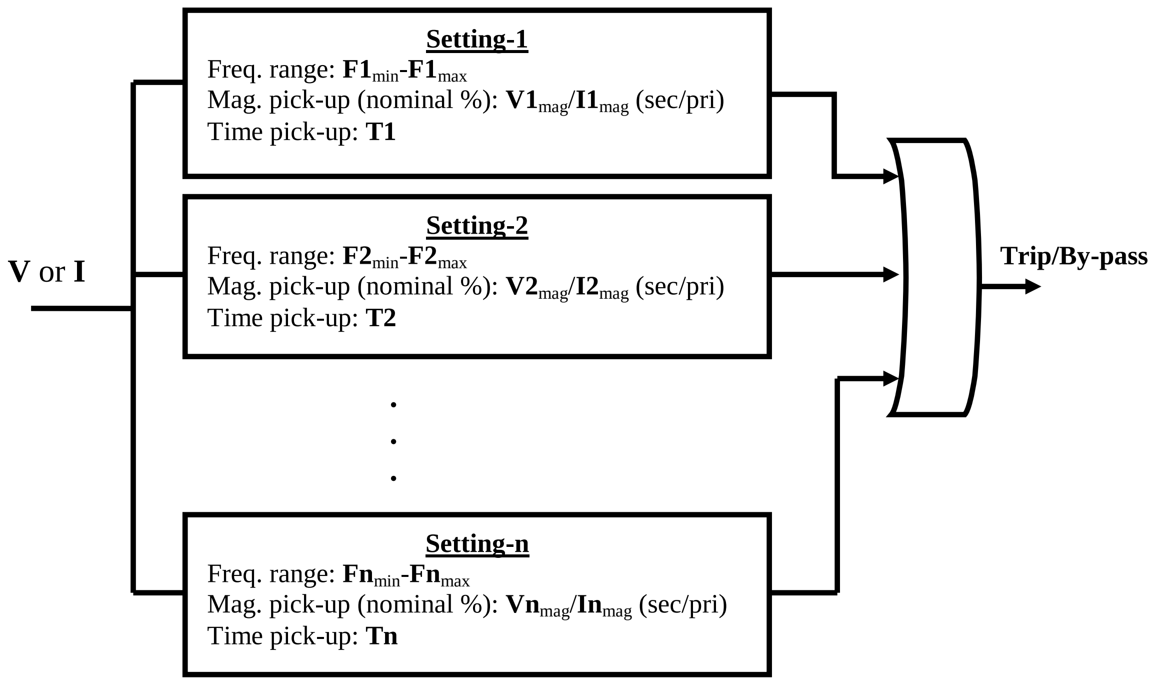

Fig. 4.   Proposed Protection Logic

As described in the above sections, development of protection settings require understanding of the nature of SSO associated with windfarms/series compensated systems and practical aspects/limitations associated with sub-harmonics. In this paper, applicability of the numerical sub-harmonic protection relay presented in [9] was investigated. This relay is capable of operating based on the current and the voltage sub-harmonics defined between a range of frequencies with magnitude and time delay settings. Figure 4 shows a generic protection logic that can be proposed for SSO protection. The inputs to the protection logic are voltage or current measurements with ***n*** - number of settings, combined into an OR logic. The logic output is used to trip the windfarm or by-pass the series capacitor or any other control action.

It should be noted the aforementioned sub-harmonic relay has been developed with more features and it could be used in different ways to provide the protection against the specific SSO problem discussed here. In addition, this relay can also be used to provide the protection against wide range of SSO applications which are not discussed here. However, the protection logic proposed in this paper provides the flexibility for user to select the settings based on the limited information available from system studies to achieve desirable performances. This logic can even be used without any information available from system studies to satisfy basic protection requirements.

Primary Sub-harmonic Protection: Current Signal Detectors

As explained above, line current measurements can be typically used as primary (fast) protection. Considering the nature of current sub-harmonics, three or four settings combinations (n=3 or 4) with inverse characteristics (shorter time delays for higher magnitudes and vice versa) would provide adequate protection. The frequency settings can be a single narrow band frequency, a combination multiple narrow band frequencies or a single wider band frequency, depending on the SSO modes available. Sub-harmonic current magnitudes above 4-5% of nominal would be considered as a possible SSO condition that needs attention. The minimum time delay allowed would be typically ~ 0.2 sec. for correct differentiation of stable (damped) SSO conditions created during transmission line faults and other switching events observed on current signals.

Secondary Sub-harmonic Protection: Voltage Signal Detectors

Secondary (slow) protection can be provided with voltage measurements. Considering the nature of voltage sub-harmonics, one or two settings combinations (n=1 or 2) with inverse characteristics would be sufficient. The frequency settings for voltage detectors would be defined similar to current detectors. Sub-harmonic voltage magnitudes above 4-5% of nominal would be considered as a possible SSO condition that needs attention. The minimum time delay allowed would be typically ~ 0.5 sec. for correct differentiation of stable SSO conditions created during CVT transients and other switching events observed on voltage signals.

Although the current sub-harmonics and the voltage sub-harmonics have been used as primary and secondary respectively, readers should be aware that depending on the availability of sensors (CTs, CVTS / PTs or both), user will have an option to select one detection method or a combination of both.

EXAMPLE CASE STUDIES

In order to understand the applicability of the aforementioned protection logic for different protection application scenarios, consider the following case studies. All cases studies are related to an application of a sub-harmonic relay installed on a 60 Hz single circuit series compensated transmission line in which a Type-III windfarm is installed in the vicinity. System study results available for these application cases are different and one application case has no information available from a system study. Protection settings are defined based on the available information. For all setting examples, the current detectors are defined with four stages whereas, the voltage detectors are defined with two stages. Frequency band settings are determined with ±3Hz error margin rounded off to 5 Hz resolutions.

Case-1

SSO Modes Available: ~13 Hz.

For this scenario, calculated frequency band is 10-16 Hz. This is approximated to 10-20 Hz range based on above 5 Hz criterion. The current detector settings were set 5%, 10%, 20% and 40% with time delays 0.5s, 0.4s, 0.3s and 0.2s respectively. The voltage detector settings were set 5% and 10with time delays 1.0 s and 0.5s respectively.

- Current detector-1 (n=4)
  - 10-20 Hz, 5%, 0.5 sec
  - 10-20 Hz, 10%, 0.4 sec
  - 10-20 Hz, 20%, 0.3 sec
  - 10-20 Hz, 40%, 0.2 sec
- Voltage detector-1 (n=2)
  - 10-20 Hz, 5%, 1.0 sec
  - 10-20 Hz, 10%, 0.5 sec

Case-2

SSO Modes Available: ~14 Hz and ~ 47 Hz.

For this scenario, calculated frequency bands are 11-18 Hz and 44-50 Hz. They are approximated to 10-20 Hz range and 40-50 Hz range based on above 5 Hz criterion. Settings can be provided with two narrow bands of frequencies (option-1) or one wide band frequency (option-2). Option-1 will provide more selective frequency detection compared to option-2. Since decisions are based on frequencies and magnitudes, both options will provide required protection for windfarms and series compensated lines

Option-1

- Current detector-1 (n=4)
  - 10-20 Hz, 5%, 0.5 sec
  - 10-20 Hz, 10%, 0.4 sec
  - 10-20 Hz, 20%, 0.3 sec
  - 10-20 Hz, 40%, 0.2 sec
- Current detector-2 (n=4)
  - 40-50 Hz, 5%, 0.5 sec
  - 40-50 Hz, 10%, 0.4 sec
  - 40-50 Hz, 20%, 0.3 sec
  - 40-50 Hz, 40%, 0.2 sec
- Voltage detector-1 (n=2)
  - 10-20 Hz, 5%, 1.0 sec
  - 10-20 Hz, 10%, 0.5 sec
- Voltage detector-2 (n=2)
  - 40-50 Hz, 5%, 1.0 sec
  - 40-50 Hz, 10%, 0.5 sec

Option-2

- Current detector-1 (n=4)
  - 10-50 Hz, 5%, 0.5 sec
  - 10-50 Hz, 10%, 0.4 sec

    - 10-50 Hz, 20%, 0.3 sec
    - 10-50 Hz, 40%, 0.2 sec
- Voltage detector-1 (n=2)
    - 10-50 Hz, 5%, 1.0 sec
    - 10-50 Hz, 10%, 0.5 sec

<u>Case-3</u>

SSO Modes Available: ~28 Hz and ~ 33 Hz.

For this scenario, calculated frequency bands are 25-31 Hz and 30-36 Hz. They are approximated to 25-35 Hz range and 30-40 Hz range based on above 5 Hz criterion. Since there is an overlap of frequency, it is more appropriate to define the settings with one wider band of 25-40 Hz.

- Current detector-1 (n=4)
    - 25-40 Hz, 5%, 0.5 sec
    - 25-40 Hz, 10%, 0.4 sec
    - 25-40 Hz, 20%, 0.3 sec
    - 25-40 Hz, 40%, 0.2 sec
- Voltage detector-1 (n=2)
    - 25-40 Hz, 5%, 1.0 sec
    - 25-40 Hz, 10%, 0.5 sec

<u>Case-4</u>

SSO Modes Available: unknown

Since there is no data available regarding the SSO modes, full range of frequency (i.e. 5-55 Hz) can be used due the following reasons:
-Decisions are made based on both frequency and magnitudes.
-For a stable/healthy power system, sub-harmonic components with higher magnitudes may not be possible.

- Current detector-1 (n=4)
    - 5-55 Hz, 5%, 0.5 sec
    - 5-55 Hz, 10%, 0.4 sec
    - 5-55 Hz, 20%, 0.3 sec
    - 5-55 Hz, 40%, 0.2 sec
- Voltage detector-1 (n=2)
    - 5-55 Hz, 5%, 1.0 sec
    - 5-55 Hz, 10%, 0.5 sec

Special Considerations

- During black start conditions, it is recommended to block the relay completely to avoid mal-operations. It should be noted that during such conditions, series capacitor and windfarms could be out of service as per the protection requirements.
- The double circuit, mutually coupled series compensated transmission lines require extra time delay of ~ 0.2 sec for all current detectors to avoid possible mis-operations due the events on the adjacent lines.
- If accurate information/data is available, settings (including frequency settings limits) could be optimized based on the results from detailed EMT-type simulations. In such situations, COMTRADE waveforms generated using the EMT-type simulation programs are recommended.

TEST RESULTS

In order to investigate the usefulness of the proposed protection logic in situations where information from a system study is not available, field recorded waveform captured by a DFR was injected into the sub-harmonic relay using a real time playback system with the basic settings provided in above Case-4. Figure-5 shows the oscillography captured by the relay. As it can be observed from the results, the trip time of the relay is around 0.5s.

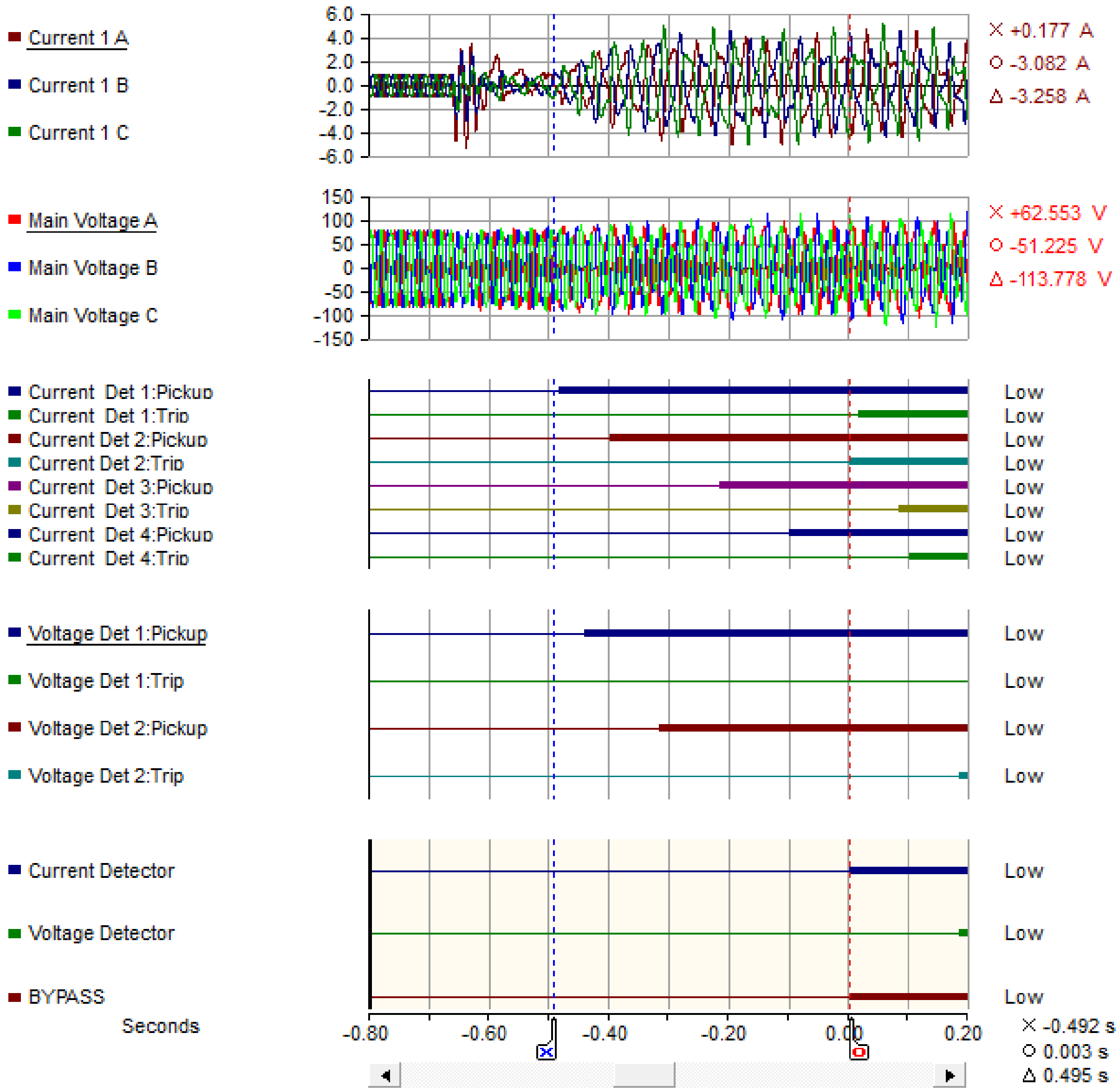

Fig. 5. Operation of the relay

The sub-harmonic spectrums of the current and the voltage signals observed by the relay are shown in Figure-6 and 7. As it can be observed, dominant sub-harmonic is around 25 Hz.

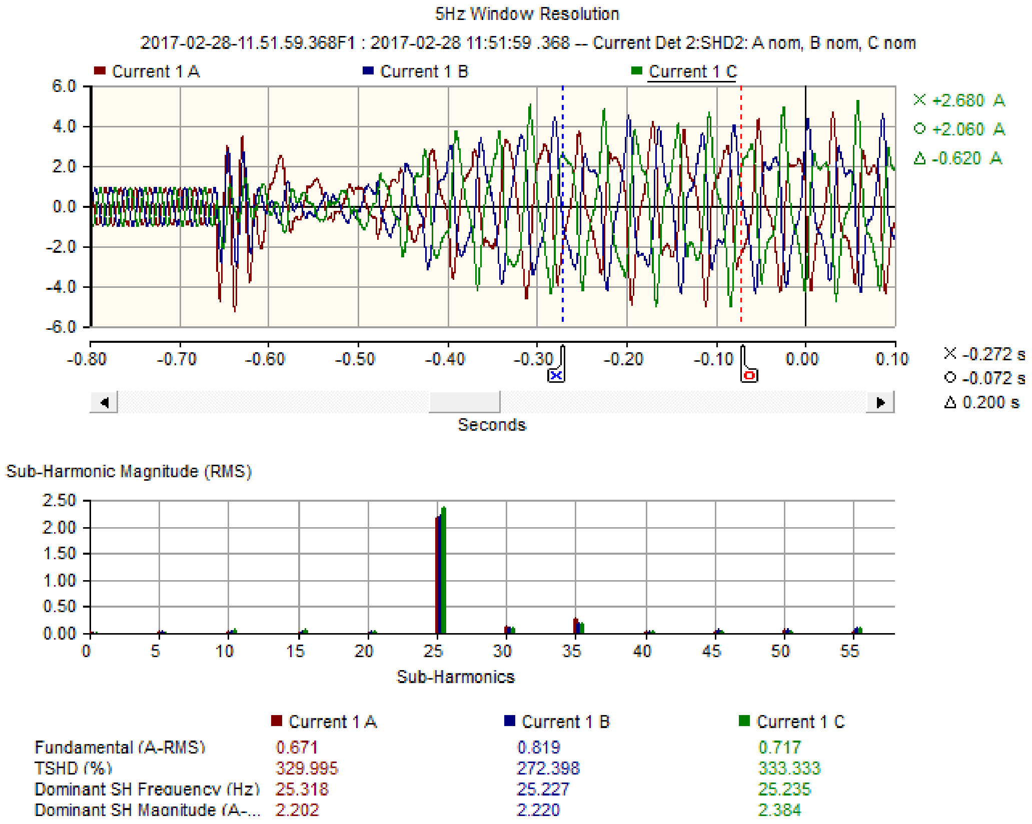

Fig. 6. Sub-harmonic spectum of current signals

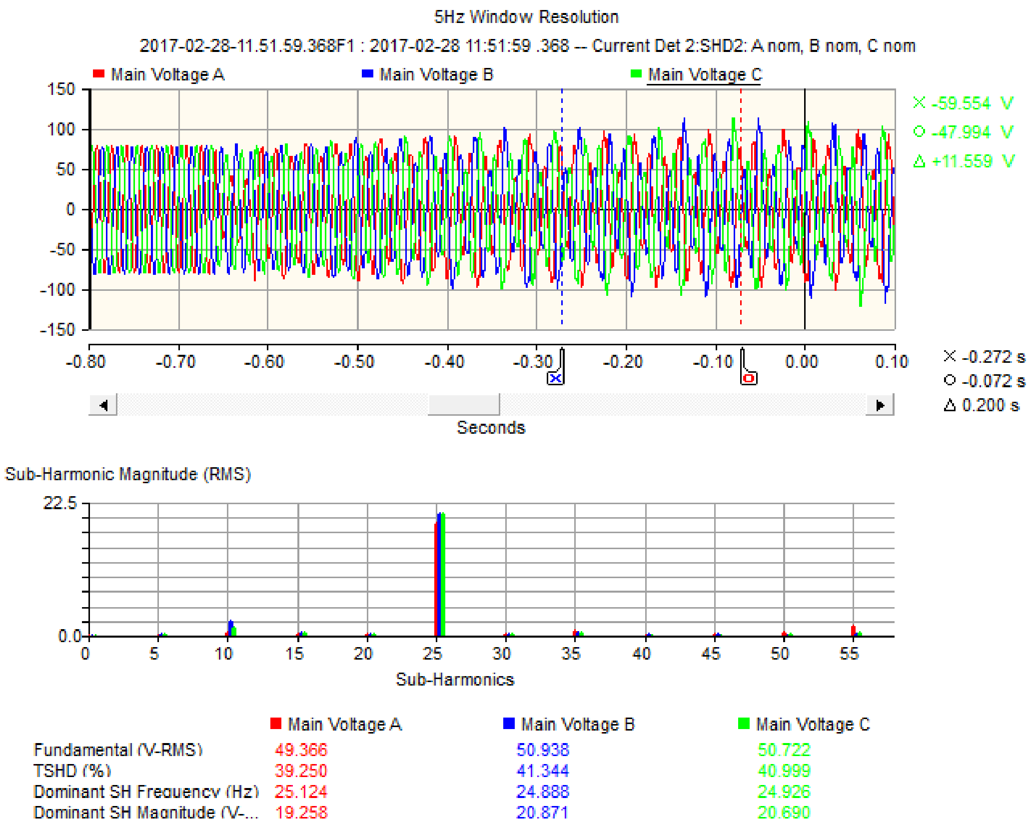

Fig. 7. Sub-harmonic spectum of voltage signals

CONCLUSIONS

In this paper, applicability of a numerical sub-harmonic protection relay to provide the protection against SSO conditions associated with interactions of Type-III windfarms and series compensated 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 SSO 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 the field recoded waveforms obtained from a digital fault recorder. Test results confirm that the investigated relay is capable of providing adequate protection against SSO conditions.

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