# Tutorial on Sub Synchronous Resonance Protection Applied to Inverter Based Renewables

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***Abstract*—With the increased use of renewables, inverter connected energy resources such as wind farms and PVs are being widely integrated into the transmission system. Events in the transmission system can cause interactions between the natural frequencies of the power system and the controllers in the inverter system. This could sometimes result in sub-synchronous oscillation conditions leading to wide system damages. On the other hand, the conventional monitoring control and protection devices that operate based on power frequency measurements may not trigger, operate or respond during these conditions.**

**This paper provides an introduction to sub-synchronous oscillation conditions generated due to the integration of inverter connected energy resources, including useful information for system, protection and control engineers.**

**Keywords—windfarms, SSCI, protection, simulation**

## I. 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 SSCI generated due to the interaction of various elements in the power system [1].

In recent literature, several SSCI events have been reported in existing installations that have wind turbine and series compensated systems [2]. System studies carried out using simulation models of the windfarms has confirmed that controllers of type-3 windfarms are more susceptible to interact with series compensated systems to generate unstable SSR 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 systems. Figure-1 shows the oscillography captured during a real SSR event captured by a digital fault recorder. As most conventional protection relays operate based on power frequency (50/60Hz) components, these resonance conditions were not detected by the relays in the system [6].

This paper focuses on the important considerations involved with protecting a power system under possible SSCI conditions. This paper covers basic protection related simulation studies used to identify the possible SSCI conditions, protection related challenges and protection methods. Specific cases are also discussed including some test results.

## II. TOOLS AND METHOD USED IN SYSTEM STUDIES

It is essential to perform system studies to understand the potential risks associated with SSCI conditions in order to introduce mitigation (or protection) measures that avoid equipment damage. Requirement of detailed system studies can be identified by observing the network topology and type of DERs involved. For instance, a DER system may face SSCI if a nearby series capacitor makes radial or near radial connection with the DER during outage conditions (e.g. N-1, N-2, etc.). This section of the paper covers different options available to study these systems [7-8].

### A. Harmonic Impedance Scanning

Harmonic impedance scans are used to derive network impedance as a function of frequency. This screening method is useful to identify the electrical sub-synchronous frequency of resonance due to series capacitors. The passive scan can be performed using electromagnetic transient (EMT) software tools such as PSCAD. The standard PSCAD master library component shown in Fig.1 captures the impedance vs frequency curve (i.e. *Z(f)*) of the electrical network's passive elements, as seen from the point of interconnection with the wind farm. Further, this technique ignores the effect of controls (from wind plants, exciters, governors, stabilizers, SVCs, VSC or HVDC links, etc.) and does not include the frequency dependence of generators.

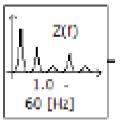

Fig. 1. Passive scan module in PSCAD Master Library

It is common practice to generate a series of impedance vs frequency curves under different load flow conditions and different network outage conditions (System Intact, N-1, N-2, and N-3). These results are used to identify the worst-case system conditions, where there is a correlation between the electrical resonances of the network and the negative damping region of nearby power electronic devices or generators. Series resonance frequencies of the post contingency network (as seen from the point of interconnection) are determined by identifying the conductance curve peaking points. The conductance curve is calculated using harmonic impedance profiles as follows:

$$G(f) = Real\left(\frac{1}{Z(f)}\right) \tag{1}$$

where, *Z(f)* is complex quantity that represents the harmonic impedance at frequency *f*.

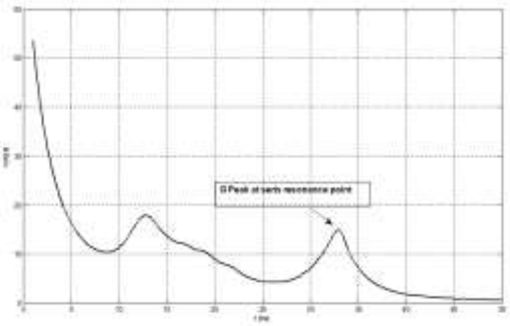

Fig. 2. Conductance curve

### *B. Dynamic Frequency Scanning*

Dynamic frequency scanning is used to calculate the damping provided by a power electronic converter or synchronous generator at sub-synchronous frequencies. This scanning is a 'screening level' analysis, where the results are compared, together with the network-side harmonic impedance scan information, to identify SSCI risks. Dynamic frequency scanning results are derived using the harmonic injections method [2]. This technique injects relatively 'low' magnitude harmonic current into the wind turbine model over the sub-synchronous frequency range. Generally, this is done by modulating the terminal voltage of the turbine with a harmonic voltage waveform (see Fig 3). Using measured currents and voltages (i.e. $i_t$ and $v_t$), corresponding phasor quantities (i.e. *V(f)*, *I(f)*) are calculated using the DFT (discrete Fourier transform) technique.

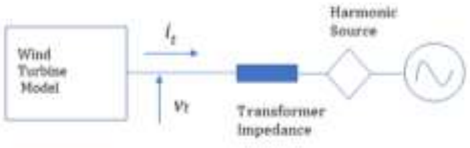

Fig. 3. Dynamic frequency scan setup

Then dynamic impedance is calculated for each frequency as follows:

$$Z(f) = \frac{V(f)}{I(f)} \tag{2}$$

The real part of this dynamic harmonic impedance *Z(f)* is considered as the damping at frequency *f* (i.e. *R(f)*). A typical damping plot of a type-3 wind turbine is shown in Fig 4. As illustrated, the turbine has a negative damping at sub-synchronous frequencies above 30 Hz. This means the turbine could face SSCI if the network has a series resonance point between 30 Hz and 60 Hz. For instance, the harmonic impedance scan results shown in Fig. 2 have a series resonance point at 32.5 Hz. Therefore, the turbine with damping characteristics shown in Fig 4 is susceptible to SSCI under the contingency that used to produce the impedance plot in Fig 2.

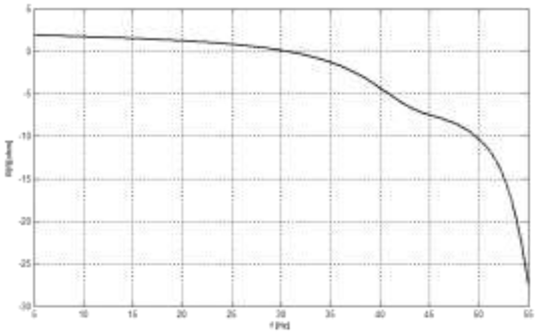

Fig. 4. Typical dynamic resistance plot of a type-3 wind turbine

### *C. Time Domain Simulation*

Once the worst contingencies are identified using the methods above, time-domain simulations are performed for the selected network configuration. Typically, electromagnetic transient simulation programs (e.g. PSCAD) are used for these types of analysis [10] rather than conversional transient stability software programs. At this level of analysis, it is a common practice to use detailed EMT type simulation models of the wind turbines. In order to make the EMT simulation study more feasible (from simulation timing point of view), the wind turbine model is scaled to represent the collective power of the wind farm. The scaling can be adjusted to define any specific number of wind units that are in operation at a given time. In this analysis, the worst contingencies identified in (A) and (B) are applied when the system is in steady-state. Current waveform at the POI can be used to determine whether or not an SSCI event triggered. The typical POI current waveform captured in an SSCI event (in time-domain EMT simulation) is shown in Fig 5.

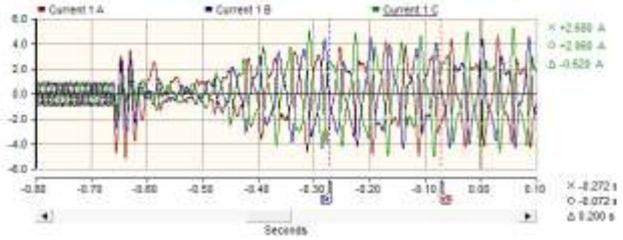

Fig. 5. Typical POI current waveform at SSCI event

## III. PROTECTION SOLUTIONS

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

### A. *Trip Off the DFR*

Figure 6 shows the arrangement of a sub-harmonic protection relay configured to bypass the series capacitors. In this arrangement, the sub-harmonic relay takes measurements from the transmission line for analysis. For this application, measurements can be taken from any point on the transmission line, and provides a more economical solution in comparison with 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 line’s full current flow. It should be noted that in this arrangement, the relay can also be used to trip the transmission line, instead of bypassing the capacitors.

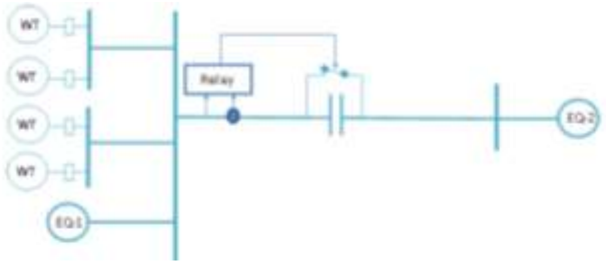

Fig. 6. Series capacitor bypassing

### B. *Bypass the Series Capacitors*

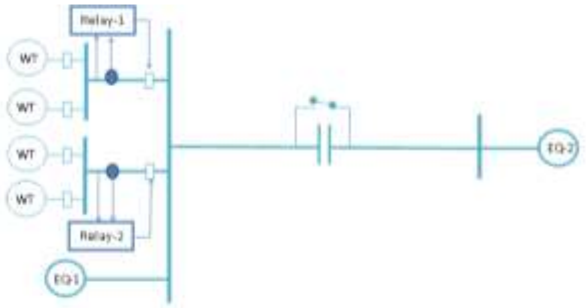

Fig. 7. Windfarm tripping

Figure 7 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 measurement 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 bypass the series capacitors or trip the transmission line completely.

## IV. UNDERSTANDING OF SUB-HARMONICS AND PROTECTION-RELATED CHALLENGES

As described in the above section, the relays could be installed at a transmission line substation or collector substation. In either application, the 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 protection settings, special attention should be given to several practical considerations described below.

### A. *Nature of Sub-Harmonics*

Sub-harmonics have a wider range of frequency, typically around 5-45 Hz for a 50 Hz power system and around 5-55 Hz for a 60 Hz power system. Therefore, accurately estimating the magnitude of a particular frequency component requires a minimum time delay proportional to the inverse of that frequency. In addition, energy signals carried at different frequencies have a different effect on the performance of different power components in the system.

### B. *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 SSCI can be generated due to the interaction of the windfarm controller with a series capacitor, normal faults can initiate the unstable SSCI. Pickup time delays used in the protection logic play a major role in differentiating stable SSCI verses unstable SSCI.

### C. *Effect of Non-Faulty Transients*

Normal transients such as transformer inrush, normal faults, current transformer saturation, etc. could mislead sub-harmonic calculations. In addition, the presence of lower-order harmonics may also mislead 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 should be given to differentiate capacitive voltage transformer (CVT) generated sub-harmonics, versus unstable SSCI generated from the system or controller interactions. In this type of application, appropriate pickup time delays should be used to cope with the physical phenomena.

### D. *Sources of Errors*

In using digital sub-harmonic protection to estimate SSCI, there are a number of sources for error. 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 that accuracies below nominal frequency (sub-harmonic range) will be different. In addition, in digital protection relays, ADC resolutions are set based on maximum voltage and current magnitude limits at nominal frequencies. The magnitude of sub-harmonics that need to be detected could be significantly lower than those maximum limits and therefore one must use special attention to select the ratings. Furthermore, depending on the estimation technique used by the relay, computational errors could be higher when estimating decimal frequencies. In selecting a suitable protection relay, all these factors should be evaluated carefully, providing appropriate margins 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.

### E. Limitations in Modelling and Simulation

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

- Unavailability of accurate system models
- Simulation bandwidth limitations
- Limitations simulating multiple contingencies
- Modelling limitations with instrument transformers, etc.

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

### F. Current Sub-Harmonics and Voltage Sub-Harmonics

One of the common queries related to SSCI conditions in windfarm/series capacitor applications is the selection of the 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 than sub-harmonics on 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.

## V. SUB-HARMONIC PROTECTION PHOLOSHPY

As described in the above sections, development of protection settings requires understanding of the nature of SSCI 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 8 shows generic protection logic that can be proposed for SSCI 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 bypass the series capacitor (or any other control action). It should be noted this sub-harmonic relay has other features that would enable it to be used in different ways to provide protection against the specific SSCI problem discussed here. In addition, this relay can also be used to provide protection against a wide range of SSCI applications which are not discussed here. The protection logic proposed in this paper provides the flexibility for a user to select settings based on the limited information available from system studies in order to achieve desirable performances. This logic can even satisfy basic protection requirements in cases where system study information is not available.

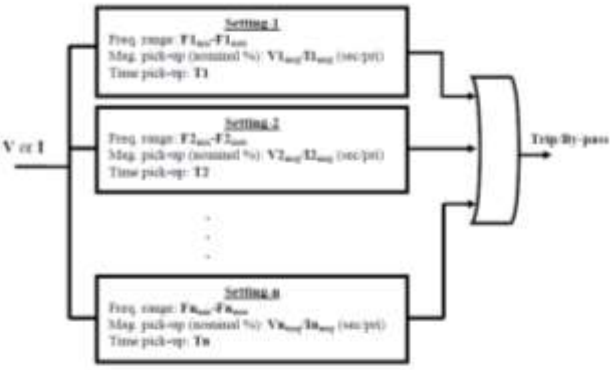

Fig. 8. Generic protection logic

### A. Primary Sub-Harmonic Protection: Current Signal Detectors

As explained above, line current measurements are 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. Frequency settings can be a single narrow band frequency, a combination of multiple narrow band frequencies or a single wider band frequency, depending on the SSCI modes available. Sub-harmonic current magnitudes above 4-5% of nominal would be considered a possible SSCI condition needing attention. The minimum time delay allowed would typically be ~0.2 sec to correctly differentiate stable (damped) conditions created during transmission line faults from other switching events observed on current signals.

### B. 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 is sufficient. Frequency settings for voltage detectors would be defined similarly to current detectors. Sub-harmonic voltage magnitudes above 4-5% of nominal would be considered a possible SSCI condition that needs attention. The minimum time delay allowed would be typically ~0.5 sec for correct differentiation of stable SSCI 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), the user has the option to select one detection method or a combination of both.

## VI. CASE STUDIES

In order to understand the applicability of this protection logic for different protection application scenarios, consider the following case studies. All case 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-3 windfarm is installed nearby. 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 ±3 Hz error margin rounded off to 5 Hz resolution.

### *A. Case-1*

SSCI Modes Available: ~13 Hz

For this scenario, the calculated frequency band is 10-16 Hz. This is approximated to a 10-20 Hz range, based on rounding to 5 Hz resolution. Current detector settings were set 5%, 10%, 20% and 40%, with time delays of 0.5s, 0.4s, 0.3s and 0.2s respectively. Voltage detector settings were set 5% and 10%, with time delays of 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

### *B. Case-2*

SSCI Modes Available: ~14 Hz and ~47 Hz

For this scenario, calculated frequency bands are 11-18 Hz and 44-50 Hz. These bands are approximated to a range of 10-20 Hz and 40-50 Hz, based on rounding to 5 Hz resolution. 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 than 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

### *C. Case-3*

SSCI 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 a range of 25-35 Hz and 30-40 Hz, based on rounding to 5 Hz resolution. 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

### *D. Case-4*

SSCI Modes Available: Unknown

Since there is no data available regarding the SSCI modes, the full range of frequency (i.e. 5-55 Hz) can be used since:

- 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)
    o 5-55 Hz, 5%, 0.5 sec
    o 5-55 Hz, 10%, 0.4 sec
    o 5-55 Hz, 20%, 0.3 sec
    o 5-55 Hz, 40%, 0.2 sec

☐ Voltage detector-1 (n=2)
    o 5-55 Hz, 5%, 1.0 sec
    o 5-55 Hz, 10%, 0.5 sec

### *E. 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 capacitors and windfarms could be out of service due to protection requirements. The double circuit, mutually coupled series compensated transmission lines, require an extra time delay of ~0.2 sec for all current detectors, to avoid possible mis-operations from events on 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, it is recommended to use COMTRADE waveforms generated from EMT-type simulation programs.

### *F. Operation of the Relay*

In order to investigate the usefulness of the proposed protection logic in situations where information from a system study is not available, field recorded waveforms captured by a DFR were injected into the sub-harmonic relay using a real-time playback system with the basic settings provided in Case-4, above. Figure-9 shows the oscillography captured by the relay. As can be observed from the results, the relay's trip time is around 0.5 sec.

## VII. CONCLUSION

This paper investigated applicability of a numerical sub-harmonic protection relay to provide the protection against SSCI conditions associated with interactions between type-3 windfarms and a series compensated system. The paper gave a brief overview of sub-harmonics and the key challenges in using numerical relays to provide protection against SSCI. It also proposed a protection setting structure that provides the flexibility for users to select basic settings, even during situations where limited information or no information is available from system studies. 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 SSCI conditions.

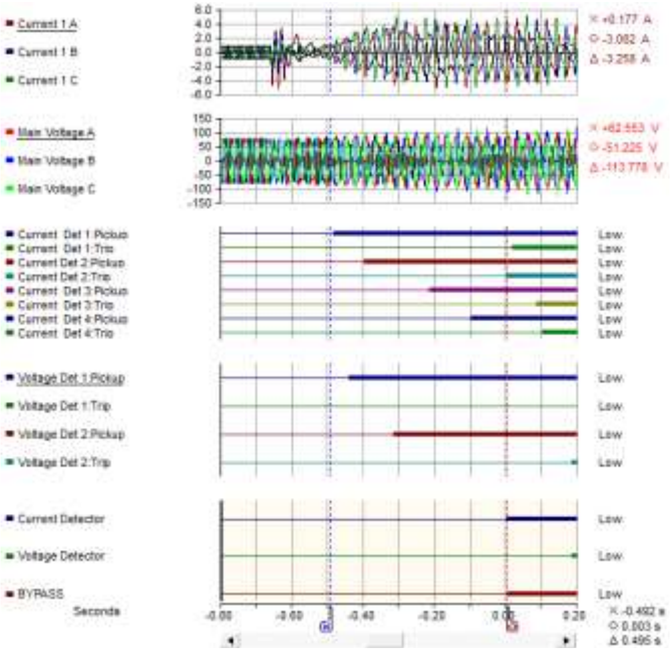

Fig. 9. Oscillography captured by the relay

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