Western Protective Relay Conference 2020

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

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Outline

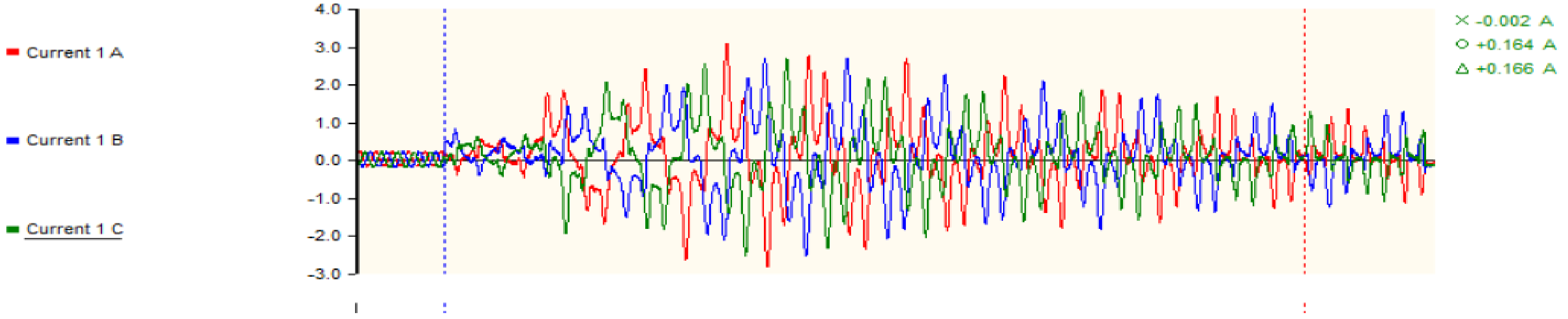
- Introduction
  - SSR/SSO applied to inverter connected renewables/generation
    - Sub-Synchronous Control Interactions (SSCI)
  - Requirement of SSCI studies
- SSCI simulation studies
  - Methods
  - Results
- Protection solutions
  - Protection methods
  - Example case studies
  - Simulation and test results
- Summary

Introduction

- Inverter connected renewable and distributed energy resources are being installed worldwide
  - Windfarms, PV (solar) systems
- Existing transmission networks are being upgraded with the addition of various compensating devices
  - SVCs, series capacitors, shunt compensators
- Inverters and networks could interact with each other to generate low frequency oscillations
  - Sub Synchronous Control Interactions (SSCI)

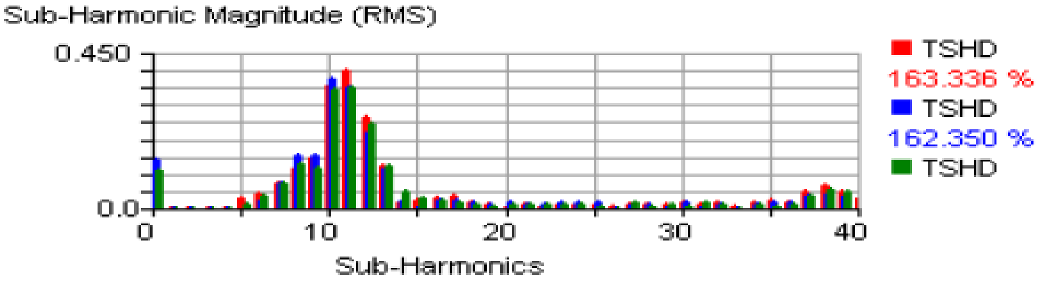
Sub-Synchronous Control Interactions (SSCI)

- Example of SSCI event captured in the field
- Type-3 wind farm & series compensated system
  - Xcel Energy, USA.



Sub-Synchronous Control Interactions (SSCI)

- Understanding the sub-harmonic (low frequency) spectrum



8-13 Hz

Freque...	Mag...	Mag ...	Mag...
7	0.075	0.078	0.076
8	0.120	0.155	0.132
9	0.148	0.155	0.117
10	0.363	0.382	0.350
11	0.403	0.355	0.354
12	0.271	0.225	0.248
13	0.126	0.122	0.125

- Conventional relays do not detect sub-harmonic conditions
  - Equipment damages are possible with some safety concerns

Requirement of System Studies

- It is essential to perform system studies to understand the potential risks associated with SSCI conditions
  - This work is part of the system integration study (series capacitors, wind systems, etc.)

- Network topology and type of inverters determines requirement for a detailed system study
  - Example: a system may face SSCI if a nearby series capacitor makes radial or near radial connection with the type-3 windfarm during outage conditions

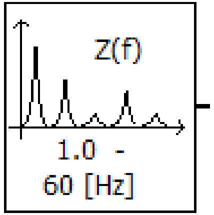
Methods Used in System Studies

- Methodologies
  - Harmonic impedance scanning
  - Dynamic frequency scanning
  - Time domain simulation

- Note: determined not by the system protection study but by the system integration study.

Harmonic Impedance Scanning

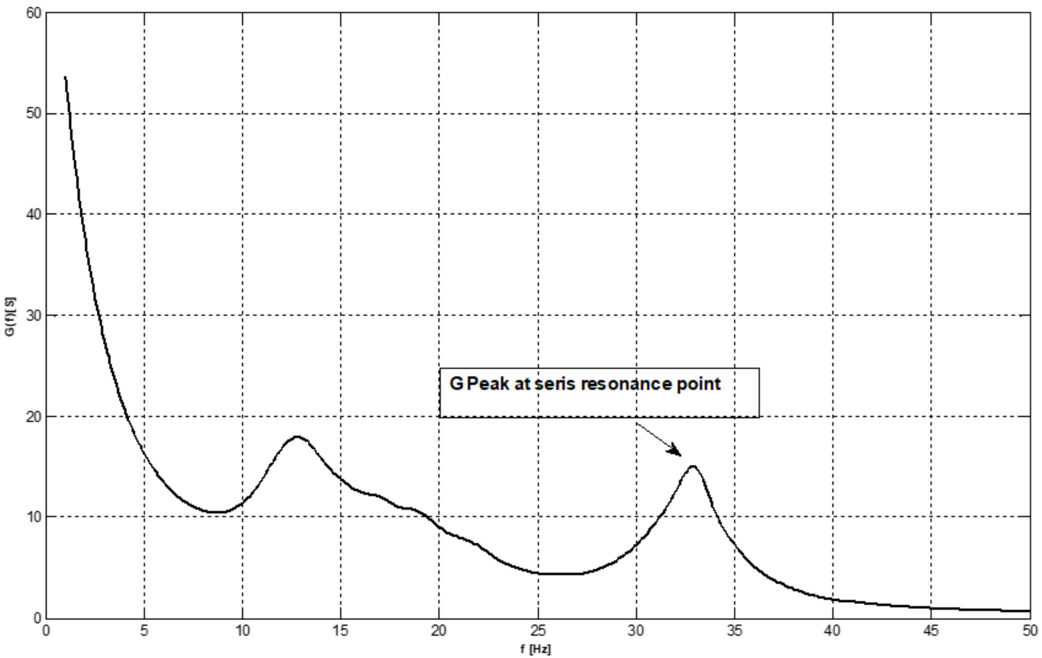
- Harmonic impedance scans (passive) are used to derive network impedance as a function of frequency



- It is useful to identify the electrical sub-synchronous frequency of resonance conditions
- The scan can be performed using electromagnetic transient (EMT) simulation software tools such as PSCAD, EMTP, etc.
  - Effect of controls are ignored

Harmonic Impedance Scanning

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

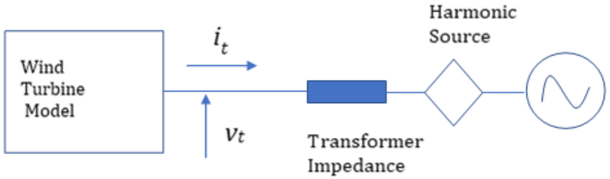


Dynamic Frequency Scanning

- This option is used to calculate the damping provided by a power electronic converter at sub-synchronous frequencies
- This technique injects relatively ‘low’ magnitude harmonic current into the inverter model (EMT power system simulation, PSCAD or EMTP) over the sub-synchronous frequency range
- Generally, this step involves modulating the terminal voltage of the turbine with a harmonic voltage waveform

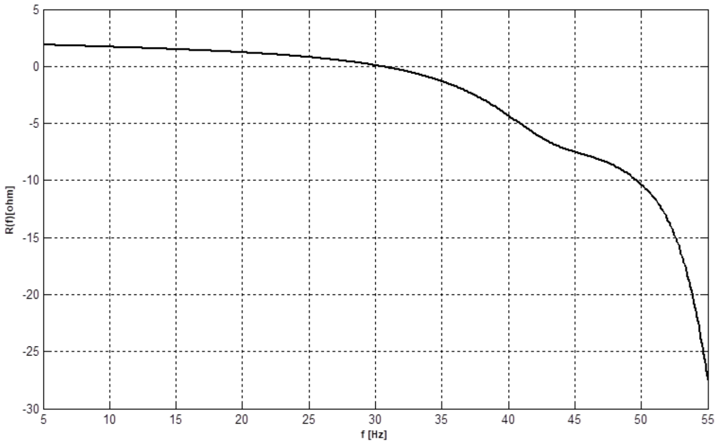
Dynamic Frequency Scanning

- Scanning setup



- Dynamic impedance $Z(f) = \dfrac{V(f)}{I(f)}$

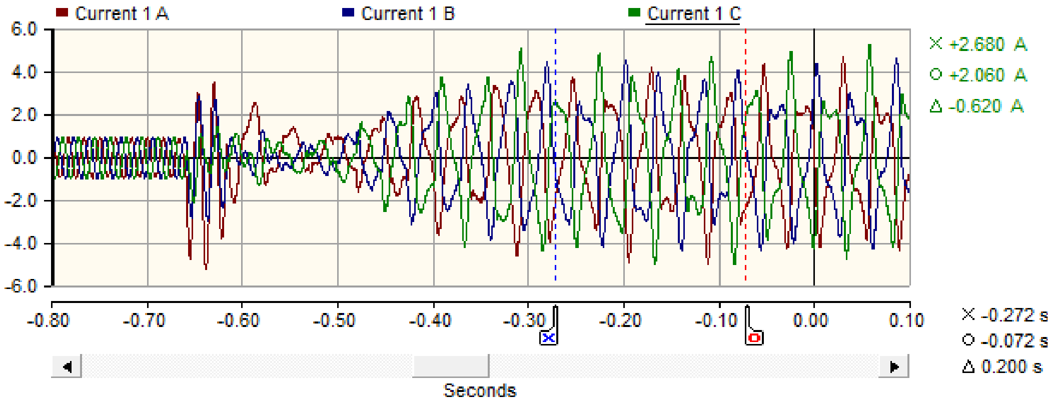
- Dynamic response plot
  - negative resistance



- The results of this study are compared with the network-side harmonic impedance scan

Time Domain Simulation

- Once the worst contingencies are identified using the previous methods, time-domain simulations are performed for the selected network configurations.
- Electromagnetic transient type (PSCAD, EMTP) simulation programs should be used for these types of analysis
  - Output

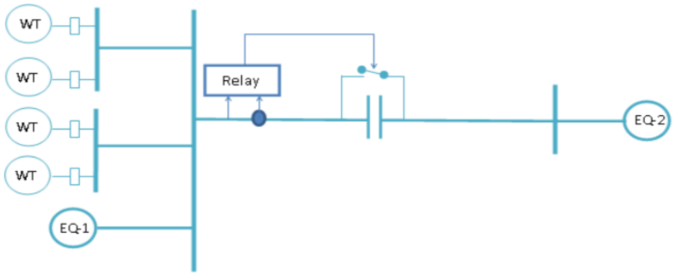


System Study Results

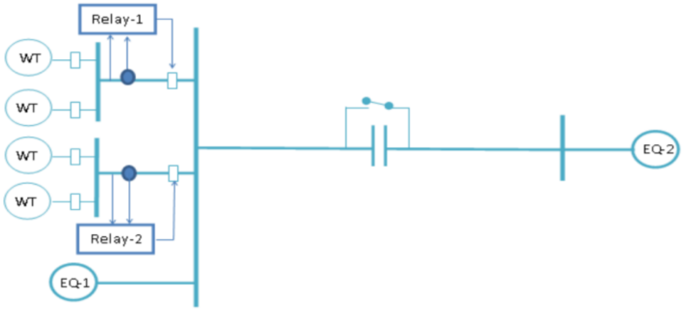
- If there is no risk of SSCI, no action is required (best case scenario)
- If there is a risk of SSCI, **mitigation solutions** are considered.
    - Controller tuning
    - Topology based mitigation
    - Protection solution
  - System study provides
    - SSCI frequencies (individual or a range)
    - SSCI magnitudes

Protection Solutions (examples)

- By-passing series capacitor



- Tripping windfarm



Protection Challenges and Practices for Interconnecting Inverter Based Resources to Utility Transmission System, IEEE PSRCC, Report of Working Group C32 of the System Protection Subcommittee, 2020

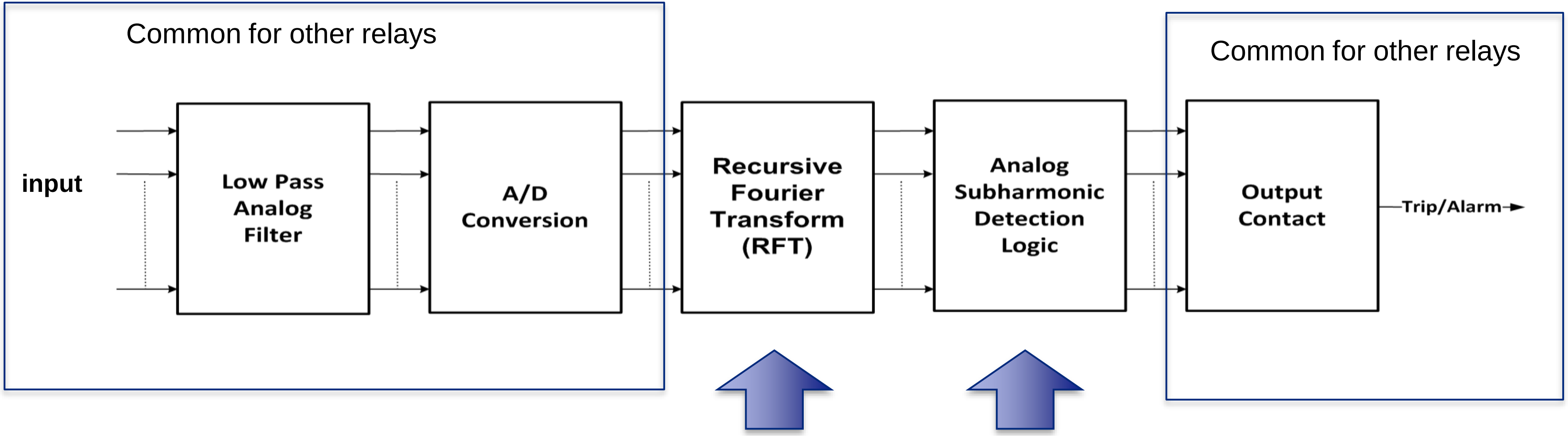
Understanding of Sub-Harmonics & Limitations

- Protection Relaying point of view
  - Nature of sub-harmonics
  - Effect of normal faults
  - Effect of non-faulty transients
  - Sources of errors
  - Limitations in modelling and simulation
    - networks with multiple inverters
    - actual system vs simulation model

SSCI Relay Features

- Operates based on voltage or current measurements
- Frequency setting range (5-55 Hz)
  - Operates based on recursive DFT
  - Combination of 1Hz and 5Hz
- Various measurement methods
  - Nominal sub-harmonic measurements
  - Sub-harmonics as a percentage of fundamental component
  - Cumulative sub-harmonics as a percentage of fundamental component
  - Detection of momentary picking up of sub-harmonics

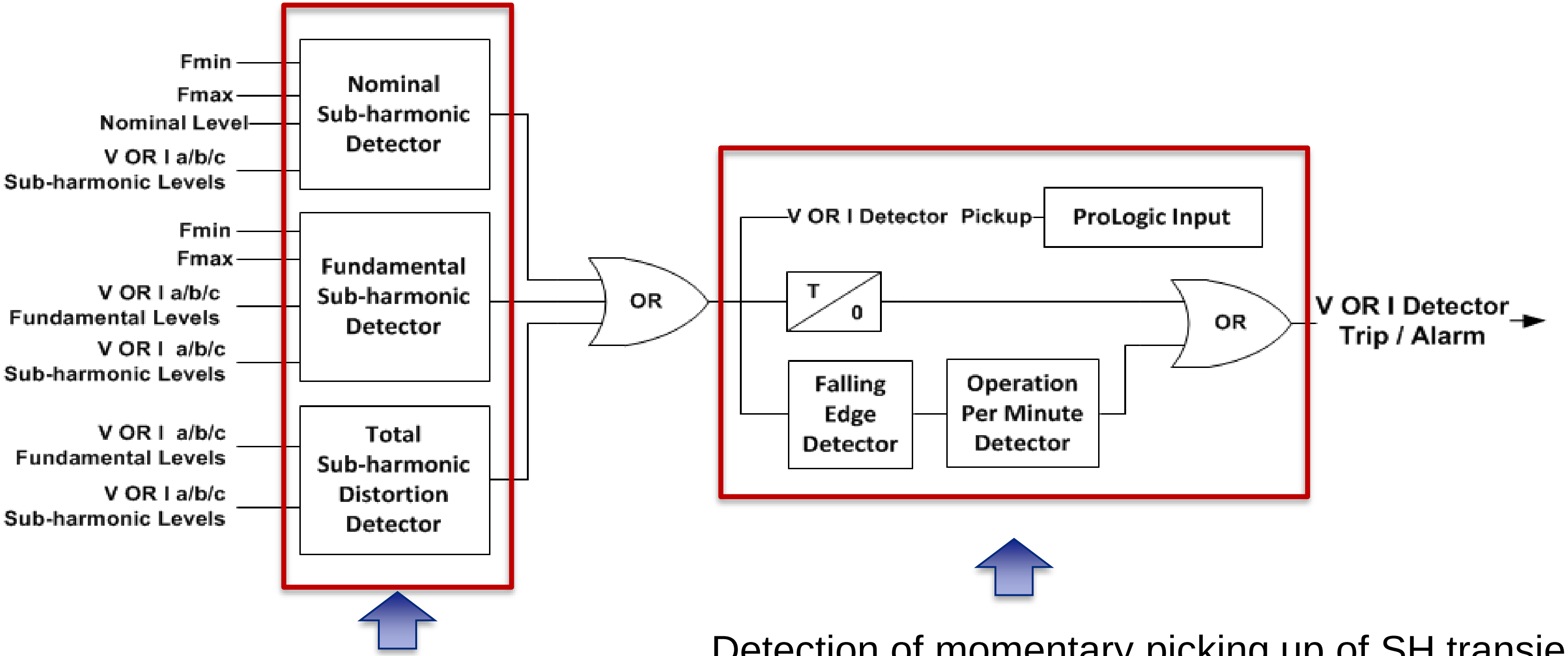
SSCI Relay Basic Algorithm



5-55Hz

We will cover this in next few slides

Sub-Harmonic Detection Logic Diagram

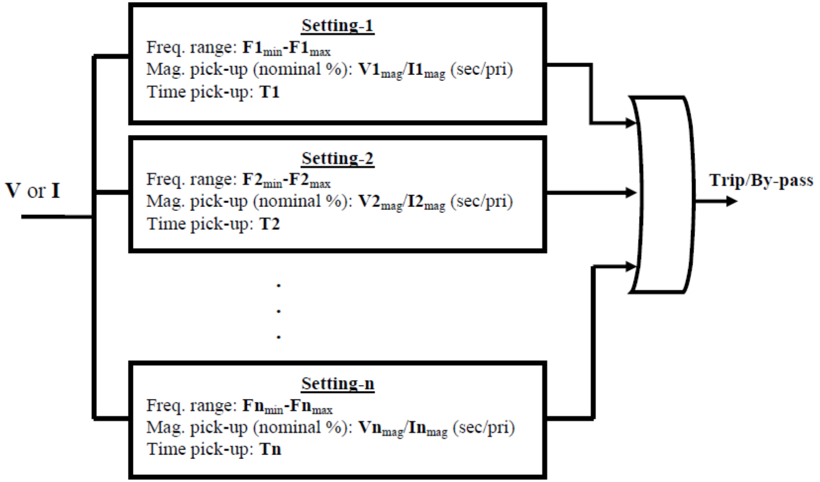


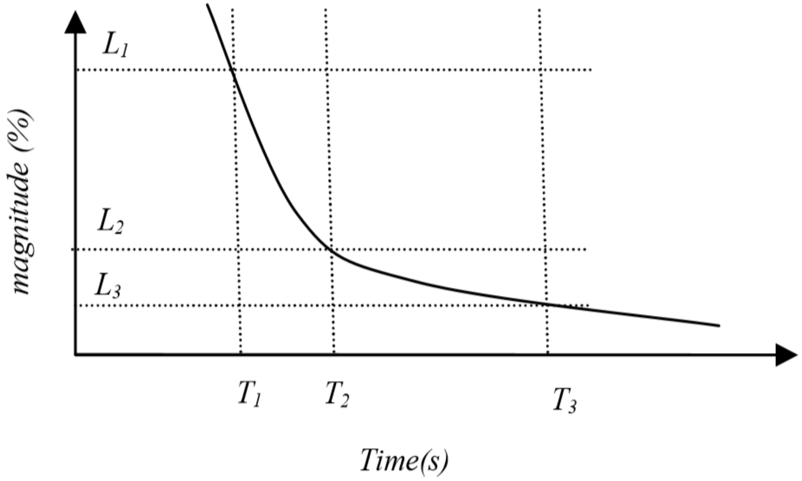
Various measurement methods

Detection of momentary picking up of SH transients

Protection Philosophy

- Formulation of inverse characteristics
  - Set to operate based on **nominal** and **total sub-harmonics**





  - Provides enhanced operation

Application Case-1

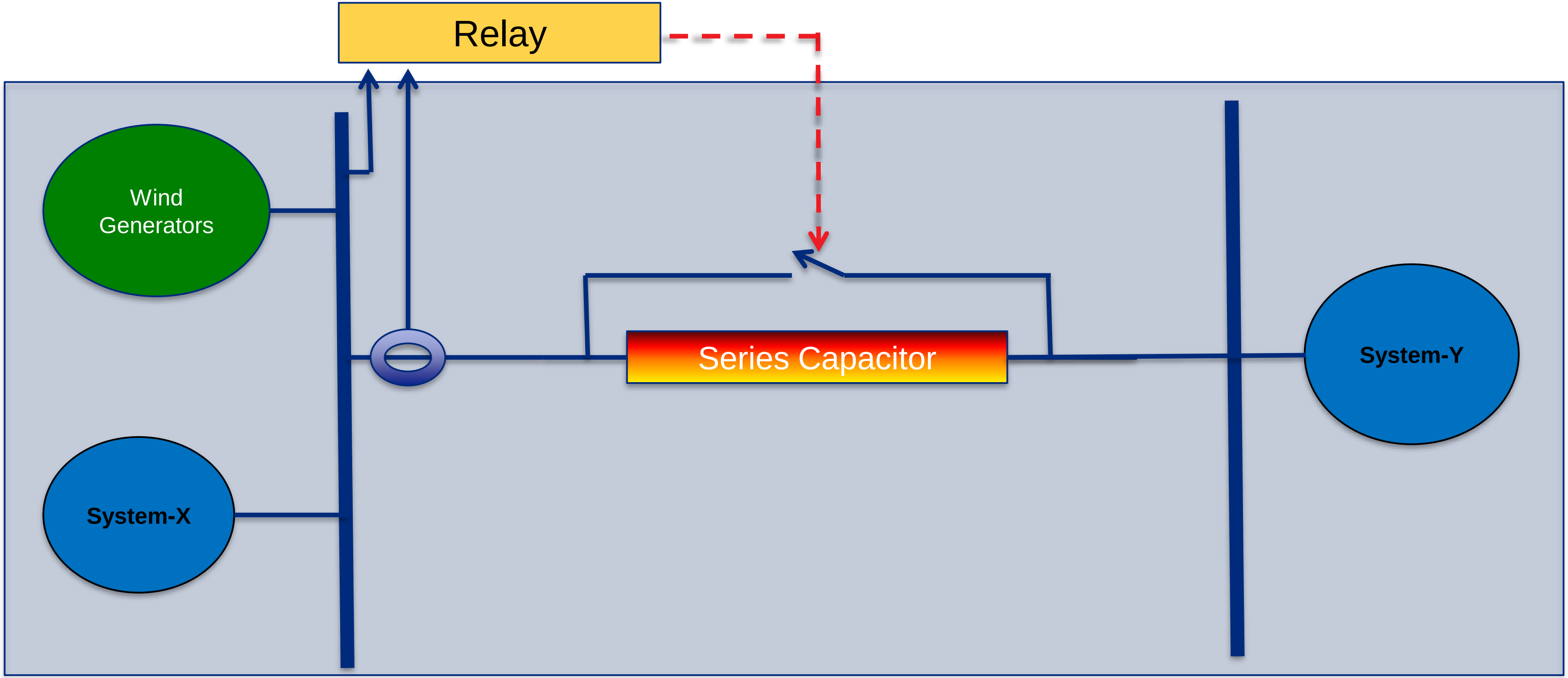
- SSCI Modes Available: ~22 Hz and ~47 Hz with > 5% Mag SSCI

  (based on system studies)
- Current detection (4 stages)
  - 20-50 Hz, 5%, 0.5 sec
  - 20-50 Hz, 10%, 0.4 sec
  - 20-50 Hz, 20%, 0.3 sec
  - 20-50 Hz, 40%, 0.2 sec
- Voltage detection (2 stages)
  - 20-50 Hz, 5%, 1.0 sec
  - 20-50 Hz, 10%, 0.5 sec

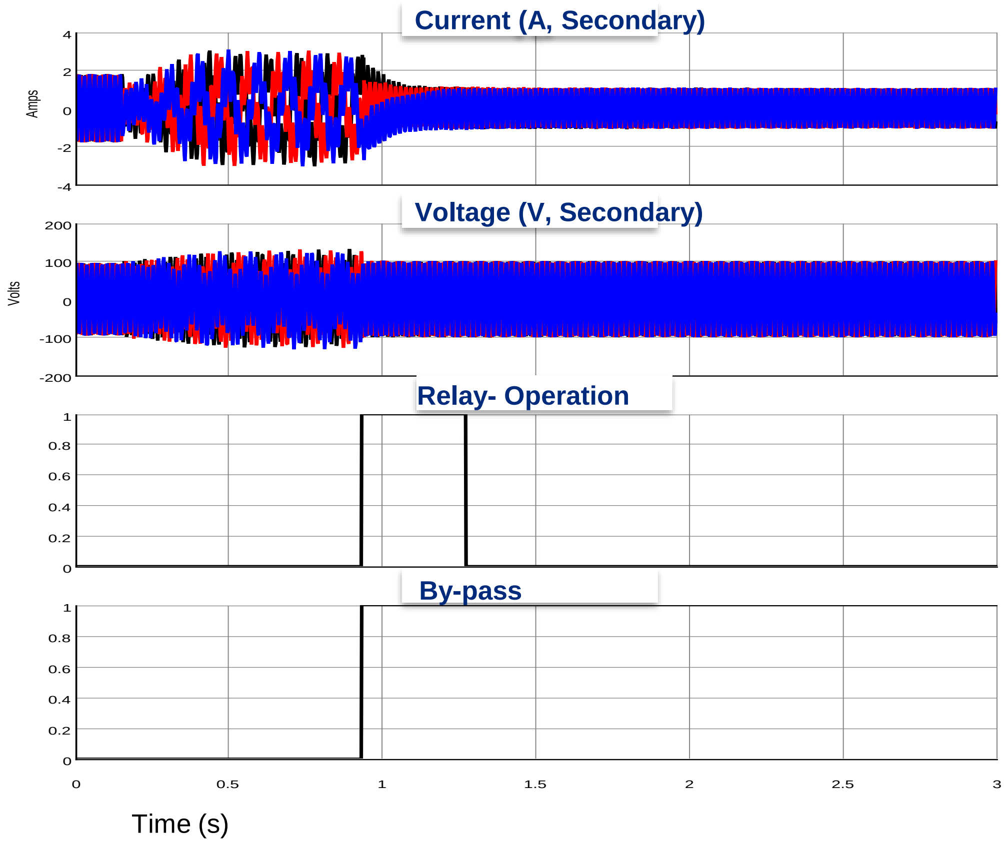
Application Case-2

- When no SSCI study has been done, generic settings can be used
- Current detection (4 stages)
  - 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 detection (2 stages)
  - 5-55 Hz, 5%, 1.0 sec
  - 5-55 Hz, 10%, 0.5 sec

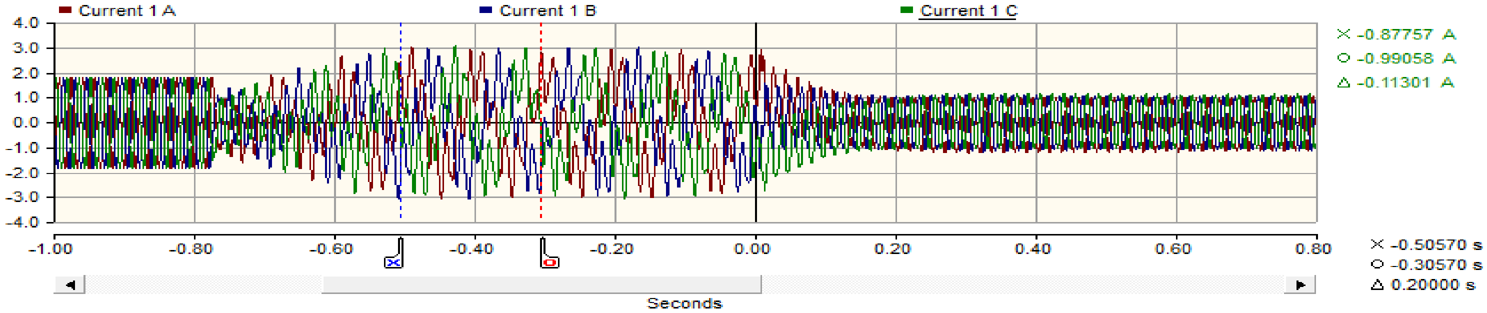
Example: Application – RTDS Testing

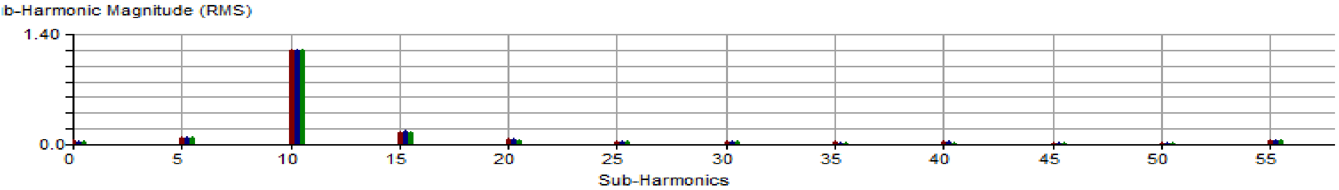


Example: Application – RTDS Testing



Example: Application – RTDS Testing





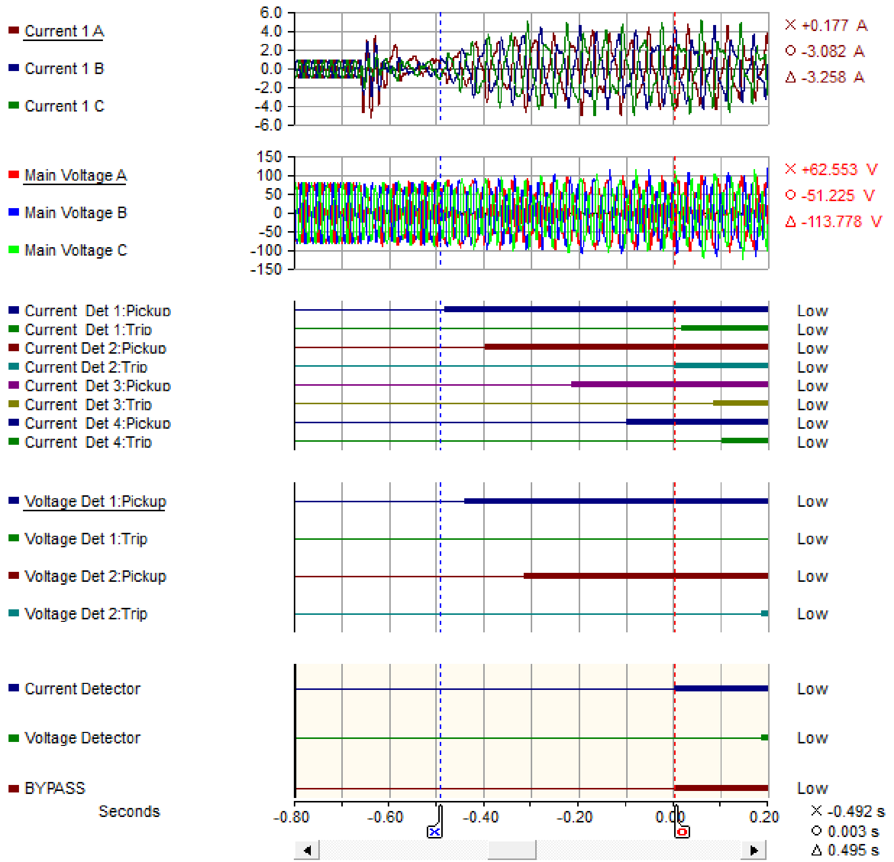
	Current 1 A	Current 1 B	Current 1 C
Fundamental (A-RMS)	0.73165	0.74200	0.76032
TSHD (%)	167.34161	165.27340	161.23167
Dominant SH Frequency (Hz)	10.57067	10.62545	10.59288
Dominant SH Magnitude (A-RMS)	1.22945	1.23565	1.23414

Frequency (Hz)	Mag (A-RMS)	Mag (A-RMS)	Mag (A-RMS)
0	0.05083	0.04703	0.04598
5	0.09718	0.09497	0.09109
10	1.20327	1.20409	1.20579
15	0.15503	0.17215	0.16221
20	0.07793	0.07090	0.06685

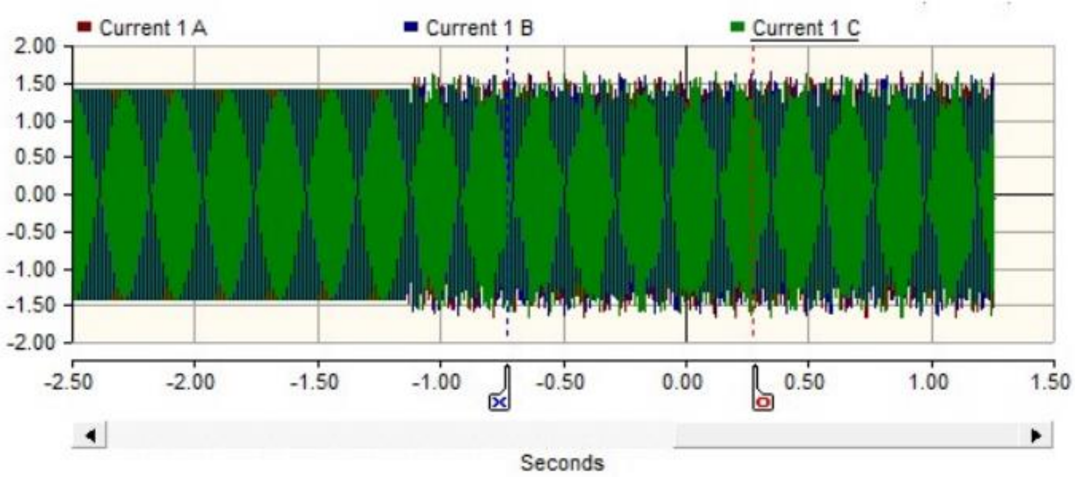
Relay Testing Using Field Reported Event (Texas)

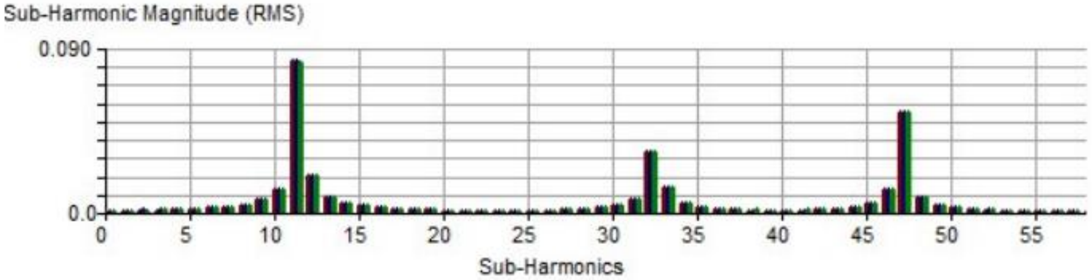
- Current detector (4 Stages)
  - 5-55 Hz, 5%, 0.5 sec
  - 5-55 Hz, 10%, 0.4 sec
  - 5-55 Hz, 20%, 0.3 sec
  - 5-55 Hz, 40%, 0.2 sec
- Voltage detector (2 Stages)
  - 5-55 Hz, 5%, 1.0 sec
  - 5-55 Hz, 10%, 0.5 sec

Note: Standard settings were assumed

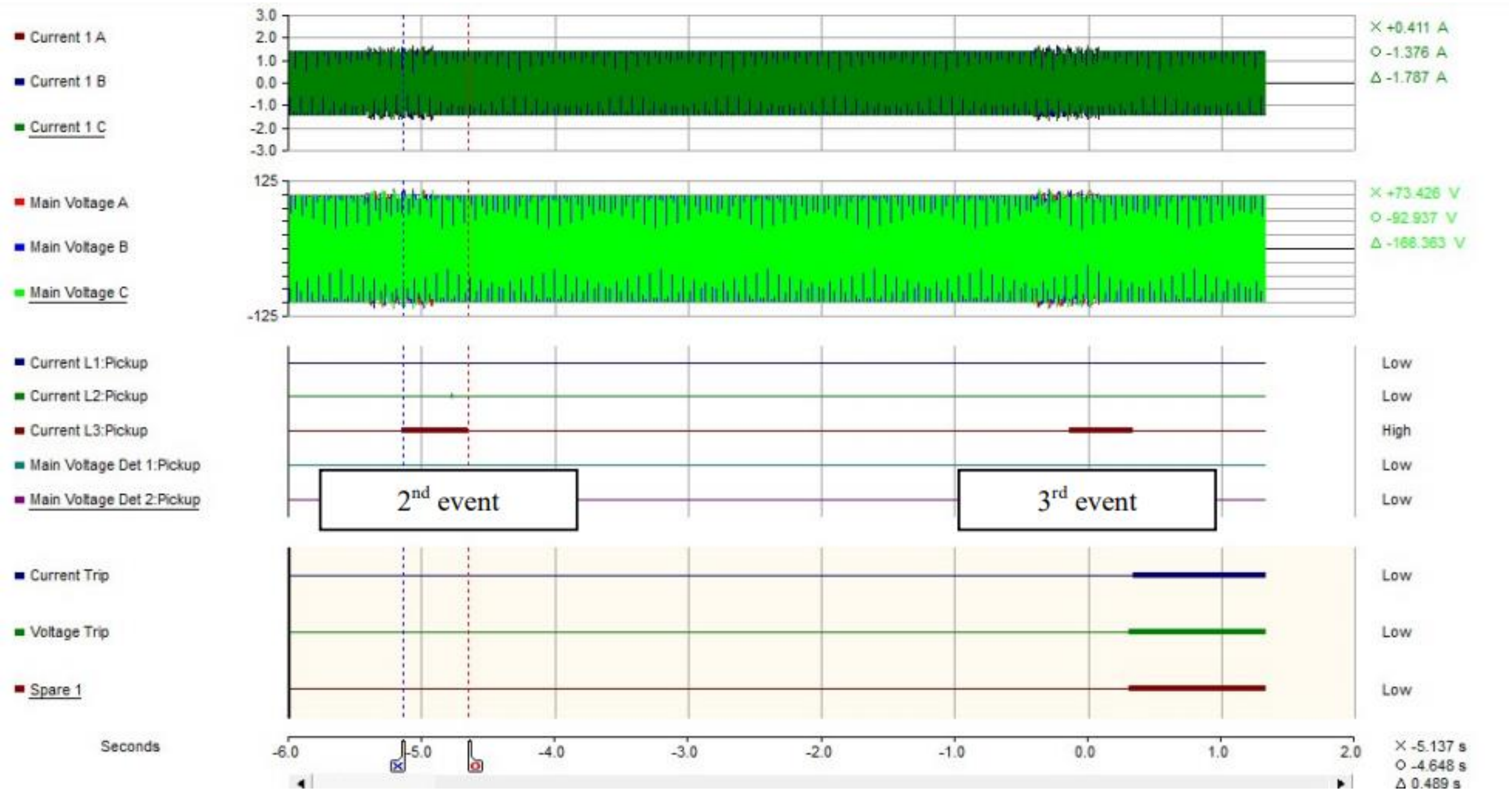


Event with Multiple Frequencies





Detection of Momentary Picking up of Sub-harmonics



Summary

- We have discussed:
  - Introduction to SSCI conditions
  - Study methods used to identify SSCI conditions
  - Applicability of a numerical sub-harmonic protection relay to provide protection against SSCI conditions
  - A protection setting structure that provides the flexibility for users to select basic settings, even when no information is available from system studies
  - Applicability of the proposed setting structure using field-recorded waveforms obtained from a digital fault recorder

FAQ

Question 1:
Are there actual installations of SSCI protection relays/schemes?

- *Yes, there are several installations covering inverter connected windfarms/solar.*

Question 2:
Is the SSCI protection the first level of mitigation?

- *It depends on the application/utility.*
- *Typically, we have seen that the control type mitigation was applied before the protection.*

FAQ cont..

Question 3:
What is the impact on other protection elements?

- *SSCI is a low frequency phenomena. Low frequencies may affect the operation of standard protection relays.*

Question 4:
Can invertor-connected generation have negative effects on standard protection?

- *Yes. There are several other issues such as lack of sufficient fault currents during faults. Please refer the IEEE PSRCC/ IEEE PES working group activities for more information.*

Thank you!

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