Hardware-in-the-loop Testing of a Sub Harmonic Protection Relay to Mitigate SSR Conditions Associated with Power System Components

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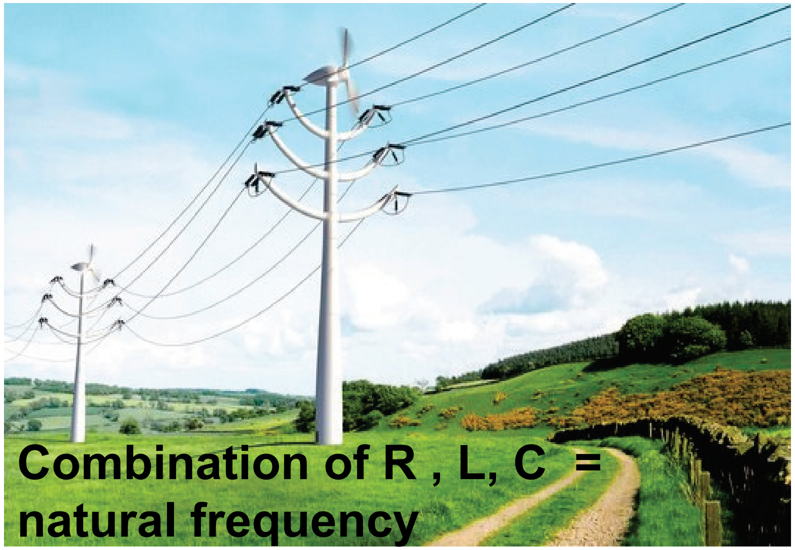
Outline

- Introduction
- Field Reported Events
- Mitigation Using a Microprocessor Based Sub-harmonic Relay
- Hardware-in-the-loop Testing Using RTDS
- Conclusion

Introduction

What is Natural Frequency ?



What is Resonance?

When you hit the prongs of one tuning fork, it vibrates due to the resonance as the mechanical excitation (hit) excites the natural frequency of the tuning fork. If you hold vibrating fork suddenly, the kinetic energy of the vibrations travel in the air and due to resonance, excites the other two tuning forks with the same frequency, and they vibrate even with out touching them….

SSR / SSTI for Synchronous Generator

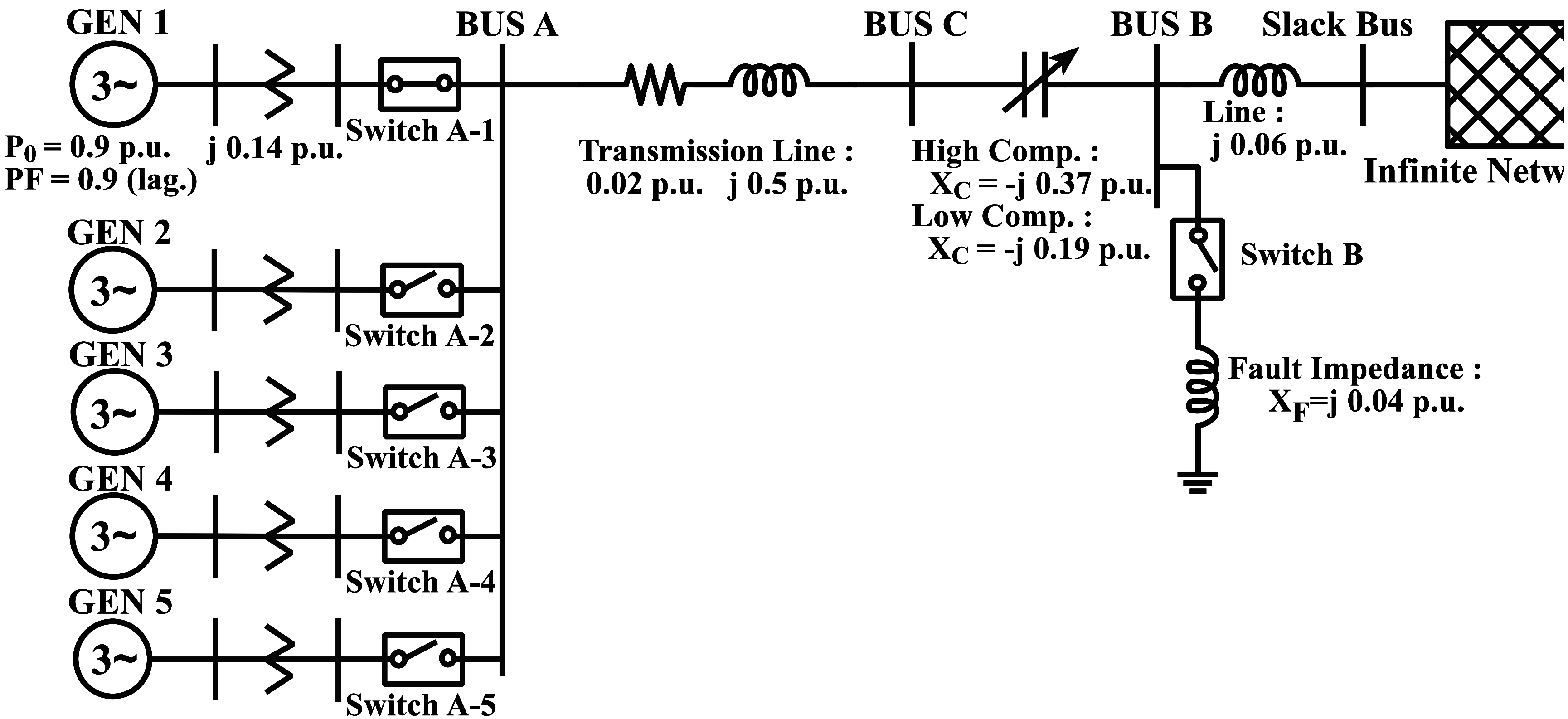


Fig. 1. Power system network for Subsynchronous Resonance (SSR) studie

Natural frequency interaction with Synchronous or Induction Generators

A series-compensated network has a natural resonant frequency (f_n) given by $f_n = f_0\sqrt{X_c/X_L}$ Hz (where f_0 is the synchronous frequency in Hz). At this subsynchronous frequency f_n, the slip s_1 is given by

$$s_1 = \frac{f_n - f_m}{f_n} \tag{1}$$

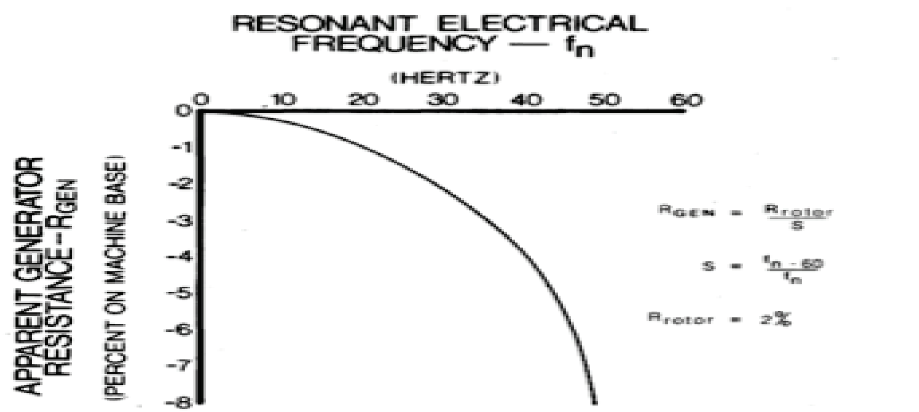


FIGURE 2. Negative Resistance Characteristics of a Synchronous Generator at Subsynchronous Frequencies

SSR/ SSTI with Synchronous Generator

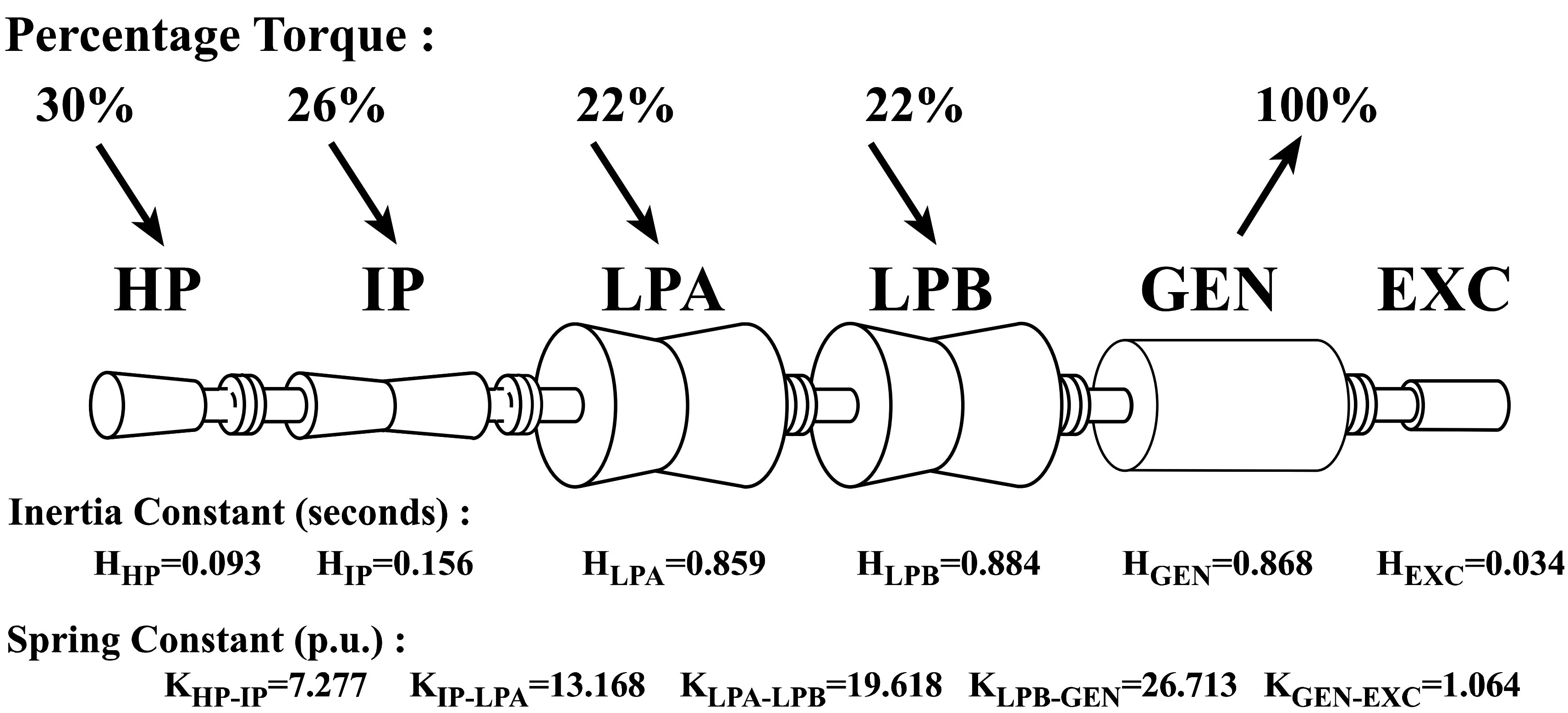


Fig. 2. Lumped spring mass model of turbine generator rotor.

SSR/SSO for Synchronous Generator (IEEE)

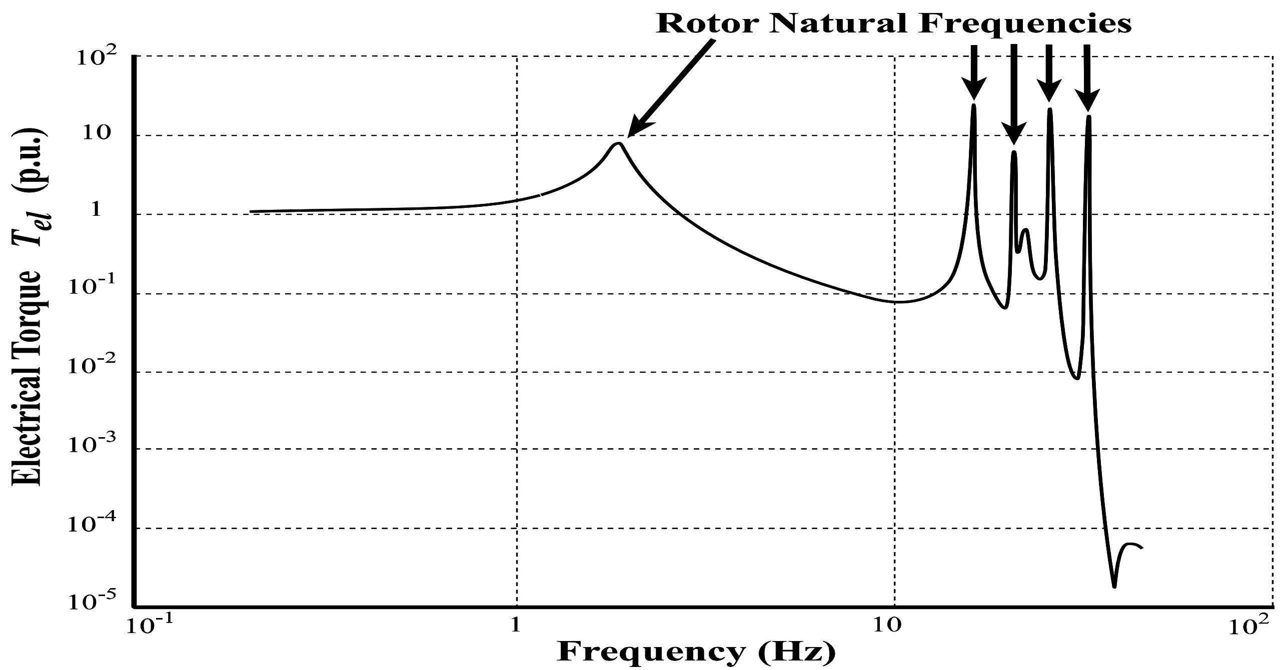


Fig. 3. Electrical torque characteristics of turbine generator.

TABLE II
ELECTRICAL SYSTEM NATURAL FREQUENCIES COMPARED WITH ROTOR NATURAL FREQUENCIES

Series Compensation (Percentage)	Network Natural Freq. f_e (Hz)	Slip frequency $60 - f_e$ (Hz)	Rotor Natural Freq. f_m (Hz)
94.00	44.125	15.875	16.289
74.20	40.000	20.000	20.195
57.40	35.625	24.375	25.500
37.00	28.750	31.250	32.283

SSR/SSO for Synchronous Generator

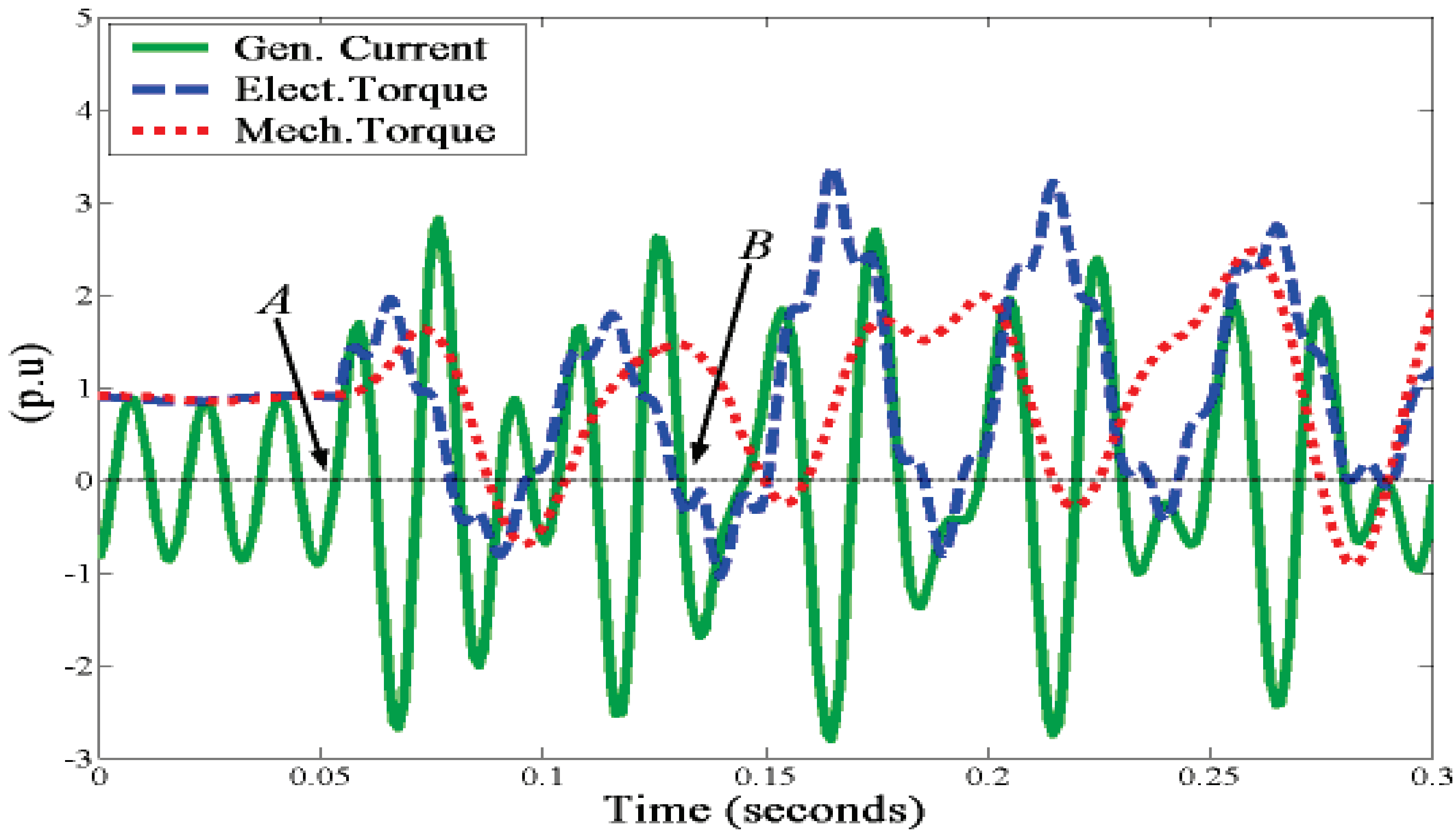
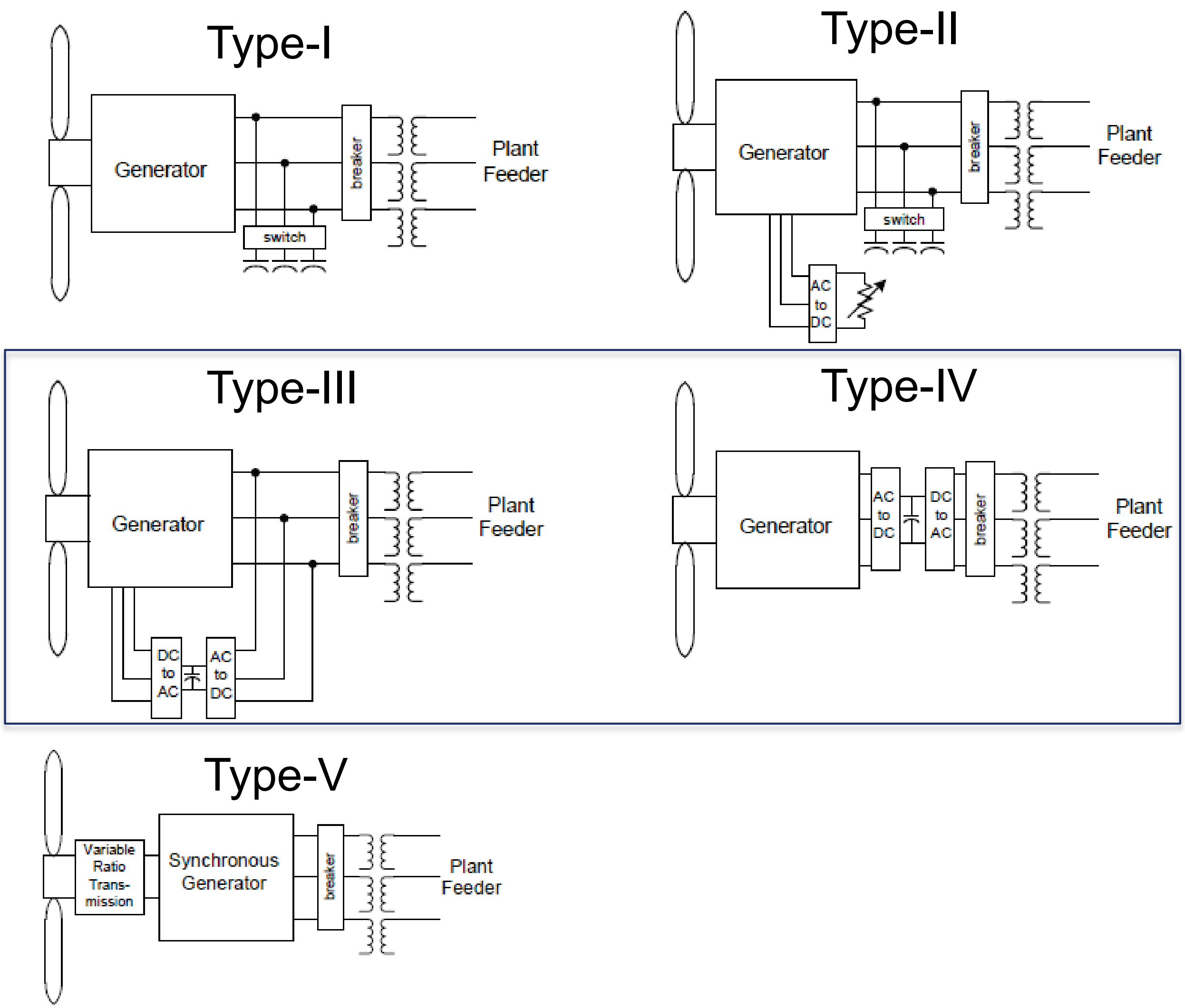


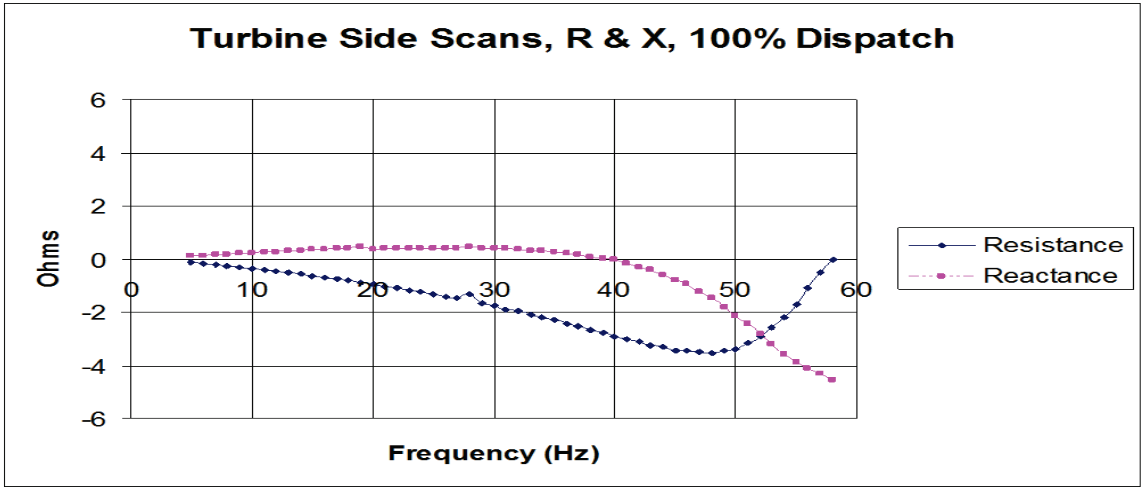
Fig. 6. Transient time domain simulation results with 74.2% series compensation ratio (generator current, electrical torque and mechanical torque characteristics as a function of time).

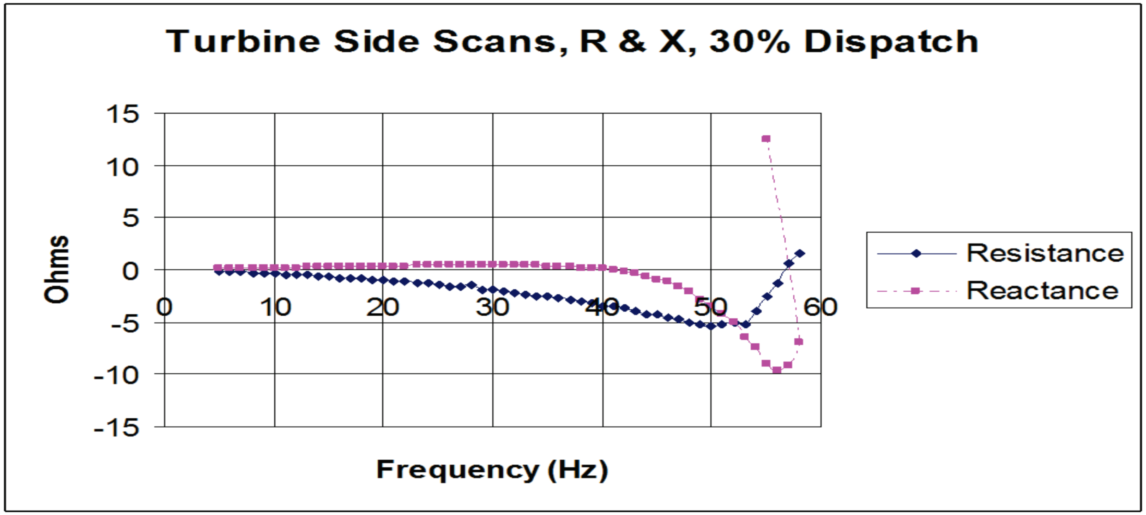
SSR/SSO for Windfarms

- Types of windfarms (IG)



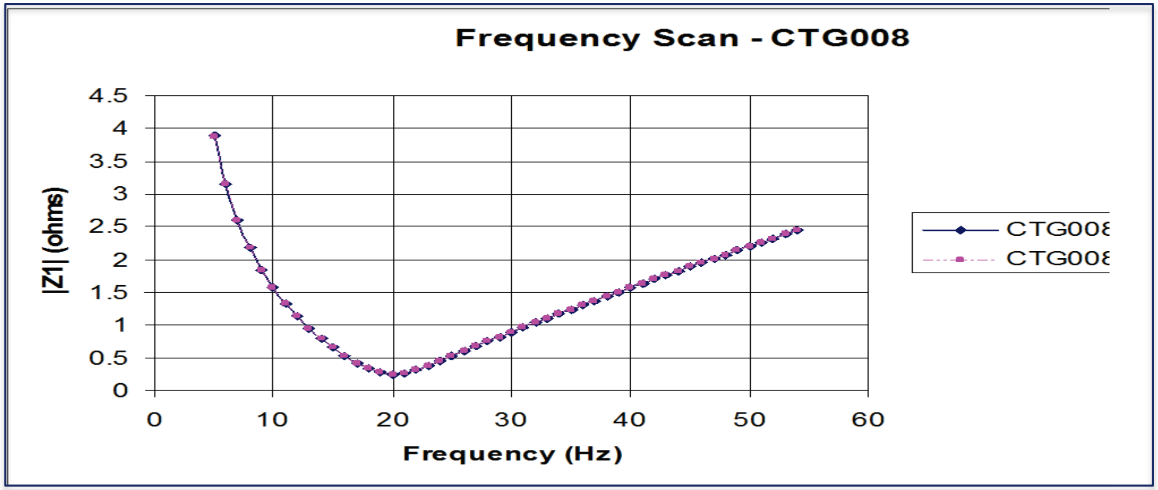
How Does Wind Turbine Side Dynamic Resistance Varies with Frequency ?

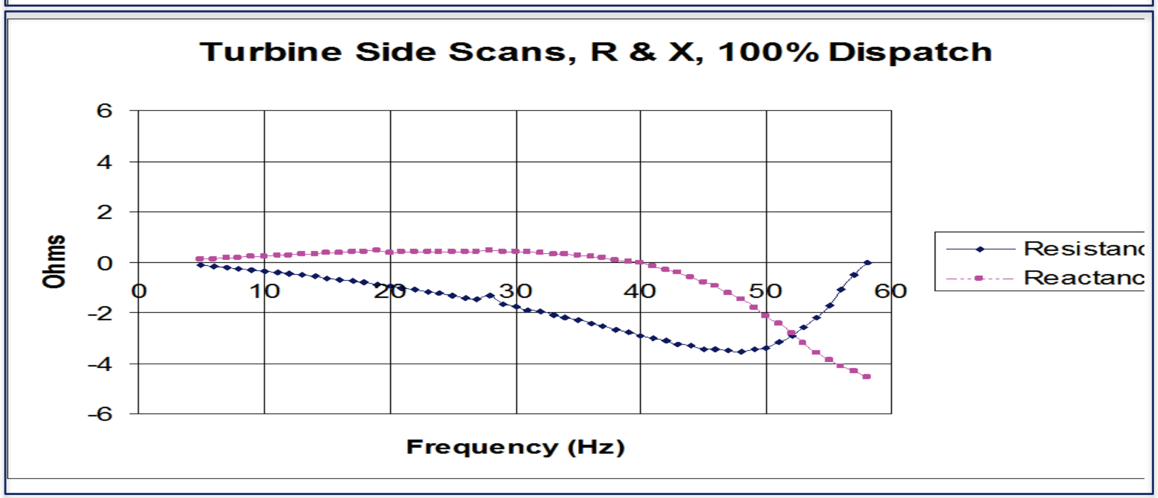




Ref: Manitoba HVDC Research Centre

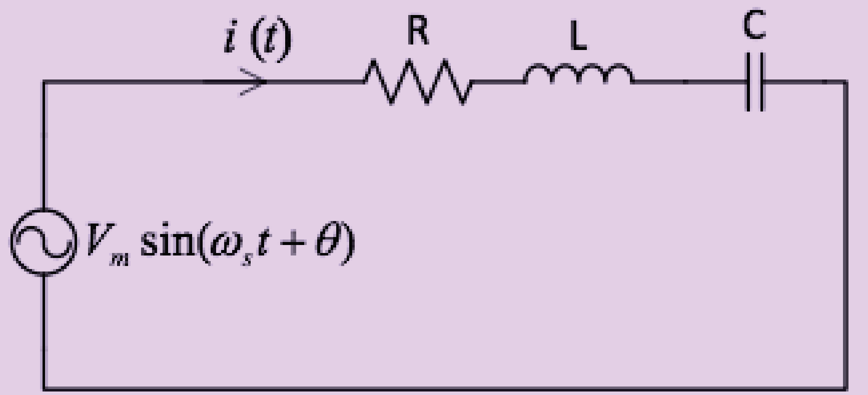
How does the Wind controller interact with the system.. ?





Ref: Manitoba HVDC Research Centre

Mathematical Analysis of Current Instability in RLC Network



$$i(t) = A\sin(\omega_s t + \psi_1) + Be^{-\zeta\omega_d t}\sin(\omega_d t + \psi_2)$$

$$\omega_n = \sqrt{\frac{1}{LC}}$$

$$\zeta = \frac{R}{2}\sqrt{\frac{C}{L}}$$

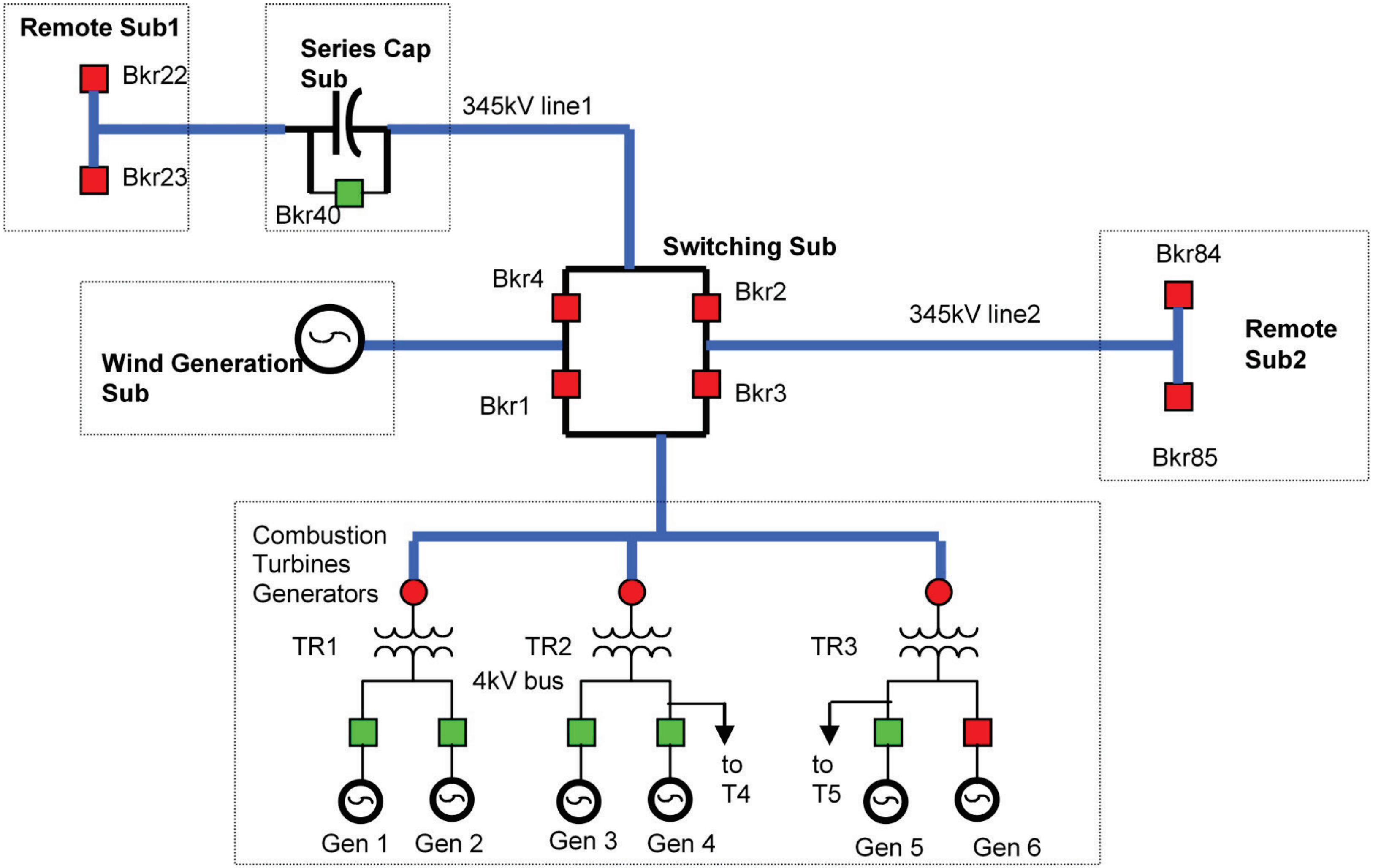
$$\omega_d = \omega_n\sqrt{1-\zeta^2} = \frac{1}{2L}\sqrt{\frac{4L - R^2C}{C}}$$

Filed Reported Events

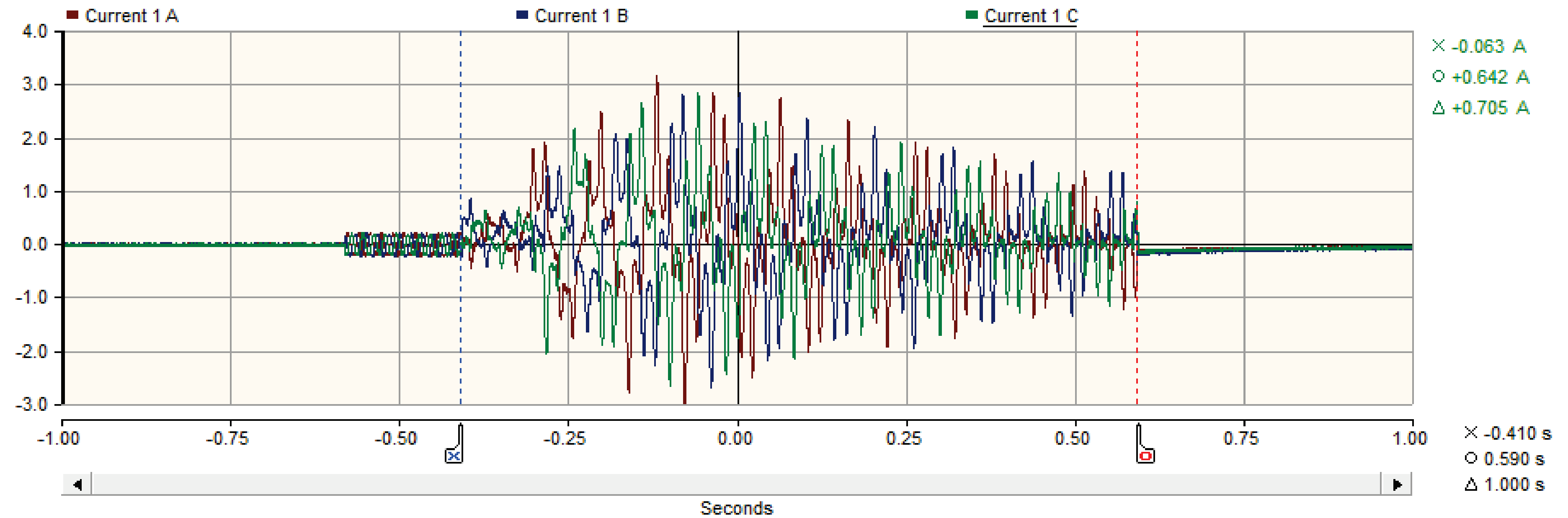
Known Real e=Events of Wind SSCI

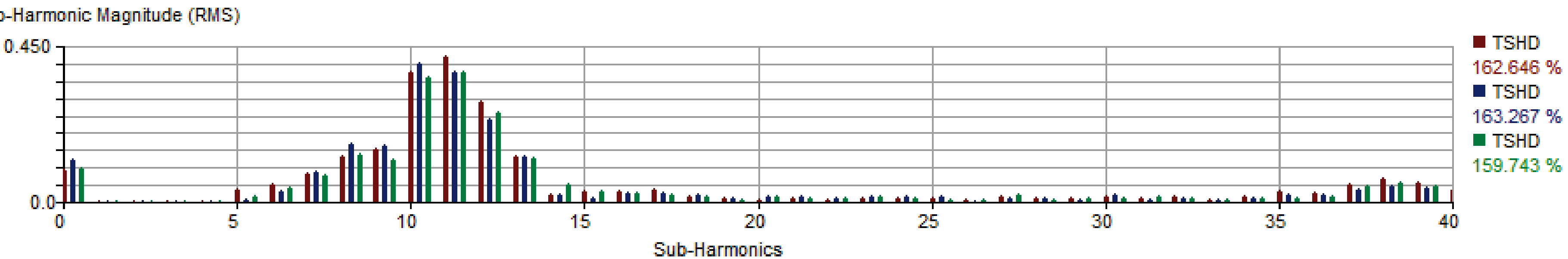
- 2008 – Xcel Energy – Minneapolis – USA – Lakefield Substation– Captured by TESLA DFR
- 2009 – ERCOT Region– TEXAS- USA – Wind Turbine Electronics Damage and Series Compensation System Damage
- 2012 – North China – SSR developed over 500s, with 4 stages, and the effective compensation was only 6.67%!!
- 2013 – North China – SSR event noticed and Manual Series Caps By pass saved the system

Xcel Energy (USA) Event -2008



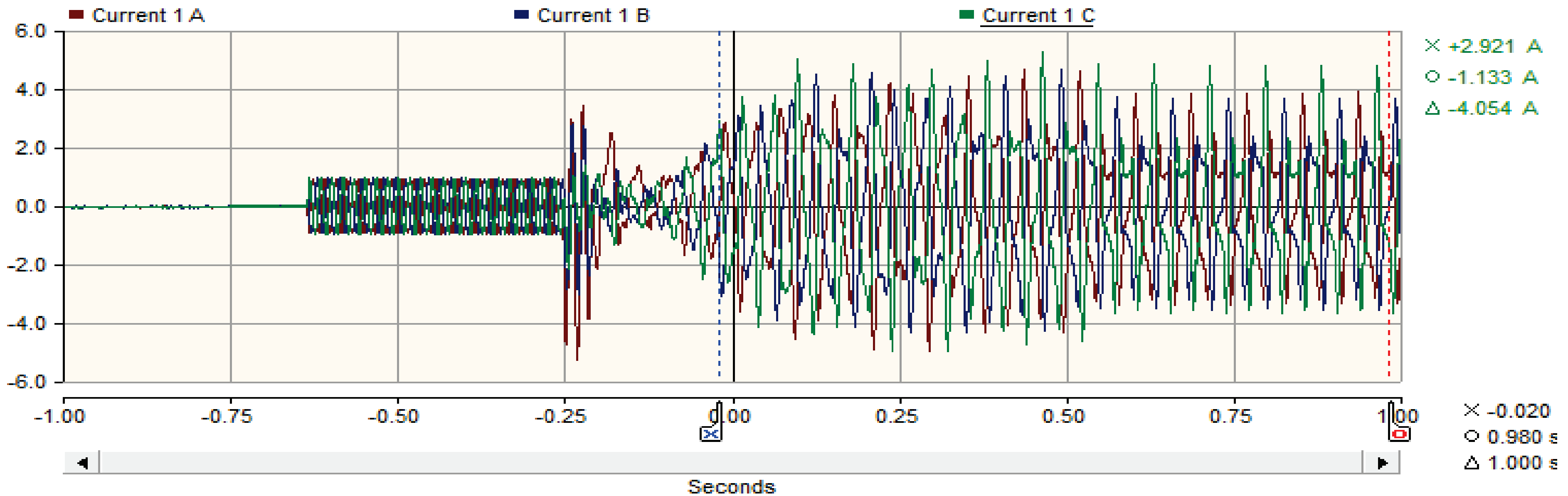
Xcel Energy (USA) – SSCI EVENT – 2008

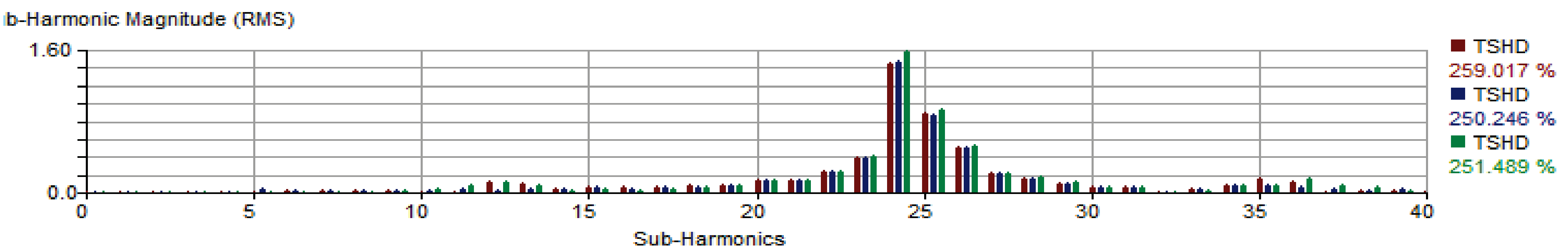




Frequency (Hz)	Mag (A-RMS)	Mag (A-RMS)	Mag (A-RMS)
6	0.054	0.033	0.042
7	0.083	0.087	0.079
8	0.133	0.171	0.141
9	0.155	0.163	0.125
10	0.375	0.402	0.361
11	0.425	0.376	0.375
12	0.290	0.243	0.262
13	0.134	0.132	0.129

ERCOT – TEXAS (USA) –EVENT – 2009





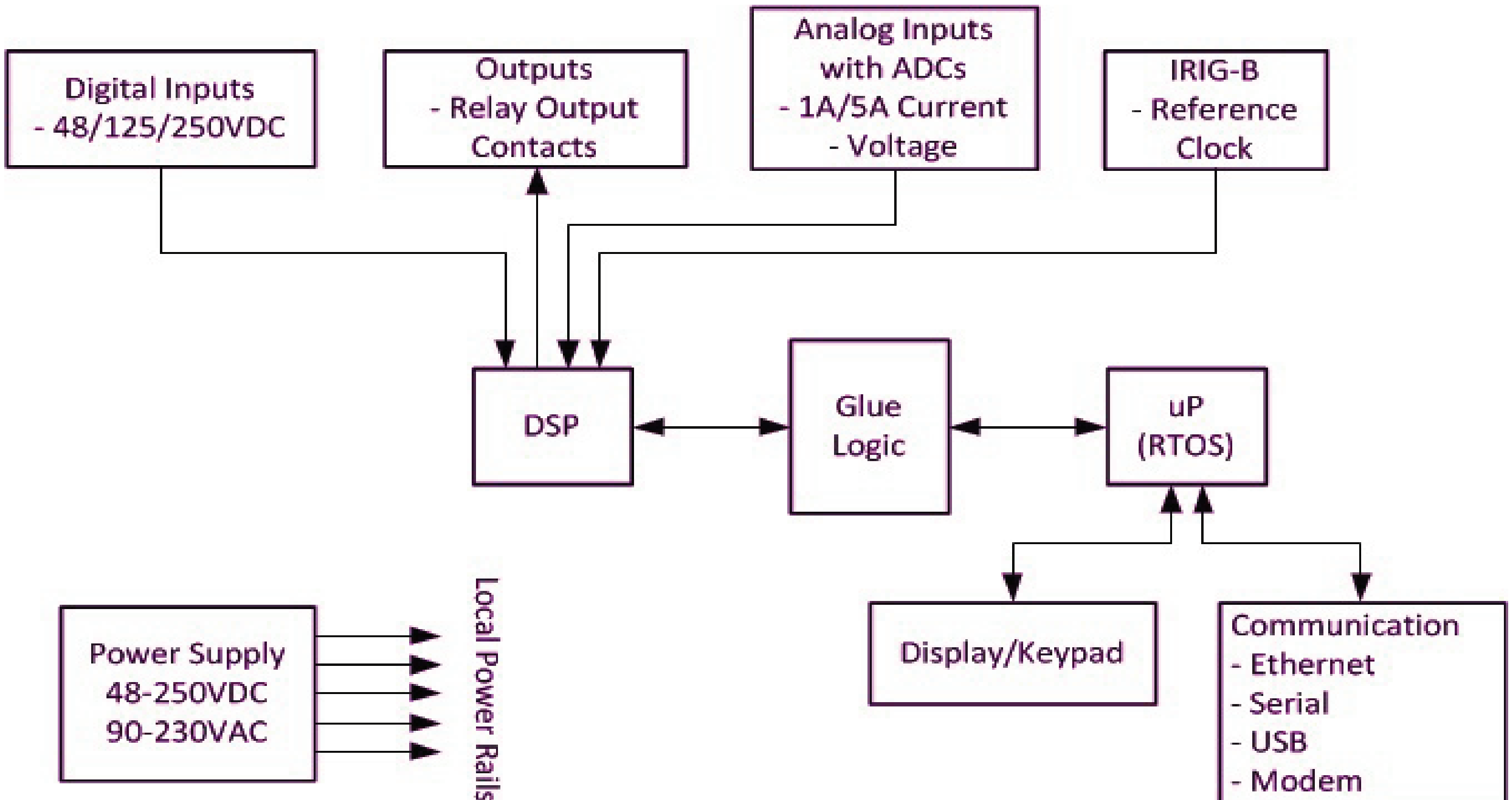
Frequency (Hz)	Mag (A-RMS)	Mag (A-RMS)	Mag (A-RMS)
22	0.243	0.232	0.238
23	0.400	0.392	0.405
24	1.460	1.473	1.590
25	0.888	0.874	0.938
26	0.516	0.510	0.534
27	0.225	0.221	0.231
28	0.161	0.165	0.185
29	0.115	0.100	0.128

Impact of SSO/SSR

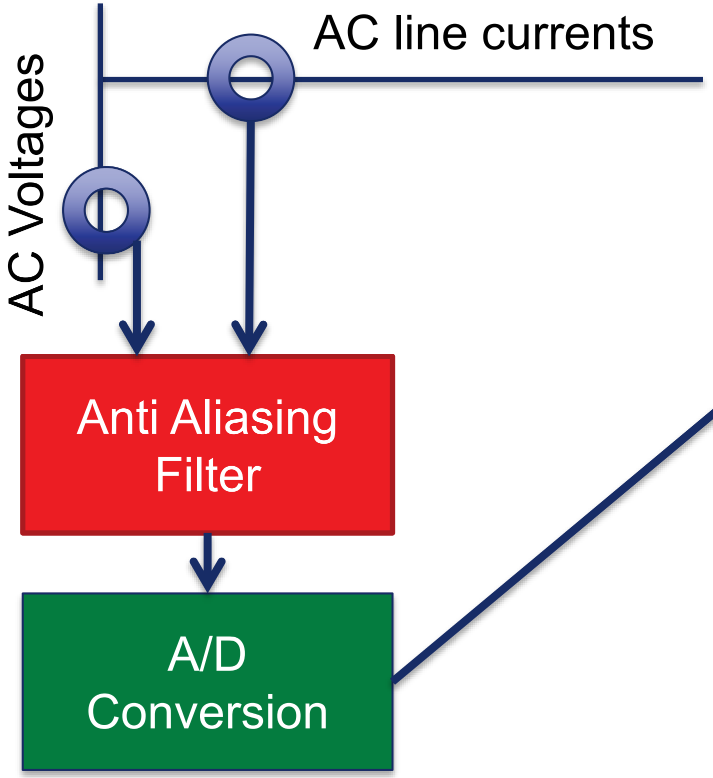
- SSO can be generated in the power system due the interaction of various power system devices.
- These SSO conditions cannot be detected/protected using 50/60Hz phasor based relays.
- SSO conditions resulting in SSR/SSCI/SSTI can create system damages and may sometimes lead to wide-area stability/protection issues.
- Mitigation/protection is essential against such SSO conditions.
- Authorities such as North American Electric Reliability Corporation has mandated the use of suitable mitigation methods for such applications.

Mitigation & Protection Using a Sub-harmonic Relay

Microprocessor Based Sub harmonic Protection Relay



Sub harmonic calculations using dual processor implementations



FPGA

Processor -1

(Field Programmable Gate Arrays)

High Speed Recursive Fourier Transform (RFT) Using 96 samples/cycle Sliding Window from high speed samples

(5760 / s on 60 Hz or 4800/ s on 50 Hz)

DSP

Processor -2

Sub Harmonic Detection Logic (5 – 45/55 Hz)

- **Band Pass Filtering (5 – 45/55 Hz)**
- **Evaluation of sub harmonic logic using MAX (f5 … f45/f55) principle.**
- **Trip / Alarm based on user configuration**

Salient Features

- Detects sub harmonics in the range of 5 Hz – 45 /55 Hz (depending on 50/60 Hz sys freq) for upto 10 channels with two trigger levels or with no summations, upto four trigger levels.
- Dual Processor Implementation of sub harmonic calculations using a novel RDFT (recursive discrete Fourier transform) with 2.08/2.5 ms sliding window and SSD (sub harmonic stability detection) algorithm with 0.2 Hz resolution.
- Faster detection of sub harmonics (100 ms - 400 mS) depending on the sub harmonic amplitude and frequency.
- Accurate estimation and tracking of decimal (or inter) sub harmonic frequencies (e.g. 22.4 Hz) within 5 Hz to 45 Hz range.
- Additional sub harmonic supervision during start-up process through second and fifth harmonic blocking.

Applications

- Suitable for faster detection of rapidly growing **SSCI** (sub synchronous controller instability) phenomena in convertor controlled DFIG (doubly fed induction generator) Wind Systems.

- Suitable for monitoring and detection of **SSTI** (sub synchronous torsional Interaction) phenomena in series compensated lines and trubines.

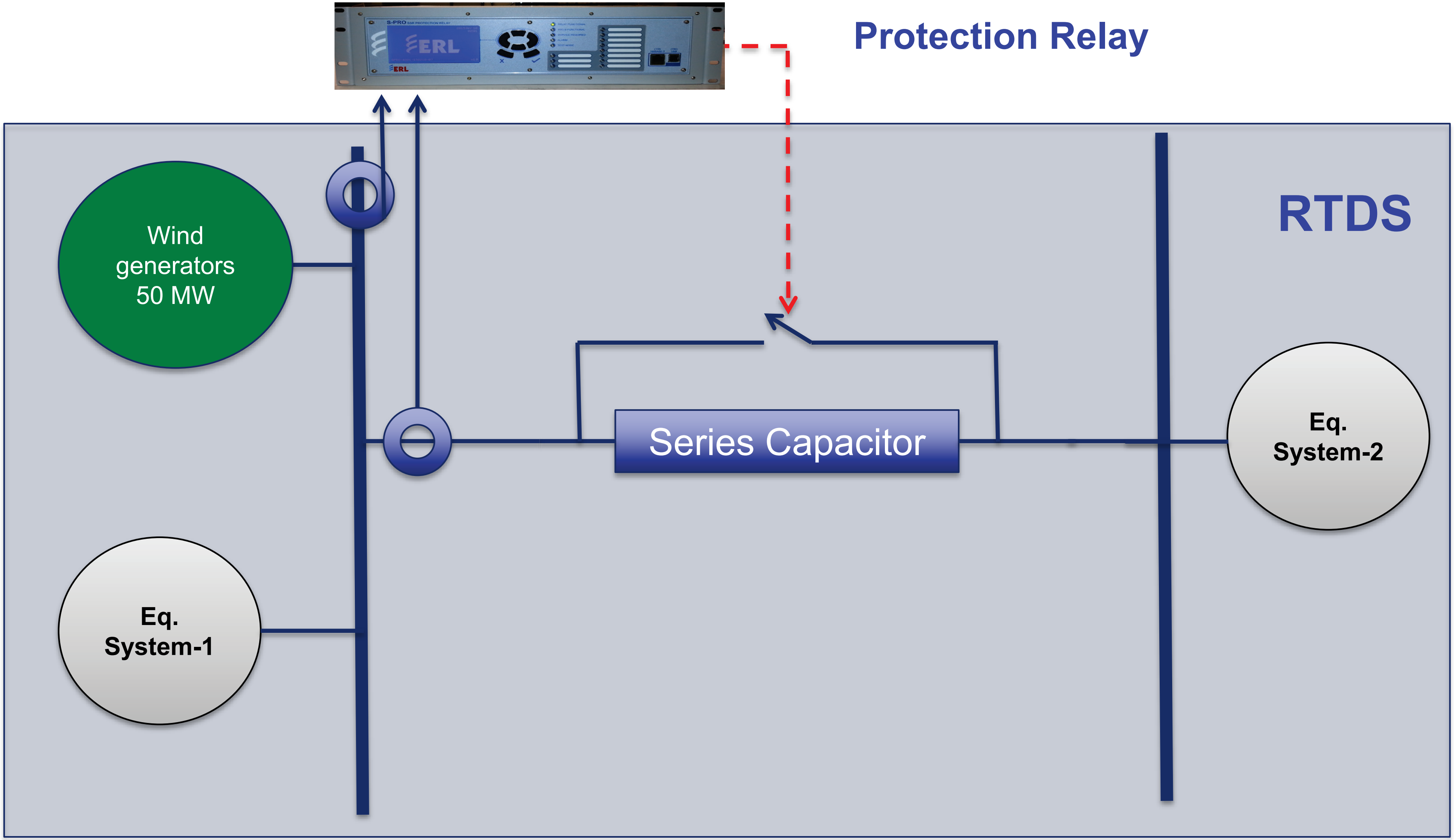
- Captures sub harmonics in HVDC / FACTS or other power controller interactions such as the Solar (**PV**) specifically with the **weak power systems**.

- Suitable for detection of sub harmonic “**Ferro Resonance**”, in the range of 5- 45 / 55 Hz.

- Detects any sub harmonic in the range of 5- 45 / 55 Hz.

Closed-loop Testing - RTDS

Test System: SSCI Protection

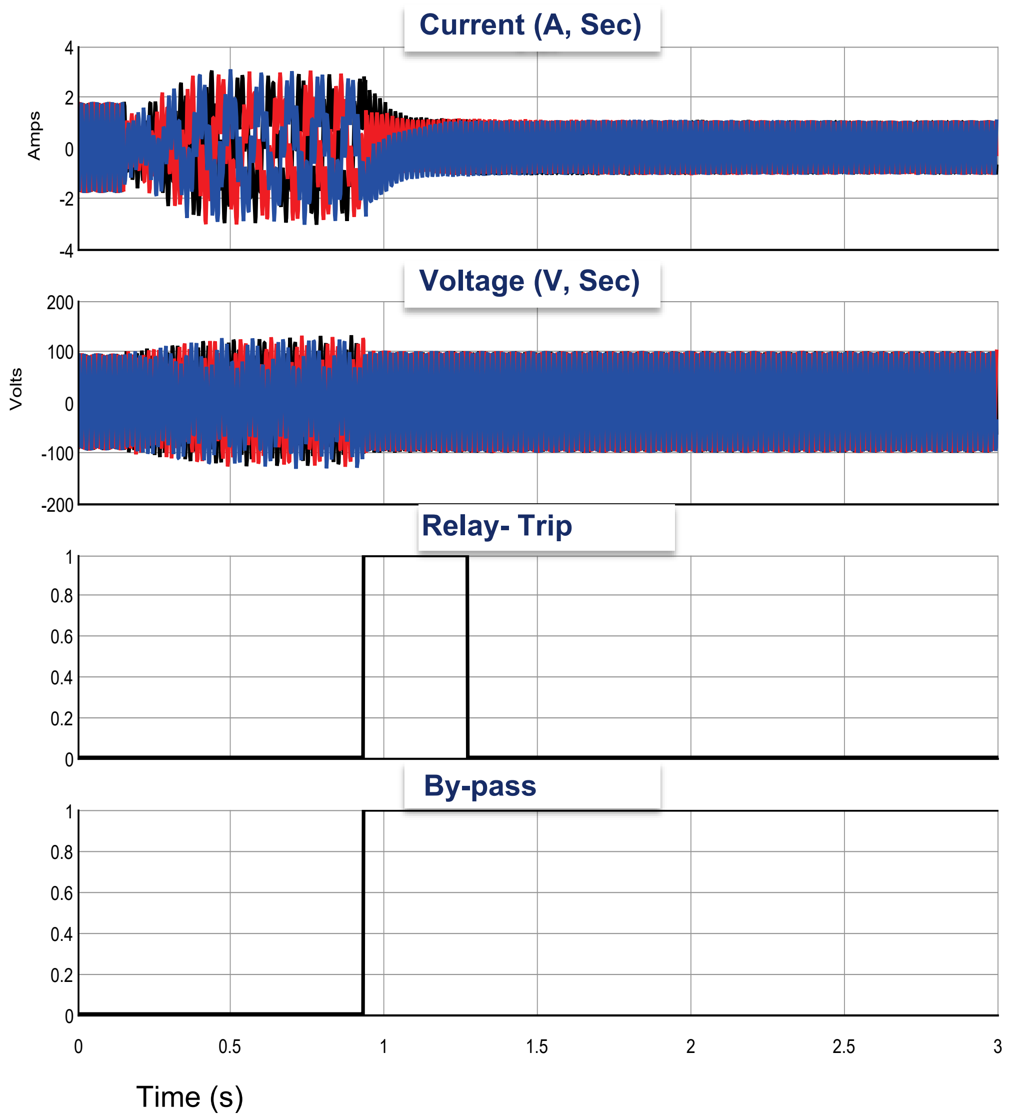


Sub-Harmonic Relay Settings

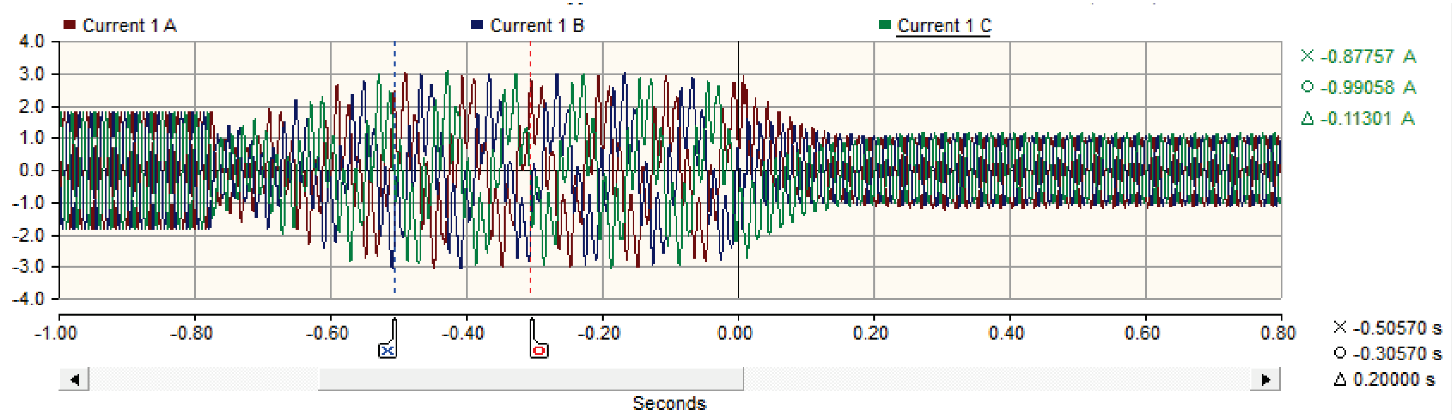
- Settings (based on modes identified from system studies)
  - Voltage sub-harmonics
    - **5-55 Hz** nominal sub-harmonics with 5% with **0.5 s** delay
  - Current sub-harmonics
    - **5-55Hz** nominal sub-harmonics with 5% with **0.5 s** delay
    - **5-55 Hz** nominal sub-harmonics with 10% with **0.4 s** delay

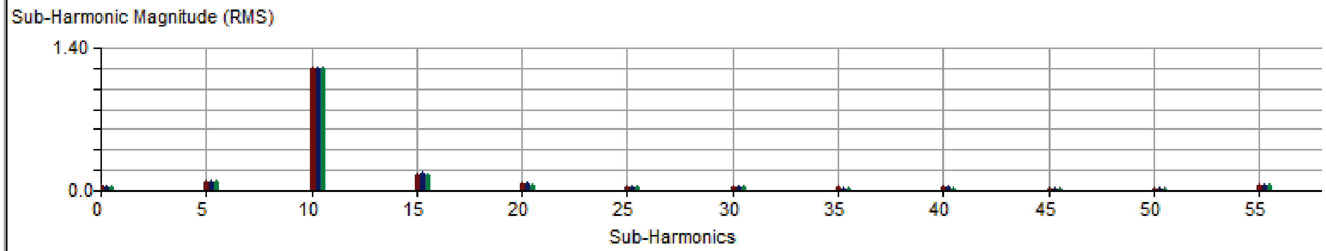
- Key considerations
  - Nature of sub-harmonics
  - Effect of normal faults
  - Effect of non-faulty events
  - Sources of errors (CTs, PTs, CVTs, etc.)
  - Limitations in modelling and simulation
  - Coordination with primary protection scheme

Mitigation of SSCI



Sub-harmonic Spectrum

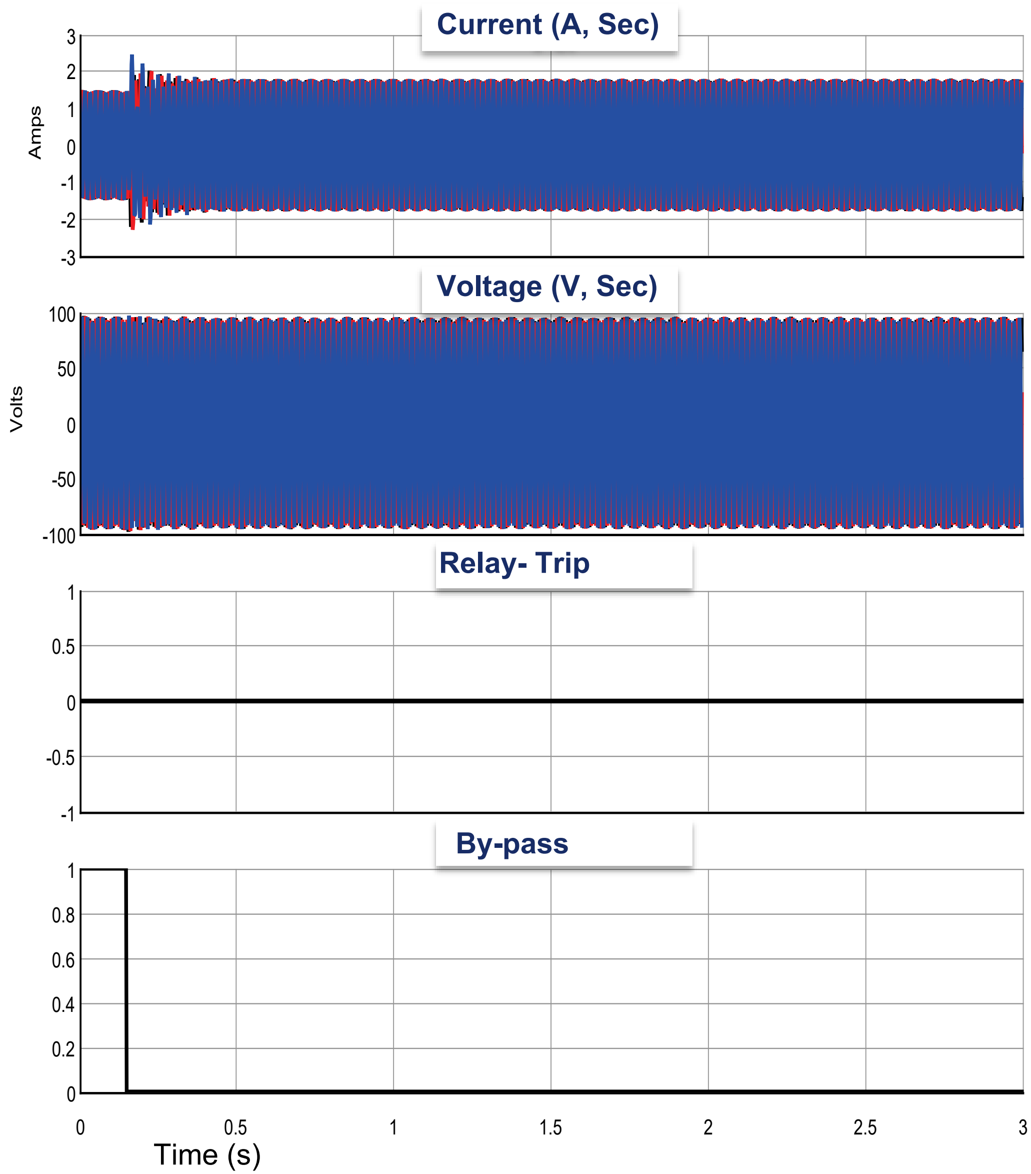




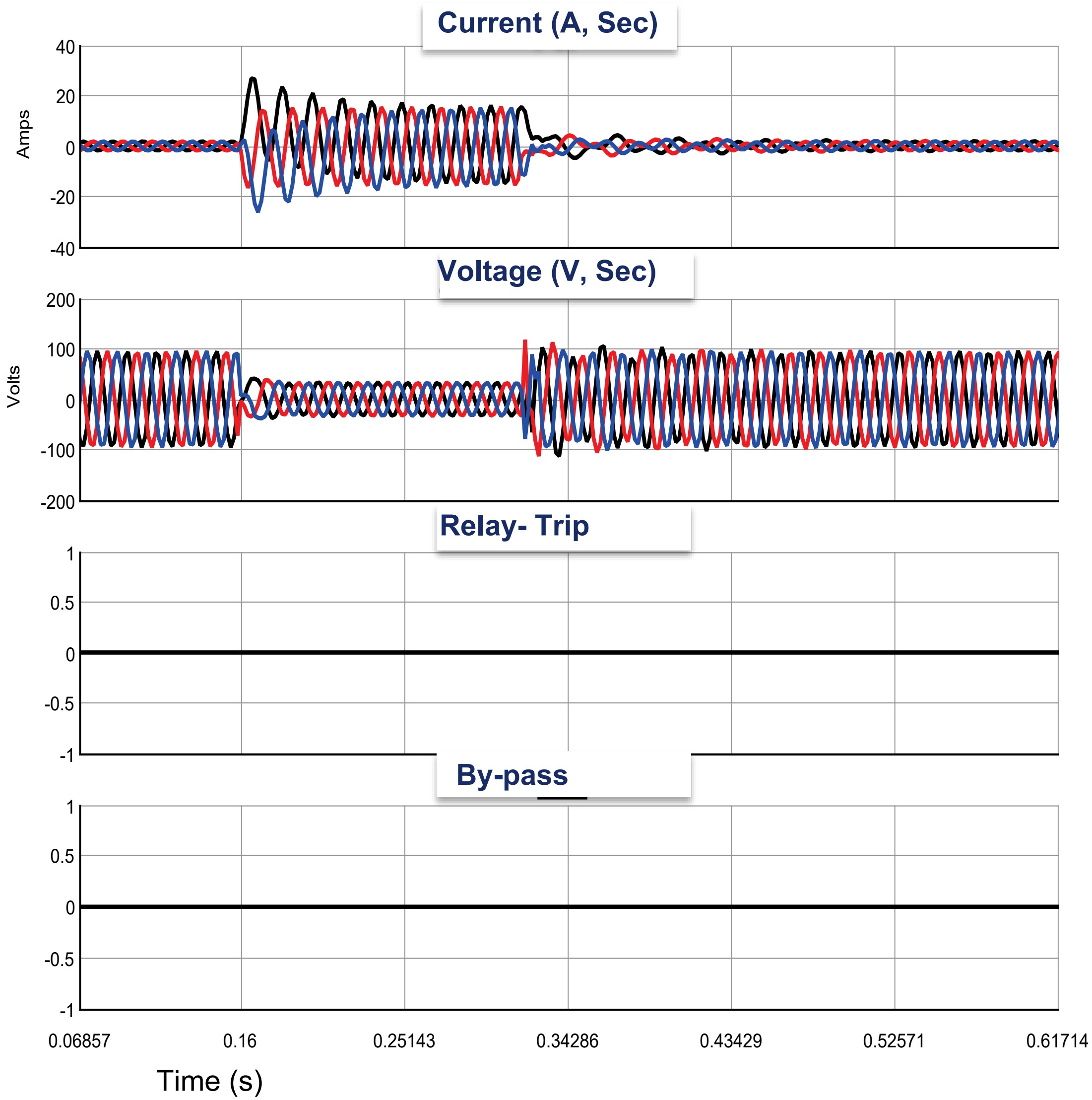
	Current 1 A	Current 1 B	Current 1 C
Fundamental (A-RMS)	0.73165	0.74200	0.76032
TSHD (%)	167.34161	165.27340	161.23167
Dominant SH Frequency (Hz)	10.57067	10.62545	10.59288
Dominant SH Magnitude (A-RMS)	1.22945	1.23565	1.23414

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

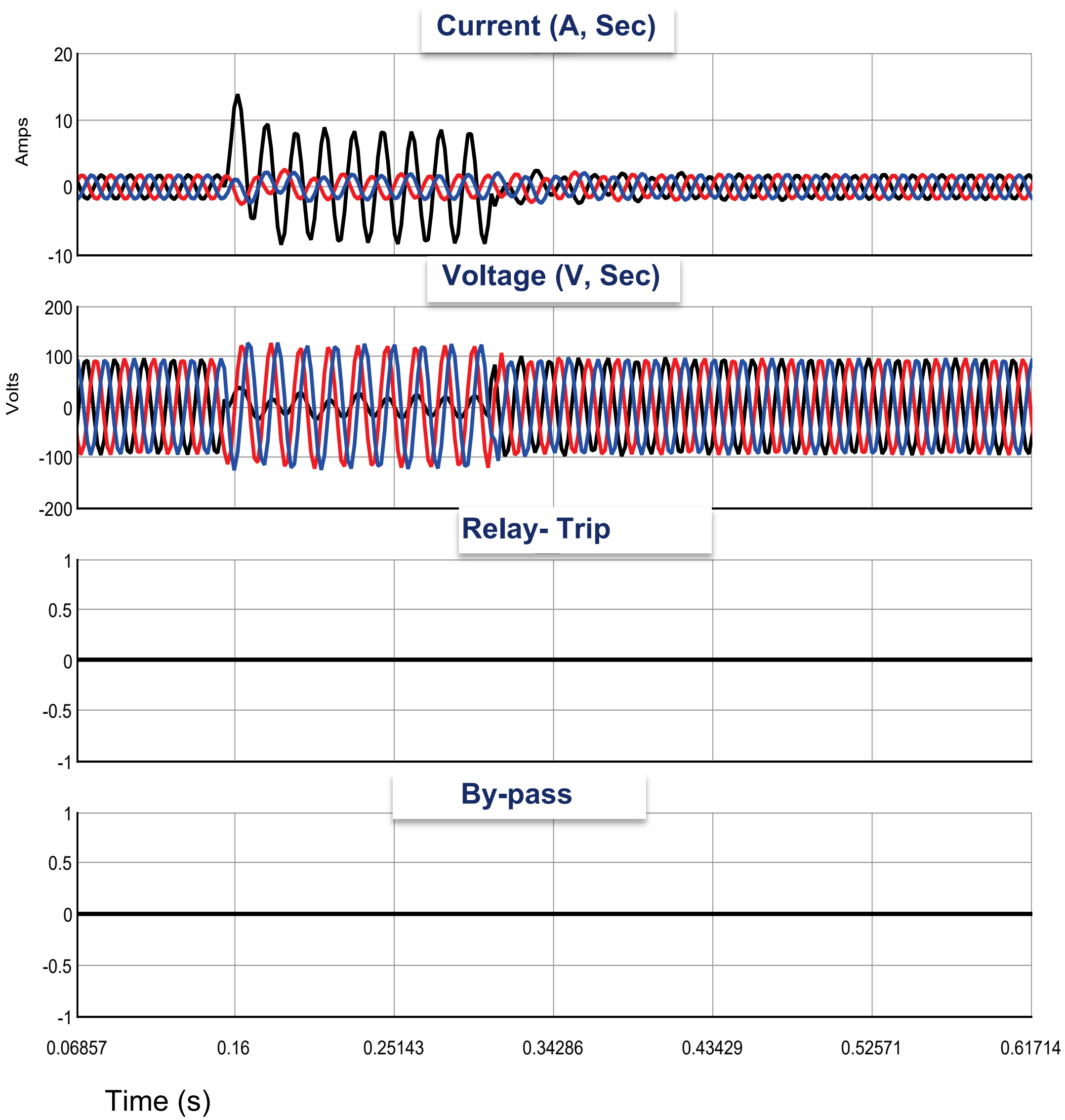
Energization of Series Capacitor



Normal Fault (3-phase)



Normal Fault (1 ph-ground)



Conclusions

- Use of a numerical relay to mitigate various SSO/SSR conditions is discussed.
  - SSCI
  - SSTI
  - SSR/SSO

- Performance of the relay was tested using SSCI conditions simulated in RTDS.
  - Type-III windfarm with fixed series compensated transmission line

- Results showed the capability of RTDS in simulating and testing an industrial numerical sub-harmonic protection relay.

Thank You!

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