Combining subsynchronous oscillations detection and synchrophasor measurements to increase power system stability
Sub synchronous oscillation (SSO) events

- 1970’s Mohave Generator plant turbine generator failure caused by near coincidence of the first torsional mode of oscillation of the turbine generator and the electrical resonance of the series capacitor and 500kV transmission network.
- 1980’s Square Butte generators and a nearby HVDC terminal observed sub synchronous torsional interaction.
- Recently, a related phenomena has been associated with modern wind turbine generator technologies:
  - October 22, 2009 two wind generation systems and series compensated system of AEP-Texas in south Texas experienced SSOs. Turbine equipment and utility equipment were damaged during the event.
Sub synchronous oscillation (SSO) events captures

1250 MW nuclear unit caused by quick ramp down for HVDC link

Peaks at 17, 83 and 117 Hz caused by Swedish railway system
Effects of SSO and sub synchronous resonance (SSR)

- **Rotor damage** due to excessive shaft torques
- High torque levels
  - **Steel** has reached the **yield point**
  - Resulting in **shaft deformation** can result in **shaft misalignment**
  - Lateral bending could lead to **shaft failure**
- Low torque levels
  - Where **endurance limit** has been **exceeded**
  - Cyclic torque causes **fatigue in the shaft**
  - **Life expended** is calculated using stress life
Synchrophasors definition

(a) \( f(t) = A \cos(\omega t), \theta = 0^\circ \)

(b) \( f(t) = A \cos(\omega t - \pi/2), \theta = -\pi/2 (-90^\circ) \)
Synchrophasors measurement system

GPS Satellite Time Synchronization

Power System

Streaming synchrophasor data on the network to the PDC for archiving...

ETHERNET

PDC/Server

PDC/Server

...data display and real time control actions
Combining SSO/SSR detection with synchrophasors

- Sub synchronous oscillation sources
  - active power sources (e.g. turbine generators)
  - reactive power sources (e.g. series capacitors)
  - HVDC converters
  - Power System Stabilizers (PSSs)
  - Static Var Compensators (SVCs)

- PMUs are placed in strategic power system locations
  - provide real-time monitoring of currents and voltages of the oscillation sources
  - support detection of sub synchronous oscillations locally via specially designed and tuned filters.
  - capture (in DFR) and stream SSO/SSR data to control center
SSO/SSR applications examples

Applications

- from simple exciter alarm
- to governor control

- FERC requires to calibrate exciters of generators (30+MW) every 5 years

- Continuous real-time monitoring provides early indications of torsional stress, and enables timely corrective actions
SSO and SSR definitions

Definitions are given by IEEE Sub synchronous Resonance WG of the System Dynamics Performance Subcommittee, June 1985.

- Sub synchronous Oscillations (SSO) are electromechanical interaction, either between a turbine-generator and passive system elements such as series capacitors, or between a turbine-generator and active system elements such as HVDC transmission equipment controls, and static VAR system controls.

- Turbine-generator electromechanical interaction with series capacitors has historically been known as the phenomena of Sub synchronous Resonance (SSR).
SSO and SSR categories

- **Induction Generator Effect (IGE)**
  An electrical phenomena that results from an electrical resonance between a series capacitor and a generator

- **Torsional Interaction (TI)**
  Occurs when the electrical system operation results in mechanical damping at the generator that is negative and sufficiently large to exceed the inherent mechanical damping of the shaft at a natural torsional frequency of the mechanical system

- **Torque Amplification (TA)**
  Shaft torsional stresses due to system disturbances which result in resonance between electrical and mechanical natural frequencies.
  - Can occur because of a resonance with a series capacitor
  - Can occur because of the control action of devices such as HVDC converters, SVC/s and STATCOM’s

- **Sub synchronous Control Interaction (SSCI)**
  Interactions between a power electronic device (such as an HVDC link, SVC, wind turbine, etc.) and a series compensated system.
How shaft of a turbo machine look like

- Properties of Turbo Machines
  - Several masses on the shaft
  - Long shaft / axle from 30m up to 100m
  - These masses can oscillate against each other

Gen = generator
Exc = exciter
HP = high pressure turbine
IP = intermediate pressure turbine
LPA/LPB = low pressure turbines
Sub-synchronous phenomena
Torsional oscillations

- For sub-synchronous considerations, lumped masses for each turbine is typically sufficient
- If there are N masses, there will be N modes
  - 1 non-oscillatory mode
  - N-1 oscillatory modes
- Each mass participates differently in each mode

- Perturbations of the mechanical system will stimulate the modes
  - Sudden change in input torque due to governor action
  - Sudden change in electrical torque (fault or step-change of load on grid)
- The energy put into each oscillatory mode will exchange between kinetic energy (mass speed) and potential energy (shaft twist = spring)
Sub-synchronous phenomena

Torsional oscillations

- Eigenvalue analysis of turbine-shaft allows the modes to be “de-coupled” and considered as N mass-spring systems.

- Mode shapes are the eigenvectors normalized on the displacement of a given mass.

- These may be normalized on the largest value in the eigenvector or on the values associated with the generator.

<table>
<thead>
<tr>
<th>Mass</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
<th>Mode 5</th>
<th>Mode 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>f (Hz)</td>
<td>0.0000</td>
<td>17.4390</td>
<td>26.1789</td>
<td>27.9803</td>
<td>36.0114</td>
<td>47.3719</td>
</tr>
<tr>
<td>HP</td>
<td>1.0000</td>
<td>1.0000</td>
<td>0.4261</td>
<td>-0.0960</td>
<td>0.9326</td>
<td>-0.7721</td>
</tr>
<tr>
<td>IP</td>
<td>1.0000</td>
<td>0.6889</td>
<td>0.1274</td>
<td>-0.0191</td>
<td>-0.3044</td>
<td>1.0000</td>
</tr>
<tr>
<td>LP1</td>
<td>1.0000</td>
<td>0.3170</td>
<td>-0.1202</td>
<td>0.0374</td>
<td>-0.6024</td>
<td>-0.1880</td>
</tr>
<tr>
<td>LP2</td>
<td>1.0000</td>
<td>-0.1264</td>
<td>-0.0811</td>
<td>0.0046</td>
<td>1.0000</td>
<td>0.0603</td>
</tr>
<tr>
<td>GEN</td>
<td>1.0000</td>
<td>-0.4821</td>
<td>0.0920</td>
<td>-0.0372</td>
<td>-0.4979</td>
<td>-0.0141</td>
</tr>
<tr>
<td>EXC</td>
<td>1.0000</td>
<td>-0.8074</td>
<td>1.0000</td>
<td>1.0000</td>
<td>0.6934</td>
<td>0.0072</td>
</tr>
</tbody>
</table>

Non-oscillatory mode (stiff-shaft)

Angular displacement of LP2 is largest. Generator displaces in opposite direction.
Power system electro-mechanical model

\[ f_{er} = f_0 \sqrt{\frac{X_c}{(X'' + X_t + X_I + X_s)}} \]

- \( f_{er} \) = electrical system subsynchronous natural frequency
- \( f_0 \) = fundamental synchronous frequency (60 Hz)
- \( X_c \) = series capacitor reactance at fundamental frequency \( f_0 \)
- \( X'' \) = generator subtransient reactance at \( f_0 \)
- \( X_I \) = generator step-up transformer reactance at \( f_0 \)
- \( X_I \) = reactance of compensated line at \( f_0 \)
- \( X_s \) = system equivalent reactance at \( f_0 \)
Frequency of induced I and V due to oscillations

\[ f_{SSR} = f_{\text{Rated}} \pm f_{\text{Mechanical}} \]

or

\[ f_r = f_0 \pm f_{er} \]

- \( f_o \) = the average synchronous frequency
- \( f_{er} \) = the resonant frequency of the electrical system
- \( f_r \) = the frequency of the rotor current as a result of \( f_{er} \)

- Thus the mechanical frequency is modulated on the fundamental power system frequency
- Component below the rated frequency is called \textit{sub-synchronous component}
- Component above the rated frequency is called \textit{super-synchronous component}
Current frequency spectrum

- Fundamental
- Sub-synchronous
- Synchronosynchronous
SSO/SSR event spectrum
SSO/SSR detection logic

\[
\begin{align*}
\text{Filter } \#1 & \quad \text{IDMT} \\
U_{\text{SUP}_2} & \quad t_a = f(U_{\text{SUP}_2}) \\
U_{\text{SUP}_2} & \quad > \text{SET_PICKUP} \\
\& & \quad \text{OR} \\
& \quad \text{TRIP} \\
\& & \quad \text{SSR RELAY} \\
\text{Filter } \#2 & \quad > \text{SET_PICKUP} \\
U_{\text{SUB}_2} & \quad U_{\text{SUB}_2} \\
\text{Filter } \#3 & \quad \text{IDMT} \\
U_{\text{SUP}_3} & \quad t_a = f(U_{\text{SUP}_3}) \\
U_{\text{SUP}_3} & \quad > \text{SET_PICKUP} \\
\& & \quad \text{OR} \\
& \quad \text{TRIP} \\
\& & \quad \text{SSR RELAY} \\
\text{Filter } \#4 & \quad > \text{SET_PICKUP} \\
U_{\text{SUB}_3} & \quad U_{\text{SUB}_3} \\
\text{Filter } \#5 & \quad \text{IDMT} \\
I_{\text{SUB}} & \quad t_a = f(I_{\text{SUB}}) \\
I_{\text{SUB}} & \quad > \text{SET_PICKUP} \\
\& & \quad \text{OR} \\
& \quad \text{ALARM} \\
\text{Filter } \#6 & \quad > \text{SET_PICKUP} \\
I_{\text{SUP}} & \quad I_{\text{SUP}} \\
\end{align*}
\]
Multi-purpose filter functionality

- A 3-phase filter extracts frequency (2-500Hz) from the connected CTs and/or VTs
- **Frequency** to be extracted is **settable**
  - Frequency of dominating oscillation can be **determined**
- Long filtering windows to achieve high frequency resolution
- Filter outputs
  - Phasor (magnitude and the phase angle) at set frequency
  - **Exact** frequency of the reported phasor
Multi-purpose filter characteristics

- **Precise** phasor calculation (magnitude and phase angle)
  - Different algorithm from the standard one-cycle Digital Fourier Filter (DFT) typically used by numerical IEDs
  - Extremely good accuracy and excellent noise rejection
  - Magnitude and phase angle can be estimated even if it has magnitude of one per mille (i.e. \( \frac{1}{1000} \))
- Can be connected to measurement and protection functions
- Calculated and measured values
  - captured in local disturbance recorder
  - send to control center using communication, e.g. IEEE C37.118.2 synchrophasor data stream
Filter Length parameter (blue data used for calculation)

1.0s

0.5s
Filter configuration: Filter Length

- Configurable Filter Length
  - Longer than 3 complete periods \[ 3 \times \frac{1000}{40} = 75ms \]
  - Longer than 5 complete periods for more accuracy \[ 5 \times \frac{1000}{40} = 125ms \]

<table>
<thead>
<tr>
<th>Value for parameter FilterLength</th>
<th>Used No of samples for calculation (fixed, independent from rated frequency)</th>
<th>Corresponding length of the input waveform in milliseconds for 50Hz power system</th>
<th>Corresponding length of the input waveform in milliseconds for 60Hz power system</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 s</td>
<td>( 128 = 2^7 )</td>
<td>128 ms</td>
<td>107 ms</td>
</tr>
<tr>
<td>0.2 s</td>
<td>( 256 = 2^8 )</td>
<td>256 ms</td>
<td>213 ms</td>
</tr>
<tr>
<td>0.5 s</td>
<td>( 512 = 2^9 )</td>
<td>512 ms</td>
<td>427 ms</td>
</tr>
<tr>
<td>1.0 s</td>
<td>( 1024 = 2^{10} )</td>
<td>1024 ms</td>
<td>853 ms</td>
</tr>
<tr>
<td>2.0 s</td>
<td>( 2048 = 2^{11} )</td>
<td>2048 ms</td>
<td>1707 ms</td>
</tr>
<tr>
<td>4.0 s</td>
<td>( 4096 = 2^{12} )</td>
<td>4096 ms</td>
<td>3413 ms</td>
</tr>
</tbody>
</table>
Filter configuration: Pass Frequency Band

- Defaults per Filter Length are provided in the Table below
- Defaults are extendable by \( \frac{1}{2} \) of Frequency band width parameter

Filter length = 0.2s

Default band = \( \pm 14 \text{ Hz} \)

Frequency band width = 5

\[
14 \text{ Hz} + \frac{5}{2} = \pm 16.5 \text{ Hz}
\]

<table>
<thead>
<tr>
<th>Value for parameter FilterLength</th>
<th>For 50Hz power system</th>
<th>For 60Hz power system</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 s</td>
<td>( \pm 22.5 \text{ Hz} )</td>
<td>( \pm 27.0 \text{ Hz} )</td>
</tr>
<tr>
<td>0.2 s</td>
<td>( \pm 11.5 \text{ Hz} )</td>
<td>( \pm 14.0 \text{ Hz} )</td>
</tr>
<tr>
<td>0.5 s</td>
<td>( \pm 6.0 \text{ Hz} )</td>
<td>( \pm 7.2 \text{ Hz} )</td>
</tr>
<tr>
<td>1.0 s</td>
<td>( \pm 3.0 \text{ Hz} )</td>
<td>( \pm 3.6 \text{ Hz} )</td>
</tr>
<tr>
<td>2.0 s</td>
<td>( \pm 1.5 \text{ Hz} )</td>
<td>( \pm 1.8 \text{ Hz} )</td>
</tr>
<tr>
<td>4.0 s</td>
<td>( \pm 0.8 \text{ Hz} )</td>
<td>( \pm 1.0 \text{ Hz} )</td>
</tr>
</tbody>
</table>
Multi-purpose filter operation

A - Waveforms of the stator three-phase currents given in primary kA
B - RMS value of the SSR current extracted by the filter in primary A
C - Frequency of the extracted SSR current provided by the filter in Hz
Filter gives SSO/SSR phasors, what about Protection?

- Filter is **connected** further to “standard 50/60Hz” **protection** functions which then provide pickup and required time delays.

- The following protection functions can be used
  - Over- or under-current protection function
  - Over- or under-voltage protection function
  - Over- or under-power protection function
  - Over- or under-frequency protection function
  - Multi-purpose protection function
  - \( V, I, f \) measurement functions; value can be shown on built-in HMI or send to any control system via communication link
Combined SSO/SSR and PMU application example
Combined SSO/SSR and PMU application example

Magnitudes of Sub and Supersynchronous oscillations exceed configured limit for Mode 1
Streaming SSO/SSR data in IEEE C37.118.2 frame

- IEEE C37.118.2 synchrophasor data stream allows for binary and analog data streaming
  - 2 data streams with 32 phasors each
  - 28 binary and 24 analog signals each
- SSO/SSR data to be provided for each oscillation mode
  - sub synchronous frequency
    - phasor (magnitude and angle)
    - output of over-voltage => sub synchronous magnitude exceeds limit
  - super synchronous frequency
    - phasor (magnitude and angle)
    - output of over-voltage => super synchronous magnitude exceeds limit
- Same analog and binary data recorded locally in a disturbance record
Conclusion

PMUs placed in strategic power system locations provide
  - real-time monitoring of I and V of the oscillation sources
  - support detection of SSO/SSR locally via special filters

Combining SSO/SSR detection and synchrophasors enables
  - early indication of potential machine torsional stress
  - initiation of mitigation techniques locally or from a central location

Special filters
  - provide extremely good accuracy and excellent noise rejection
  - cover a broad range of frequencies
  - support various applications
References


Questions?
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