Sub-Synchronous Oscillations

26 March 2020
Topics

Introduction to SSO
- Principles, Origins & Impact
- Management of SSO

SSO Monitoring
- Benefits, Technology

Case Study: GB
- Projects
- Infrastructure
- Learning

Conclusions
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Introduction to SSO
Introduction to SSO: Power System Oscillations

Oscillations are inherent in the Grid, due to network + plant

**Usually present but well damped** – by design & running of network, tuned plant controls

**Risk:** poor damping due to interaction, plant malfunction or conducive conditions

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**“VLF”**

- **Governor**
  - Common
  - 0.1 Hz

**“LF”**

- **Electro-Mechanical**
  - Inter-Area / Local / Plant
  - 2 Hz

- **Torsional**
  - Turbine mechanical
  - 4 Hz

**“SSO” – SSR, SSTI, SSCI**

- **Control**
  - Voltage, power electronics
  - 50 / 60 Hz

- **Grid Resonance**
  - Capacitor + network

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**Reliable, accurate observability**

- ~12 Hz

- 50/60 fps PMU data

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**Real-Time Monitoring Tools & Capabilities** until recently

- **Less Common**
- **Common**
- **Rare**

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Introduction to SSO: SSO Sources & Interactions

- **Torsional Modes**
  - Generator Shaft
  - Frequency

- **RLC Modes**
  - Network RLC Circuit
  - Change with Grid Topology
  - Frequency

- **Control Modes**
  - Power Electronic Converters
  - Mobile
  - Frequency

- **Sub-Synchronous**
  - Torsional Interaction
  - Sub-Synchronous Resonance
  - Network Resonant Frequencies

- **Turbine Shaft Mechanical**
  - Resonant Frequencies

- **Control Oscillations**
  - Fixed
  - Sub-Synchronous Control Interaction

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Introduction to SSO: Sub-Synchronous Oscillations

Potential interaction between turbogenerator mechanics, network resonance introduced by series compensation and/or control modes associated with power electronic plant.

Also potential for control instability.

**Impact:** plant wear & stress, constraint to avoid risk, network disruption due to protection action, or plant damage.

**Mitigations:** studies, control/filter design, plant protection, operational restrictions

**Need for monitoring:**
- Validate models & studies
- Early warning of unexpected behavior which might escalate or cause cumulative damage
- Inform protection settings, procedures and investigations

**Challenge:** visibility of SSO range (2-46/56Hz)
Introduction to SSO: Related Services & Components

Services

Specialist services
Planning, design, stability studies
Generator shaft line measurement & model
Measurement-based analysis

Monitoring Protection & Control

WAMS-SSO monitoring system
Torsional Stress Relay (shaft protection)
SSR Relay (e.g. SC bypass)

Plant Control

Series capacitors
Thermal generation
Renewable generation
SSO Monitoring
SSO Monitoring: Technology

Waveform Measurement Unit

- Uses standard hardware: PMU / DFR platform
- Uses standard protocol: IEEE C37.118.2
  - 200/240fps rates atypical, but encouraged by standard
- New signal processing is straightforward to standardise
  - Simple downsampling: filter requirements easy to define
- Uses existing infrastructure: PDCs, communications networks
  - Increased communications bandwidth and PDC software enhancement may be needed for 200/240fps
- Standard function – not GE-specific – easy to replicate

Monitoring & Analysis Software

- Situational Awareness Displays
  - Unified view of mechanical & electrical oscillations
  - Geographical display to identify key participants
  - Alarms on damping & amplitude
  - Manage by frequency band
- Results stored for historical review
- Detailed spectrogram analysis of raw data for events, fast-moving modes & super-synchronous components
SSO Monitoring: Benefits

- **Wide-area visibility**
  - Identify main participants
  - Effective & efficient response
  - Targeted action & investigation

- **Continuous visibility**
  - Detect intermittent behaviour
  - Early warning
  - of potential SSO problems

- **Real-time visibility**
  - Detect low-level Interactions
  - System security
  - Asset protection
  - Maintenance
  - Real-time operator alarms
  - Mitigate risk
  - when commissioning new plant

- **Historical visibility**
  - Detect low-level Interactions
  - Reduce risk: catch unpredicted modes
  - Model validation
  - Confidence in models & studies
  - Shaft, network, PE control
  - Optimised protection & alarms
  - Baseline behaviour
  - Operational procedures

- **Generator speed**
  - Directly observe mechanical behaviour
  - Confirmation of interactions
  - and torsional modes
Case Studies
Case Study: Great Britain SP Energy Networks

SSO monitoring has been **operational in GB for 5 years**: Significant insight & experience has been gained

- GB Innovation Project
- Demonstrate WAMS benefits
- GB-wide: 3 UK Transmission Owners + Operator
- PMU & WMU monitoring at Transmission substations
- April **2014 - March 2018**

**Monitoring hardware**  
- 14 circuits, 10 sites

**Software:** GE PhasorPoint WAMS
- 3 TO + SO data centres

**SSO Analysis:**  
- Periodic Review  
- Plant Commissioning

SPEN Series Compensation Project takes next step...
- +14 circuits, +3 sites
- +4 generator units (V, I & ω) across 2 sites
- HA server infrastructure
Case Study: Great Britain SP Energy Networks – Key Learning

Series Compensation commissioning supported - no issues observed

Torsional modes visible in grid measurements

Many other modes observed (all low amplitude): likely power electronic
• Some mobile in frequency, a few occasionally close to torsional modes
• Most modes well-behaved and localised
• A few showed poorer damping periods
• A few observable over wide area
• Some investigations triggered as prudence

Mitigated Risk: supported SC commissioning (no issues observed)

Early warning
Identified PE modes

Targeted investigation

Optimised protection & alarms
Tuned thresholds & bands

Histogram of Detected Mode Frequency over 31 days

Approximate Occurrence (% of review period)

Frequency (omitted for reasons of confidentiality)

4 3 2 1
Case Study: **Sub-Synchronous Torsional Interaction**

Known torsional mode
- Visible in grid

Suspected control mode
- Seen over a **wide area**
- **Sporadic** occurrence
- **Mobile frequency**

**Signs of interaction**
When control mode close to torsional mode: **low amplitude**

**Monitoring fed investigation:**
- **Location** from mode shape
- **Timings** of occurrence

**Suspected source identified**
End user equipment malfunction

**Monitoring for recurrence**
Case Study: Control Instability

Sudden onset of large power oscillations in a network region

Detected by WAMS monitoring

WAMS analysis highlighted suspected location and related grid condition.

Investigation identified Grid user.

WAMS data provided and used to develop a solution.

Response of nearby generators captured
Case Study: Control Instability Leading to Post-Fault De-Load

- Wind farm shut itself down due to an unstable control system response to the disturbance voltage dip -> WF acts to raise voltage -> oscillation develops

- Hornsea tested & modelled in line with Grid Code Oscillations considered, no reason to suggest 9th August behaviour Issue already identified, but only expected when final unit connected Control upgrade brought forward to resolve

Impact: Generator £4.5m “voluntary payment”

Solutions
- **Compliance Monitoring:** commissioning / long-term
  - Early warning of generation noncompliance

Unstable Control System Oscillation

Earlier lightning strike - not bad enough to cause shutdown

Wind Farm onshore voltage

- 130 MVAR, ~8Hz Damping Ratio 4%

Wind Farm Reactive Power

Shutdown Event

Lightning strike causing short circuit on NETS

Hornsea 1B and 4C WTGs de-load due to overcurrent

Wind Farm voltage

Wind Farm output

- 700 MVAR, ~10Hz

Source: chart traces from Orsted technical report included in Appendix to published NGESO Technical Report on the events of 9/8/19
Conclusion

- We are seeing increasing proliferation of Power Electronic converters
- Sub Synchronous Oscillations are a real concern due to potential for interaction between Power Electronics, Series Compensation and Turbine Generators
- Monitoring is emerging as a key element to manage SSO risk and provide early warning of issues to avoid disruption or plant damage.
- A novel Waveform Measurement Unit (WMU) provides visibility to monitor SSO (4-46/56 Hz), and also a view of the super-synchronous range to guide analysis
- A WAMS server software module provides real-time alarming, comprehensible geographic views and data for study, investigation & review.
- The WMU approach is fully IEEE C37.118.2 compliant, and can utilize the same platform, protocol and infrastructure as conventional WAMS.
- Monitoring of SSO has now been operational in GB for four years and significant insight and experience has been gained.
Supporting Information
Why 200/240Hz Waveform Data?

Sampling rate (by Nyquist) must $>2f_{\text{max}}$; practically $4x/5x f_{\text{max}}$ necessary $\rightarrow 200\text{Hz for 50Hz bandwidth}$

Options:
1. Waveform $\rightarrow$ RMS/PMU calc $\rightarrow$ filter $\rightarrow$ downsample
2. Waveform $\rightarrow$ filter $\rightarrow$ downsample

Chosen 2 (80Hz LP filter) to avoid windowing distortion and differentiate modulated from added oscillations.
Why 200/240Hz Waveform Data and not RMS?

Amplitude Modulation 20Hz

Frequency Modulation 10Hz

Added sub-synchronous 30Hz

E.g. Power electronic control mode

Added super-synchronous 70Hz

E.g. Torsional oscillation seen in V&I

In Waveform, modulation differentiated from addition by presence of sidebands

In Waveform, cannot differentiate sub-synchronous from super-synchronous

In RMS, cannot differentiate modulation and addition

In RMS, cannot differentiate sub-synchronous from super-synchronous

Frequency Modulation almost unobservable in RMS
Portfolio of GE WAMS Applications
Real-time Applications

Future Applications
- Fault Location
- Automated Reports
- CIM Integration Source
- Dynamic Dispatch Training System
- Very Low Frequency Monitoring
- Line Parameter Estimation

Advanced Applications
- Oscillatory Stability Monitoring
- System Disturbance Monitoring
- Short Circuit Capacity
- Asynchronous Systems
- Sub Synchronous Oscillation Monitoring
- Oscillation Source Location

Standard Applications
- Islanding, Resynchronization & Blackstart
- Voltage Magnitude & Angle
- Dynamic Angle Reference
- System Frequency & df/dt
- Active & Reactive Power
- Symmetrical Components

Interfaces
- MyViews
- System Condition Monitoring
- Rate of Change
- User Defined Calculations
- Replay
- Composite Events

Real-time Interfaces
- ISD
- DNP3
- MODBUS
- IEC 60870-5-104
- IEEE C37.118 & 224

Historical Interfaces
- SQL JDBC/ODBC

APIs
- Web Services
- SOAP
- WEB-API
- REST/JSON

Data import/export
- COMTRADE CSV

External Databases
- Phasor Analytics
Engineering Analytics Applications

Advanced Analytics
- Optimal PMU Placement
- Dynamic Performance Baselining
- Post-Event Analysis
- Oscillatory Stability Analysis
- Frequency Response Characterization
- Model Validation & Calibration
- Study Linear State Estimator (LSE) / Contingency Analysis (CA)

Base Applications
- Spectral Analysis
- Custom Views
- Correlation Analysis
- Trending Analysis
- Custom Analytics
- Pre-Defined Calculations
  - Sequences
  - MW/MVAR
  - Angle Difference
- Data Quality & Availability Statistics

Data Management
- Snapshot and Case Management
- Data Exports
- Reporting Templates
- Chart Annotation
- Data Conditioning
- On Demand Reporting
- Historical Alarms & Events

Interfaces
- Phasor Data
  - PhasorPoint
  - COMTRADE
  - CSV
- SCADA Data
  - PhasorPoint
  - HDR Files
- Simulation
  - TSAIT
  - PSLF
  - CSV
- Fault Recorder
  - COMTRADE
- Oscillatory Modes
  - PhasorPoint
  - CSV
- External Historians
  - OSI PI
  - openPDC/Historian
- Model Imports
  - NETMOM
  - CIM