Special Studies – SSO/SSCI

ELECTRANIX
SPECIALISTS IN POWER SYSTEM STUDIES

ESIG
ENERGY SYSTEMS INTEGRATION GROUP

Type of SSO

Distinguish between terms…

- “SSR”: Sub-Synchronous Resonance
  - Interaction between the mechanical/torsional masses in a generator (or wind turbine) and the electrical resonance from a series capacitor.
  - “SSTA”: Torque Amplification: Increase in peak shaft torques leading to higher fatigue.
- “SSTI”: Sub-Synchronous Torsional Interaction
  - Interactions between the mechanical/torsional masses in a generator (or wind turbine) and a power electronic device (such as an HVDC link, SVC, IBR etc…).
- “SSCI”: Sub-Synchronous Control Instability
  - Interactions between a power electronic device (such as an HVDC link, SVC, IBR etc…) and a series compensated system.
- “SSFR”: Sub-Synchronous Ferro Resonance
  - Interactions between a saturated transformer and a series compensated system.

	Series Cap	Power Electronics	Gas Turbine	Transformer
Series Cap	--	SSCI	SSR	SSFR
Power Electronics	SSCI	Control Interaction	SSTI	--
Gas Turbine	SSR	SSTI	--	--
Transformer	SSFR	--	--	--

Real World SSCI Events

(IEEE transaction on power systems: Yunzhi Cheng et all :Real-World Subsynchronous Oscillation Events in Power Grids with High Penetrations of Inverter-Based Resources)

1. (2007) A SSO event occurred in south central Minnesota when a 100-MW type-3 wind power plant (WPP) was inadvertently left radially connected to a 345-kV series compensated transmission line.
2. (2009) Tripping of a transmission line left multiple type-3 WPPs radially connected to a series compensated 345-kV transmission line in South Texas. Large 20-30 Hz overcurrent appeared within 150 ms, causing severe damage to the series capacitor and WPPs. Wind controller was modified.
3. (2010) Oklahoma Gas & Electric (OG&E) observed 13-Hz oscillations at two nearby WPPs. The oscillations occurred when wind farm output was above 80 percent of its rated level and the magnitude of oscillation reached 5% of the 138-kV voltage.: Wind controller was modified.
4. (2011) 4-Hz oscillations were observed at a type-4 WPP in Texas region after a transmission line tripped.
5. (2011-2014) Since 2011, oscillations were observed by BPA during high wind generation conditions. A 450MW type-4 WPP located in Oregon was identified as the source. Voltage controller was modified.
6. (2011-2012) OG&E reported two wind oscillation events, one in December 2011 and another one in December 2012. Both were triggered due to line outage. For the 2012 event, 3-Hz oscillations appeared at a 60-MW WPP after a line outage. Wind controller was modified.
7. (2012-2013) During the one-year period, more than 58 oscillation events were reported in North China with oscillation frequency of 6-9 Hz. The oscillations ocurred due to interaction between tye-3 WPPs and 500-kV double circuit series compensated transmission lines connecting Guyuan station with Inner Mongolia and North China grids. SSCI
8. (2014-2015) 30-Hz oscillations appeared when type-4 WPPs located in Xinjiang China with connection to a 750 kV system started to export power. The oscillations spread to the main grid and caused the subsynchronous resonance (SSR) protection relay of a 600-MW thermal power plant located 48 km away to trip the power plant. Initial research indicated that such oscillations are triggered due to interaction between WPPs with weak grid interconnection. SSR, SSTI and SSCI
9. (2015) Poorly damped 20-Hz oscillations were observed in root mean square (RMS) voltage of a 44-kV distribution feeder in Hydro One, Canada after the energizing of a 30 MVAr shunt capacitor at the substation. Weak system

10. (2016) In November 2016, PMUs captured oscillations for multiple days at a solar farm in AEP.
11. (2017) 37-Hz and 63-Hz oscillations were observed in instantaneous voltages and currents at a 600-MW type-3 WPP (300 turbines, each 2 MW) connected to a 220 kV grid in northwest China.
12. (2017) 7-Hz oscillations in real power, reactive power, and RMS voltage appeared in a First Solar's solar farm in California. Weak system and PV controller was modified.
13. (2017) Three separate SSO events occurred in South Texas. The frequency range is 22-26 Hz in instantaneous currents. Wind controller was modified.
14. (2015-2019) 7-Hz voltage oscillations were observed in Australia's West Murray zone under low system strength and high penetrations of IBRs. Weak system
15. (2018-2019) 3.5-Hz oscillations were observed in real power and reactive power measurement for two 230 kV type-4 WPPs in Hydro One after a planned 230-kV bus outage. The outage caused a significant reduction in system strength viewed from the WPPs. A nearby 150 kV solar PV also reported undamped reactive power oscillations. Weak system
16. (2019): 9-Hz oscillations were observed 10 minutes before the August 2019 Great Britain (GB) power system disruption . Weak grid oscillations were later identified as the reason why an 800-MW offshore WPP went to the de-loading stage. The WPP vendor upgraded the control software afterwards. Weak system and wind controller was modified
17. (2020) 7-Hz oscillations, 17-19 Hz voltage oscillations were reported for the Southeast Australia region including Victoria, New South Wales, etc. Weak system
18. (2021) 22-Hz oscillations in RMS voltage related to a solar PV farm were reported by Dominion Energy in eastern U.S.. In instantaneous currents and voltages, 38-Hz and 82-Hz components were observed.
19. (2021-2022) South Africa

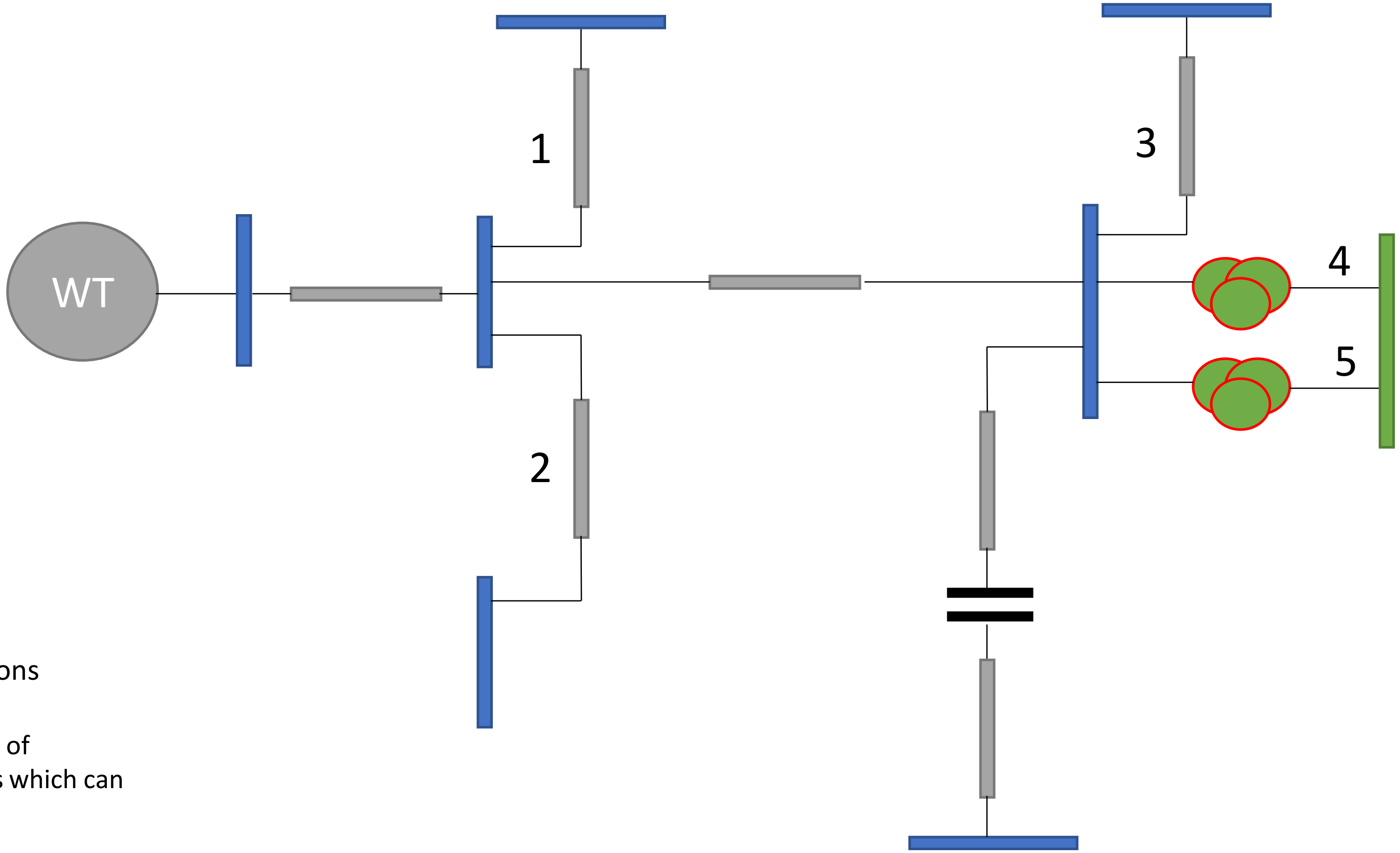
When SSO studies are Required

- SSO event occurs, leading to sustained oscillations or the tripping of multiple plants and potential equipment damage.
- High concentration of inverter-based resources (IBRs) located near series-compensated lines.
- Installation of new series-compensated transmission lines in proximity to existing IBRs or synchronous generators.
- Adding non-series-compensated lines in proximity to existing series-compensated infrastructure.
- Integration of IBRs or large loads close to synchronous generation.
- Adding SVCs, STATCOMs and HVDC near series compensation or synchronous generators.

Types of SSO Analysis

1. Screening Studies
    - SSR/SSCI: Harmonic Impedance Scans (dynamic and passive)
    - SSTI: Unit Interaction Factor/ Radiality factor: based on short circuit calculations
2. Advanced Screening Studies
    - System wide eigen-analysis which uses curve-fitting of frequency scans to represent state equations of black-box models
3. Perturbation Analysis/combined impedance analysis
    - SSR/SSTI: Used to evaluate generator electrical damping vs frequency
    - SSCI: Used to evaluate Effective Dynamic Impedance of a power electronic device
4. Full Detailed Time Domain Analysis
    - SSR/SSTI/SSCI/SSFR/SSTA: Uses fully detailed models of all devices

SSCI Risk : Screening Network Scans

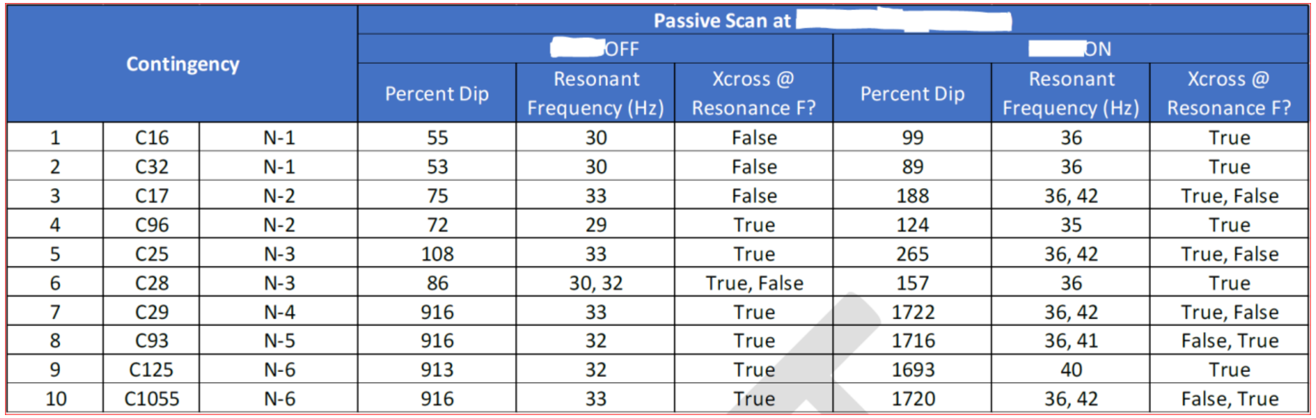


2^5 = 32 combinations

2^n (where n is number of transmission elements which can be taken as outages)

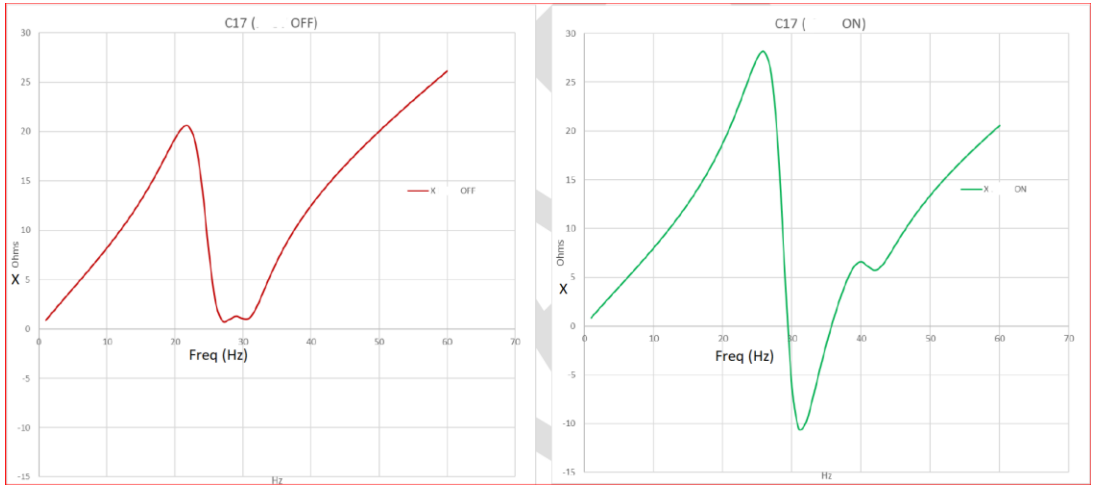
SSCI Risk : Screening

Passive System scanning and identifying SSCI risk at each IBR location with and without upgrade



Contingency			Passive Scan at [redacted]					
			[redacted] OFF			[redacted] ON		
			Percent Dip	Resonant Frequency (Hz)	Xcross @ Resonance F?	Percent Dip	Resonant Frequency (Hz)	Xcross @ Resonance F?
1	C16	N-1	55	30	False	99	36	True
2	C32	N-1	53	30	False	89	36	True
3	C17	N-2	75	33	False	188	36, 42	True, False
4	C96	N-2	72	29	True	124	35	True
5	C25	N-3	108	33	True	265	36, 42	True, False
6	C28	N-3	86	30, 32	True, False	157	36	True
7	C29	N-4	916	33	True	1722	36, 42	True, False
8	C93	N-5	916	32	True	1716	36, 41	False, True
9	C125	N-6	913	32	True	1693	40	True
10	C1055	N-6	916	33	True	1720	36, 42	False, True

System X vs. Frequency



Pre - upgrade

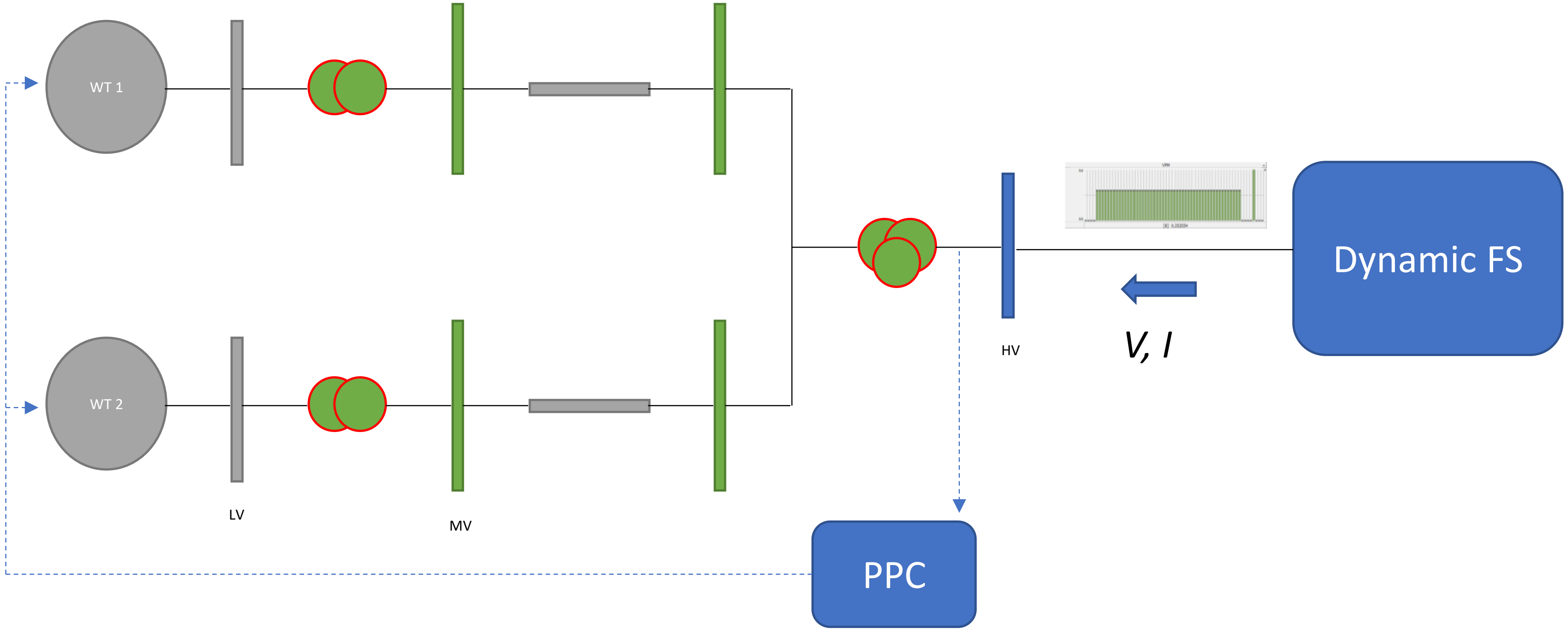
Post - upgrade

Check for

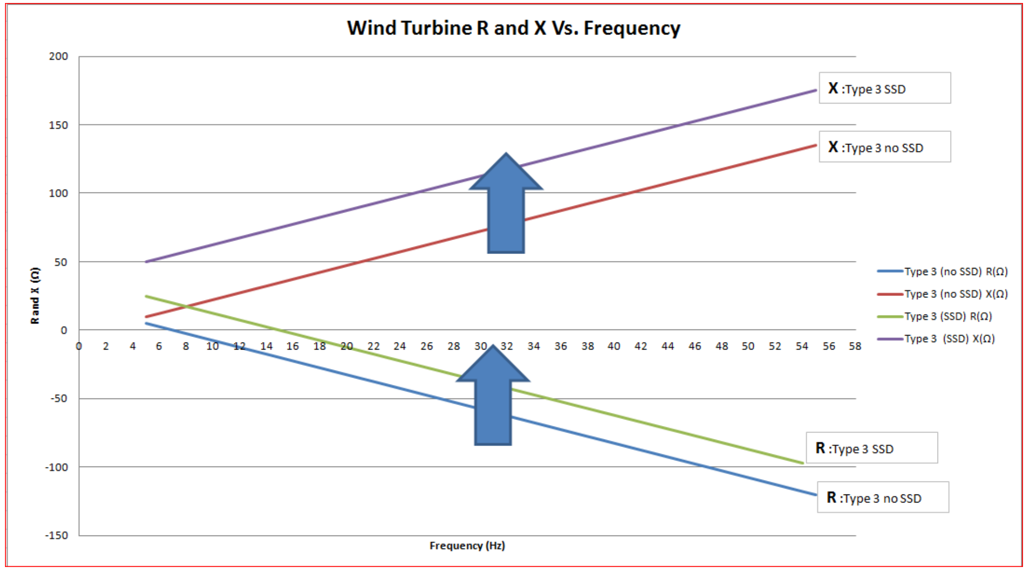
- **Increase in resonant frequency**
- **Increase in percentage inductance dip**
- **Whether inductance cross the X axis at resonance**

Requires further detailed investigation

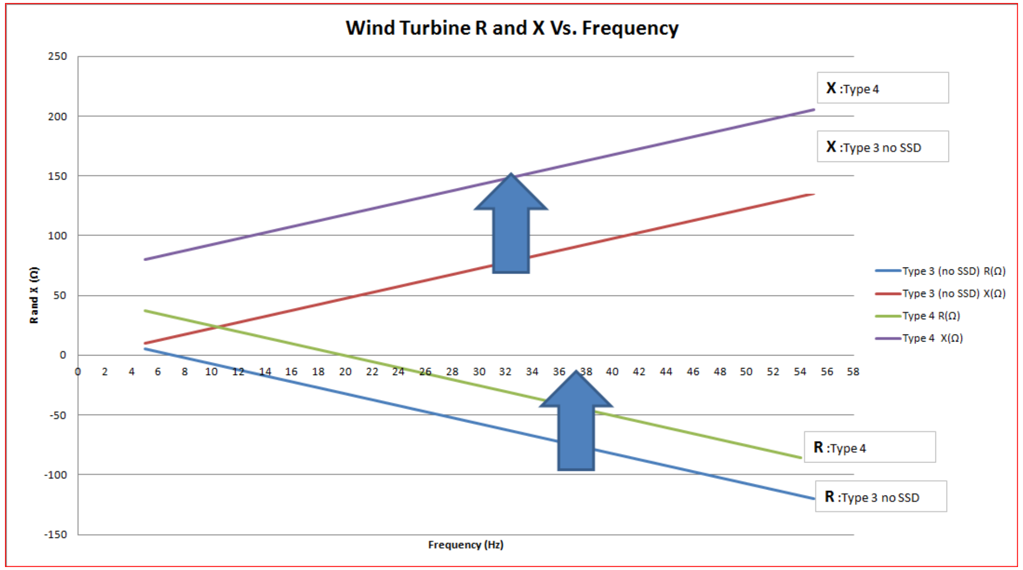
SSCI Risk: Screening Dynamic Frequency Scan



SSCI Risk: Screening
Dynamic Frequency Scan Results



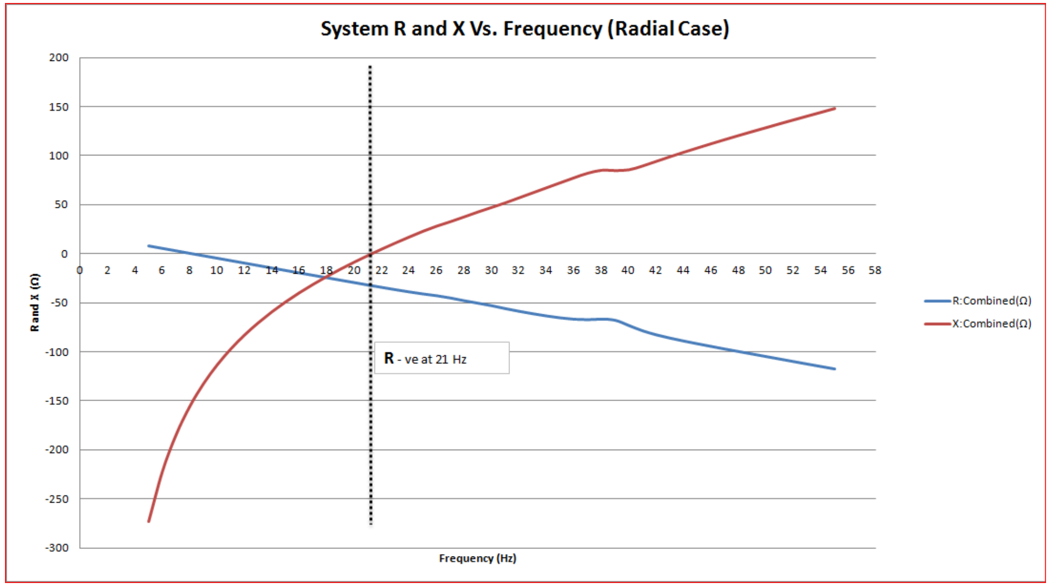
Type 3 with and without SS damping controller

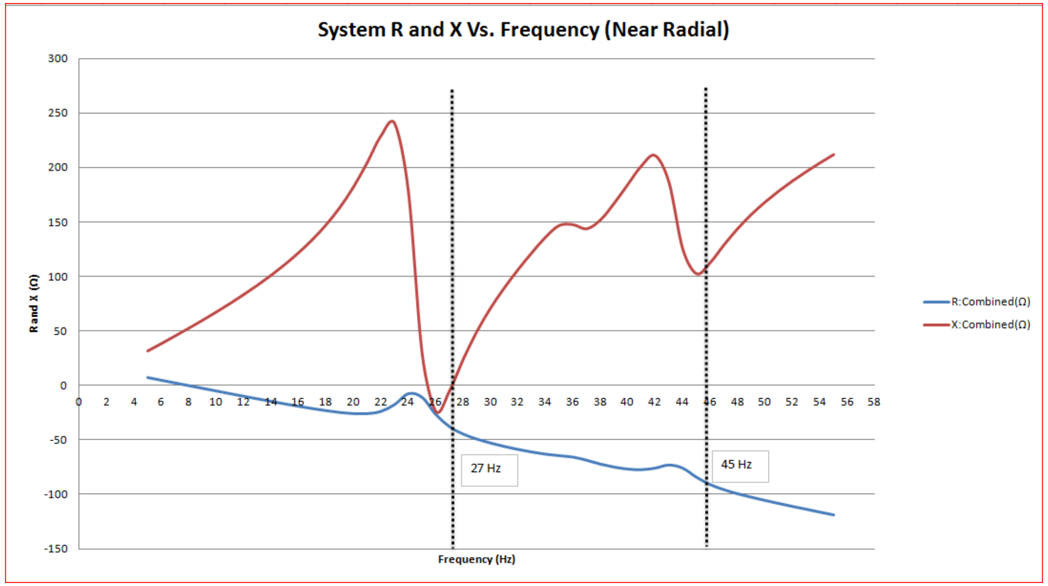


Type 3 and Type 4

SSCI Risk: Screening
Adding Dynamic and Passive Scan Results

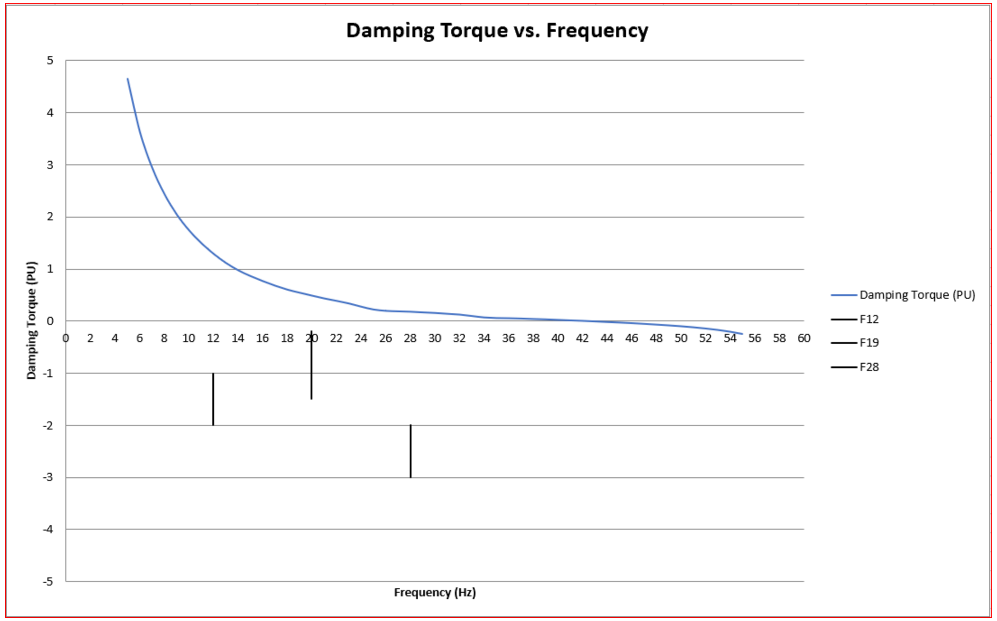
- Dynamic impedance scans of the inverters and system impedances can be added together to estimate the overall damping and resonant frequencies for critical contingencies. (Caution is required, there are approximations built into this!). It is important to note that these are screening techniques. **All final conclusions must be based on fully detailed time domain simulations of critical contingencies.**


System R and X Vs. Frequency (Radial Case)

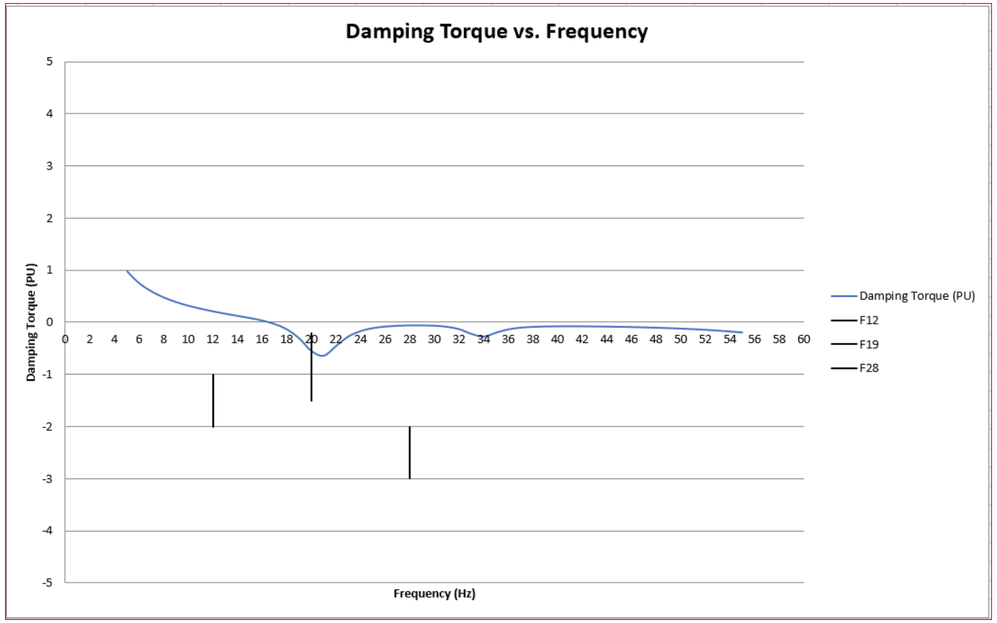

System R and X Vs. Frequency (Near Radial)

SSR Risk : Screening

Damping calculation of synchronous generators compared against mechanical damping



Pre - upgrade



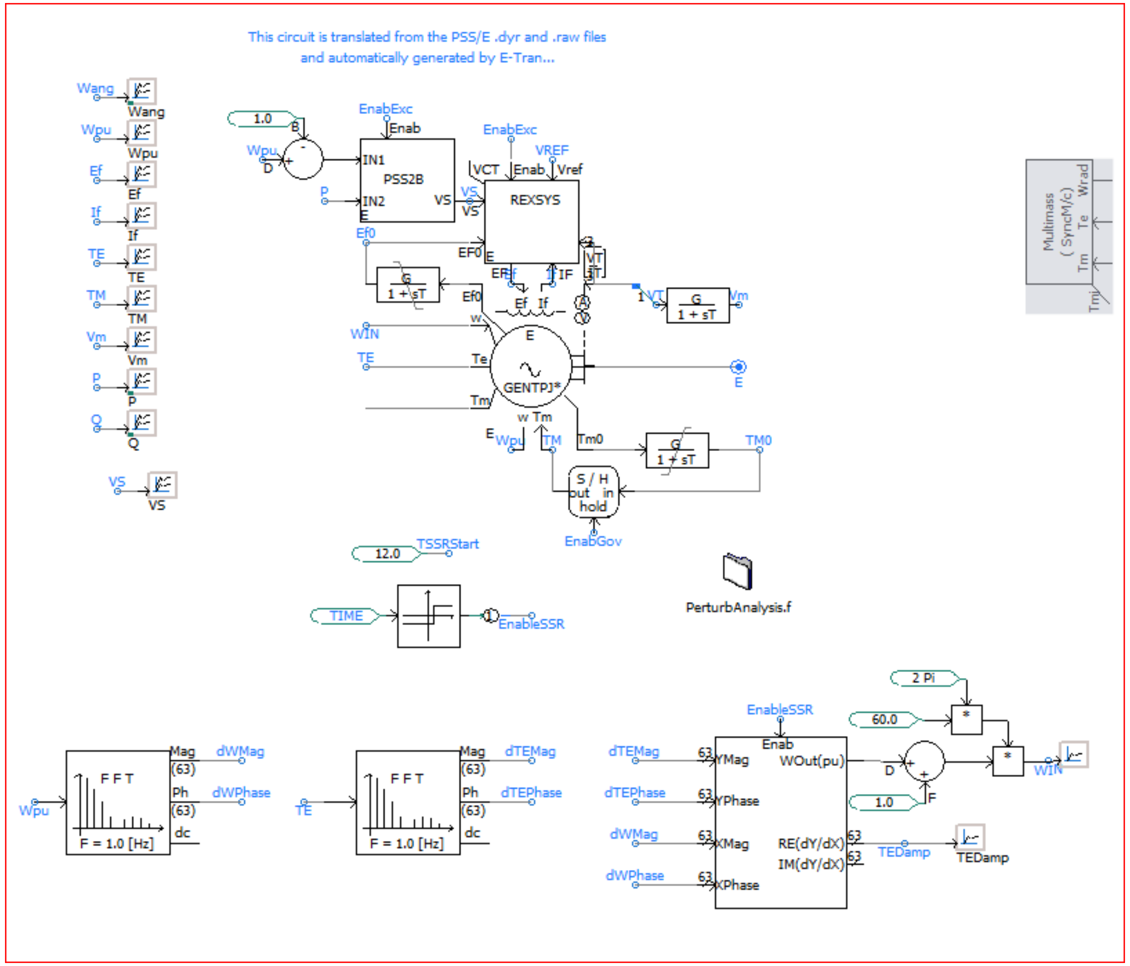
Post - upgrade

Requires further detailed investigation

SSR Risk:

Dynamic Frequency Scans (Perturbation)

- Force the speed to be 1 pu plus a small oscillation at 5-55 Hz
- Measure the relative magnitude and angle between the electrical torque and delta W
- The electrical damping is the real part of dTe/dW

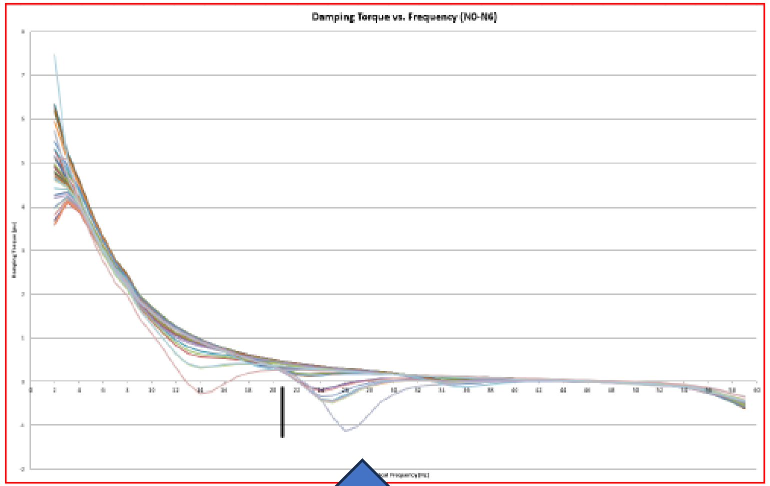


This circuit is translated from the PSS/E .dyr and .raw files and automatically generated by E-Tran...

SSTI Risk : Screening

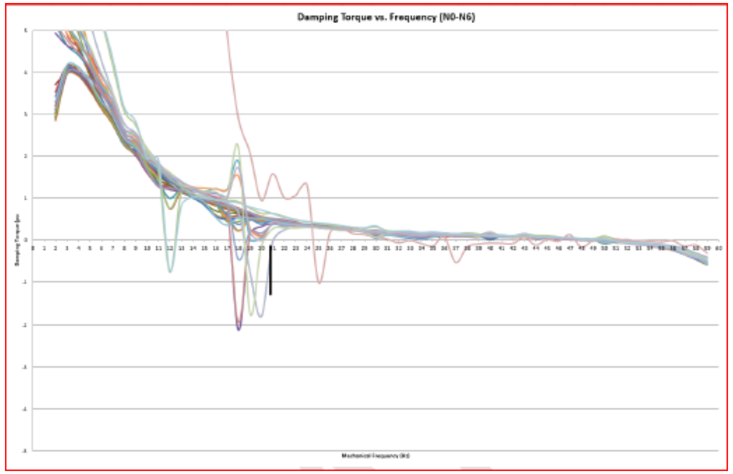
Perturbation Analysis of synchronous generators with detailed IBR plants

- Installing IBRs near synchronous generators may lead to increased negative damping at the generator terminals and shift the negatively damped regions toward the torsional mode range



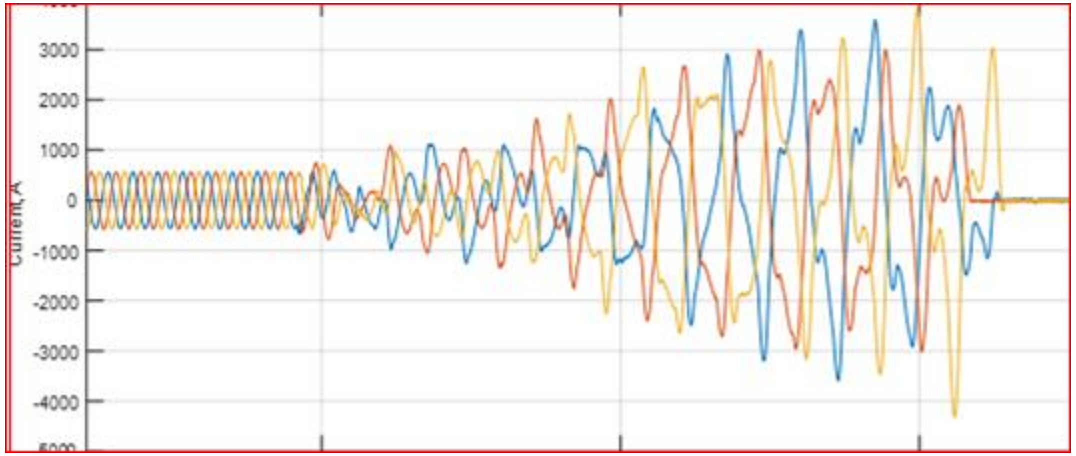
Synchronous generator Damping plots with IBR not in service

Synchronous generator Damping plots with IBR in service

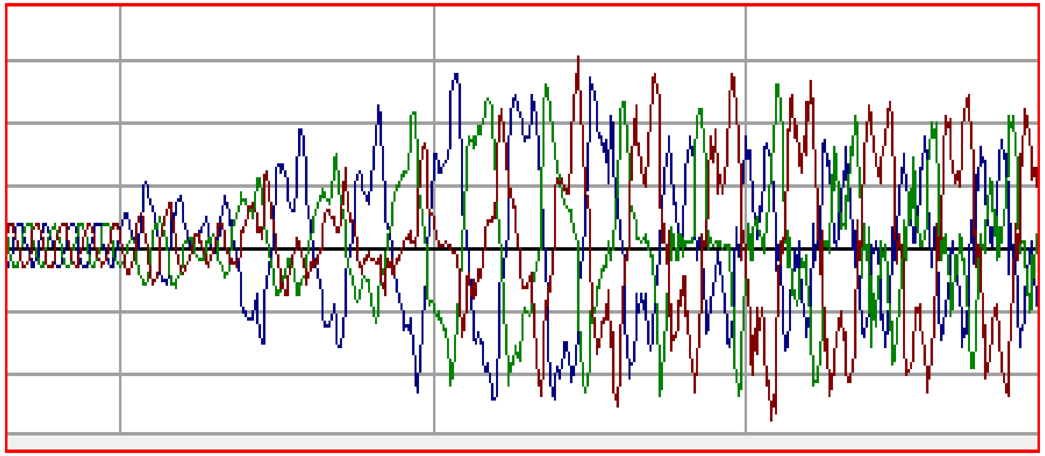


SSFR Risk

- A saturated plant transformer can oscillate with a series capacitor, leading to undamped oscillations that may require either tripping the plant or bypassing the series capacitor to stop them.
- The situation worsens when multiple plants are connected in close proximity to the series capacitors.



Field Measurement- Current

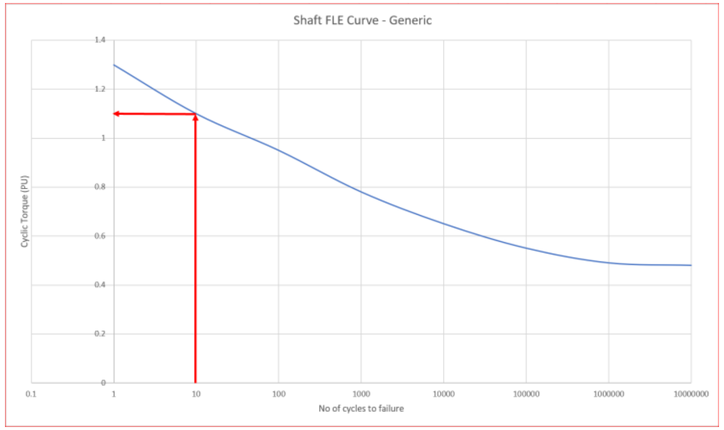


EMT Simulation - Current

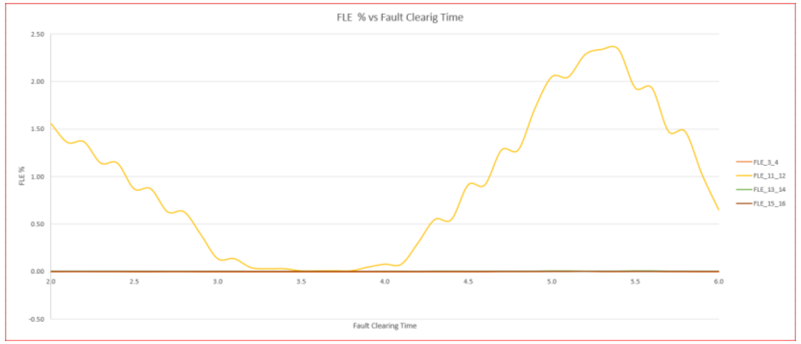
SSTA Risk : Detailed Study

- Fatigue curve / S-N Curve
- FLE : Fatigue Life Expenditure
- Generally, FLE = 1% for a fault is acceptable
- Introducing series compensation can elevate the torque experienced by the generator shaft, potentially causing mechanical failure
- Depends on fault clearing time

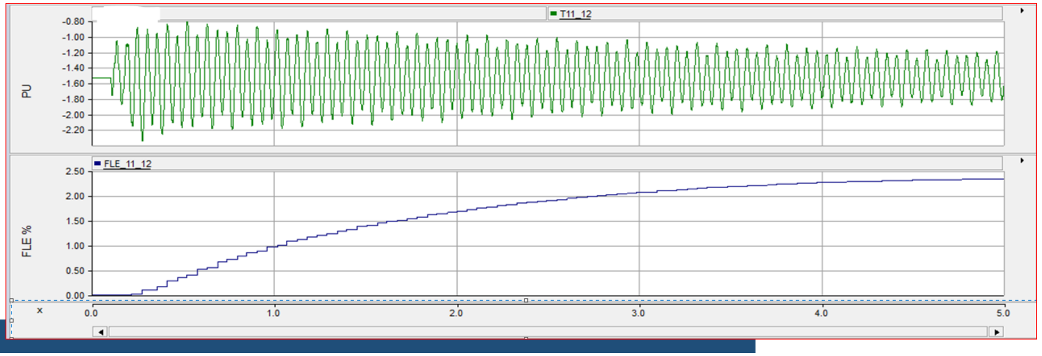
shaft fails after 10 occurrences of 1.1 per unit torque : FLE = 100%



FLE % sensitivity to fault clearing duration



Sample Cyclic Torque Event and Percentage of FLE Utilized - Cumulative



Data Requirement at Each Stage of SSO Studies

Study Stage	Screening Studies			Detailed EMT Studies		
	High Level system Screening for SSCI and SSR	Detailed SSCI Screening	Detailed SSR Screening	SSFR	SSTI	SSTA
Power flow case and dynamic data records	Yes	Yes	Yes	Yes	Yes	Yes
Detailed IBR EMT model		Yes		Yes	Yes	
Synchronous generator torsional model			Yes		Yes	Yes
Torsional mechanical damping			Yes		Yes	Yes
Detailed system model				Yes	Yes	Yes

Potential Mitigation and Protection Measures for SSO Issues

SSO Issue	Mitigation and protection schemes						
SSCI	IBR inverter and PPC tuning	Addition of GFM BESS with positive damping	RAS schemes				SS relay
SSR			RAS schemes	SSDCs on excitation systems	Passive damping Filters /Blocking Filters		Torsional Stress Relay (TSR)
SSFR			RAS schemes			Switchable Arresters	SS relay
SSTI	IBR inverter and PPC tuning	Addition of GFM BESS with positive damping	RAS schemes		Passive damping Filters /Blocking Filters		Torsional Stress Relay (TSR)
SSTA			RAS schemes		Passive damping Filters /Blocking Filters		Torsional Stress Relay (TSR)

Challenges in SSO Studies

- **Detailed System Modeling:** Includes accurate representations of series compensation and frequency-dependent transmission line models.
- **Accurate IBR EMT Models:** Must be consistent with the actual field firmware to accurately reflect dynamic behavior and requires OEM-provided models.
- **Synchronous Generator Shaft Modeling:** Requires torsional models with mechanical damping data, along with FLE/S-N curves. (Nearly impossible to get from OEMs)
- **Multi-Stakeholder Coordination:** Involves collaboration among OEMs, TOs, and ISOs : and complex NDAs.
- **Time-Intensive EMT Simulations:** EMT studies are complex and require significant time, knowledge and computational resources.
- **Mixed SSR and SSCI Interactions:** Systems may exhibit a combination of SSR and SSCI, which can be difficult to isolate and analyze.
- **Numerous Operating Scenarios:** A large number of possible network conditions and concurrent transmission projects increase the scope and complexity of the study.