SSO Screening and Detailed Studies

ERCOT IBRWG Presentation – October 11, 2024

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What is SSO?

- **Sub-Synchronous (<60 Hz) Oscillations** include a large family of oscillations.
- Most famous event examples include:
  - SSR - Mohave Unit: Broken generator shaft – 1970 and 1971 (happened twice before the phenomenon was understood
  - SSCI - Wind Farm: Damaged series capacitor and wind turbine circuitry - 2009
- Series capacitors are a cheap way to add transmission capacity, but **Series capacitors and IBRs do not play nicely together!** Detailed PSCAD study is always required, and any new generation or system topology change requires re-study.
- Note: in Texas there are series capacitors everywhere!!
- Note: building a new series capacitor in an IBR heavy area is like dropping a study bomb on the region! You will keep study consultants busy for years to come… ☺

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.
  - “TA”: 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, wind turbine etc…).
- “SSCI”: Sub-Synchronous Control Instability
  - Interactions between a power electronic device (such as an HVDC link, SVC, wind turbine 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	--	--	--

Types of SSO Analysis

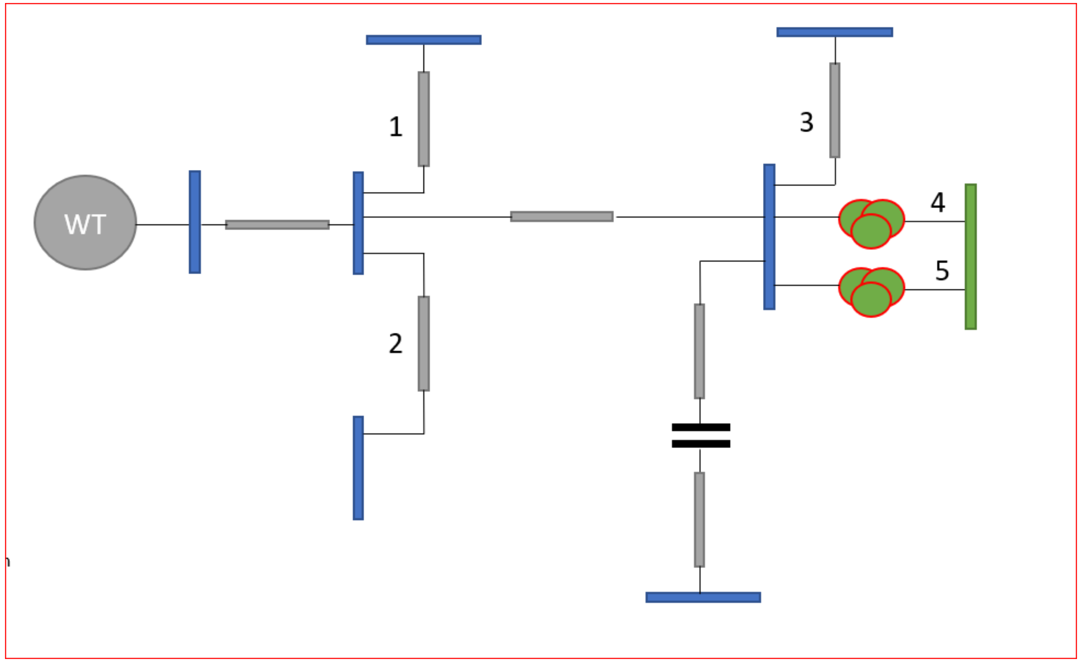
1. Screening Studies
   - SSR/SSCI: Harmonic Impedance Scans (dynamic and passive)
   - SSTI: Unit Interaction Factor/ Radiality factor: based on short circuit calculations
2. Advanced Screening Studies
   - System wide eigen-analysis which uses curve-fitting of frequency scans to represent state equations 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

Note on Studies

- These studies are among the most complex EMT studies currently being done. In Texas, assuming the most experienced study engineers, a correctly performed study looks like this:
  - PSCAD model with 15 detailed IBRs, 450 busses
  - Single contingency will use a high-performance computer (128 cores) and take approximately 1-2 hours to run.
  - Entire study timeline (assuming good quality data) will take between 6 weeks and 6 months, depending on whether issues are encountered.
- The control and protection settings adjusted during the SSO study should be implemented in the real firmware.

Pre-Screening : Pre identification of susceptible Generators and Contingencies

- This is an analytical pre-identification of generators and contingencies for screening studies.
- If a significant number of lines (e.g., more than N-6) must be removed to make the generator radial, and the generator is electrically distant from the series-compensated line, as well as the contingency being highly unlikely, the generator can be excluded from SSCI studies.



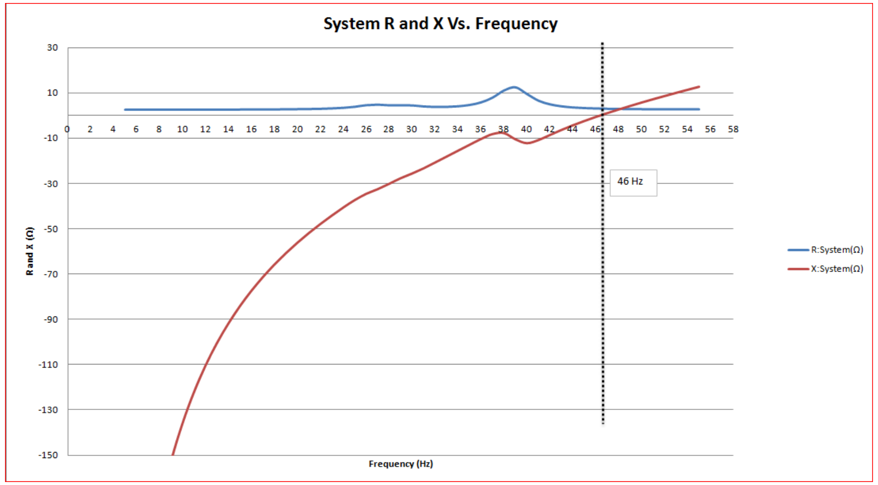
$2^5 = 32$ combinations

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

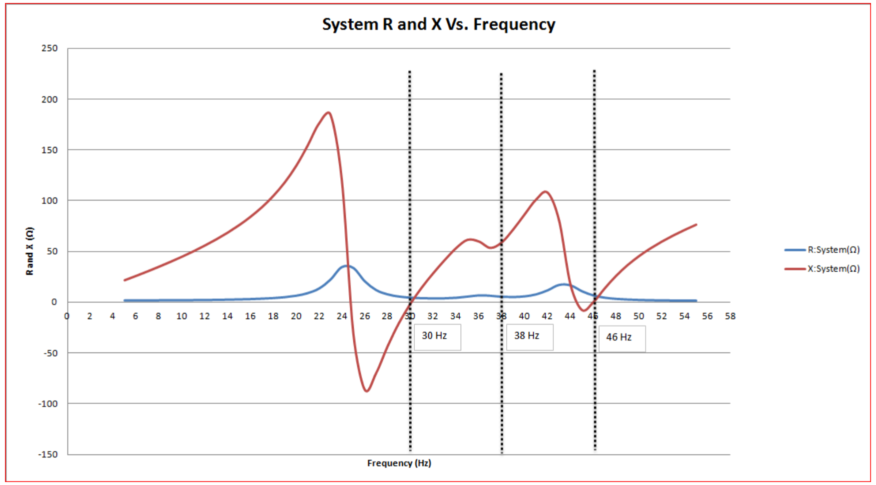
Screening : Passive Frequency Scan (System)

- The passive frequency scanning method looks for electrical resonances in the system in the range of 2 Hz to 55 Hz.
- Series system resonances can be observed when a series compensated line is radially or near radially connected to a generator.
- If a generator is radial to a series compensated line then the system inductance is negative at lower frequencies and turns positive above the series resonance frequency.
- If a generator is connected to a series compensated line parallel with other lines (or shunt devices), then a dip in the reactance can be observed.

Radial Case to series capacitor



Near Radial Case to series capacitor

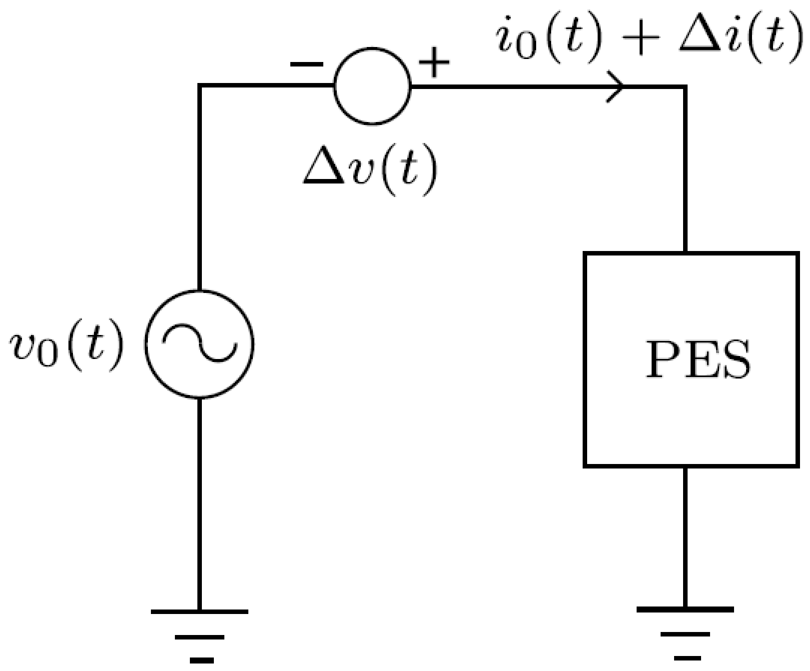


Passive Scan : Assumptions

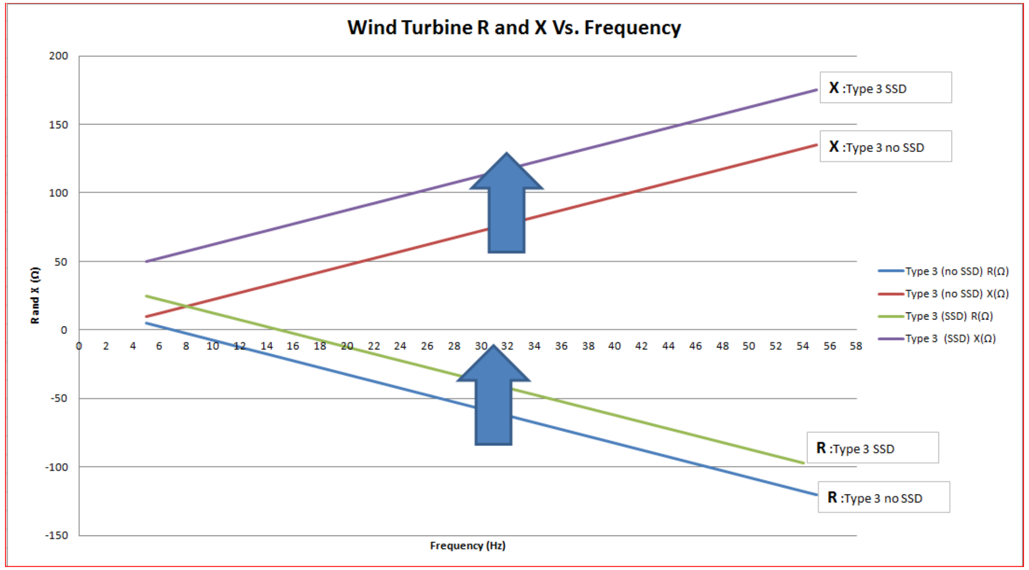
- Representation of nearby power electronic devices such as SVC, STATCOM and HVDC are approximate and relatively inaccurate.
- Representation of other nearby wind farms in the model are fixed at an assumed 60Hz impedance (generally inaccurate). (Note: *Frequency dependence impedance of wind turbine can be used and mostly not available).*
- Generator and transformer saturation is not considered with passive scanning.
- Response of exciters, governor and power system stabilizers cannot be represented in frequency scans.

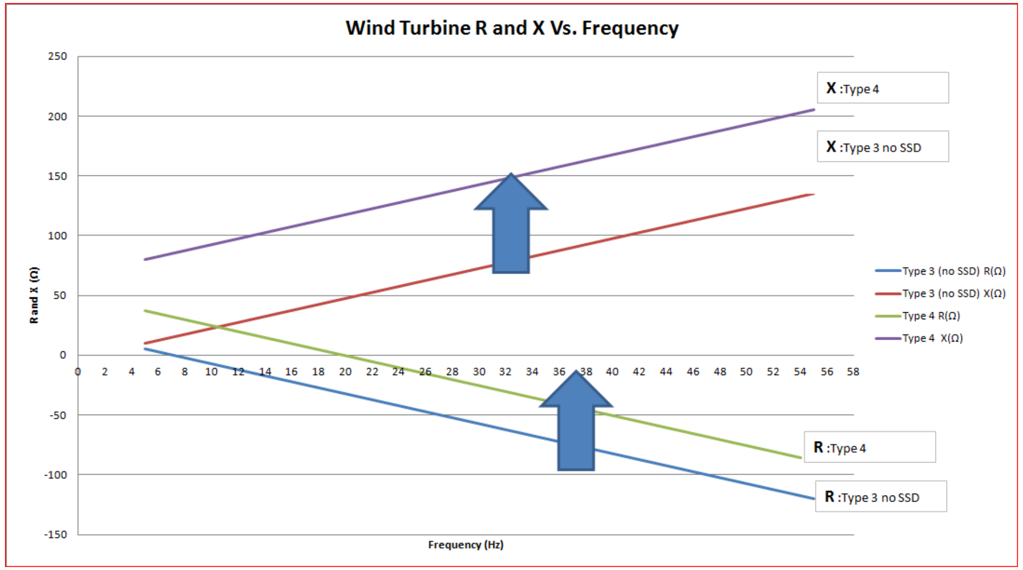
Screening : Dynamic Frequency Scan

- Small magnitude voltage harmonics are injected to the fundamental waveform at the POI of an IBR plant at a range of sub-synchronous frequencies.
- R and X values are calculated at the IBR plant terminal for each sub-synchronous frequency.
- In order to capture a range of controller and plant operating conditions, the following operating modes are often used for dynamic frequency scanning:
    - Full/partial generating with all turbines are in service
    - Full generation with low number of turbines are in service
    - Unity, capacitive and inductive reactive power generation
    - Low, medium and high perturbation magnitudes



Screening : Dynamic Frequency Scan Results





Type 3 with and without SS damping controller

Type 3 and Type 4

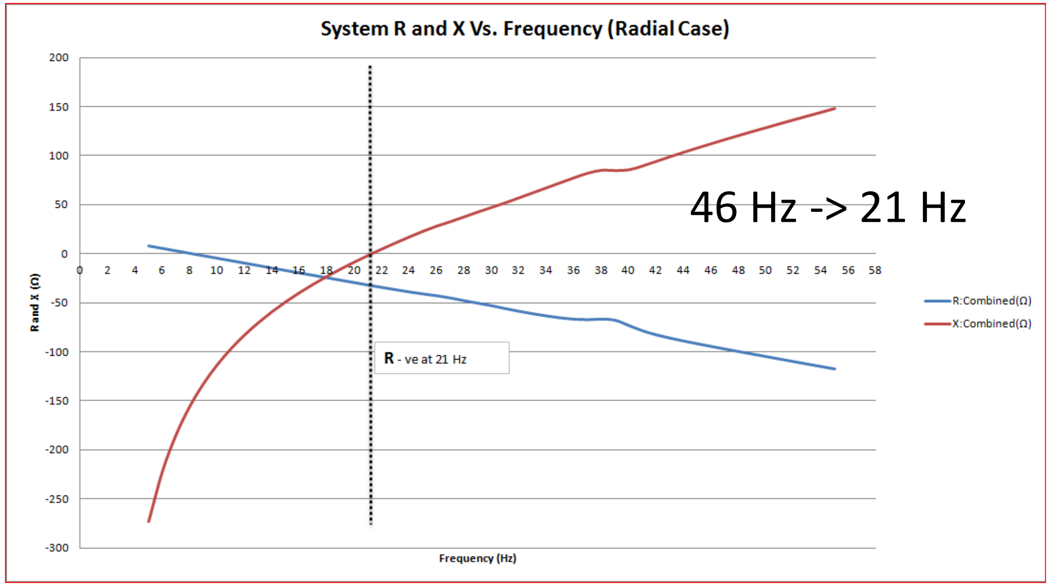
Note: Generally, PV solar R and X Vs frequency characteristics are similar to Type 4 wind

Dynamic Scan : Assumptions

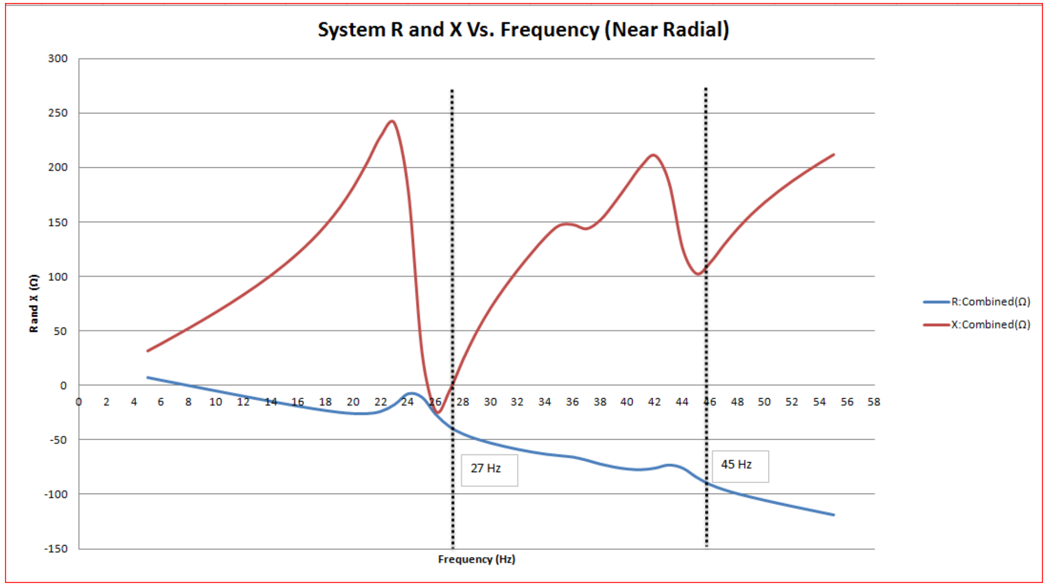
- Results depend on perturbation magnitude in most of the cases.
- Results depend on internal control system design such as limiters and non-linearities. These must be modeled extremely accurately.
- Results depend on active and reactive power generation levels.
- Some wind turbines may not be stable for harmonic voltage injection and not be able to produce stable impedance curves.
- Dynamic scans are mostly done with positive sequence harmonic injection and some detailed models show completely different results with negative sequence harmonic injection as well as d-q domain harmonic injection.

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.



Unstable SSCI



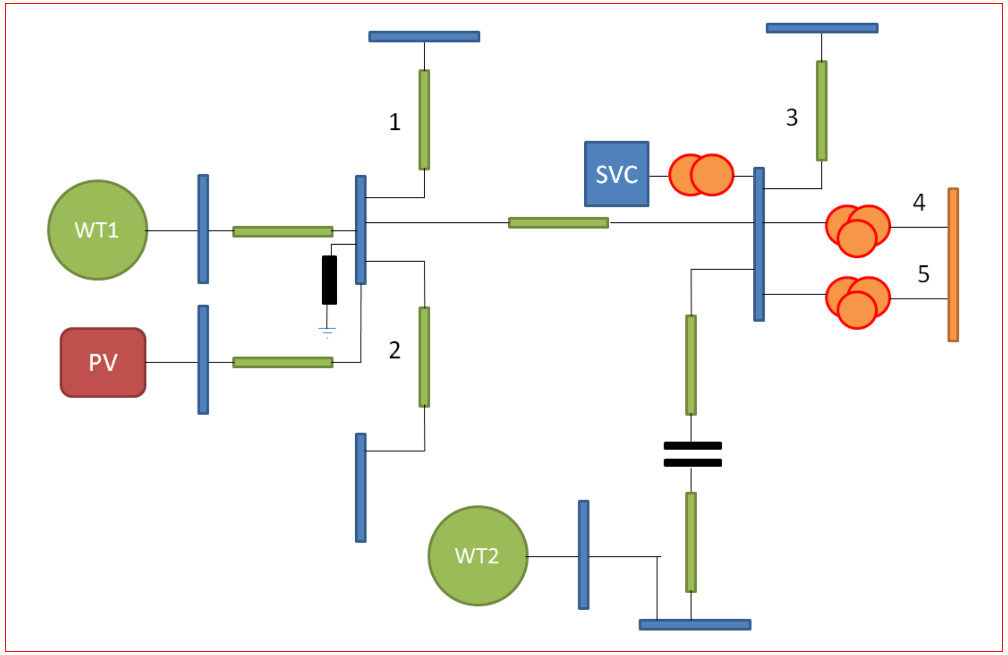
Unstable SSCI

EMT Type Detailed Studies and Modeling

- An EMT case is created that correctly represents the frequency dependency of the system.
- All cases identified as "high risk" in screening are run in the full detailed PSCAD model of the system.
- Additional notes:
  - Transformers should have saturation enabled (time domain simulations). Transformer saturation effects can impact post fault recovery and instigate resonance issues.
  - Series capacitors with MOVs and bypass logics should be modeled in detail.
  - Transmission lines should include frequency dependency

EMT Type Detailed Studies and Modeling

- **Important point!!** It is useful to check performance when only the plant of interest is in operation, as well as when all the nearby generation is in operation. More generation in the system may **shift the sub-synchronous frequency** to higher frequencies. Most wind turbines show higher negative damping at higher frequencies.

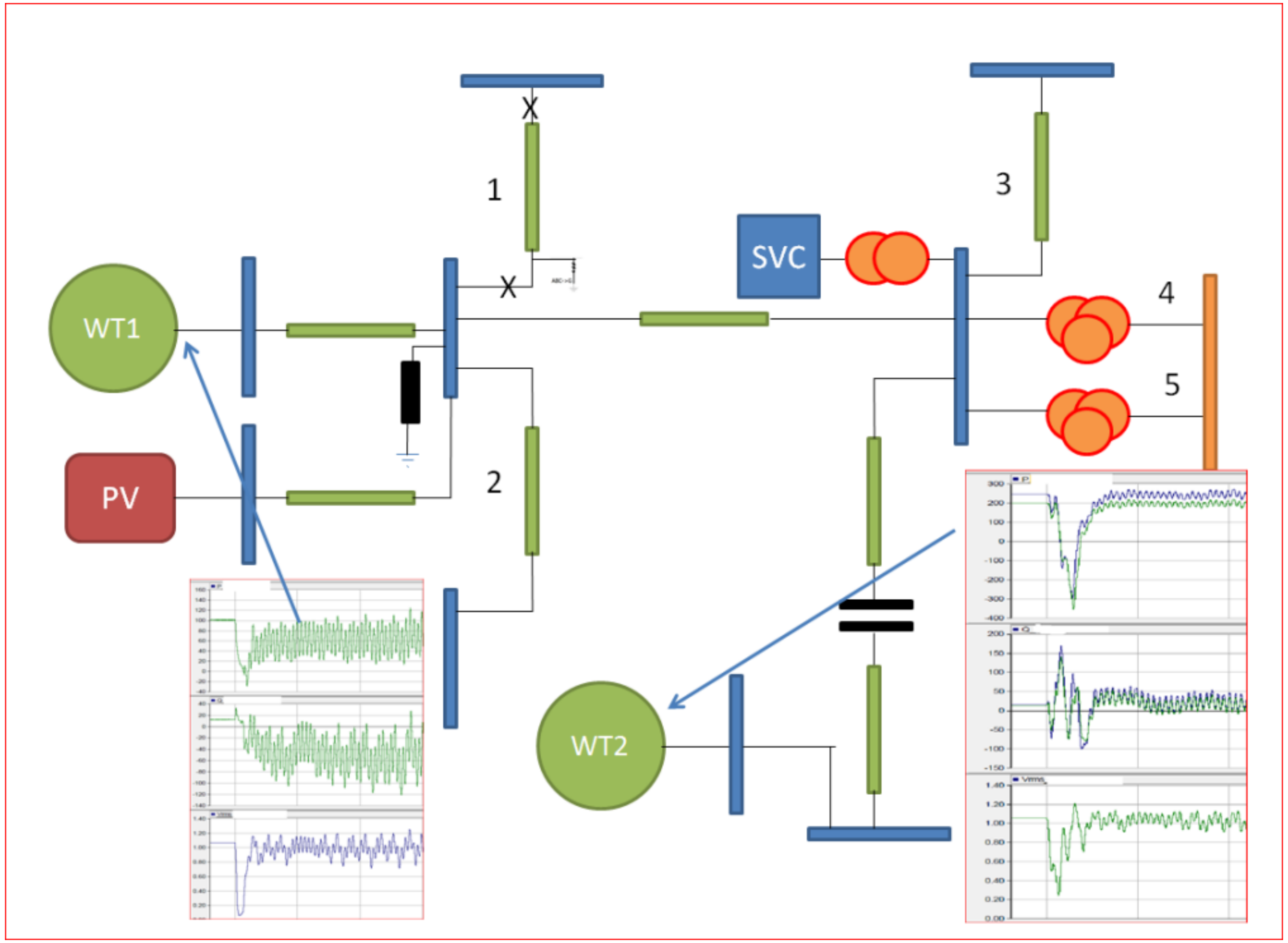


$$f_r = \frac{1}{2\pi\sqrt{LC}} \text{ (Hz)}$$

- ❑ Combined resonance frequency with WT1 only in service : 22 Hz -> SSCI Stable
- ❑ Combined resonance frequency with All nearby plants in service: 36 Hz -> SSCI Unstable

EMT Type Detailed Studies and Modeling

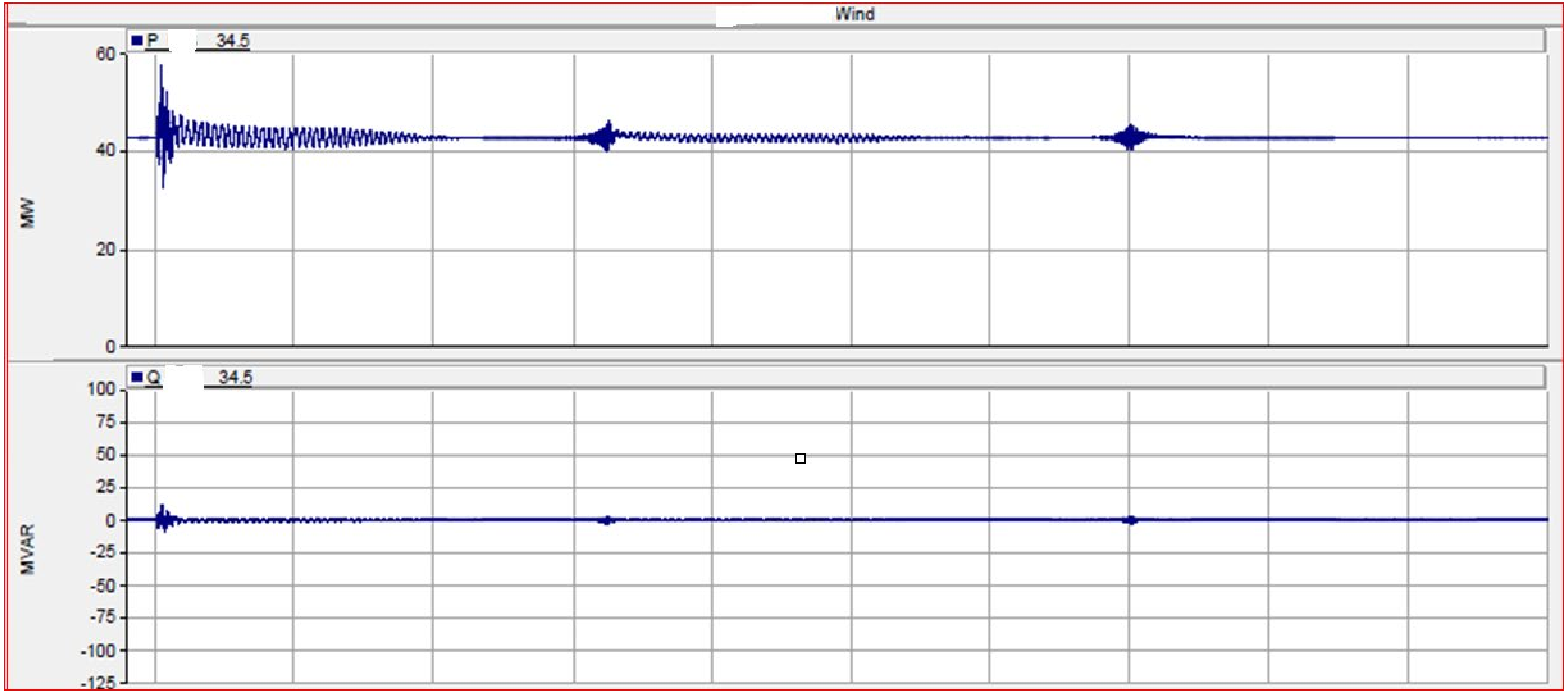
- Detailed models of nearby wind, solar, SVCs, STATCOM and HVDC etc are required (both sides of the series capacitor)



Sensitivities of Detailed Studies

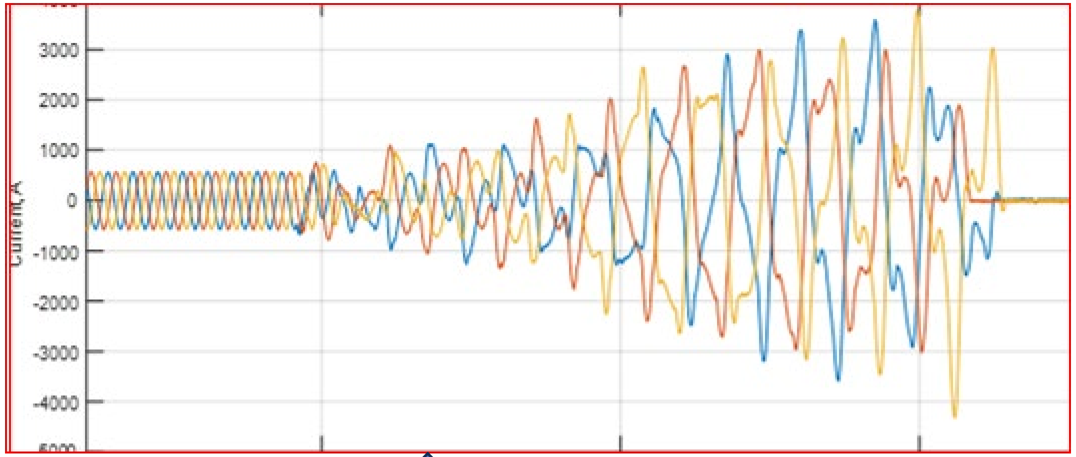
- Sensitivities studies may be necessary with nearby switched shunts on and off.
- Sensitivity studies may be necessary with nearby conventional generators turned on and off. These machines change system resonant conditions and may add damping.
- A check is required for close in and remote 1ph and 3ph faults.
- A check is required for line opening conditions with no fault.
- A check is required for full and partial generating cases with 100% turbines in operation.
- A check is required at unity, capacitive and inductive reactive power generation operating conditions.

Damping controller enabled/disabled?

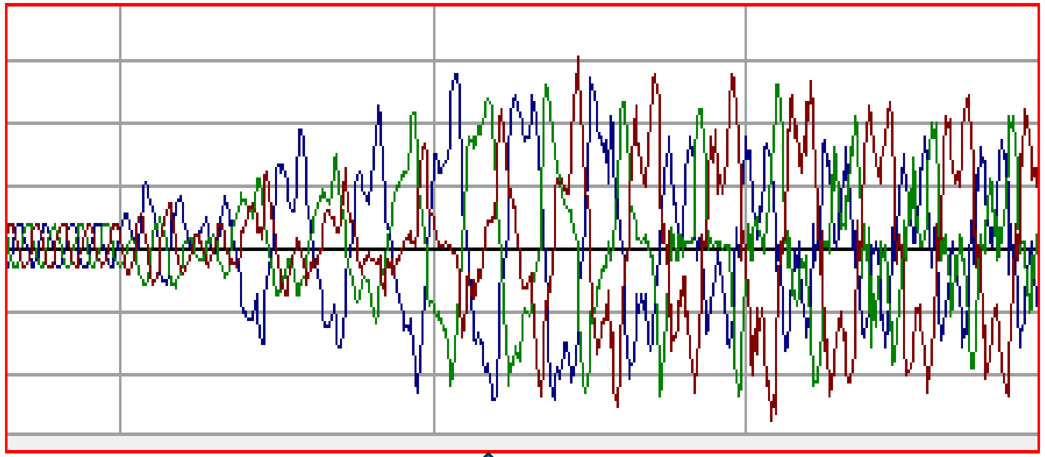


Sub Synchronous Ferro Resonance (SSFR)

- A saturating 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.



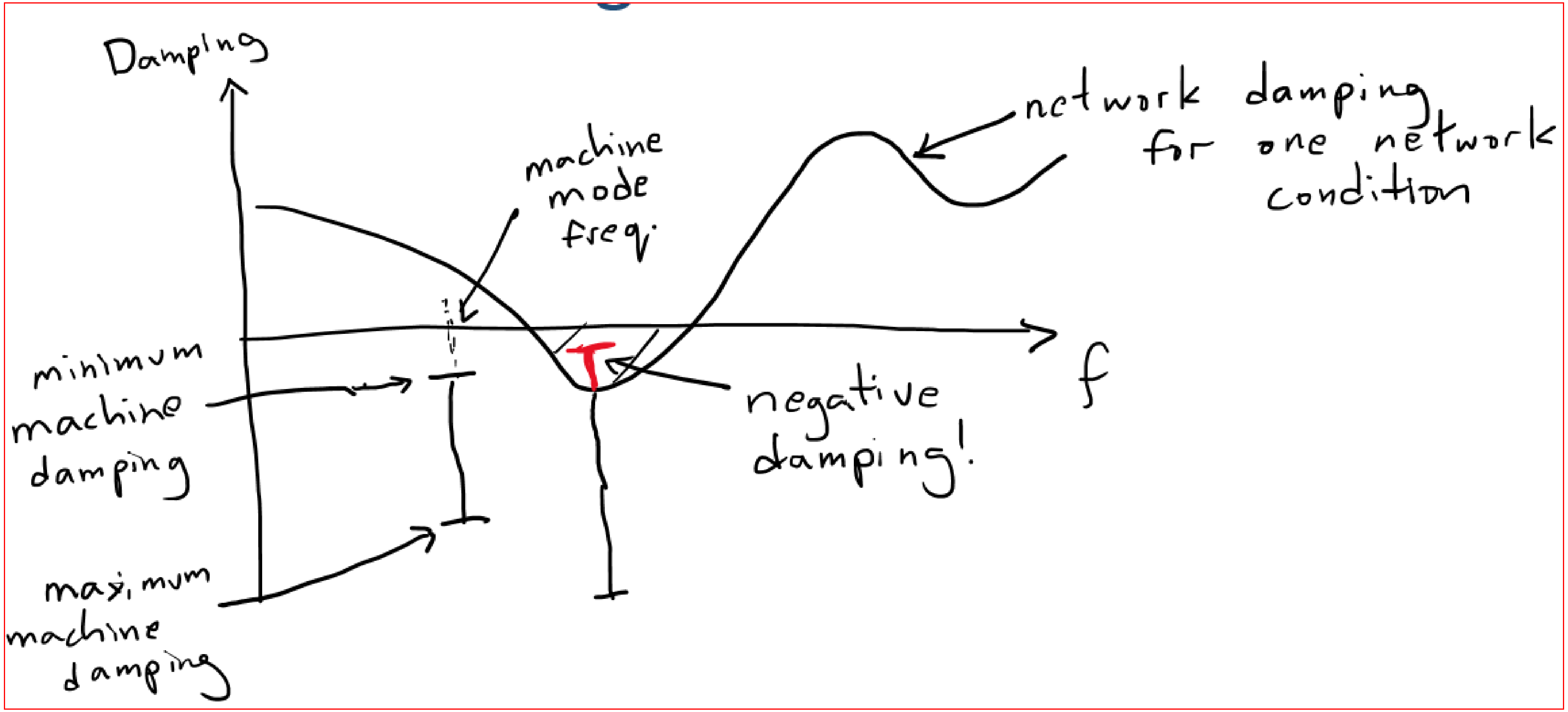
Field Measurement


PSCAD Simulation

ERCOT SSFR process

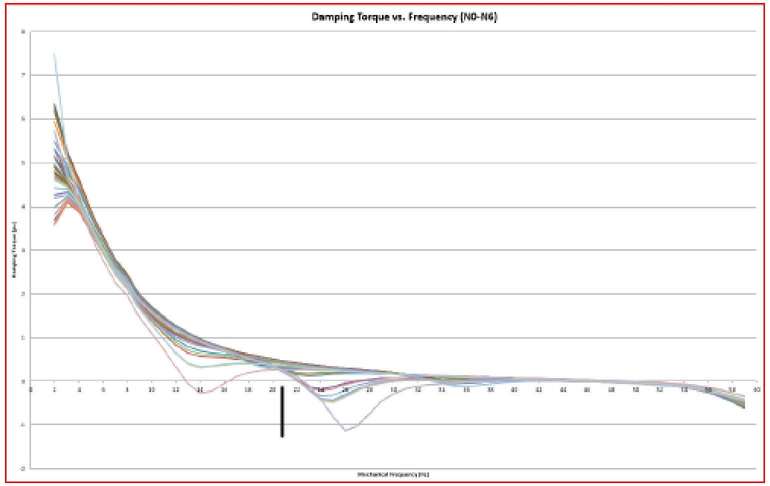
- SSFR is treated as a power quality issue, and isolating the plant using an SSFR detection relay is an acceptable approach.
- SSFR issues should be identified through detailed EMT studies, and additional vulnerable SSFR scenarios, such as the plant inverter being offline and transformers being in service, may need to be considered.
- An SSFR detection relay can be tuned and tested by recording voltage and current waveforms in COMTRADE format and playing back into the SSFR detection relay. This ensures that the relay operates during oscillations, and does not operate when the oscillations are damped.
- SSFR relay parameters should be customized to site specific conditions.

Understanding SSR/SSTI Results Plots



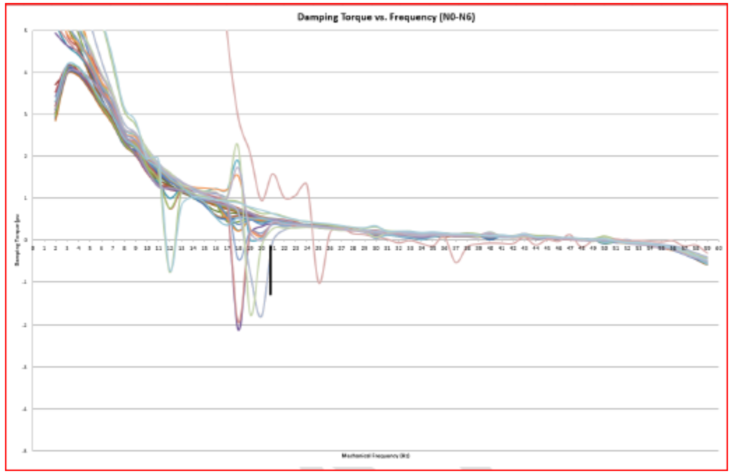
Sub-Synchronous Torsional Interaction (SSTI)

- SSTI needs to be checked when connecting wind/solar near existing thermal plants.
- Generally, IBR with better SS performance improves SSTI and vice versa.
- Typical perturbation analysis at thermal plant is not enough for SSTI analysis with nearby IBR. Detailed time domain study is required with multi-mass models to capture non-linearities of IBR.



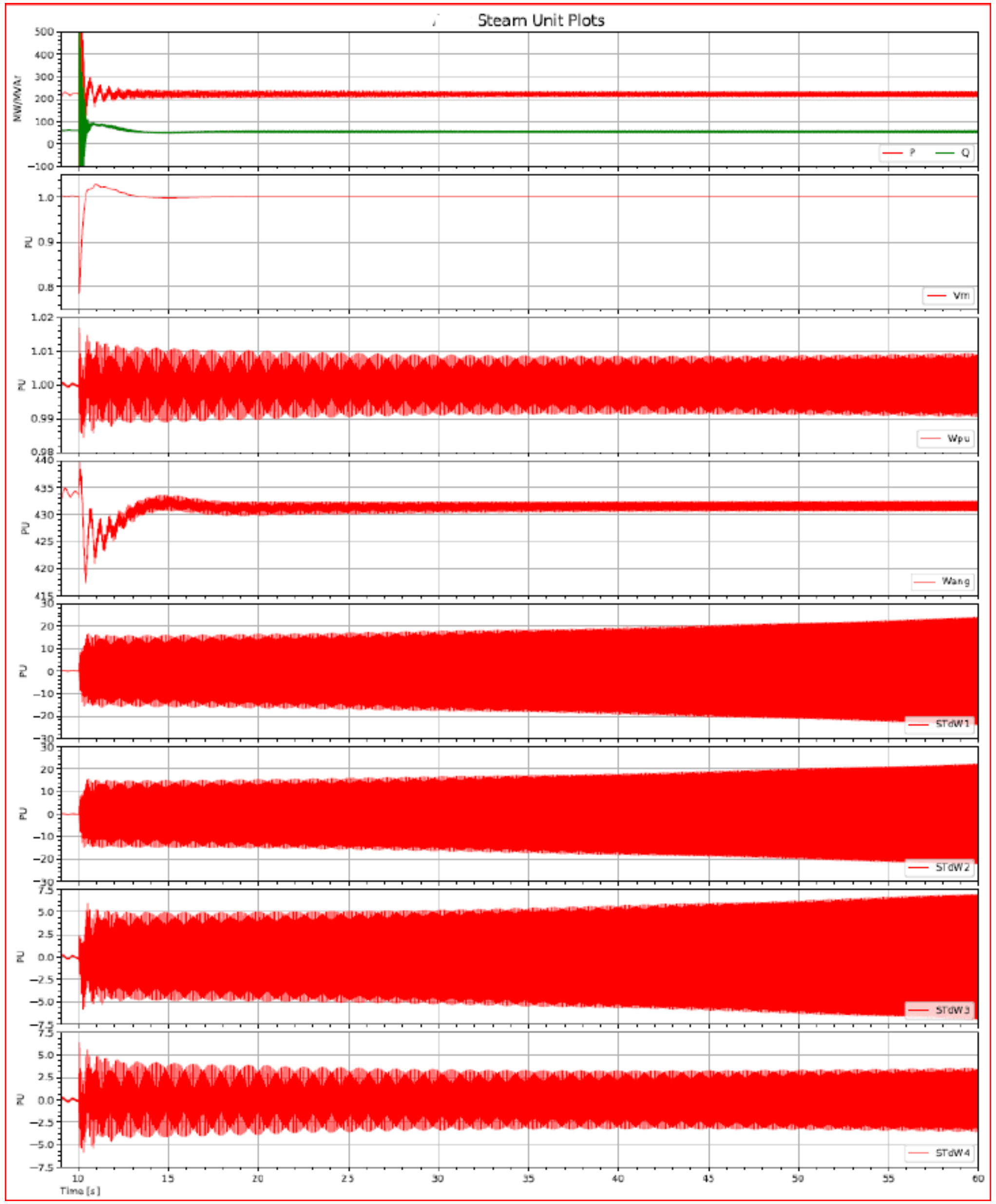
Synchronous generator Damping plots with IBR is not in service

generator Damping plots with IBR is in service



Example plot of SSTI with IBR integration:

- SSTI due to multiple IBR integration at combined cycles plant.
- IBR shows unstable SS performance

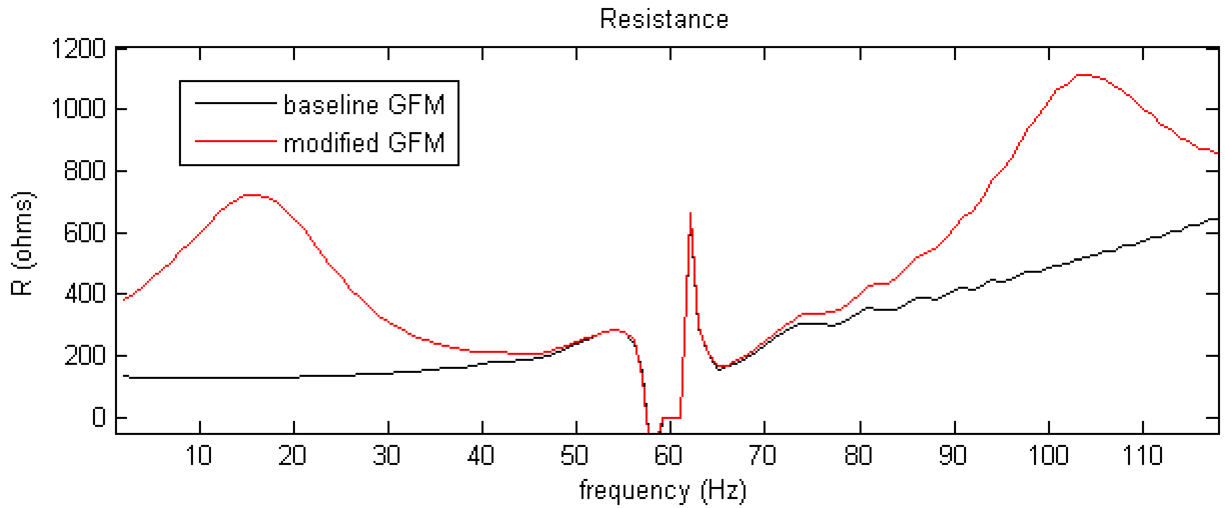


SSCI/SSR/SSTI/SSFR Mitigation and prevention

- Select sites electrically away from Series Capacitors
- Add SS damping controller or control parameter tuning of IBR.
- Bypass Series Capacitor (may not be allowed) – RAS Schemes.
- Select series compensation level to avoid problems.
- Select turbines with minimal SSCI issues.
- Add shunt compensation with stabilizers (SVC/STATCOM) ?
- Series capacitor bypass filters.
- Synchronous generator torsional blocking filters
- **Grid forming BESS**
- Protection :
  - ❑ SSCI detection relays at POI and series capacitor terminal for SSCI and SSFR
  - ❑ Torsional Stress Relay (TSR) at synchronous generators for SSR and SSTI

GFM provides system damping, including SSCI

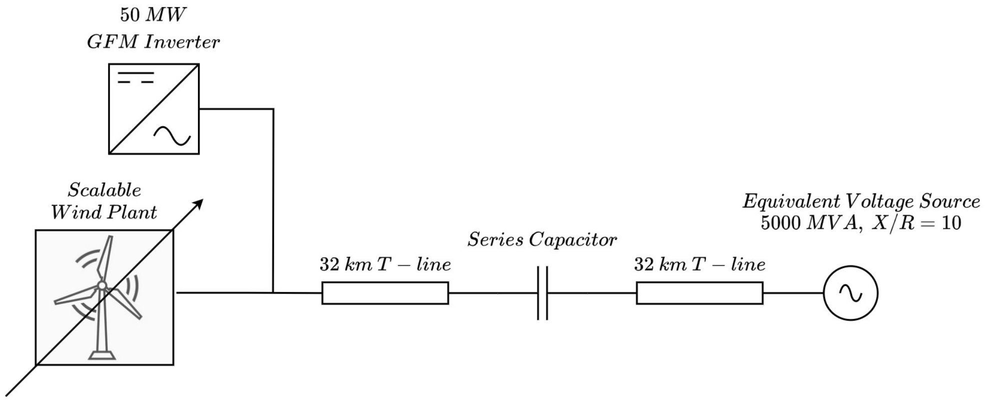
- GFM generally provides positive system damping in sub-synchronous frequency range
- Minor control changes (e.g. virtual impedance) can increase damping impact

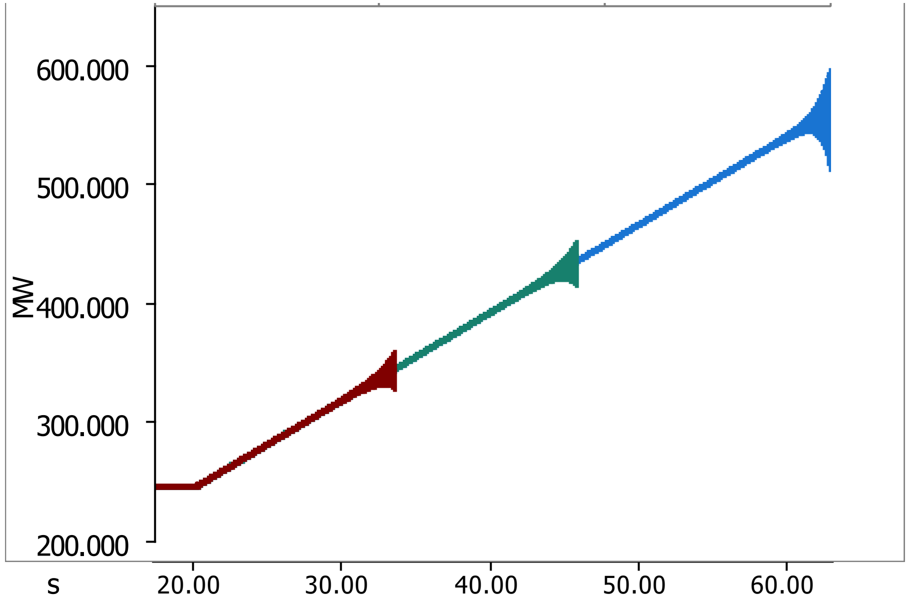


Credit: Research effort by Lukas Unruh – standby for paper or contact lu@electranix.com

Power system damping, including SSCI

- Research example shows GFM stability benefits in series compensated system with Type 3 Wind Plant
- Stable limit of Wind Plant MW output increased by 200 MW with addition of 50 MW GFM
- Relatively small amount of GFM may provide substantial stability benefits





Thank You!

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