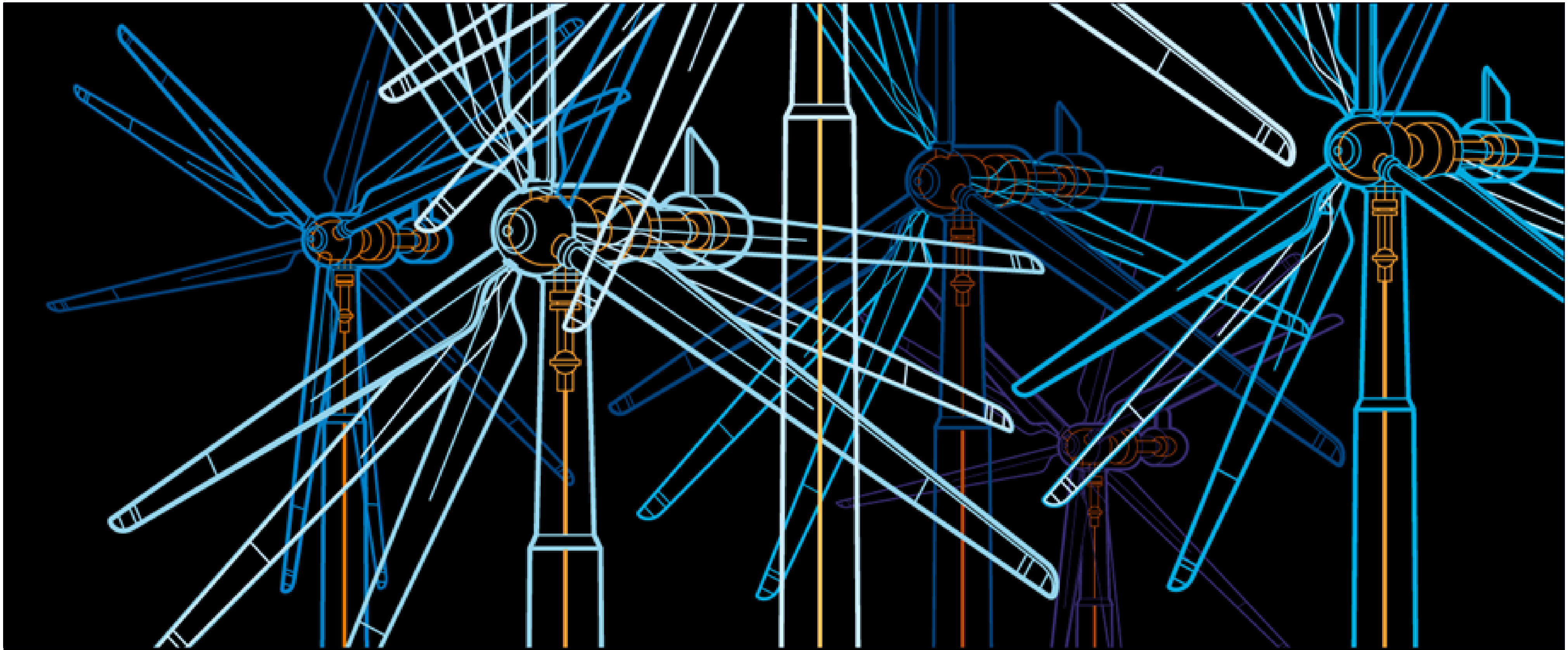
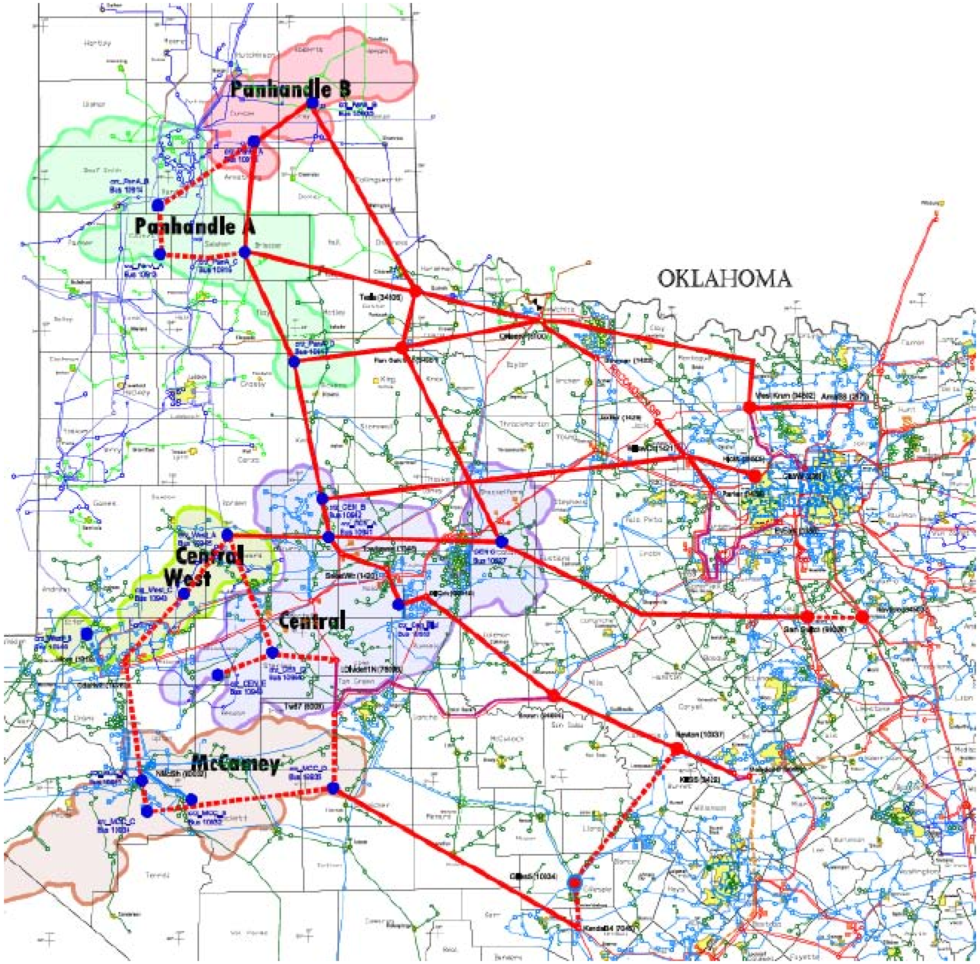


Willie Wong / John Daniel, Grid Systems Consulting / Austin, Texas, March 12, 2010

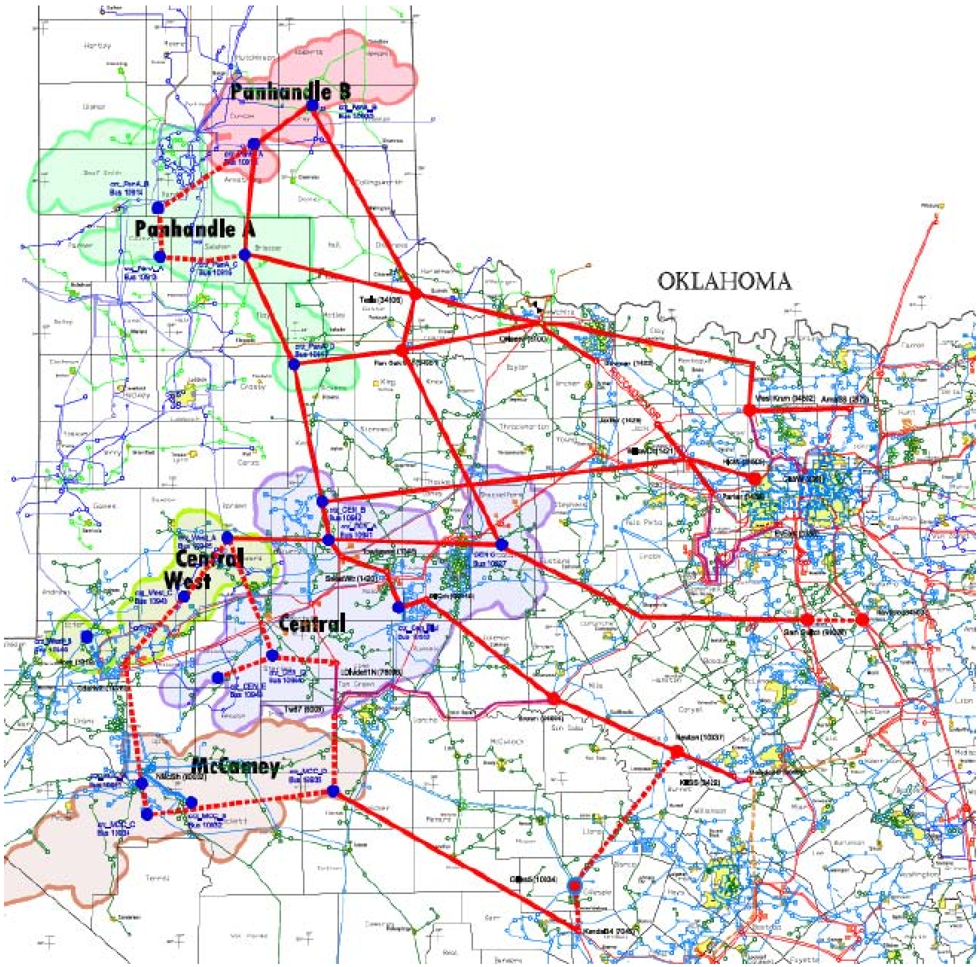
ERCOT CREZ Reactive Study
ERCOT RPG Meeting

ERCOT CREZ Reactive Study Overview



- A large-scale, complex study to determine the reactive compensation needs for the CREZ transmission to bring wind energy from West Texas to the eastern load centers.
- Both shunt and series reactive compensation needs are being considered
- Ambitious goals and schedule
- Excellent support being received from ERCOT and the TSPs

ERCOT CREZ Reactive Study Overview



Four (4) basic study categories

1) Reactive Compensation Requirements – series and shunt compensation
2) Subsynchronous Interactions (SSI) between wind generation and reactive compensation
3) SSI between thermal generation reactive compensation
4) Equipment Specifications

ERCOT CREZ Reactive Study
1) Reactive Compensation Requirements

- **Purpose:** Determine shunt and series reactive compensation needs for optimal economics and power transmission
- **Critical Results to Date:**

  Steady-State analysis of a Maximum Export scenario shows

  - A minimum of about 800 Mvar additional shunt compensation around Riley is required to meet voltage stability requirements following critical contingencies (typically double circuit outages).
  - Increases in series compensation are not cost-effective in reducing those requirements, but a substation at Clear Crossing would help.
  - Reductions in series compensation levels lead to large increases in additional shunt compensation requirements and in the number of critical contingencies.
  - System stress is dependent on wind generation assumptions. An additional scenario, with similar wind generation levels, but stressing the southern part of CREZ, is being investigated.

ERCOT CREZ Reactive Study
1) Reactive Compensation Requirements

- **Work in Progress:**
  - Completion of steady-state analyses of maximum export scenarios with development of overall compensation strategy.
  - Study of minimum export and peak load scenarios, which are likely to provide insight on inductive compensation requirements.
  - Setup of dynamic model, with existing and future wind generation, and load dynamics.
- **Future Work:**
  - Dynamic Studies. Development of a series and shunt compensation strategy that will meet both steady-state and dynamic needs.
- **Challenges:**
  - Complexity of study (multiple scenarios, series vs. shunt compensation, passive vs. active, etc.)
  - Enormous amounts of data
  - Additional scope being identified as study progresses

ERCOT CREZ Reactive Study
2) Subsynchronous Interactions with Wind Farms

- **Purpose:** identify issues related to SSI between wind farms and series compensation
- **Critical Results to Date:**
  - Evaluations for WTGs on worst case *radial* system
  - Simulations have shown self-excitation for series compensated radial systems with low resistance
  - Self-excitation is theoretically possible for three types of WTGs
  - DFIG types have severe SSI control interaction with series compensated radial systems
  - Studied bypass filter configuration damped out the self-excitation but did not fully eliminate SSI control interaction for DFIG WTGs in simulations on radial system
  - Thyristor controlled series capacitors eliminated all SSI and self-excitation for radial system

ERCOT CREZ Reactive Study
2) Subsynchronous Interactions with Wind Farms

- **Work in Progress:**
  - Developing the full CREZ system in PSCAD to evaluate SSI on full network
- **Future Work:**
  - Simulations of all four types of WTGs on the full system to more fully evaluate SSI potential
  - Simulations of Bypass Filters or Thyristor Controlled Series Capacitors for locations where SSI mitigation needed
- **Challenges:**
  - Industry only beginning to fully appreciate and understand the phenomena involved

ERCOT CREZ Reactive Study
3) SSI with Thermal Generation

- **Purpose:** identify issues related to SSI between thermal generation and reactive compensation
- **Critical Results to Date:**
  - Preliminary subsynchronous resonance (SSR) evaluations completed for four (4) of six (6) thermal plants identified – Comanche Peak, Tradinghouse Creek, Willow Creek, Oklaunion
  - First three units have initial indications** of SSR with as little as four (4) lines out of service
  - Oklaunion has initial indications** of SSR with as little as two (2) lines out of service
  - Evaluations of mechanical torsional modes at Oklaunion and Willow Creek highlights concern for some but not all torsional modes

** - *not necessarily a problem*

ERCOT CREZ Reactive Study
3) SSI with Thermal Generation

- **Work in Progress:**
  - Verifying torsional modes of concern for Tradinghouse Creek
  - Obtaining torsional data for Comanche Peak
- **Future Work:**
  - Refine SSR evaluations for four completed units
  - Perform SSR evaluations for Hays and Odessa-Ector
  - Perform Subsynchronous Interaction evaluations for active shunt compensation (e.g. SVC) and nearby thermal units (requires completion of reactive compensation requirements)
- **Challenges:**
  - Difficult to obtain machine torsional data. Plant owners, TSPs and ERCOT have been very helpful in approaching manufacturers.

ERCOT CREZ Reactive Study
4) Equipment Specifications

- **Purpose:** Identify steady-state and dynamic requirements for the reactive equipment including any requirements related to SSI mitigation
- **Critical Results to Date:**
  - The steady-state requirements have been documented in the reactive power study
  - A report discussing line voltage profiles for series compensation has been delivered
  - The potential impact of SSI has been identified and potential solutions evaluated
- **Work in Progress:**
  - The study for the dynamic requirements is underway
  - Study of SSI impact on the full system has been started

ERCOT CREZ Reactive Study
4) Equipment Specifications

- **Future Work:**
  - Complete evaluation for shunt capacitors and reactors requirements
  - Complete evaluation and specifications for series capacitors
  - Perform evaluation and specifications for SVC, Statcoms and synchronous condensers.

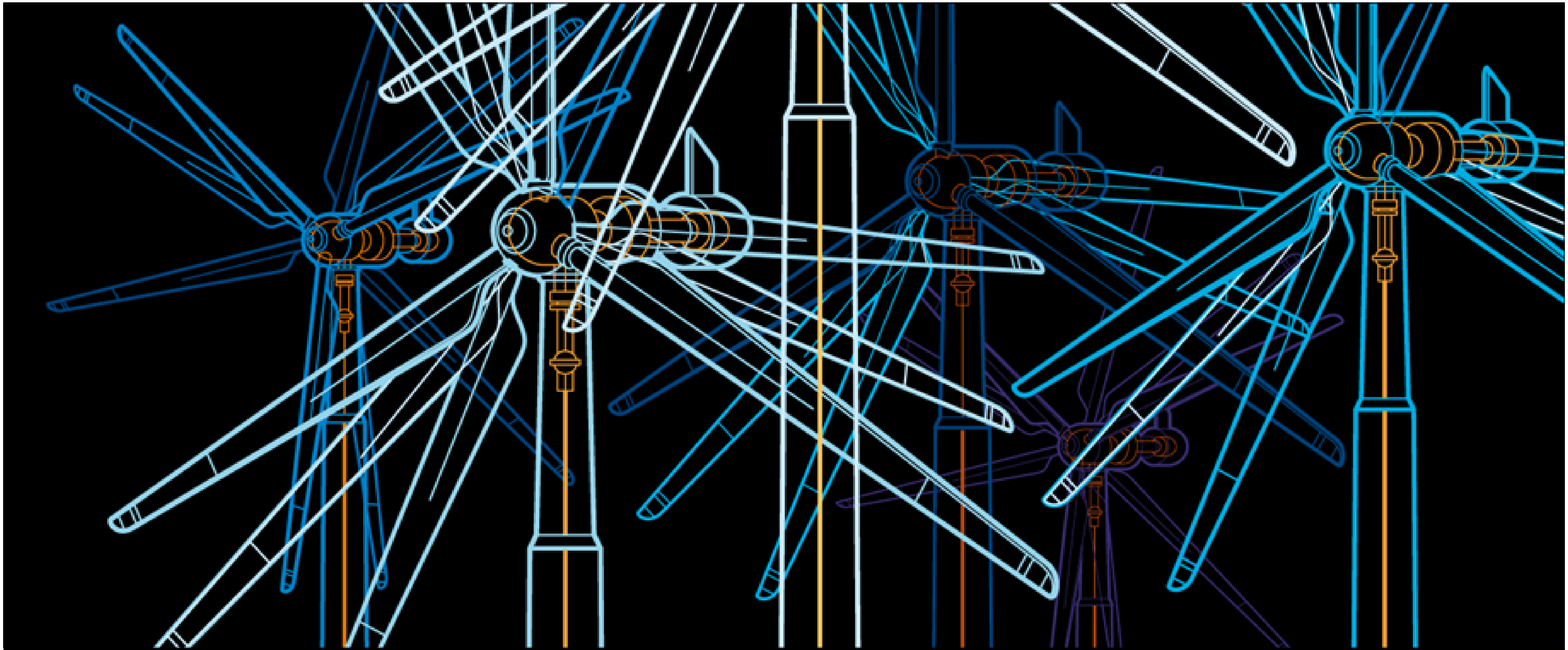
- **Challenges:**
  - Obtaining all data and study results in a timely manner to finalize an optimum solution

ERCOT CREZ Reactive Study Deliverables

- Report providing
  - Recommendations for reactive compensation levels
    - Shunt and series compensation
    - Switched, fixed or active
  - Discussion of potential SSI issues for wind plants and thermal units
  - Discussion of possible SSI mitigation methods
  - Equipment functional requirements

ERCOT CREZ Reactive Study Conclusions

- The study is large scale and complex with ambitious goals and schedule.
- Involves a large number of stake holders that provide many good but often diverse ideas and opinions.
- Extensive amounts of data are needed and must be correlated. It can be challenging to obtain in a timely manner.
- Study results are rapidly increasing our understanding of reactive needs and their impact on the system and equipment
- Data issues have caused some delays in the study schedule.
- A major concern is that the data and criteria used to draw conclusions are acceptable to all stakeholders.



Don Martin/John Daniel, Grid Systems Consulting / Austin, Texas, March 12, 2010

ERCOT CREZ Reactive Study
RPG SSI Discussion

Subsynchronous Interactions

- IEEE defines several terms** associated with subsynchronous phenomena (for synchronous machines)
- Most generic term is Subsynchronous Oscillations (SSO)
- Common usage and recent experience has resulted in additional terms
- We have discussed it generally as subsynchronous interactions (SSI) because the oscillations can be caused be multiple types of interactions

** IEEE SSR Working Group, "Terms, Definition and Symbols for Subsynchronous Oscillations," IEEE Trans., v. PAS-104, June 1985

- Subsynchronous Oscillations (SSO)
  - Subsynchronous Resonance
    - Self-excitation
      - Torsional Interaction
      - Induction Generator Effect
  - Device Dependent SSO
    - PSS Interactions
    - Subsynchronous Torsional Interactions (SSTI)
      - HVDC
      - SVC
      - Statcom
      - etc.
    - Subsynchronous Control Instability (SSCI) of WTGs

Subsynchronous Interaction Evaluations

- Wind Turbine Generators
  - Self-excitation – potential induction generator effect
  - Control interactions (SSCI) – potential control instability due to interaction with series compensated line resonance
- Thermal Generators
  - SSR – potential torsional interactions between turbine generator mechanical modes and series compensated lines
  - Self-excitation – potential Induction generator effect
  - SSTI – potential destabilization of mechanical modes by control operation of active devices (SVC, Statcom, etc.)

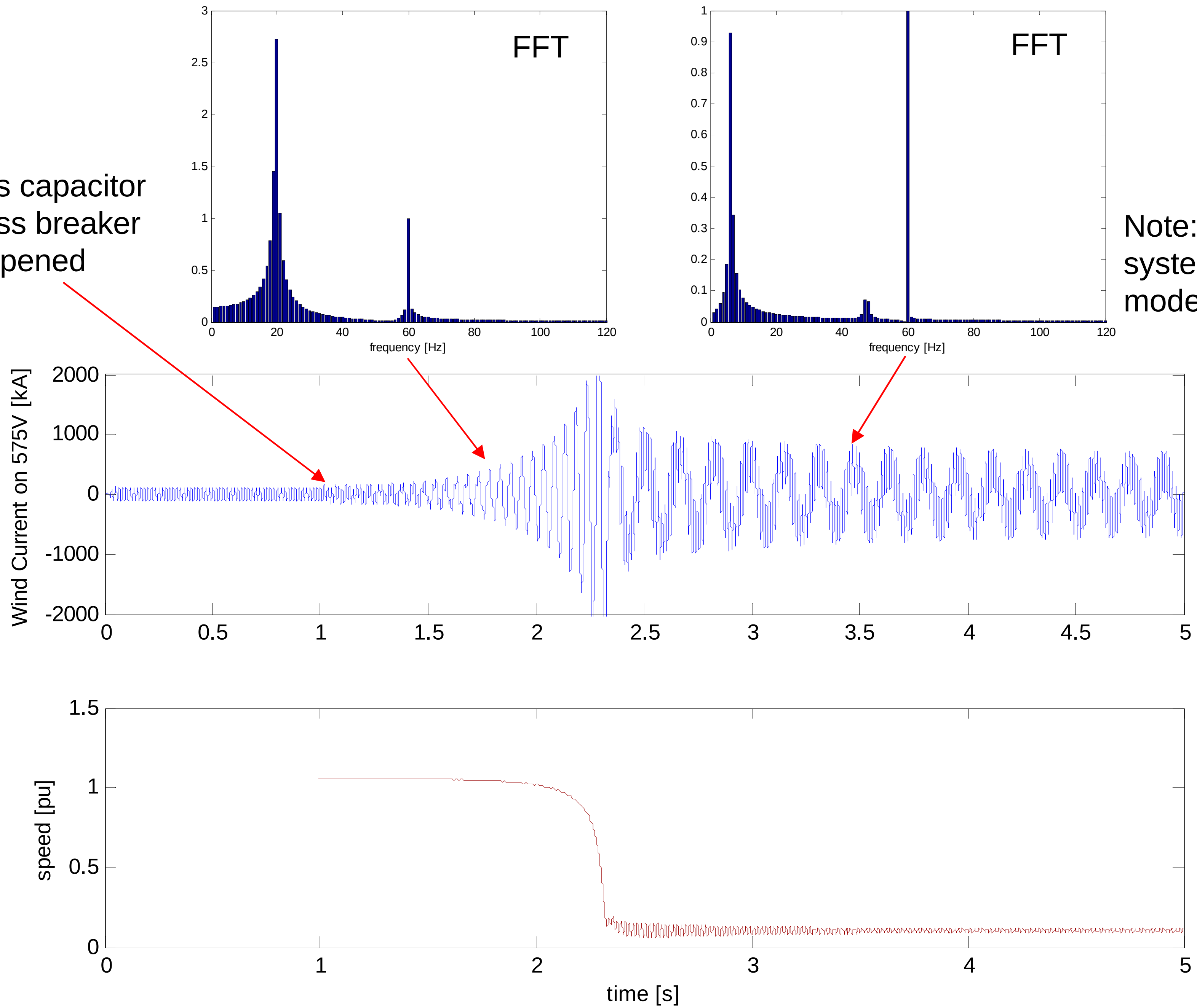
WTG: Self-Excitation

- Similar to well described self-excitation of induction machines when using series capacitors on the stator terminals.
- ABB first noted the potential for self-excitation of wind turbine generators connected to series compensated transmission in 2003 paper [1]
- Self-excitation can result in two conditions.
  - Stable machine operation at a low subsynchronous frequency (speed)
  - A classical induction generator effect (IGE) at a higher subsynchronous frequency

[1] "Integration of Large Wind Farms into Utility Grids" (see part 2 - performance issues) by Pourbeik, P., Koessler, R.J., Dickmander, D.L., Wong, W., IEEE Power Engineering Society General Meeting, 2003, Publication Date: 13-17 July 2003, Volume: 3, page: 1525

WTG: Self-Excitation - asynchronous machine (type 1), 100MW farm

Series capacitor bypass breaker opened



Note: protection systems not modeled.

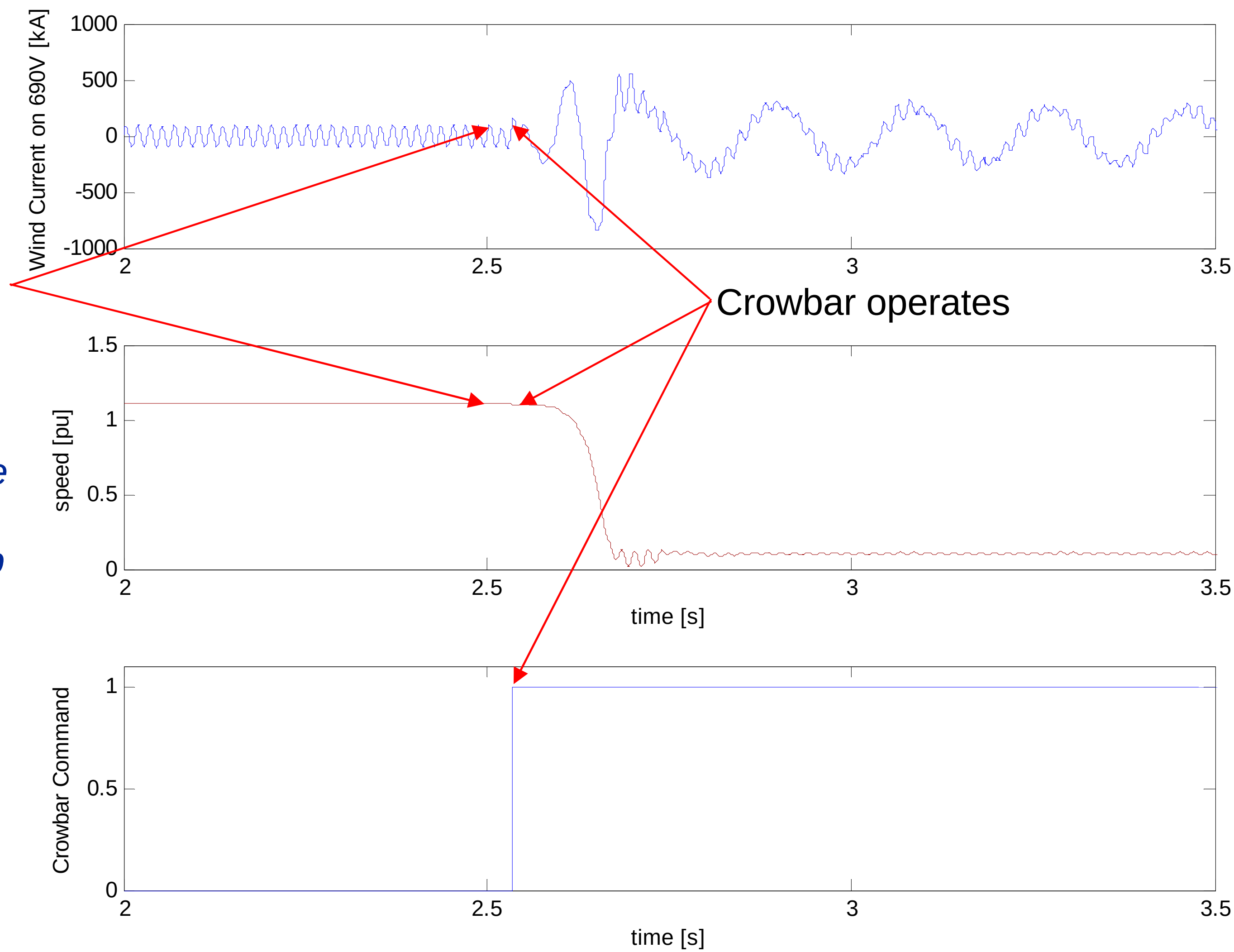
WTG: Self-Excitation

- IGE becomes less damped (more likely) for larger rotor resistances and/or smaller network losses.
- Theoretically possible for
  - Type 1 WTGs (fixed speed asynchronous generators)
  - Type 2 WTGs (variable speed asynchronous generators)
  - Type 3 WTGs (DFIG) under crowbar action
- Difficult to have sufficient system losses to provide positive damping with
  - Type 2 with external rotor resistance above 0Ω
  - Type 3 with typical crowbar resistances

WTG: Control Interactions - Type 3, 100MW farm

Protection systems disabled to emphasize response when <u>crowbar</u> is active

Series capacitor bypass breaker opened

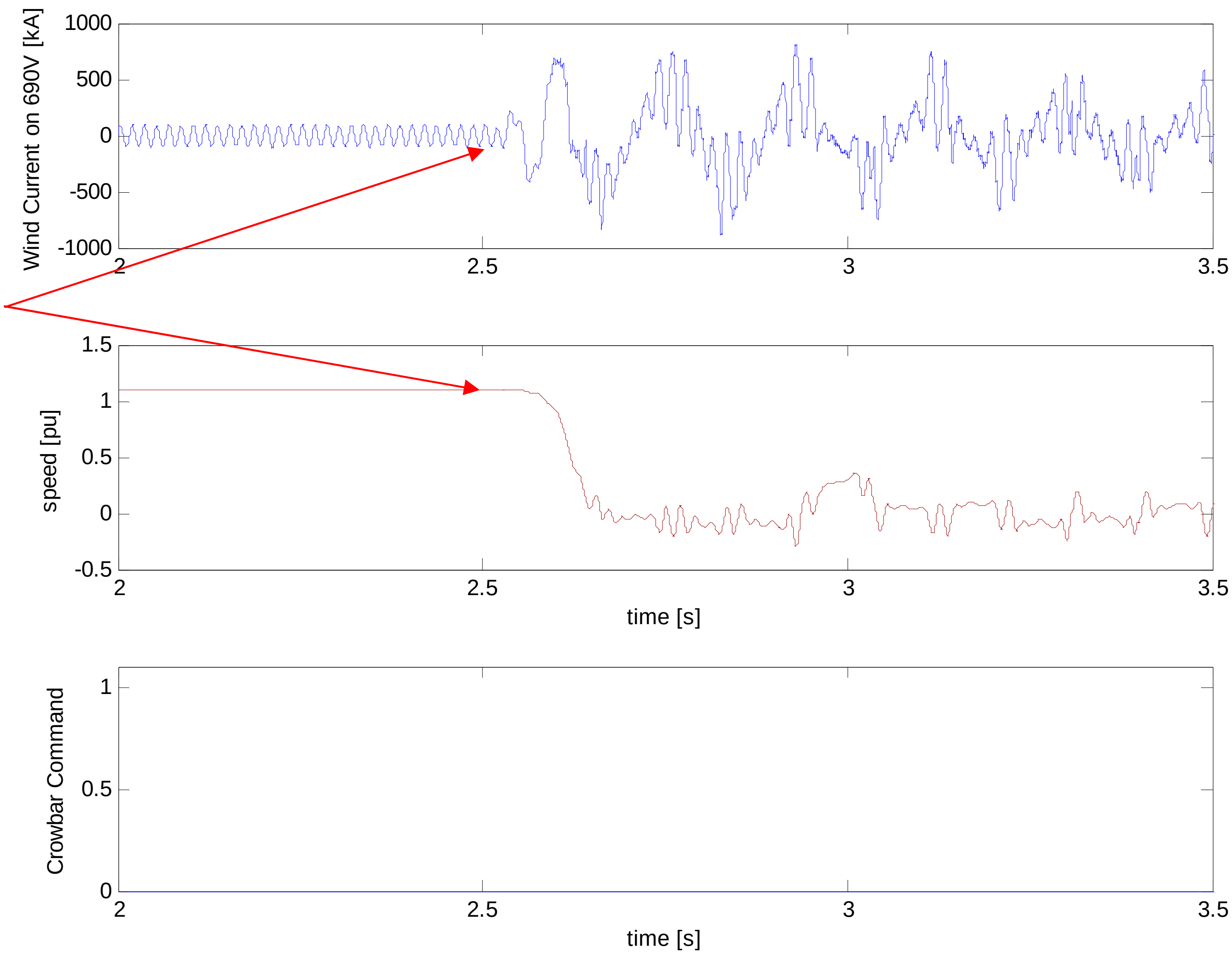


Other issues are likely to cause protection to trip WTGs or farm

WTG: Control Interactions - Type 3, 100MW farm

Artificial Case - protection systems and converter crowbar disabled to emphasize control response to conditions

Series capacitor bypass breaker opened



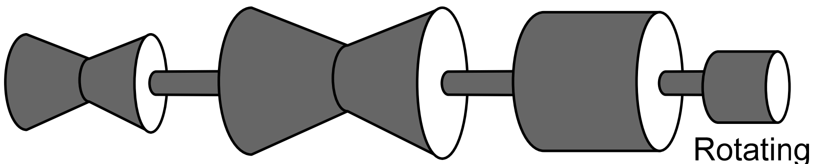
WTG: Control Interactions

- Type 3 WTGs appear susceptible to control interactions when radially connected to series compensated transmission lines (10% to 70% compensation)
- Radial connection may occur either by design or due to contingency event
- SSI may be due to
  - WTG controls interacting with series compensation
  - Crowbar action initiating self-excitation
- Manufacturers may be able to adjust controls to help address response to SSI conditions
- System level mitigation device may also be applied

Thermal Generation: Subsynchronous Resonance

CONCERN

Destabilizing mechanical torsional modes of thermal generation

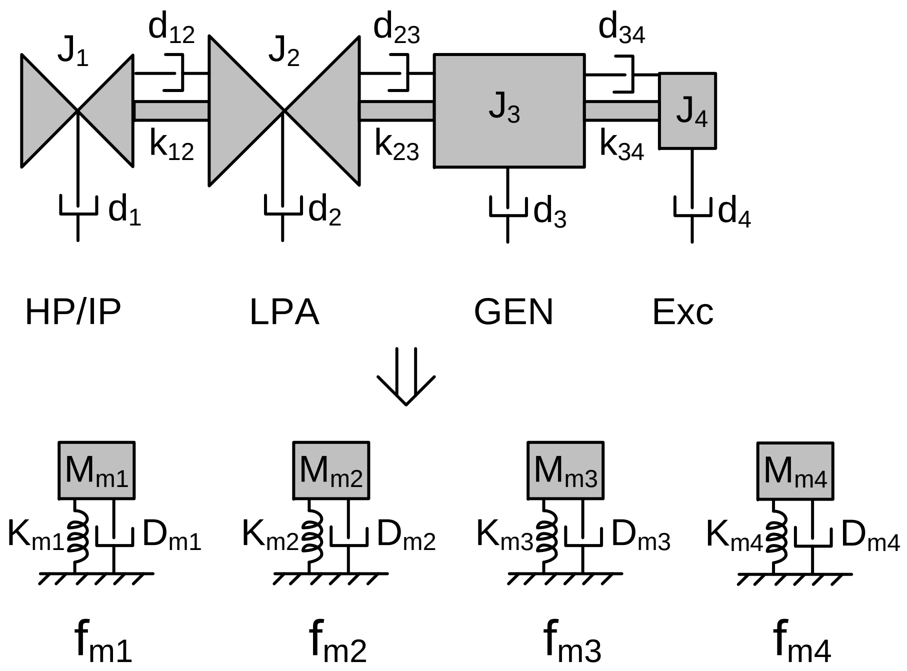


- The machine's mechanical system can be represented as a series of large lumped masses connected by shafts.
- A system perturbation will cause the masses to "swing against" each other – accelerated and decelerate in an oscillatory manner – and at multiple frequencies
- This stresses the shaft between the masses as its "spring" acts to pull them back together.

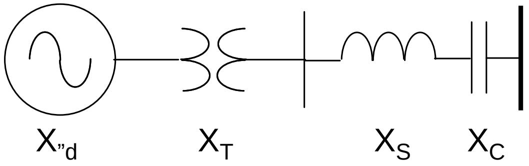
Thermal Generation: Subsynchronous Resonance

- Modes can be mathematically decoupled and evaluated independently
- N masses result in N-1 oscillatory mechanical modes with different frequencies of oscillation. Many will be below synchronous speed.
- Inherent mechanical damping – due to materials and steam damping – will be positive.
- Mechanical oscillations will result in network current components at f_0-f_{mi} and f_0+f_{mi}

  (f_0 = 60 Hz)

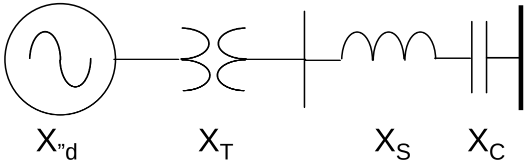


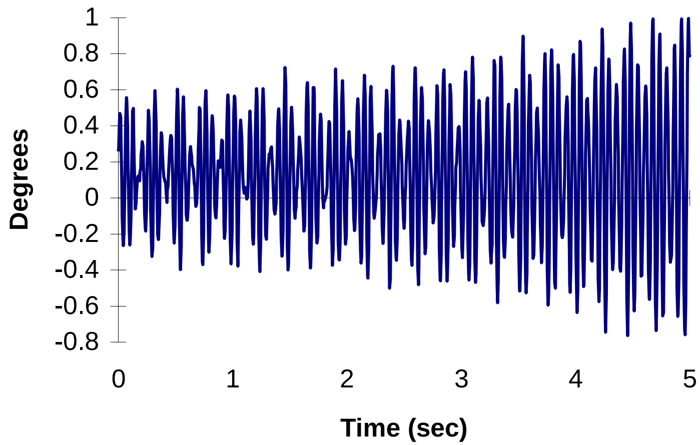
Thermal Generation: Subsynchronous Resonance



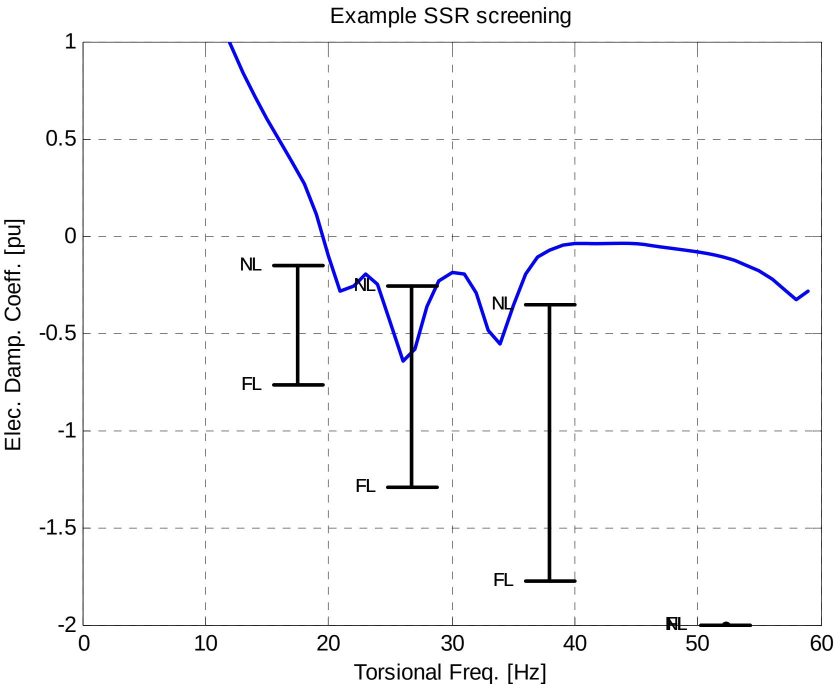
- A series compensated line will create an electrical resonance
- Because $X_C < X_S$, the resonant frequency is always subsynchronous
- If resonance frequency matches frequency of currents created by a mechanical mode oscillation, the resulting electrical damping by the system on that mode may be negative.

Thermal Generation: Subsynchronous Resonance

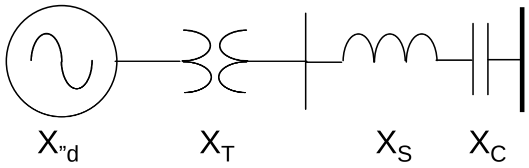




- If total damping – mechanical + electrical – is negative, the mode is unstable and will grow
- Screening investigations are possible to determine if more detailed evaluations or protection are warranted



Thermal Generation: Subsynchronous Resonance



- Outages, nearby machines and the amount of series compensation can effect potential for detrimental response.
- If not addressed, SSR can result in expensive damage to the turbine-generator shafts.

Plants being evaluated for SSR

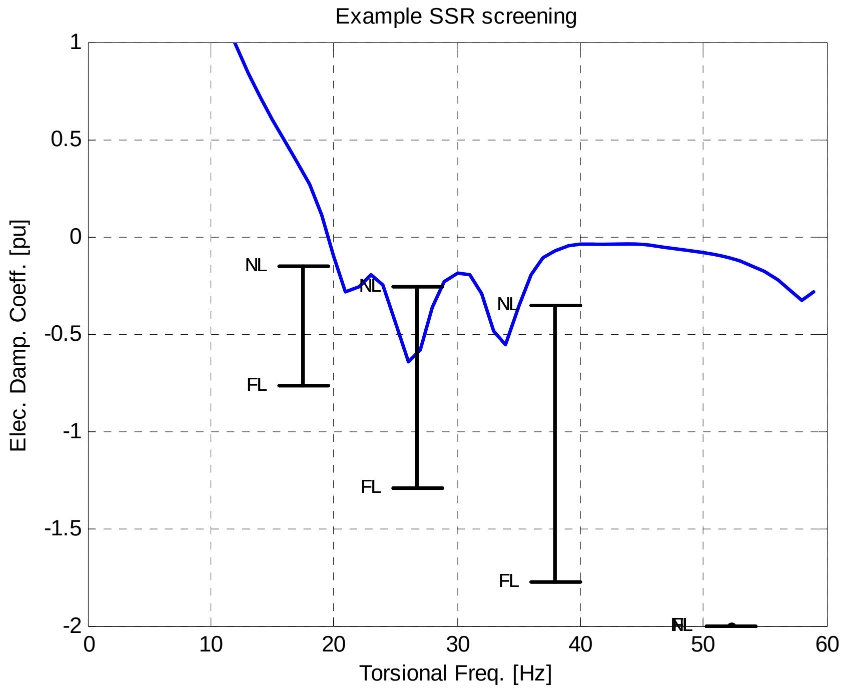
- Comanche Peak
- Tradinghouse Creek
- Willow Creek
- Oklaunion

Additional plants to be evaluated

- Hays
- Odessa-Ector

Thermal Generation: Subsynchronous Resonance

- SSR Screening process
  - Calculate impedance of network from behind the studied generator looking out into the system for frequencies from 0 to 120Hz
  - Interpret the results from the rotor reference frame
  - Compare to (negative) modal mechanical damping
  - Repeat for other outages, equipment service status and series compensation level
- Original frequency scans are also good for evaluating potential induction generator effect on thermal units



Thermal Generation: Subsynchronous Resonance

Screening results to date indicate that:

- Comanche Peak, Tradinghouse Creek and Willow Creek may begin to see initial indications** of SSR with 4 or more outages.
- Oklaunion has initial indications** with 2 or more outages
- Evaluations of torsional modes at Oklaunion and Willow Creek highlight concern for some but not all torsional modes.
- Torsional modes are being checked at other plants to verify whether resonances may be an issue.

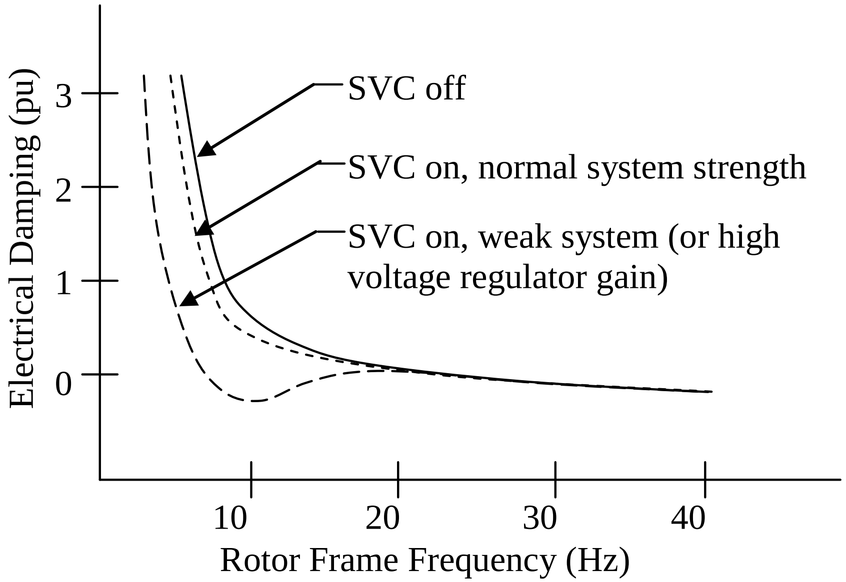
** - not necessarily a problem

Thermal Generation: Induction Generator Effects

- The “induction generator effect” involves only electric system dynamics – not mechanical.
- Subsynchronous torques are created by the subsynchronous currents
- The machine acts as an induction machine at this frequency so rotor resistance appears as negative on the stator.
- If there are insufficient losses in the machine and system to overcome this negative resistance, sustained or growing torques will result.
- No induction generator effects have been found for the evaluated thermal units.

Thermal Generation: Subsynchronous Torsional Interaction

- Part of the controls of active devices such as HVDC, SVC and Statcoms try to regulate system voltage at their terminals
- Control response may make the system provide a destabilizing torque to some torsional modes of near by generators



Note: Controls can be designed that *improve* damping at specific frequencies

Thermal Generation: Subsynchronous Torsional Interaction

- SSTI evaluation process
  - Establish compensation requirements (in process)
  - Identify locations requiring active shunt compensation (future)
  - Identify nearby thermal generation to be studied
  - Model system with shunt compensation using generic controls
  - Evaluate each generator for detrimental SSTI with active shunt compensation

Potential Means of Addressing SSI

- Design around the issues
  - Limit series compensation to values that do not produce SSI
  - Alter controls of active devices involved in SSI to eliminate conditions that produce it
- Operate around the issues
  - fully or partially bypass the series compensation at the system contingency that is one less than that which produces SSI

Potential Means of Addressing SSI

- Control and Protection – Mitigation devices to de-couple and/or damp oscillations
  - TCSC
  - Series Capacitor Bypass Filter
  - SSR Blocking filter
  - Series Voltage SSR damper

Potential Means of Addressing SSI

- Back-up protection
  - Indirect – transfer trip scheme to remove series compensation based on network topology or load flow condition
  - Direct – detect SSI:
    - at the turbine generator to protect the machine (e.g. torsional stress relay to trip the unit)
    - at the series capacitor (e.g. SSI relay to bypass cap)

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