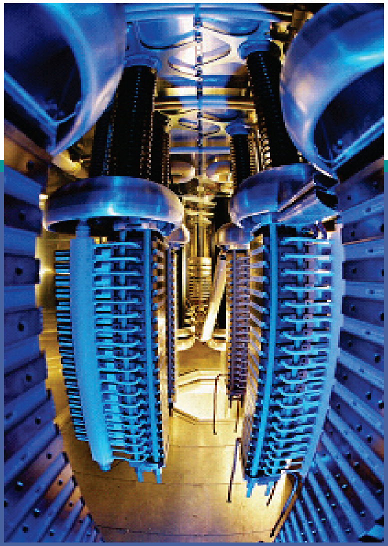
Summary of the CREZ Reactive Study

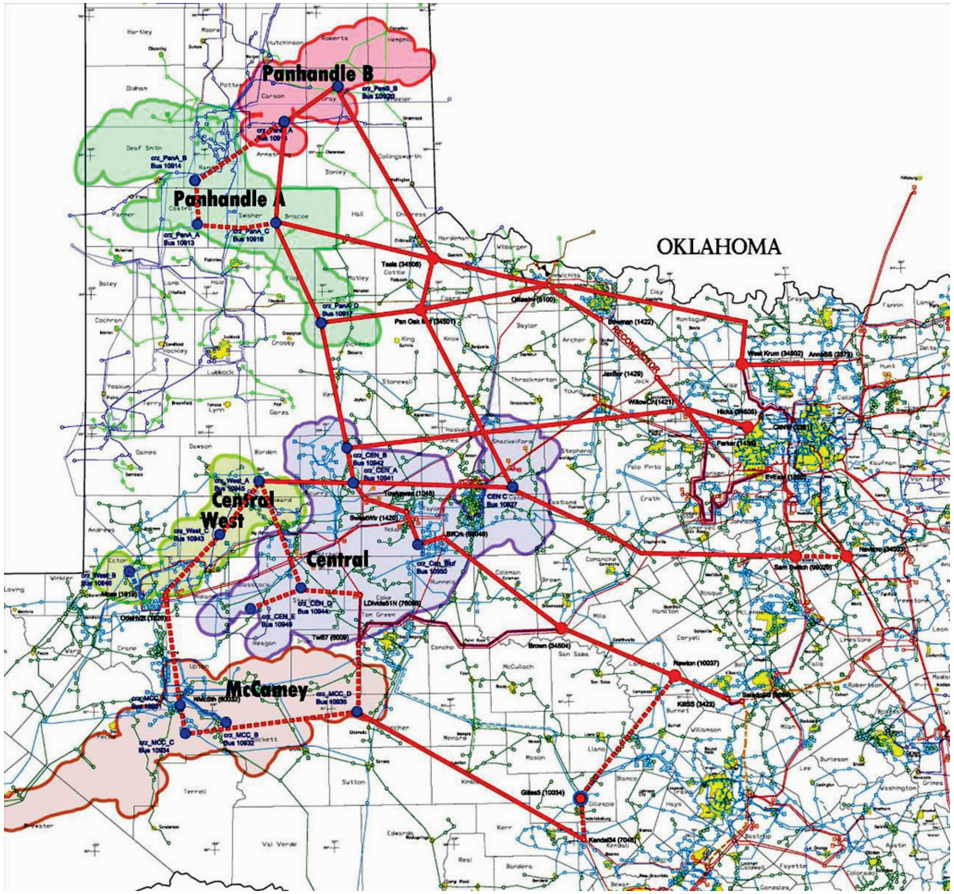


Warren Lasher
Manager, Long-Term Planning and Policy

Regional Planning Group

October 15, 2010

Project Overview



As originally devised, the study had three major work areas:

- Determine design specifications of CREZ series compensation
- Provide location, size and response of shunt compensation
- Evaluate potential impacts of sub-synchronous interactions with ERCOT equipment

The study was conducted by a team of consultants from ABB, Inc., led by Willie Wong.

Topics for Discussion

- **Study Background**
  - Cases and Input Assumptions
- **Issues for Discussion**
  - System Strength
  - Initial Build Case
  - SSR/SSI
- **Study Results**
- **Next Steps**

Study Background

- **CREZ Reactive Study was managed in a joint effort by ERCOT and the CREZ TSPs:**
  - Oncor
  - ETT/AEP
  - LCRA
  - Lone Star
  - STEC
  - WETT
  - Cross Texas
  - Sharyland

- **An overview of this study was presented at the RPG meeting on 11/13/2009; interim results were presented at the ROS Meeting on 3/11/2010 and at the RPG meeting on 3/12/2010.**

Cases and Input Assumptions

- **Three steady-state AC cases were initially developed**
  - Maximum Exports (High wind, low load)
  - Minimum Exports (Low wind, low load)
  - Peak Load
  - Max Edison case was later developed to stress southern portion of the CREZ system (High central and southern CREZ wind, low load)
- **Cases contain incremental CREZ wind (from CREZ Transmission Study) and generation units that are operational or have a signed interconnection agreement**
- **The CREZ transmission system was included in the cases. As details of the CREZ system changed, the cases were updated**
  - Example: line impedances were adjusted to reflect expected line lengths as routing information was developed and to reflect TSP choice of conductor

Cases and Input Assumptions (Cont.)

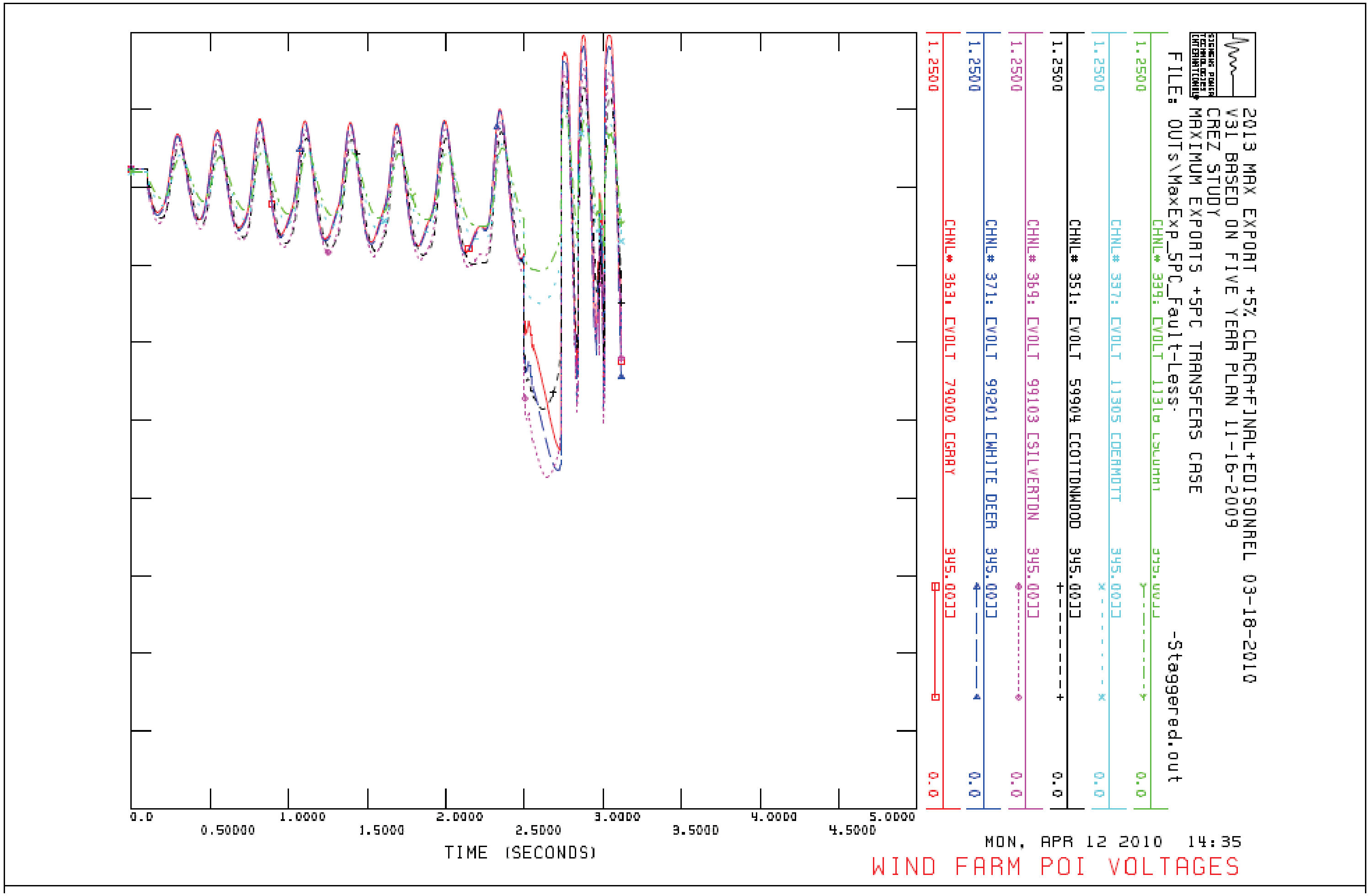
- Models for existing wind units were obtained from Phase II of the LVRT study (the most up-to-date information available at that point in the study)
- New CREZ wind was assumed to be 85% Type III turbines (GE 1.5MW) and 15% Type II turbines (Vestas V80 1.8 MW). These assumptions were designed to be conservative, given that Type IV turbines would be expected to provide faster dynamic response. CREZ Type II turbines were supplemented with small dynamic shunt reactive devices to meet ERCOT reactive power requirements.
- Stability analysis was conducted using PSSE ver. 30.
- Dynamic load models were developed by the TSPs and ABB

Cases and Input Assumptions (III)

- **Criteria for unacceptable system response in dynamic simulations:**
  - Triggering of Under-Voltage Load Shedding (where applicable)
  - Voltage does not recover to pre-contingency values (TSP-specific) in appropriate time (10 seconds)
  - Triggering of Under-Frequency Load Shedding (UFLS)
  - Motor stalling
  - Simulation results do not show well-damped oscillations

Initial Stability Results

- **Initial simulations indicated the presence of two sources of instability: small signal and large signal.**



Graphical representation of oscillatory (small signal) behavior

These results are indicative of power system interactions due to low system strength

Issue 1: System Strength

Short Circuit Ratio (SCR) describes the system strength (a.k.a. small-signal fundamental-frequency source impedance) at a particular point in the network with respect to the corresponding amount of wind power generation:

$$SCR = \frac{system\ strength}{wind\ power} = \frac{S_{sc}}{P_{wind}}$$

↓ low SCR – weak system and/or
(<5) high wind penetration

↑ high SCR – strong system and/or
(>20) low wind penetration

Wind turbine manufacturers generally state that locations with SCR < 2 require additional study. Locations with SCR < 1.5 may be very difficult for at least some turbine types.

Impact of Low SCR

There has been little or no industry experience connecting a substantial amount of wind power into an area of a power system with no existing synchronous generation. These conditions result in unusually low SCR.

What does low SCR in CREZ mean?

1. Model Limitations

3. Physical issues

2. Modeling/Physical ambiguity

Novelty of this problem leads to an ambiguity in distinguishing between physical and modeling issues

Model Limitations

- The extent to which the available dynamic models accurately describe the physical impacts of low SCR is uncertain.   There is no clear information from software developers and vendors regarding how their models are affected by low SCR.
- New software tools may need to be identified that can accurately reflect the impacts of low SCR and high levels of power electronics-based devices to analyze and evaluate cost-effectiveness of solutions

Physical Issues

- Wind turbines and other power electronics-based devices (such as SVCs and STATCOMs) may not be able to operate at very low SCR levels. There is little industry experience in developing significant capacity of wind generation in areas with very low SCR values.
- SCR limitations for power electronics components have been studied for some applications. As an example, HVDC using line-commutated thyristor valves require short-circuit capability equal to or greater than two times the rating of the converters.
- Voltage and power oscillations are likely to develop in a system with very low SCR ratio. Those oscillations can be induced by control device interaction between wind turbines or dynamic reactive compensation devices. Different control schemes in post-fault conditions can oscillate against each other by trying to control the same variable such as voltage in different directions.

System Strength Solutions

- Devices that increase system strength:
  - Traditional synchronous generation
  - Synchronous condensers (either specialized devices or decoupled generator from a thermal generating unit)
  - Series capacitors (reduce impedance to other parts of the grid)
- Some wind turbines may not be as susceptible to low SCR conditions
- More information is needed to analyze alternatives and determine the most cost-effective solution.

Initial Build Case

- To allow the CREZ Reactive Study to proceed and inform near-term equipment decisions, a new case, the Initial Build Case, was developed
- The new case contained as much wind as can be included and still maintain acceptable levels of SCR.
- Solutions developed for this case should be in-line with potential full build-out solutions and yet allow time for additional analysis before incremental expenditures

Case Comparison

Comparison of Generation Levels in the CREZ Transmission Optimization Study (CTOS) and CREZ Reactive Cases

	CTOS	Minimum Exports	Initial Build	Maximum Exports
Wind Installed Capacity MW	18,455	21,958	17,517	21,958
Wind Dispatched Level MW	12,975	2,562	12,802	15,430
Other Generation Dispatched MW	21,725	37,317	27,646	25,534

Reactive Device Recommendations

CREZ system reactive device needs are indicated through steady-state and dynamic analysis of the specified cases.

- Initial Build case indicates the need for capacitive and dynamic reactive equipment.
- Minimum Exports case indicates need for shunt reactors to control high voltage conditions. Additional shunt reactors specified by TSPs to allow maintenance and operation of circuits.
- Series capacitors found to be cost-effective; however, levels of series compensation is limited by the need to insulate circuits for higher voltages and SSI/SRR phenomena. Series compensation levels set at 50% of line impedances.
- Ratings of series compensation equipment determined based on maximum line loadings under contingency from Maximum Export/Maximum Edison cases

Additional Recommendations

- Using average-weather-year wind patterns, ABB reviewed the number of times shunt reactive equipment would be switched in and out of service across a year. Additional shunt equipment, or multiple smaller devices, were recommended for locations where a significant number of switches were noted.
- Dynamic analysis indicated that two grid changes would increase the overall stability of the system:
  - Connection of circuits at the Clear Crossing location (Dermott to Willow Creek and Edith Clarke to West Shackelford were not connected in the original CREZ Transmission Plan)
  - Connection of all circuits at the Tesla substation (one circuit from Silverton bypassed Tesla and connected to Edith Clarke, and one circuit from Gray bypassed Tesla and connected to Riley in the original CREZ Transmission Plan). Series comp. on second circuit from Silverton to Tesla.
  - These changes have been incorporated into the CCN applications for these circuits

Reactive Device Recommendations

The following capacitive devices are being recommended at this time based on the analysis conducted by ABB:

Station	Shunt Capacitors (MVAr)	SVC (MVAr)
RILEY	316	
KRUM	50	
TESLA		300
EDITH CLARKE		
SILVERTON		
COTTON		
SCURRY	100	
WEST SHACKLEFORD		
GRELTON	50	
BROWN	200	600
KILLEEN	100	
BIG HILL	144	
PARKER		300
HAMILTON		200

Reactive Device Recommendations

The following reactive devices are being recommended at this time:

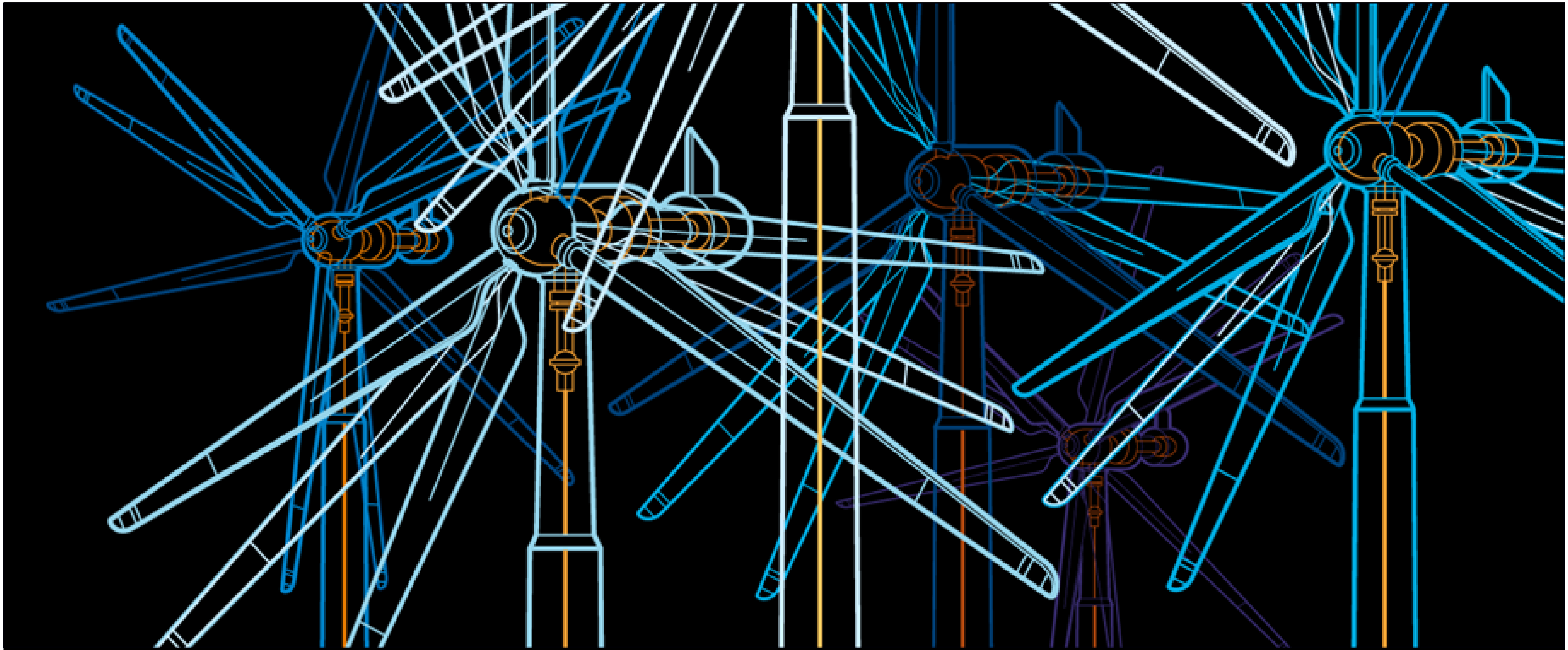
Bus Number	Bus Name	Reactor Requirements by Bus, Verified by Chronology Case (MVAR)	Bus Number	Bus Name	Reactor Requirements by Bus, Verified by Chronology Case (MVAR)
1421	WILLOWCK_5 345.00	-100 (1 x -100)	99703	RILEY_R 345.00	-200 (4 x -50)
1444	BROWN 345.00	-200 (2 x -100)	99704	GILLESP_R 345.00	-100 (2 x -50)
6100	OKLA7A 345.00	-30 (1 x -30)	99705	EDISON1_R 345.00	-100 (2 x -50)
11047	TONK 345.00	-100 (1 x -100)	99706	EDISON2_R 345.00	-100 (2 x -50)
11046	TONK_R 345.00	-100 (2 x – 50)	99708	BIGHILL_R 345.00	-100 (2 x -50)
11304	DERMOTT_R 345.00	-100 (2 x -50)	99709	NAZRTH_R 345.00	-50 (1 x -50)
11317	SCURRY_R 345.00	-100 (2 x -50)	99710	HEREF_R 345.00	-200 (4 x -50)
11422	SWEAST_R 345.00	-100 (2 x -50)	99712	COTTON_R 345.00	-100 (2 x -50)
60503	TESLA7C 345.00	-200 (4 x -50)	99713	WHITED_R 345.00	-100 (2 x -50)
60512	CLRXN1 345.00	-300 (6 x -50)	99714	GRAY_R 345.00	-150 (3 x -50)
68010	Romney1 W 345.00	-100 (2 x -50)	99715	WSHACK_R 345.00	-200 (2 x -100)
68050	Romney2 W 345.00	-100 (2 x -50)	99716	EDITH_R 345.00	-200 (4 x -50)
99103	SILVERTON 345.00	-150 (3 x -50)	1430	GRAHAM 345.00	-150 (2 x -75)
99701	KRUM_R 345.00	-100 (1 x -100)	99719	GRAHAM_R 345.00	-300 (4 x -75)
11406	CEN BLUFF 345.00	-100 (1 x -100)	6444	SARC7A 345.00	-100 (1 x -100)

Sub-Synchronous Analysis

ABB presented a thorough discussion of the technical details of sub-synchronous resonance and sub-synchronous interaction at the RPG meeting on March 12, 2010. The presentation can be found here:

http://www.ercot.com/content/meetings/rpg/keydocs/2010/0312/ABB_RPG_presentation.pdf

The following slides are from that presentation.



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

ERCOT CREZ Reactive Study
RPG SSI Discussion

Power and productivity for a better world™

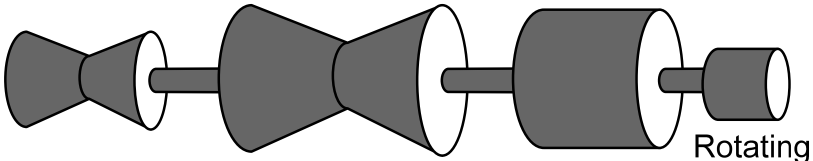
Subsynchronous Interaction Evaluations

- 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.)

Thermal Generation: Subsynchronous Resonance

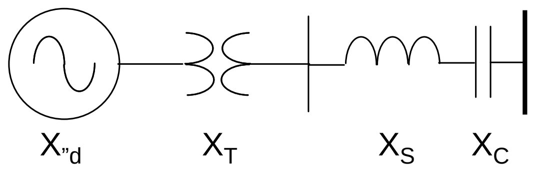
CONCERN

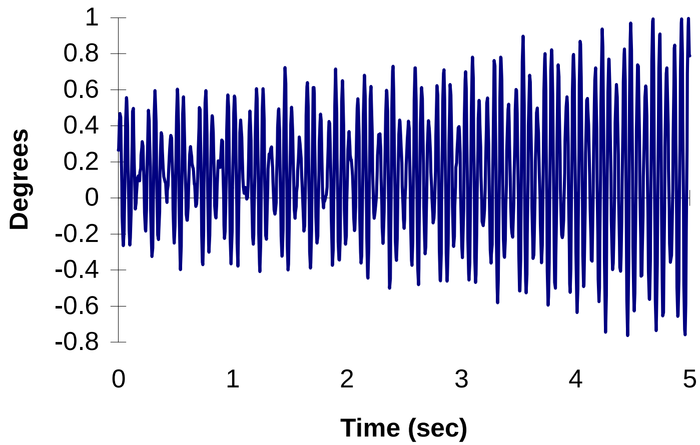
Destabilizing mechanical torsional modes of thermal generation



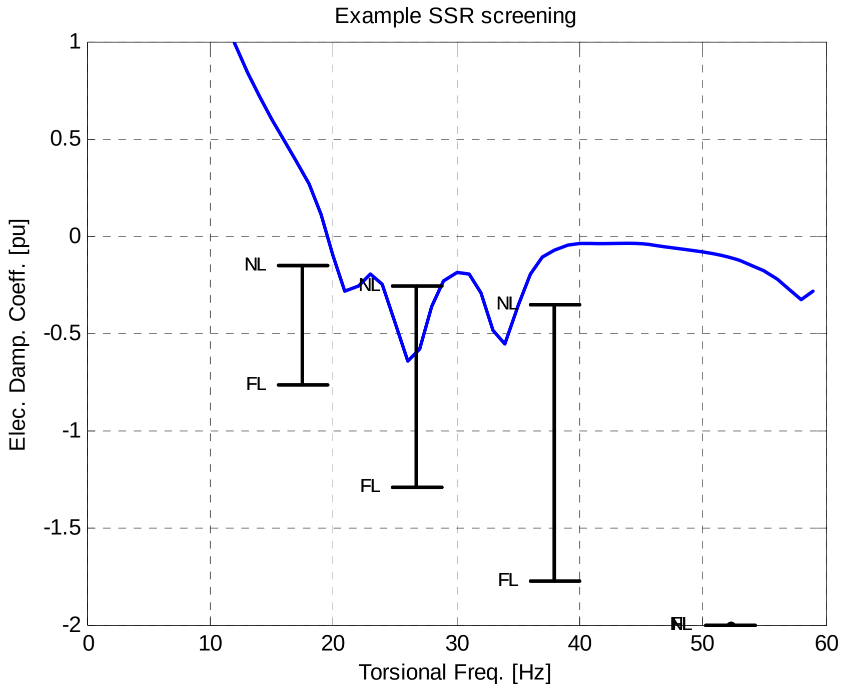
- The machine's mechanical system can be represented as a series of large lumped masses connected by shafts.
- A system perturbation will cause the masses to "swing against" each other – accelerated and decelerate in an oscillatory manner – and at multiple frequencies
- This stresses the shaft between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

Thermal Generation: Subsynchronous Resonance

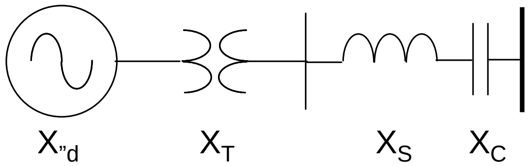




- If total damping – mechanical + electrical – is negative, the mode is unstable and will grow
- Screening investigations are possible to determine if more detailed evaluations or protection are warranted



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

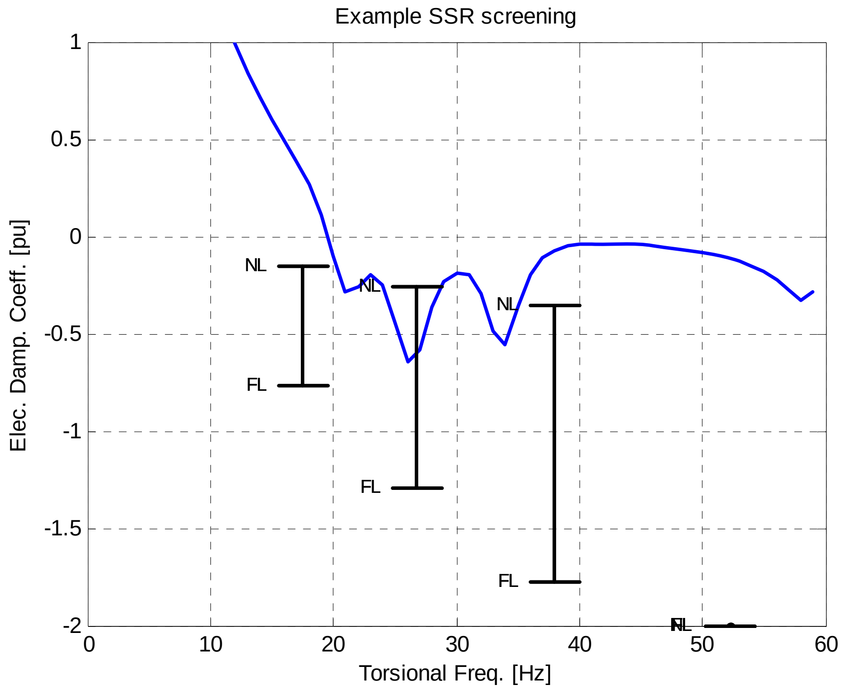
- Comanche Peak
- Tradinghouse Creek
- Willow Creek
- Oklaunion

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



WTG: Self-Excitation

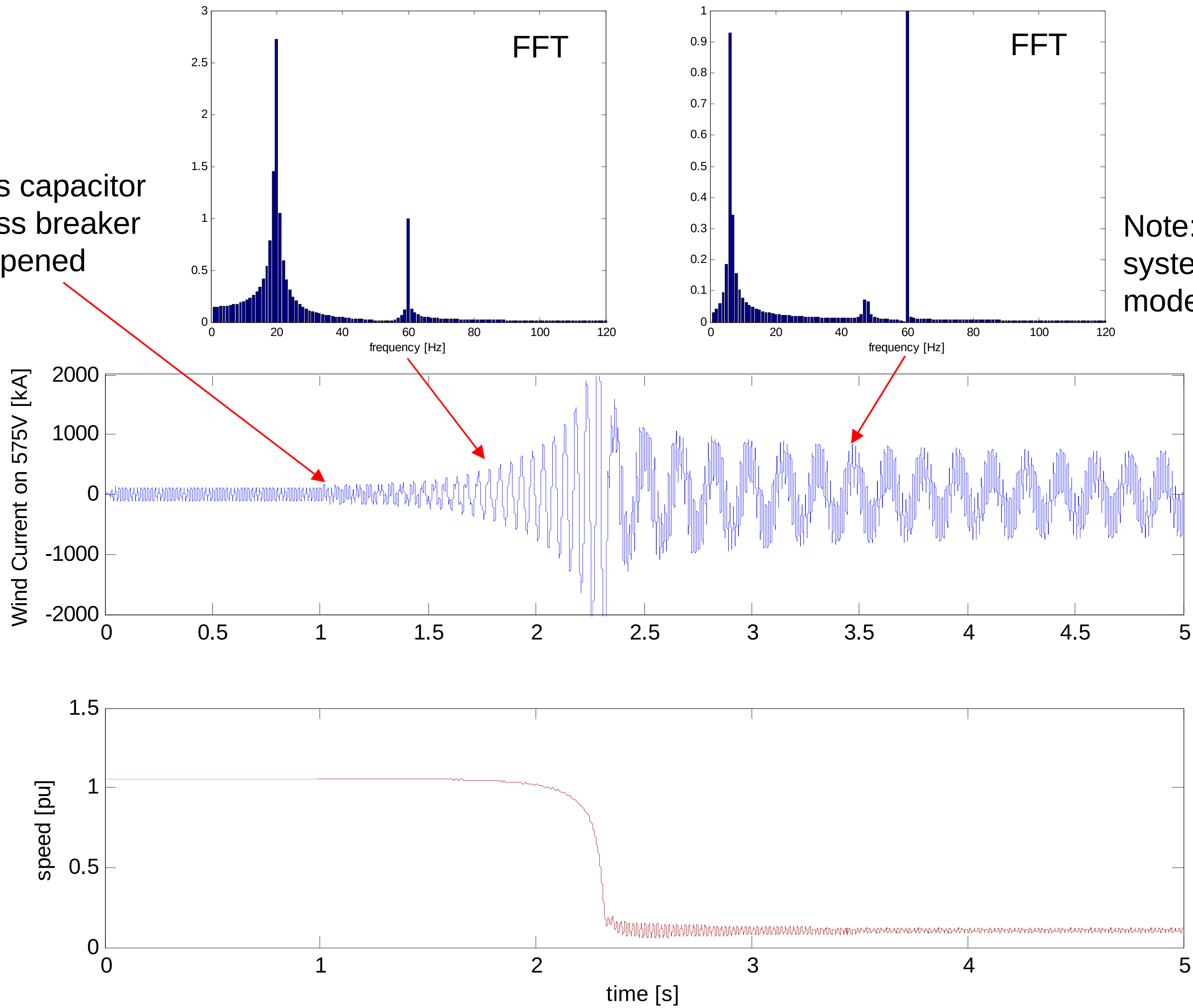
- Similar to well described self-excitation of induction machines when using series capacitors on the stator terminals.
- ABB first noted the potential for self-excitation of wind turbine generators connected to series compensated transmission in 2003 paper [1]
- Self-excitation can result in two conditions.
  - 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.

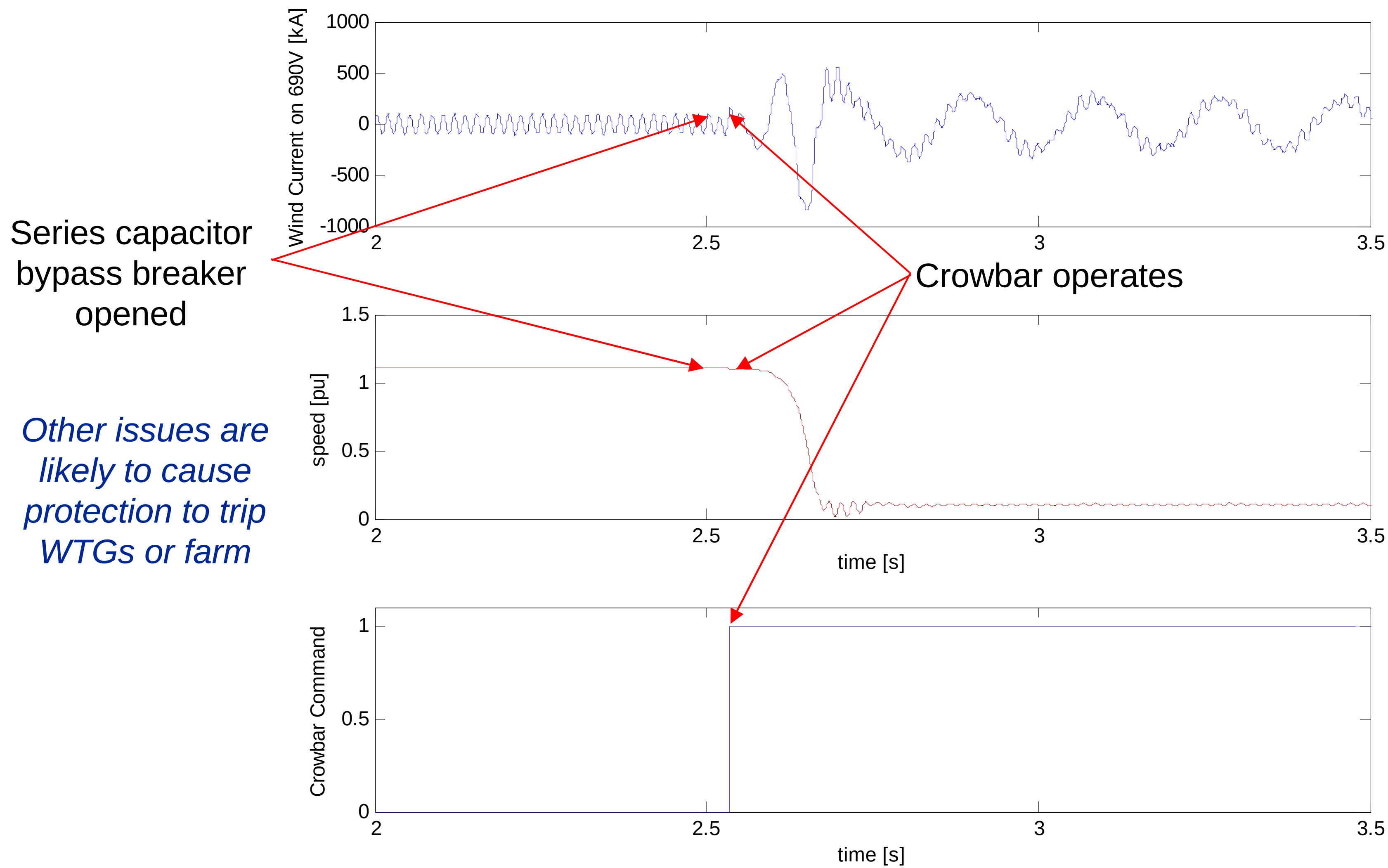


WTG: Self-Excitation

- 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



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

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)

Power and productivity
for a better world™

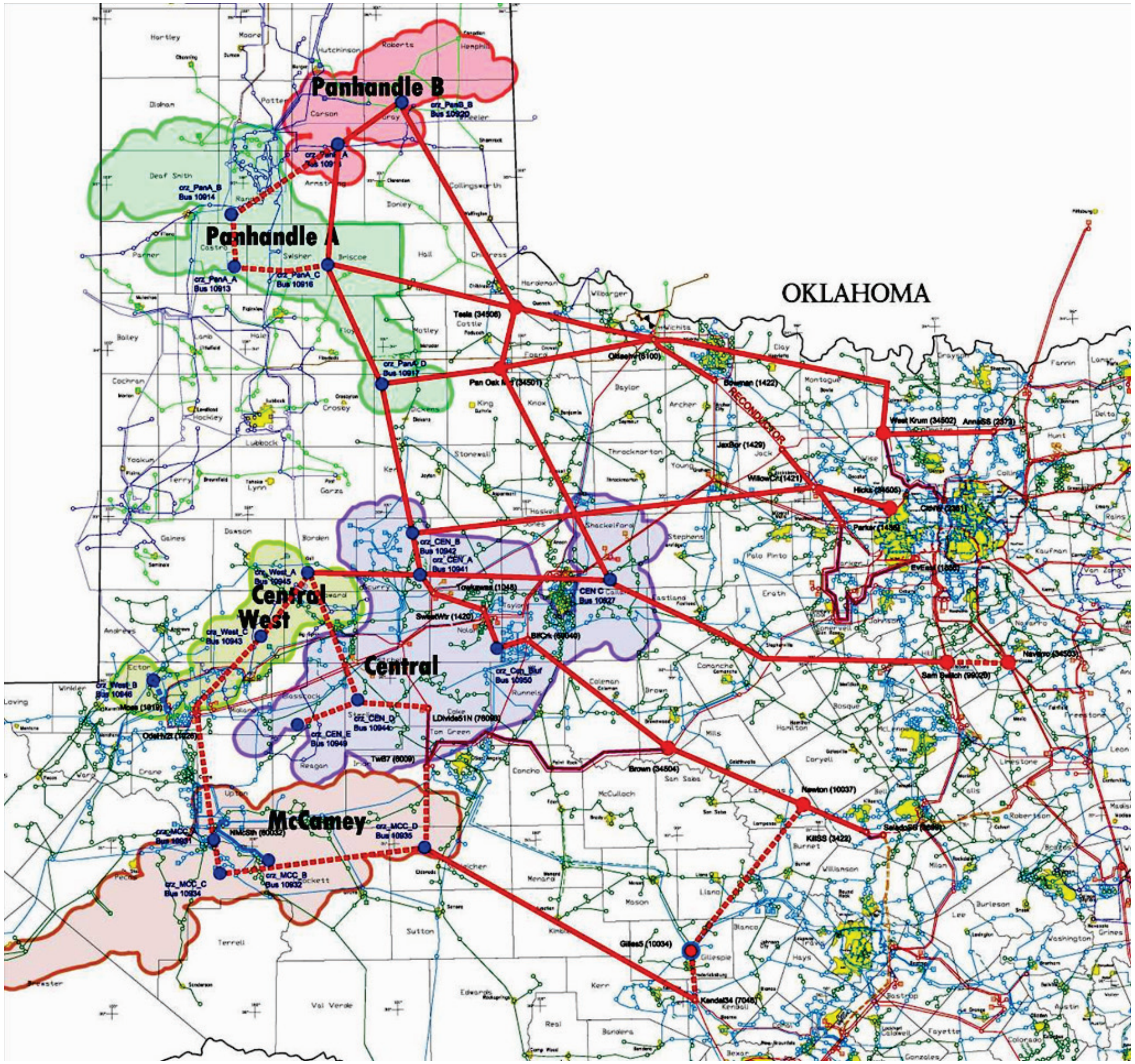
ABB

Geography of SSI

Locations most prone to have Sub-Synchronous Interaction (for Type 3 turbines):

1) West Shackelford – SSI with no contingencies
2) Big Hill – SSI after 1 contingency
3) Dermott – SSI after 1 contingency

Locations directly connected to a compensated line or potentially in a radial or semi-radial configuration following the outage of one or a few nearby circuits will be SSI prone.



Options to Mitigate SSI/SSR

Transmission System Options
- Damping/Passive filters
- Protection schemes
- Thyristor Control Series Capacitors

Generator Options
- Modifications to current Type III turbine technologies
- Type IV turbines may be less affected
- Type V turbines?

Cost-effective strategy may be a combination of the above options.

Analysis will require detailed PSCAD (or similar) system models and wind turbine models.

Conclusions

- ERCOT will recommend installation of the reactive devices specified through analysis of the Initial Build, Minimum Exports, and Peak Load cases
  - Maintain flexibility to adjust location and size of dynamic reactive devices to reflect actual development of wind generation and other changes to the transmission grid
  - Maximum wind development possible before selecting cost-effective solution(s) to low system strength conditions
- Maximum Exports/Max Edison cases represent potential reactive device solutions to the full CREZ build-out. Cost-effectiveness of this solution is not known at this time.
- ERCOT is discussing with TSPs the options for SSR/SSI mitigation

Further Study

- System Strength Analysis
  - Identify new tool(s)
  - Evaluate cost-effectiveness of solutions
- SSR/SSI Analysis
  - Develop new process/modeling tool
  - Evaluate cost-effectiveness of solutions
- Stakeholder/regulatory review of solutions and cost allocation
- Modifications to Generation Interconnection requirements/process to reflect need for additional SSI studies
- Modifications to Operating Procedures

Questions?