Investigation of Sub-Synchronous Phenomenon in Wind Farms

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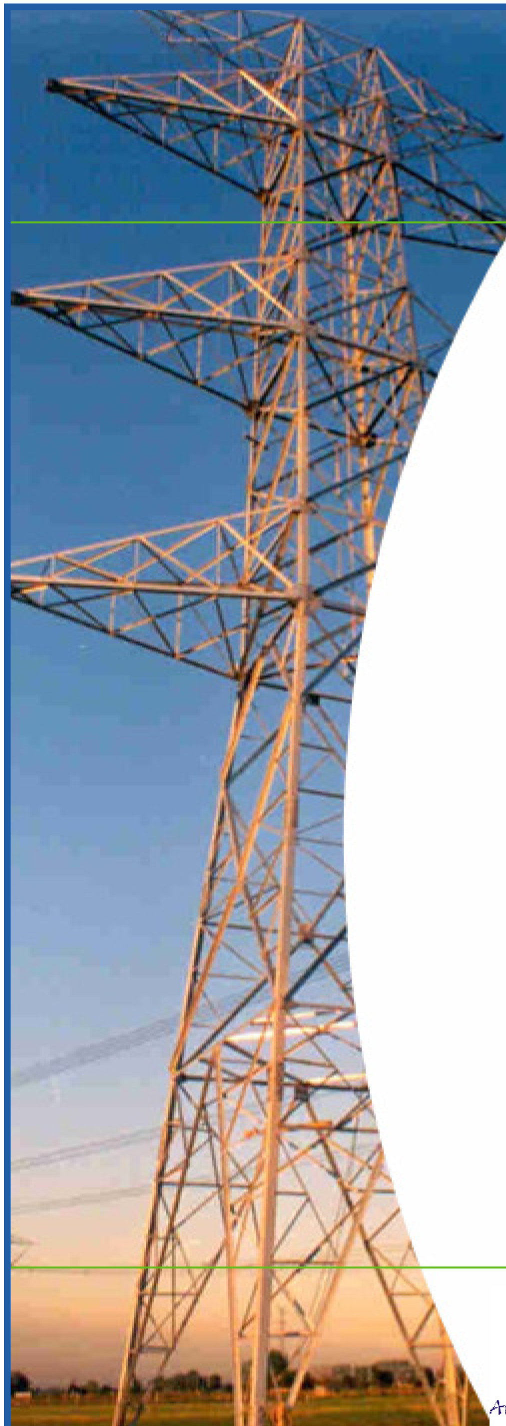
Agenda

- Introduction/Background
- Investigation Objectives
- Investigation Approach
  - The Big Picture: Approach Overview
  - Identification of credible and critical conditions
  - Application of Screening Techniques
  - Corroboration with Electro-Magnetic Transient (EMT) Simulations
- Radial Vs Non-Radial Conditions
- Key Observations/Conclusions
- Future Reading

Introduction/Background



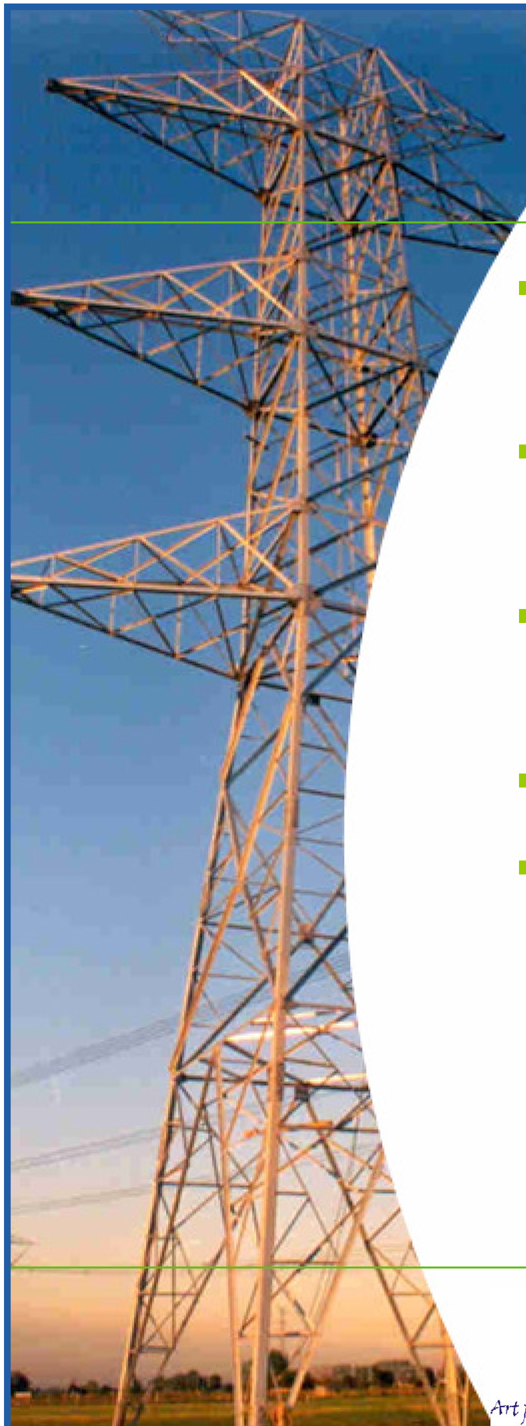
Introduction/Background

- First instance of SSCI observed in ERCOT system – October 2009
  - Tripping of 345kV line on AEP-TCC system resulted in WGR being radial to series caps
- Increased instance of WGR interconnection in electrical vicinity of series compensated lines
  - Lower Rio Grande Valley
  - 345kV CREZ Transmission System
- Need for investigation of sub-synchronous control/torsional interaction issues associated with WGR interconnection
  - Quantify risk of SSI associated with WGR, if any

Introduction/Background

- Ability to demonstrate "design level" immune capability for potential SSI
  - Tripping and/or temporary "ride through" may not be acceptable as a **primary mitigation action**
- Two stages of test procedures
  - Test Radial System
    - Ability to modify the extent to series compensation
    - Ability to alter the strength of the system at POI
  - Actual ERCOT ETRAN-converted PSCAD case
    - Prior knowledge of the system vital
    - Credible system conditions

Investigation Objectives

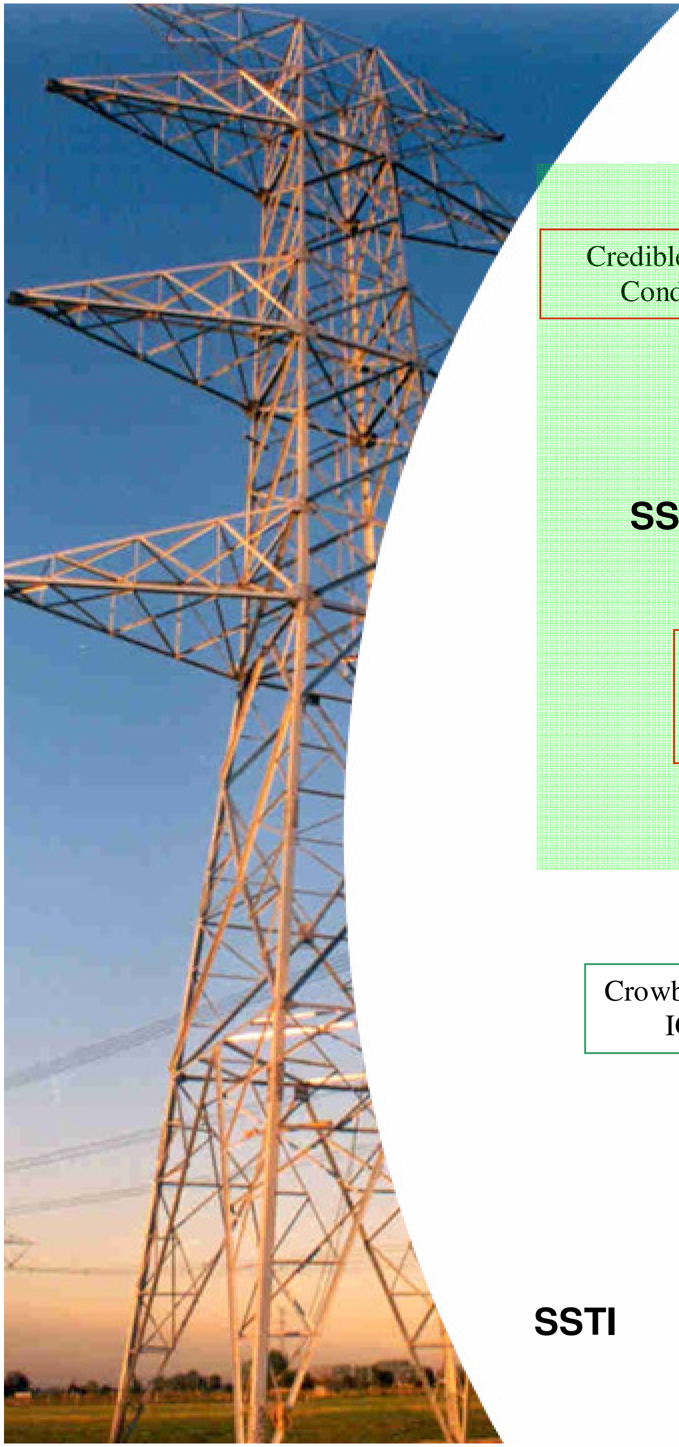


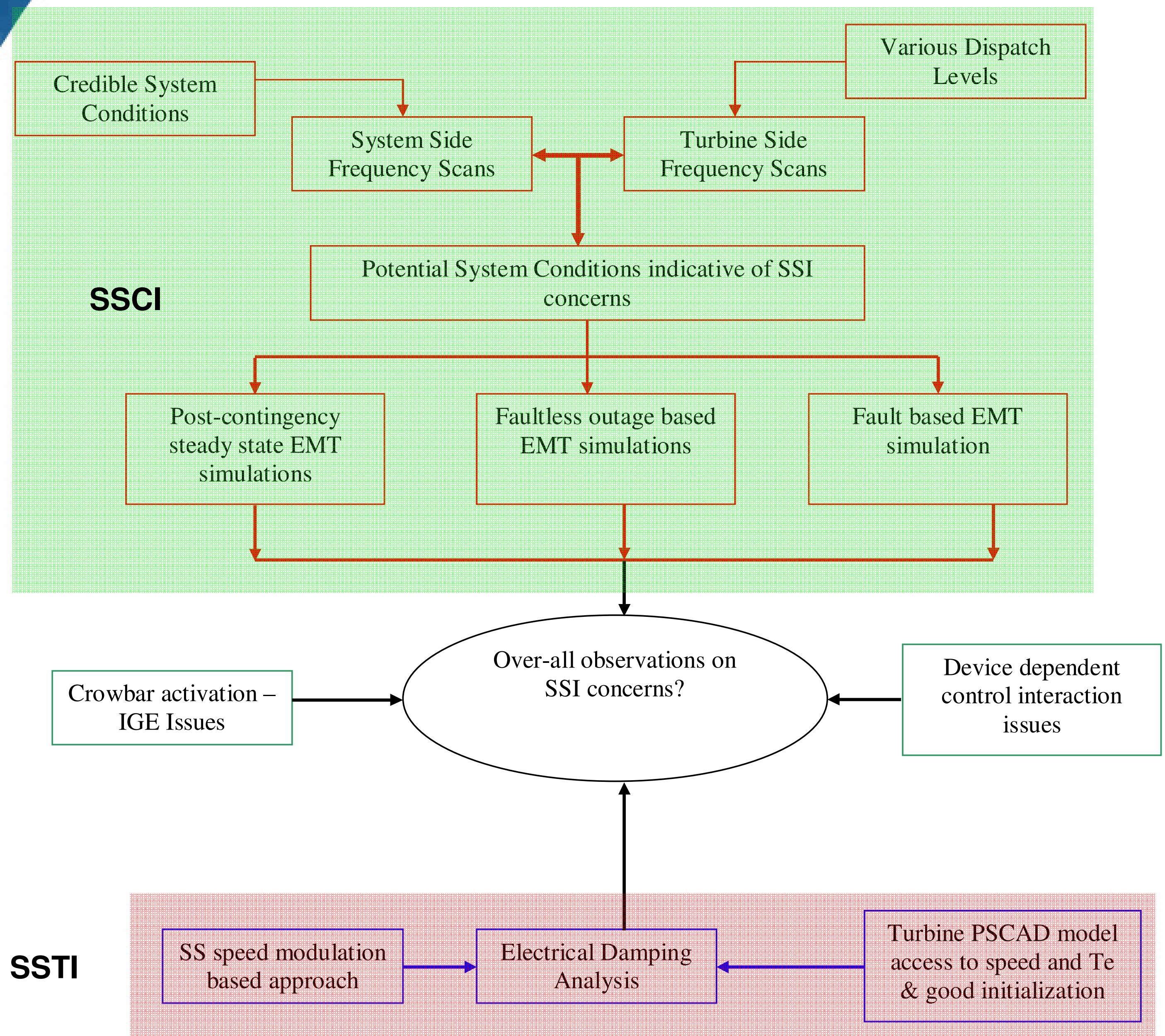
Investigation Objectives

- Outline comprehensive study approach
  - Spanning all aspects of SSI
- Develop, validate & apply screening approaches for various SSI phenomenon
- Corroborate adequacy of screening approaches via detailed EMT simulations
- Establish standard methodology for performing such investigations
- Obtain industry/academia feedback and develop consensus
  - Utility/ISO Forums
  - IEEE PES General Meeting Panel Sessions
  - IEEE Journals
  - Utility Wind Integration Group (UWIG) Forum

Investigation Approach

The Big Picture

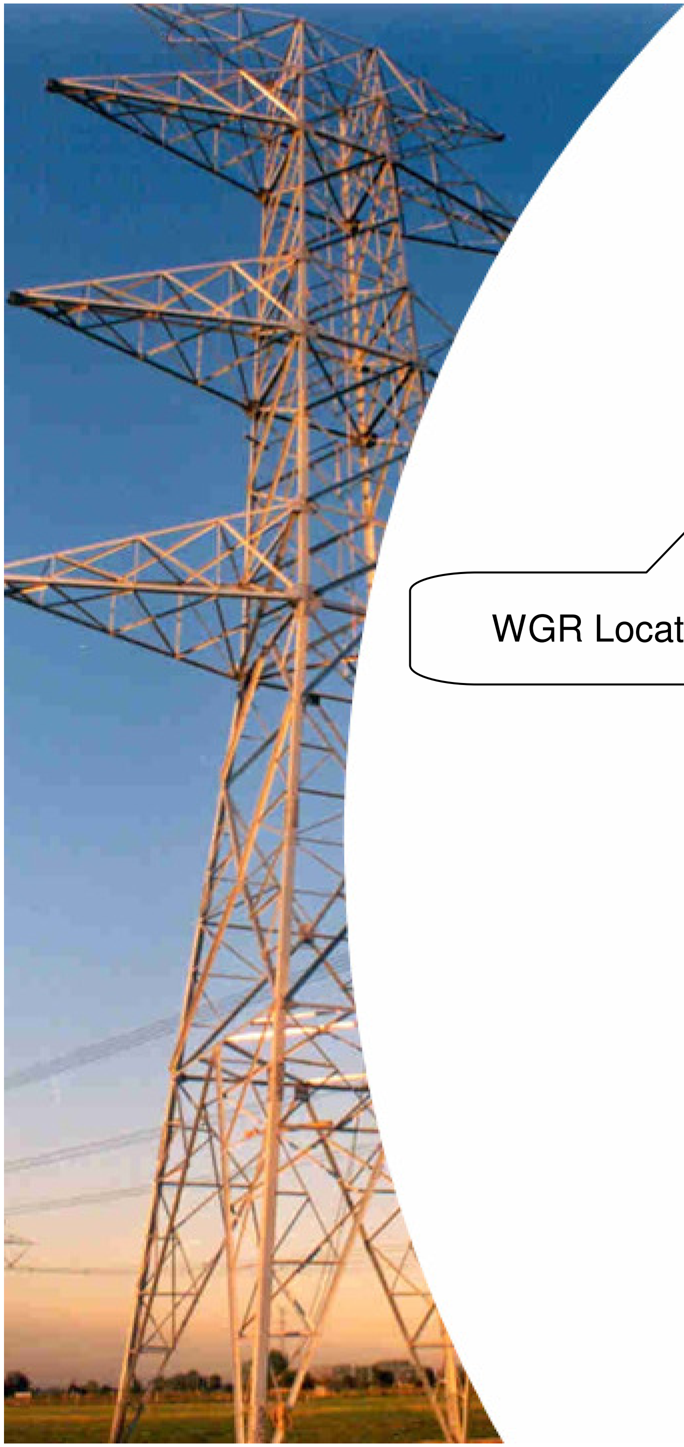


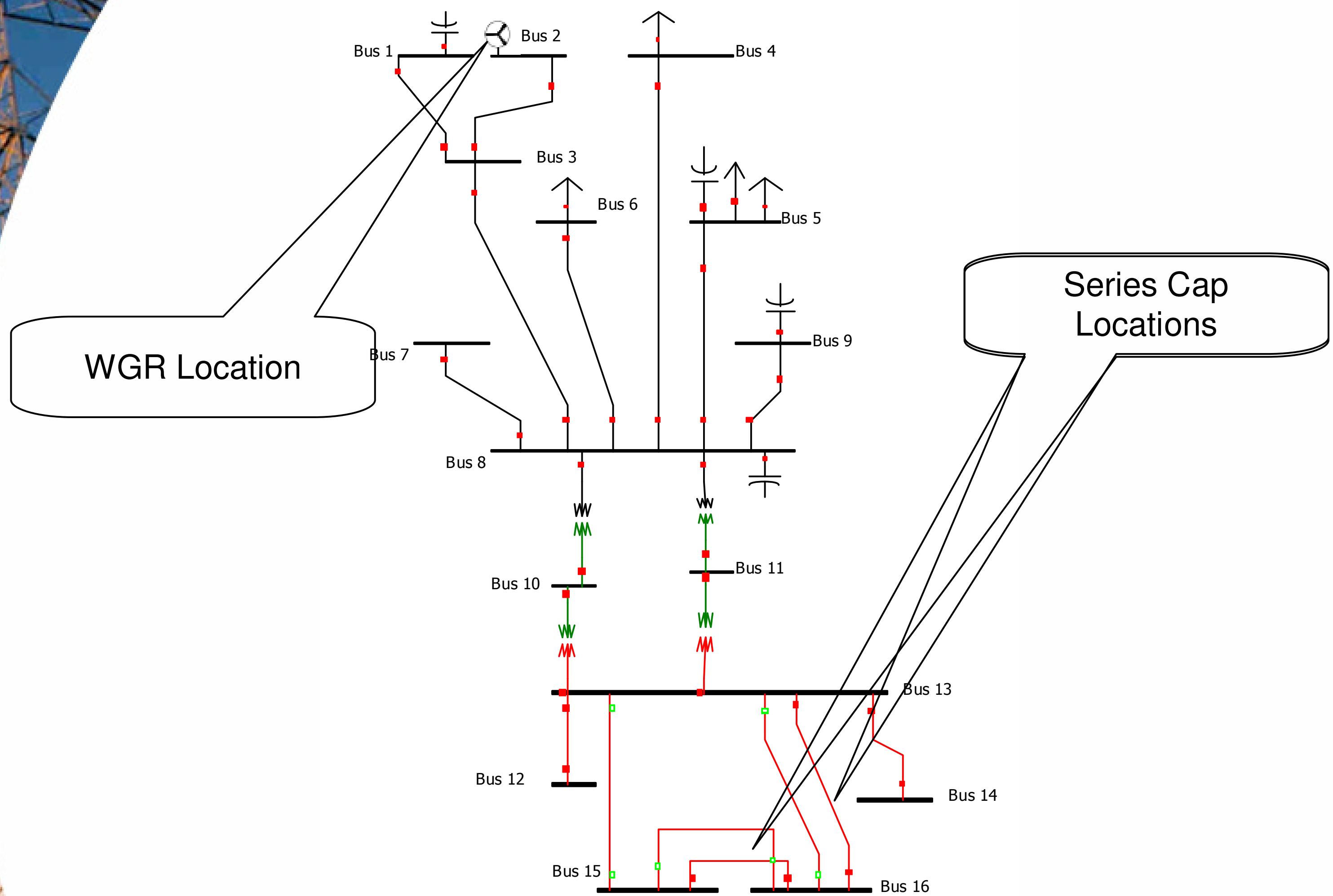


Identification of Credible/Critical System Conditions

- Objective #1 – Credible System Conditions
  - Assess/quantify risk of SSCI under credible system conditions
    - Planning Contingencies
- Objective #2 – Critical System Conditions
  - Identify conditions resulting in elevated SSCI risk
    - Provide utility/ISO with knowledge regarding "N-x" conditions resulting in SSI concerns
    - Critical conditions
      - Sub-set of credible conditions
      - Above and beyond the credible conditions

Identification of Credible/Critical System Conditions





One-line Schematic, Sample ERCOT System

Identification of Credible/Critical System Conditions

Planning Contingencies

CTG Label	Contingency Definition
CTG#1	OPEN Line from Bus 8 TO Bus 5 CKT 1
	OPEN Line from Bus 8 TO Bus 4 CKT 1
	Open Transformer Bus 8 to Bus 10 to Bus 13 CKT 1
CTG#2	OPEN Line from Bus 8 TO Bus 5 CKT 1
	OPEN Line from Bus 8 TO Bus 4 CKT 1
	OPEN Line from Bus 9 TO Bus 8 CKT 1
CTG#3	OPEN Line from Bus 8 TO Bus 5 CKT 1
	OPEN Line from Bus 8 TO Bus 4 CKT 1
	OPEN Line from Bus 8 TO Bus 6 CKT 1
	OPEN Line from Bus 6 TO other buses downstream
	OPEN other lines
CTG#4	OPEN Line from Bus 8 TO Bus 5 CKT 1
	OPEN Line from Bus 8 TO Bus 4 CKT 1
	OPEN Line from Bus 4 TO other buses downstream
	OPEN other lines
CTG#5	OPEN Line from Bus 8 TO Bus 5 CKT 1
	OPEN Line from Bus 8 TO Bus 4 CKT 1
	OPEN LINE from Bus 5 to other buses downstream
	OPEN Line from Bus 4 TO other buses downstream
	OPEN other lines

Critical Conditions: Above & Beyond Planning Contingencies

CTG Label	Contingency Definition
CTG#6	OPEN Line from Bus 8 TO Bus 6 CKT 1
	OPEN Line from Bus 8 TO Bus 5 CKT 1
	OPEN Line from Bus 8 TO Bus 4 CKT 1
	OPEN Line from Bus 9 TO Bus 8 CKT 1
	OPEN Line from Bus 8 TO Bus 7 CKT 1
CTG#7	OPEN all lines outlined in CTG#6
	OPEN Line from Bus 13 TO Bus 12 CKT 1
	OPEN Line from Bus 13 TO Bus 14 CKT 1
CTG#8	OPEN all lines outlined in CTG#7
	OPEN Line from Bus 3 TO Bus 1 CKT 1

Credible & Critical System Conditions, Sample System

Screening Techniques

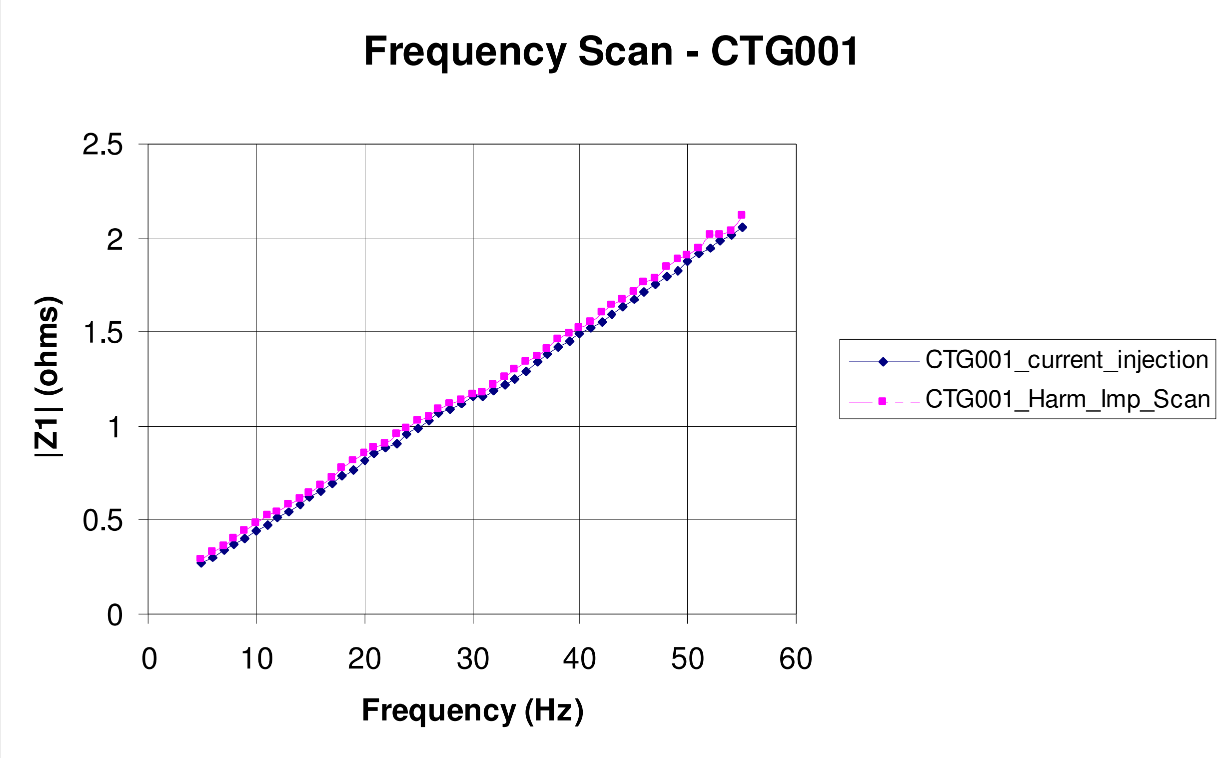
- SSCI Screening
  - System Side Frequency Scans
    - Assess system impedance (R & X) at sub-synchronous frequencies as seen from WGR connection
      - Disconnect turbine when looking into system unless accurate model for turbine available from SSCI standpoint
      - Refrain from utilizing power flow and/or short circuit representations of turbine models for frequency scans
    - Impedance dips indicative of potential series resonance
      - More insight obtained by assessing R & X
    - Insight into system conditions under which WGR may exhibit SSCI issues
    - Traditional frequency scanning techniques in commercial software can be used

Screening Techniques

- SSCI Screening
  - Turbine Side Frequency Scans
    - Assess turbine impedance (R & X) at sub-synchronous frequencies
    - Negative R at sub-synchronous frequencies indicative of negative damping
    - Traditional frequency scanning techniques do not work
      - Assume power electronic devices to be in off-state
      - Special techniques need to be utilized for turbine side scans
        - Proprietary Voltage/current injection technique utilized by PwrSolutions

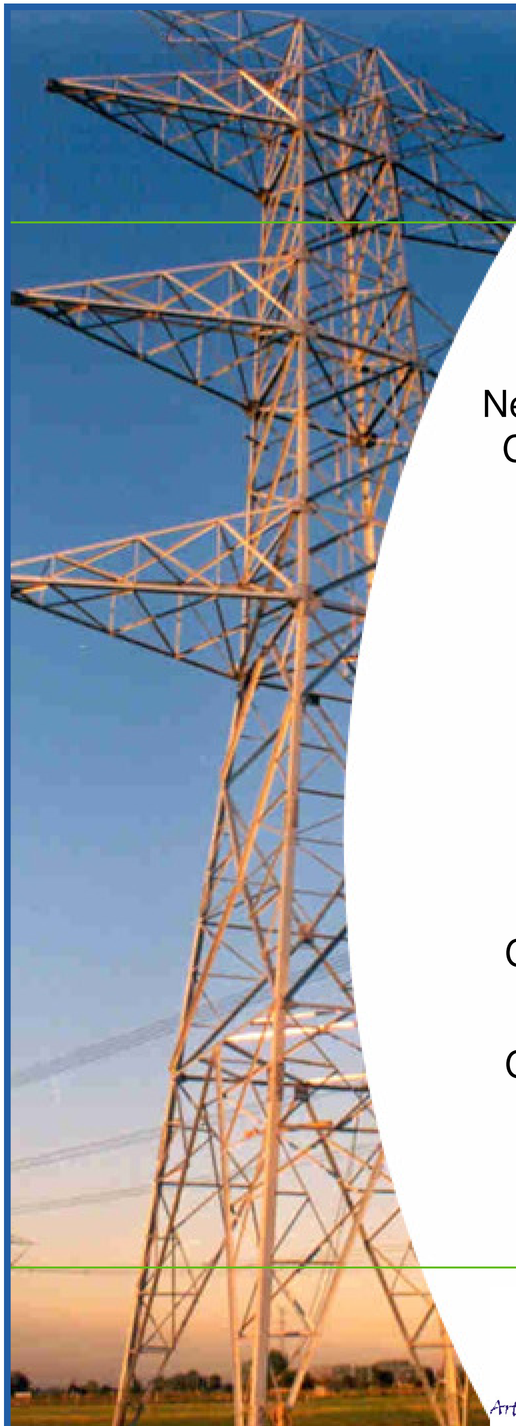
Screening Techniques

Trend of System Frequency Scans observed
to be similar for CTG#1 through CTG#5

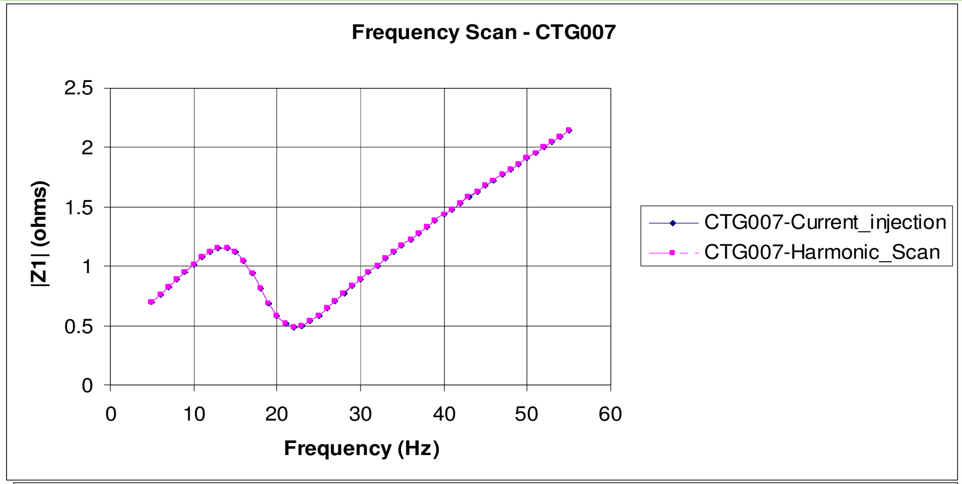


Transmission System Side Frequency Scans, CTG#1

Screening Techniques

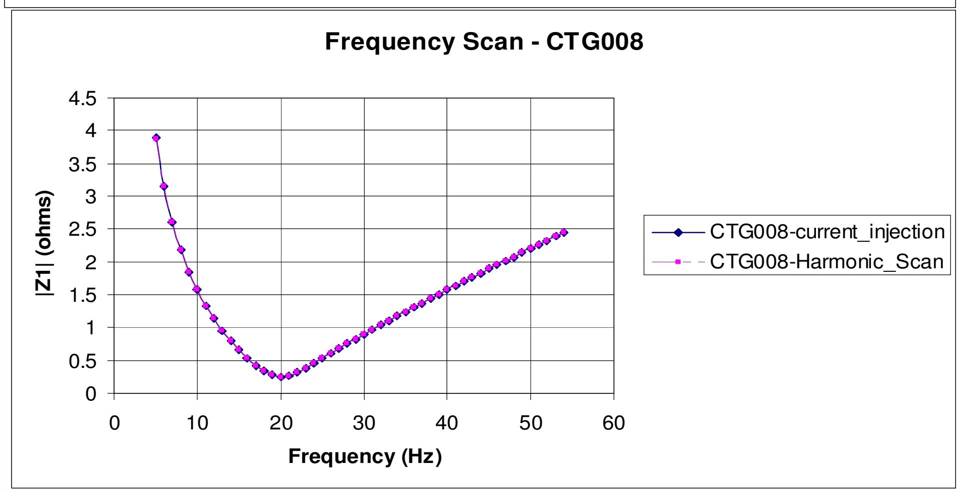


Near Radial Condition



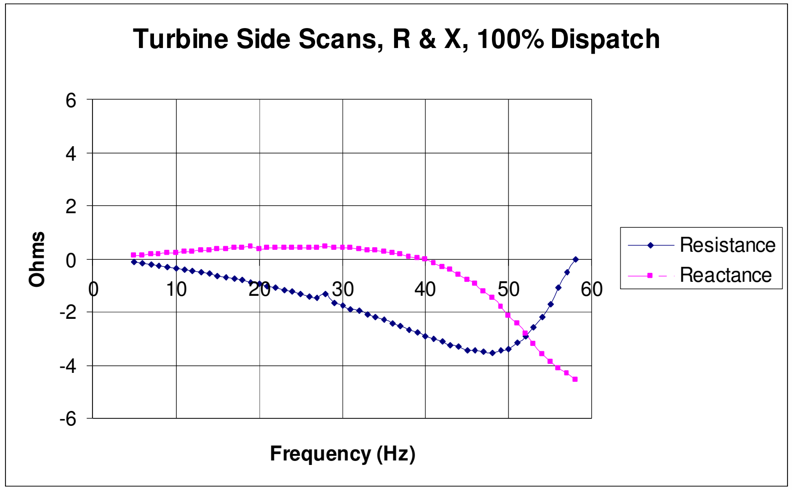
Radial Condition

"*N-8*" Condition



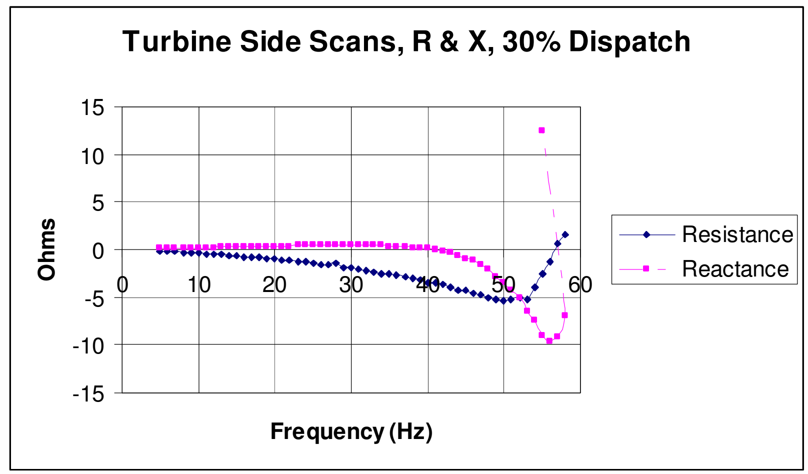
Transmission System Side Frequency Scans, CTG#7 & CTG#8

Screening Techniques



100%
Dispatch
Level

30% Dispatch
Level



Turbine Side Frequency Scans

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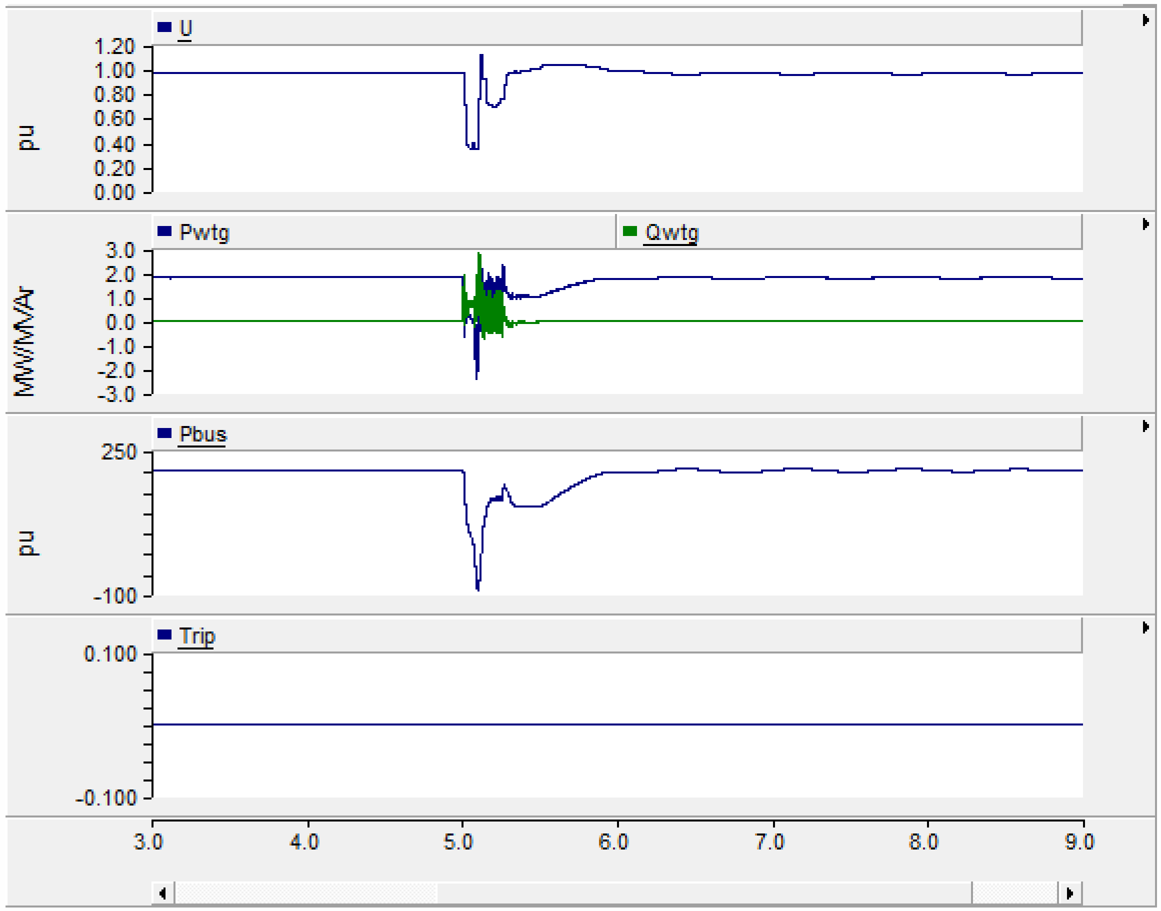
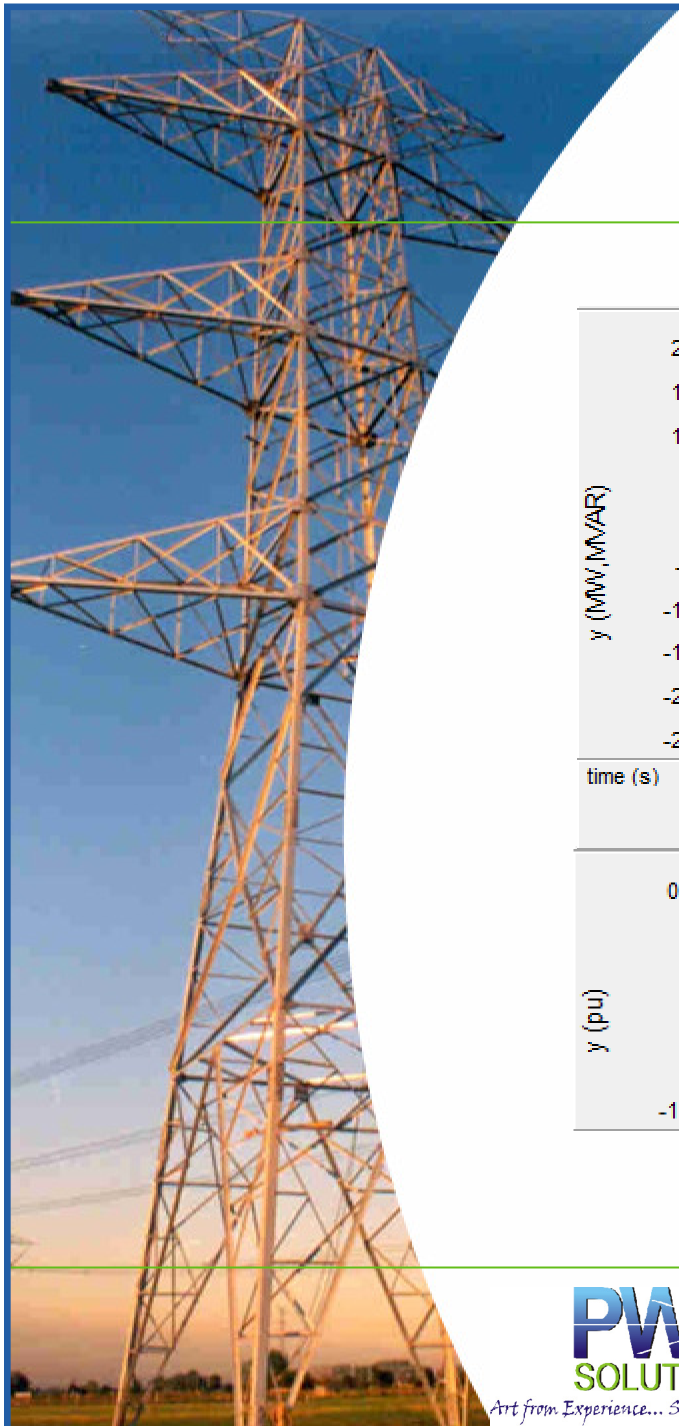
Screening Techniques

- System Side Scans
  - CTG#1 through CTG#5 not indicative of system conditions resulting in SSCI concerns
    - No SSCI issues under credible system conditions
  - CTG#7 & CTG#8 indicate impedance dips
    - Potential SSCI concerns
    - Need to be investigated via EMT simulations
    - Need to assess other aspects of system reliability under these conditions
- Turbine Side Scans
  - Turbine R negative over entire range of sub-synchronous frequencies
  - Negative damping at system resonant frequency for critical conditions i.e. CTG#7 and CTG#8

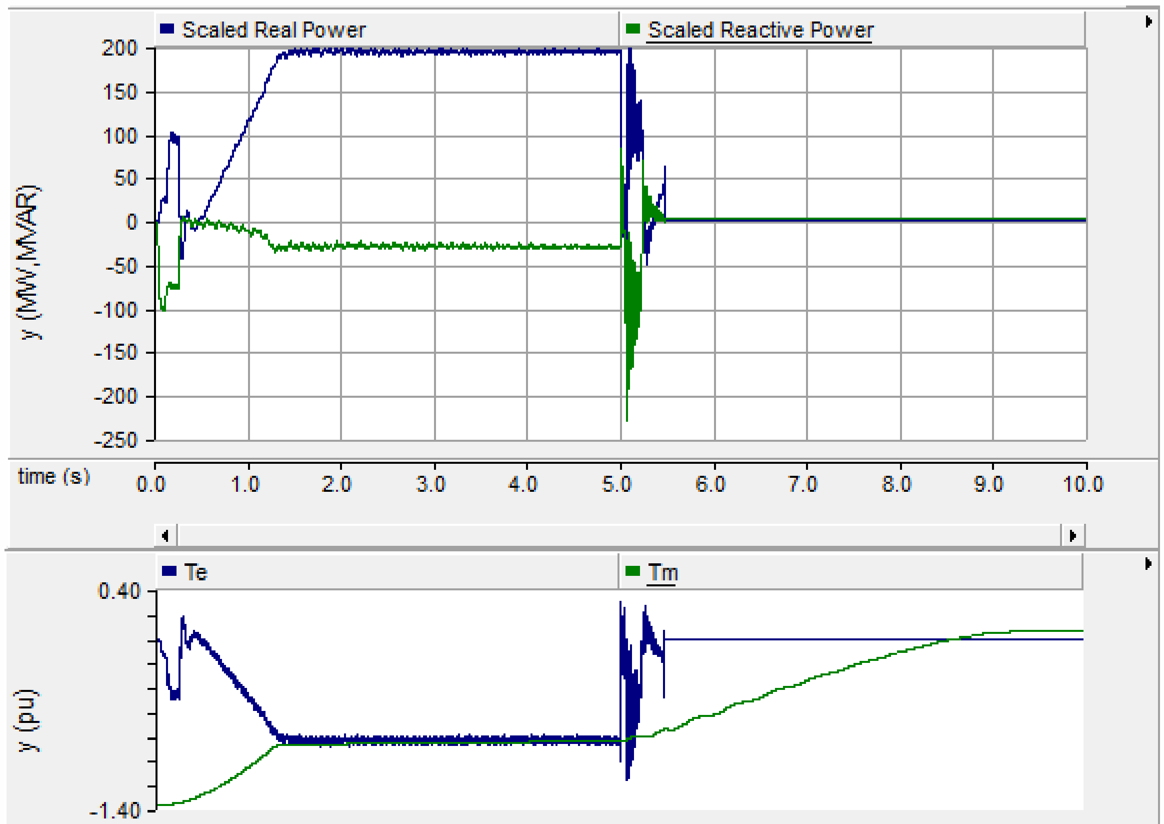
EMT Simulations



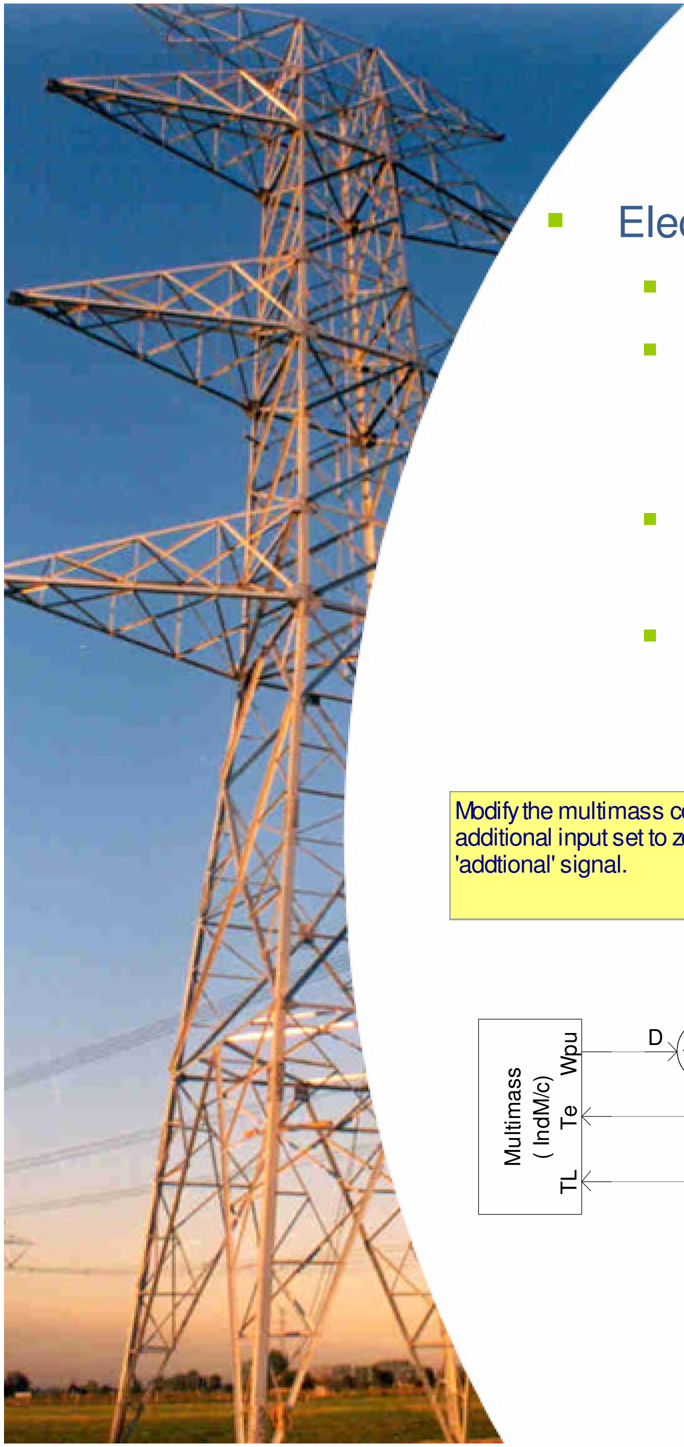
EMT Simulation, Fault-based outage, CTG#1



EMT Simulations



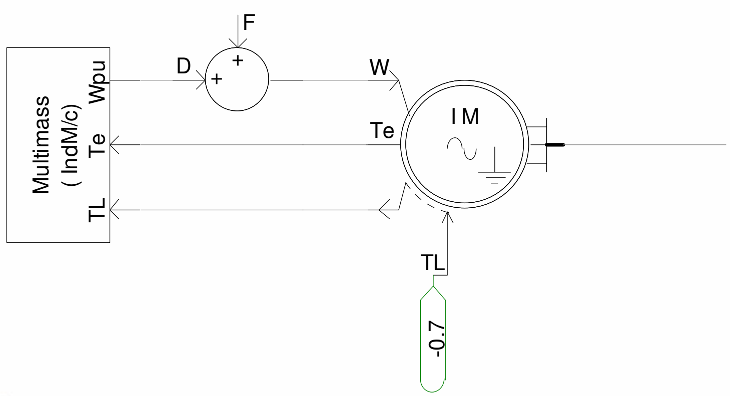
EMT Simulation, Fault-based outage, CTG#8



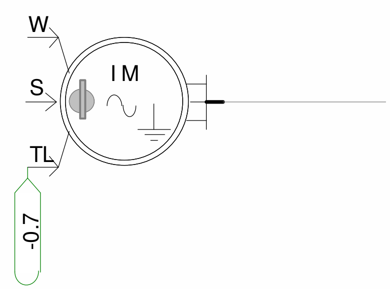
Screening Techniques

- Electrical Damping Analysis
  - Assess potential SSTI concerns associated with turbine
  - Turbine PSCAD model used to modulate turbine speed
    - Inject SS variation in the turbine speed signal
    - Frequency of modulation signal equal to SS frequencies of interest
  - Assess electrical torque (Te) and phase relation between Te & machine speed
  - Determine damping factor (De) as a function of sub-synchronous frequency

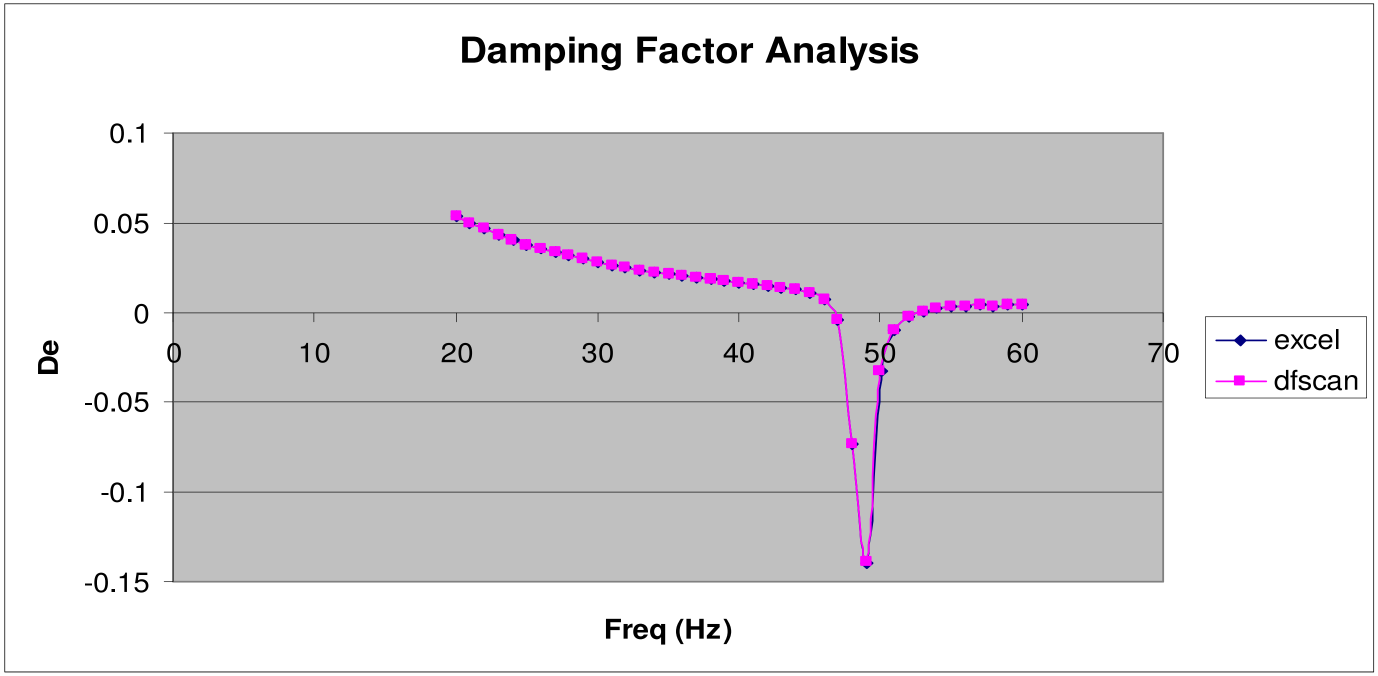
Modify the multimass connection as shown with the additional input set to zero. We need access to the 'addtional' signal.



If multimass model is not used, provide access to 'W' and 'S' inputs of the machine model

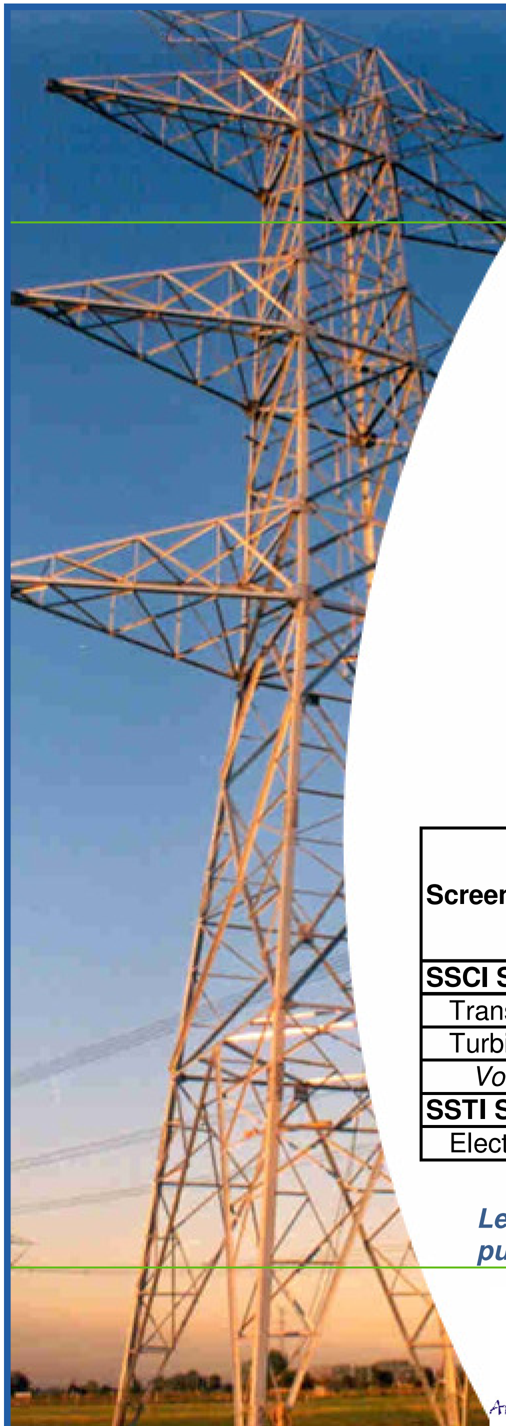


Screening Techniques



Electrical Damping Analysis, Sample DFIG Turbine Model

Screening Techniques



- Final Word
  - Varying levels of complexity in screening techniques
  - Some screening studies require PSCAD turbine model
    - Turbine vendors moving towards providing black-box models
  - Application of techniques will vary from ISOs, utilities, turbine vendors & expert consultants

Screening Techniques	**PSCAD Turbine Model Requirement**	**Possible with non-confidential data available to Utility/ISOs**	**Within commerical software capability**
SSCI Screening			
Transmission System Frequency Scans	No	Yes	Yes
Turbine Side Frequency Scans			
Voltage/Current Injection Technique	Yes	No	No
SSTI Screening			
Electrical Damping Analysis	Yes	No	No

Level of detail required in the PSCAD turbine model has been discussed in publications provided in Future Reading

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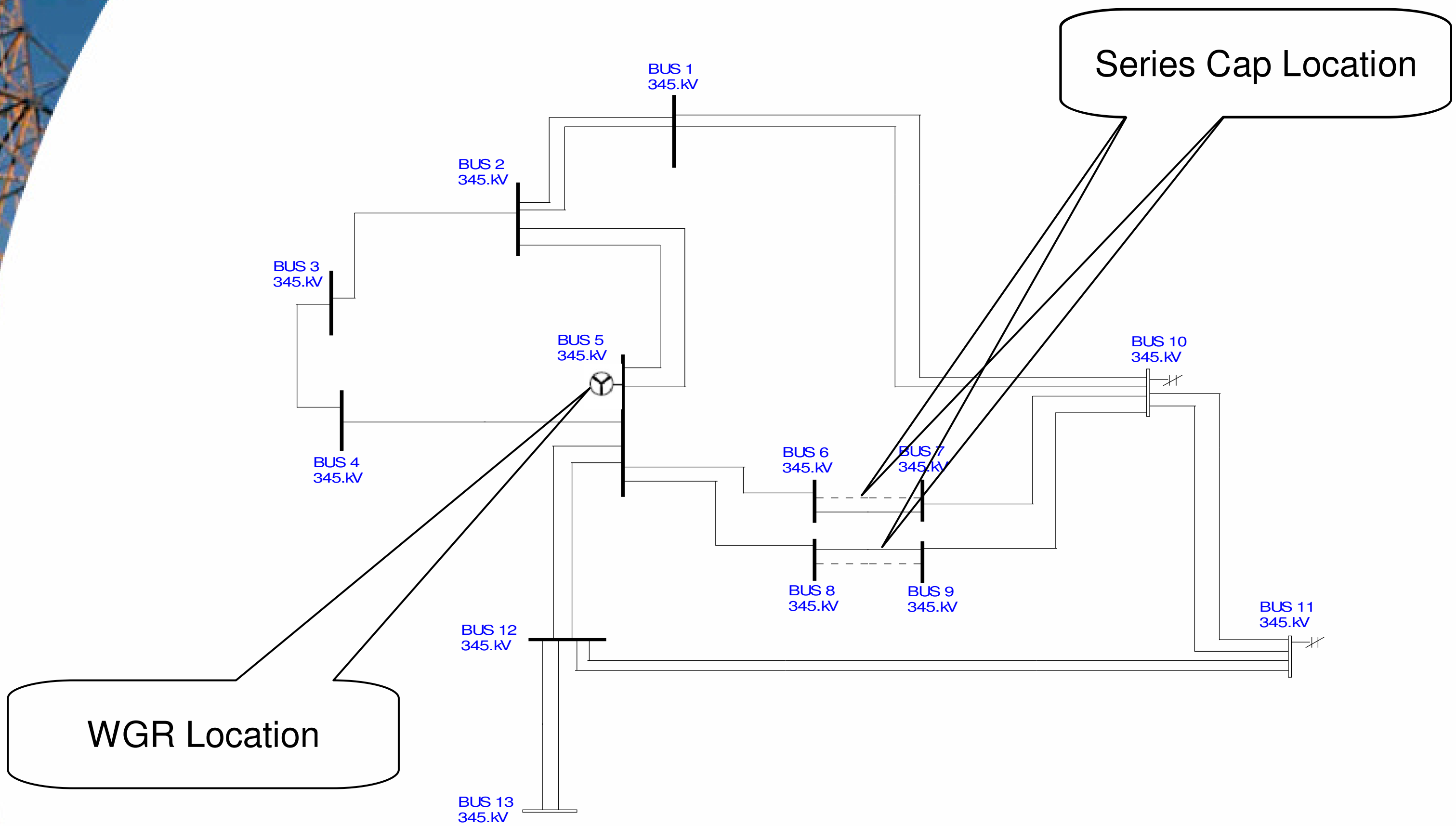
Radial Vs Non-Radial Conditions

Radial Vs Non-Radial Conditions

- Discussion open regarding potential SSCI concerns under non-radial conditions
- Scenarios studied so far indicate SSCI concerns restricted to radial conditions
- Does that preclude non-radial conditions from SSCI susceptibility?
  - Non-radial conditions cannot be excluded from SSCI investigation
  - Needs further investigation
- Key Issues to focus on:
  - Strength of the equivalent of parallel branches vis-à-vis the series compensated line reactance
  - What is an infinitely weak parallel branch equivalent vis-à-vis series compensated section
    - Radial Condition

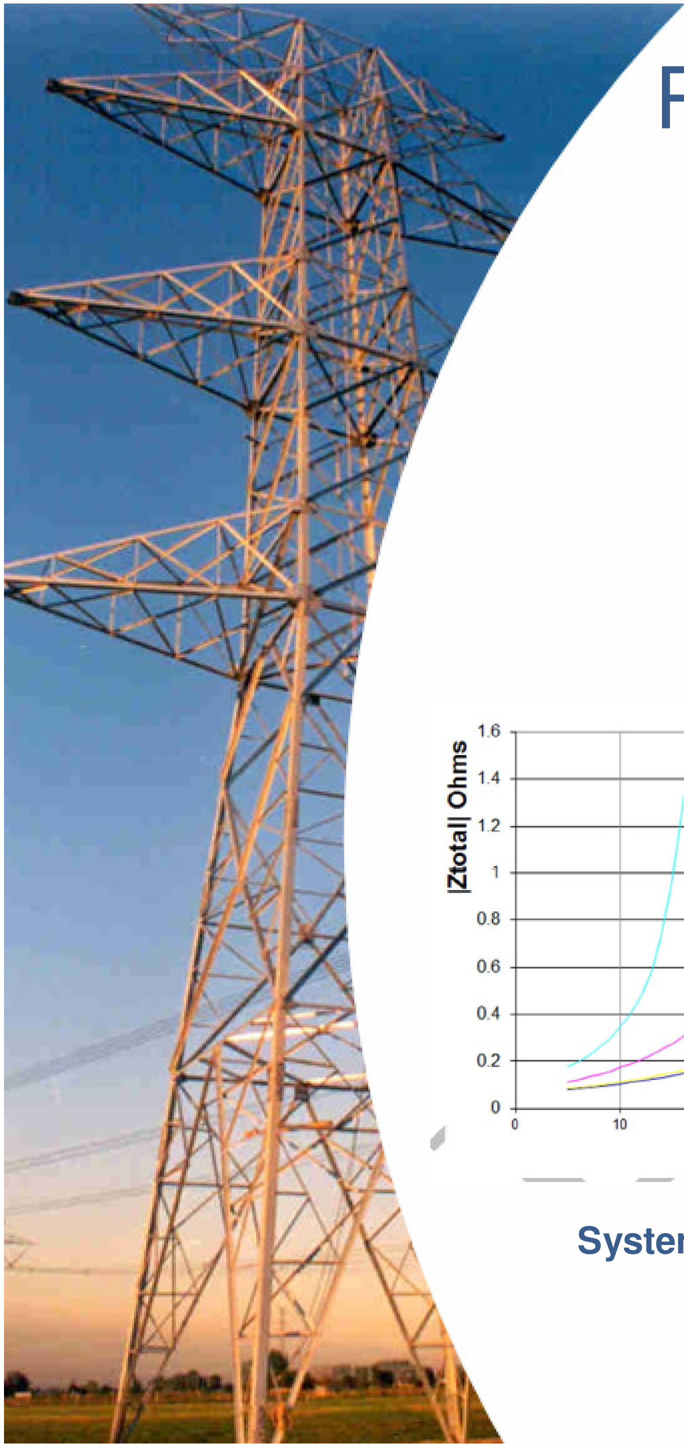
Radial Vs Non-Radial Conditions



One-Line Schematic, Sample ERCOT CREZ System

Radial Vs Non-Radial Conditions

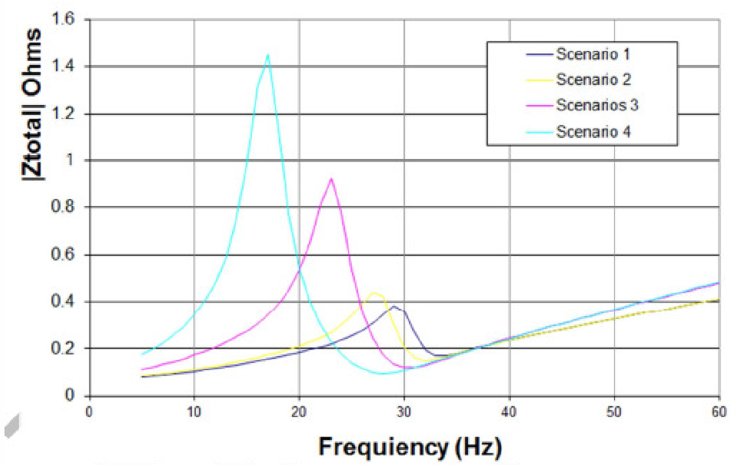
- Driving point reactance from WGR POI assessed via four (4) techniques
  - Method #1: PSCAD Frequency Scan Technique
  - Method #2: Short Circuit Calculation on frequency dependent network
  - Method #3: Frequency scaling of equivalent network derived from short circuit
  - Method #4: Network Reduction
- Driving point reactance assessed for different contingency conditions
  - Remember: R & X provide more insight into SSCI potential
  - None of the conditions result in WGR being radial to series caps



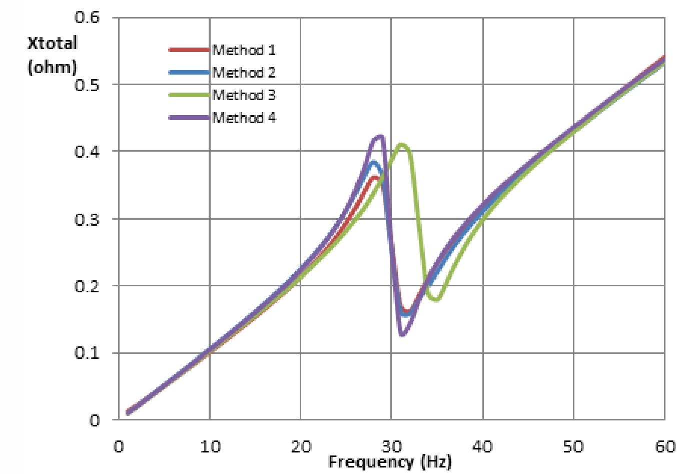
Radial Vs Non-Radial Conditions

Scenario #	System Conditions
1	All lines in-service
2	Bus 5 - Bus 2 Double Circuit Out
3	Bus 5 - Bus 12 Double Circuit Out
4	Bus 5 - Bus 2 Double Circuit & Bus 5 - Bus 12 Double Circuit Out

Scenario Definitions

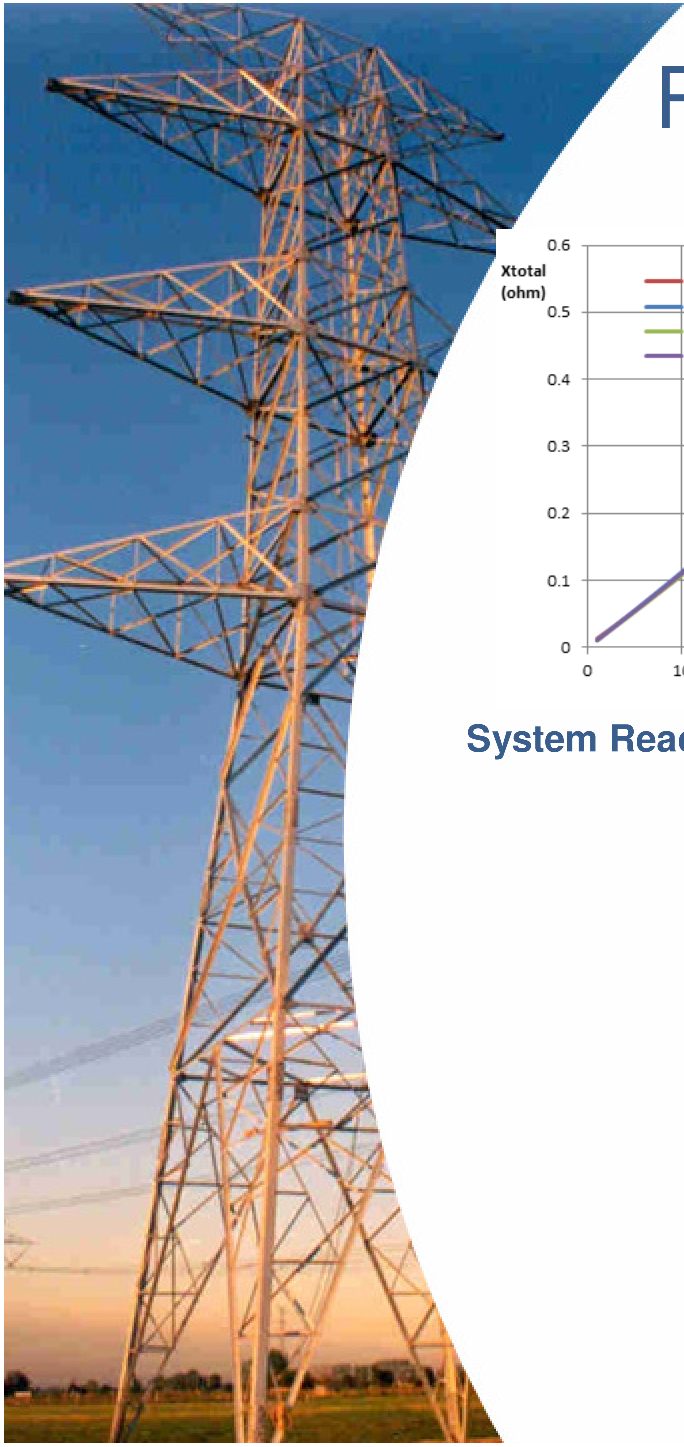


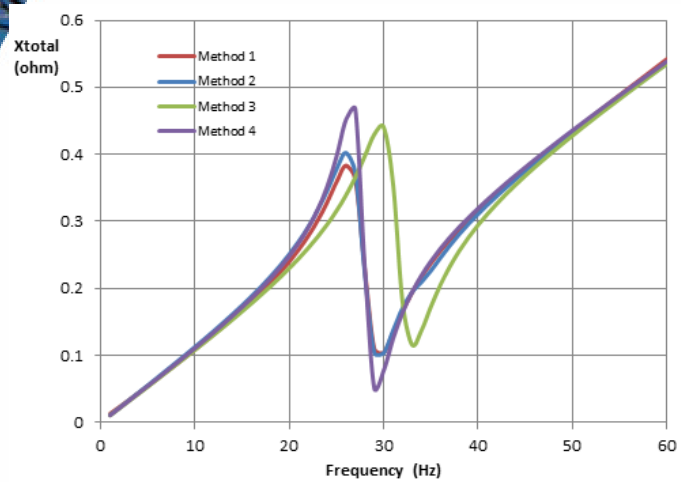
System Impedance Scans



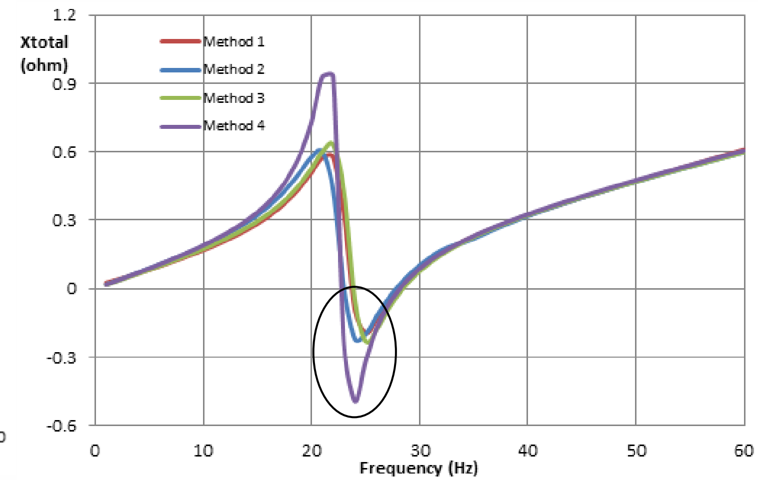
System Reactance Scans, Scenario #1

Radial Vs Non-Radial Conditions

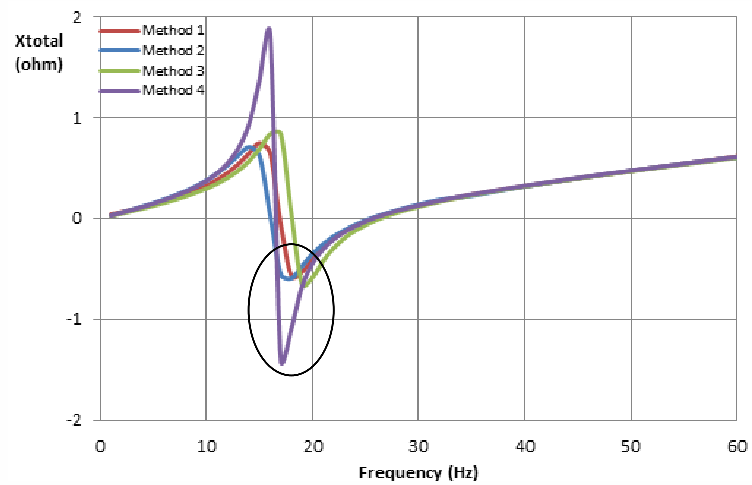




System Reactance Scans, Scenario #2



System Reactance Scans, Scenario #3

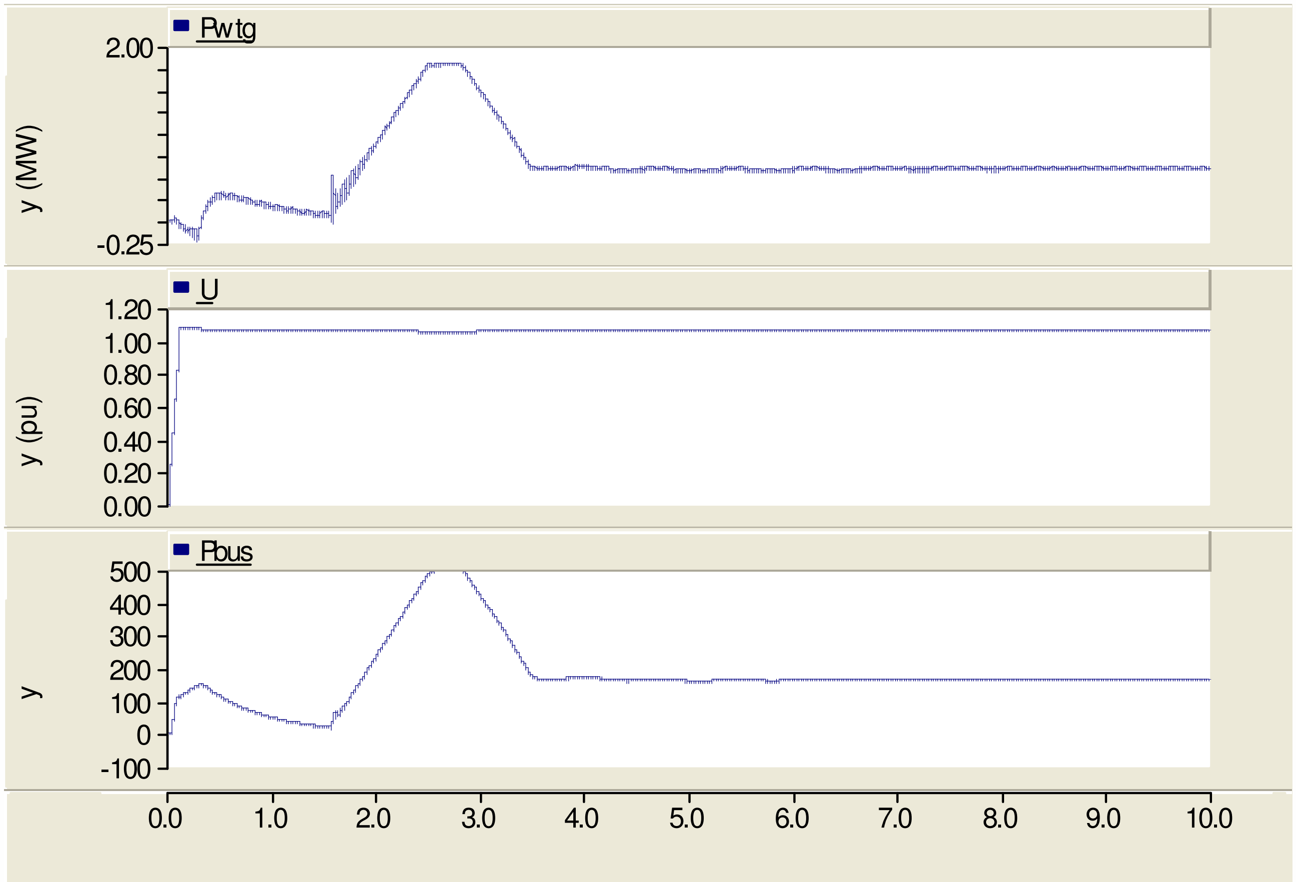


System Reactance Scans, Scenario #4

Radial Vs Non-Radial Conditions

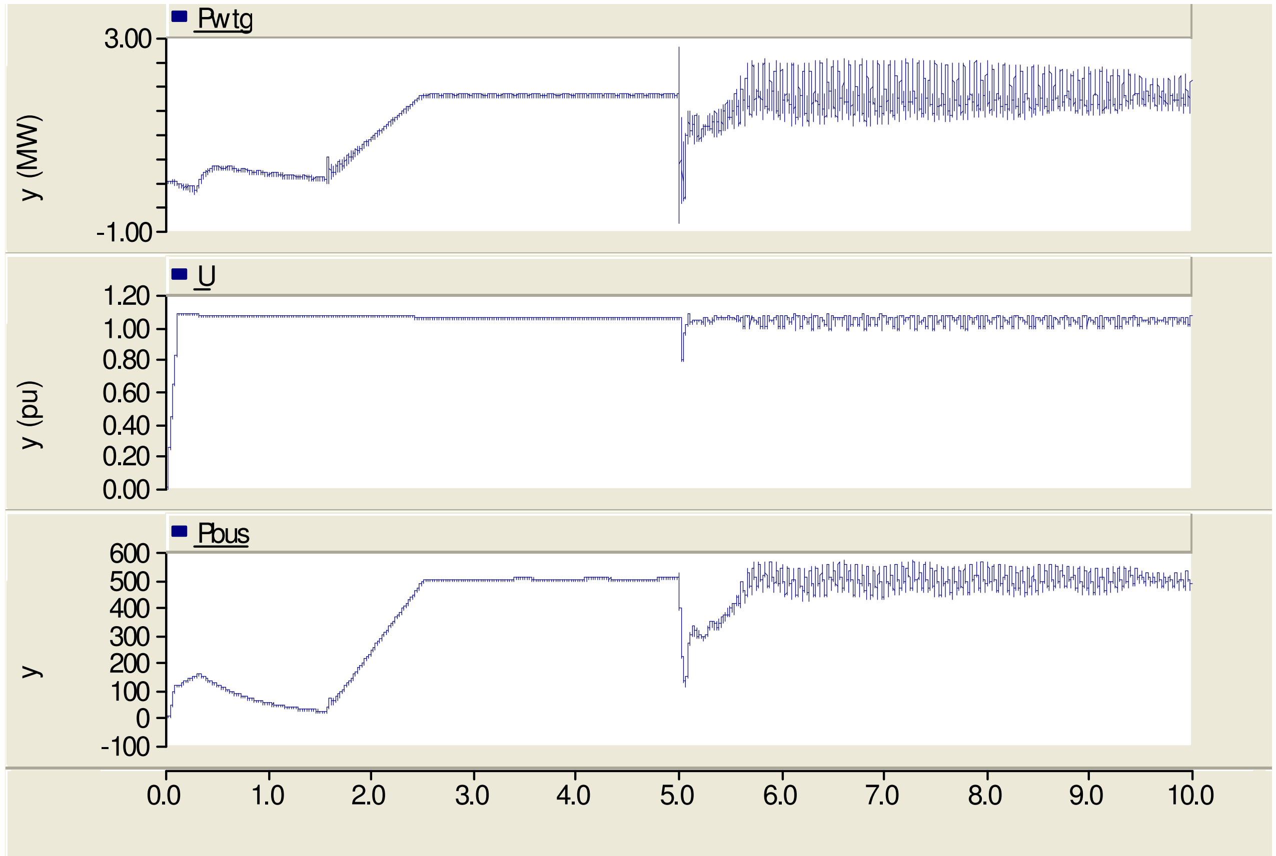
- Key Observations from X_{total} evaluation for Scenarios 1 through 4
  - No reactance cross-over for Sc#1 and Sc#2
  - However, X_{total} does go negative at certain SS frequencies for Sc#3 and Sc#4
- Corroboration by EMT simulation
  - 500 MW wind farm modeled at Bus 5
  - Typical station transformer data
  - No collection system modeled

Radial Vs Non-Radial Conditions



EMT Simulation Results, Faultless Outage, Sc#1

Radial Vs Non-Radial Conditions



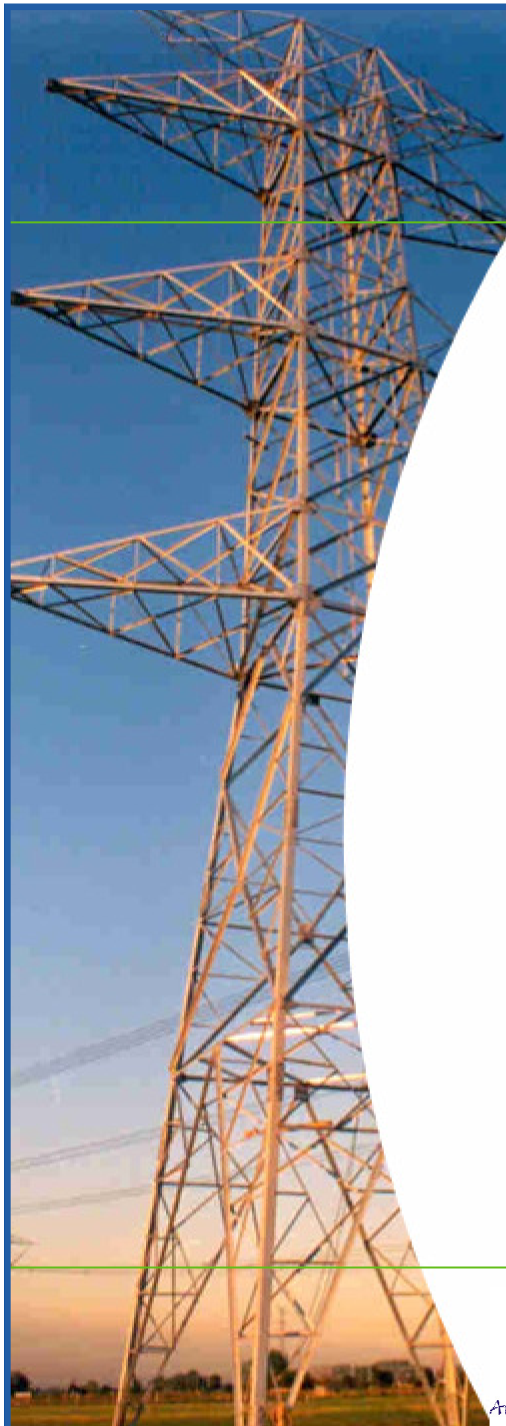
EMT Simulation Results, Sc#3, Fault based outage

Key Observations/Conclusions

Key Observations

- Comprehensive approach for investigating SSI issues presented
  - Screening Techniques
    - Varying degrees of complexity, data requirements & applicability for utility, ISO, turbine vendor and/or consultant use
  - Corroboration with detailed EMT simulations
  - Need for standardizing SSI investigation techniques
    - Findings under publication at various IEEE panel sessions/journals
    - Industry feedback via presentations at forums such as RPG
- SSCI concerns may not be restricted to radial conditions
  - ERCOT CREZ system an ideal example
  - System side reactance scans provide insight into potential for SSCI concerns under non-radial conditions

Future Reading



Future Reading

- "***Advanced Screening Techniques for Sub-Synchronous Interaction in Wind Farms***", M. Sahni, D. Muthumuni, B. Badrzadeh, A. Gole, A. Kulkarni, IEEE PES T&D Panel Session, 2012
- "***Sub-Synchronous Interaction in Wind Power Plants- Part I: Study Tools and Techniques***", B. Badrzadeh, M. Sahni, D. Muthumuni, Y. Zhou, A. Gole, IEEE PES General Meeting Panel Session, 2012
- "***Sub-synchronous Interaction in Wind Power Plants- Part II: An ERCOT Case Study***", M. Sahni, B. Badrzadeh, D. Muthumuni, Y. Cheng, H. Yin, S-H. Huang, Y. Zhou, IEEE PES General Meeting Panel Session, 2012
- ***"Reactance Cross-Over based Approach for Investigating SSCI Concerns under Non-Radial Conditions***", Y. Cheng, M. Sahni, D. Muthumuni, B. Badrzadeh, IEEE Transactions on Sustainable Energy (under submission)

Questions

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