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Presentation to:

IEEE PES Southern Alberta (Calgary) Chapter

Sub-synchronous Interaction and Harmonic Control Instability associated with HVDC and Wind Plant Installations

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OUTLINE

- General background
- Definitions of SSI, SSTI, SSCI and CI
- Commonly used tools and techniques
- Commonly used mitigation measures
- Requirement of re-examine the possibility of SSTI and/or SSCI and CI
- Discussions

GENERAL BACKGROUND

GENERAL BACKGROUND

- Why HVDC Systems?
  - ✓ Long distances
  - ✓ Asynchronous systems
  - ✓ Restricted right-of-way
  - ✓ Directing power flows
  - ✓ Managing AC system problems
  - ✓ Long cables
  - ✓ Visual impact
  - ✓ Staging and expansion

Line Commutated Converters (LCC)	Voltage Source Converters (VSC)
Thyristor based	IGBT based
Requires AC filters and shunt compensation	Generally does not require AC filters
Voltages up to ±800 kV	Voltages up to ±500 kV
Power transfer up to 6400 MW	Power transfer up to 1000 MW
Long history of operation	First introduced by ABB mid 1990s
Mercury arc valves since 1960s	
Thyristor valves since 1970s	

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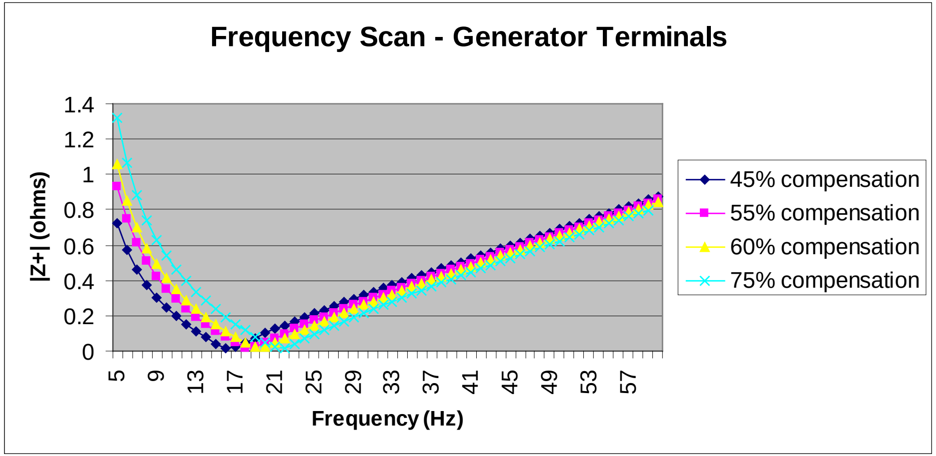
GENERAL BACKGROUND

- Wind turbine generator
  - ✓ **Type 1:** Squirrel Cage Induction Generators driven by fixed-speed, stall-regulated wind turbines
  - ✓ **Type 2:** Induction Generators with variable external rotor resistance driven by a variable-speed pitch regulated wind turbines
  - ✓ **Type 3:** Doubly-Fed Induction Generators (DFIG), driven by a variable-speed pitch regulated wind turbines. Rotor is fed from a three-phase variable frequency source (two voltage-source converters linked via a capacitor).
  - ✓ **Type 4:** Synchronous or Induction Generators with full converter interface (back-to-back frequency converter), driven by variable-speed, pitch regulated wind turbines

GENERAL BACKGROUND

- Series compensation and impact on SSR
  - ✓ Network resonance points can shift to the sub synchronous frequency range (<60 Hz)
  - ✓ Higher the level of series compensation, the resonant point moves toward the system frequency
  - ✓ higher risk of SSR related issues



$$f_e = f_0\sqrt{\frac{X_c}{X_l}}$$

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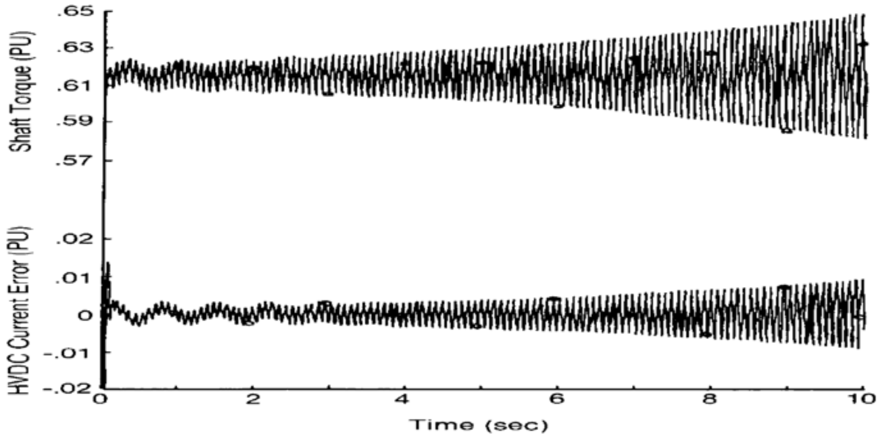
EVENT - SSR

- SSR
  - ✓ Torsional Interaction (TI)– Torsional interaction between the turbine-generator shaft and the electrical grid. The first reported damage to the shaft of a generating unit was observed at the Mohave Generating Station in Southern Nevada in the 1970s.
  - ✓ The resonance was established between torsional mechanical modes on the turbine generator shaft and series compensation on the transmission lines.
  - ✓ This classical form of SSR has since been widely studied and understood. What people are normally referring to when they discuss SSR.

EVENT - SSTI

- SSTI
  - ✓ SSTI was first observed in 1977 at Square Butte in North Dakota
  - ✓ The current control loop of an HVDC converter near the generating plant acted to destabilize a torsional mode under certain system conditions
  - ✓ The 11.5 Hz torsional mode became unstable upon switching out one ac line

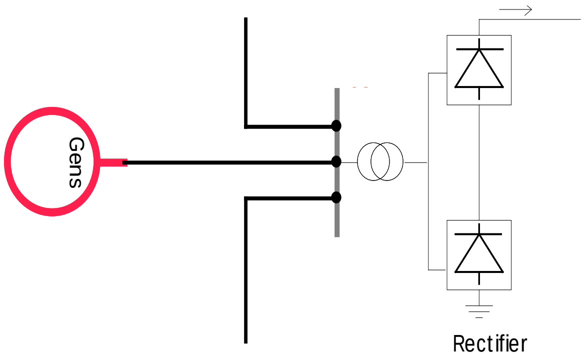


Response to switching out Center Station line at Square Butte

"Torsional Interaction Between Electrical Network phenomena and Turbine-Generator Shafts: Plant Vulnerability," EPRI Technical Report 1013460, 2006

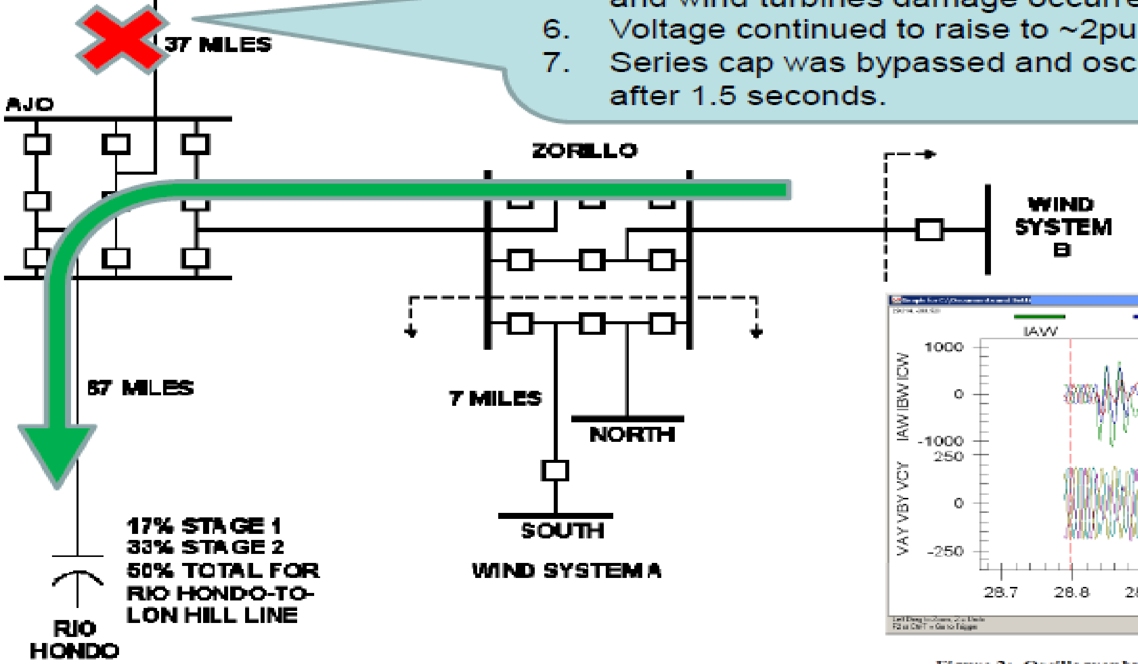
EVENT - SSTI

- SSTI - Interaction with HVDC converter controls
  - ✓ An issue associated with conventional (LCC) HVDC schemes
  - ✓ Turbine-generator located near a rectifier and having a weak connection to the ac network are vulnerable to SSTI
  - ✓ The current and power controller of a HVDC can provide negative electrical damping in 10-30Hz range
  - ✓ Can be easily mitigated through proper design of HVDC control, i.e., SSDC



Sub-synchronous Control Interaction: October 2009 SSCI Event

1. Single Line to ground fault
2. Open the line breaker to clear the fault in 2.5 cycles
3. Wind farms are radial connected to series cap 345 kV line
4. SSCI occurs
5. After 200ms (12 cycles), system voltage exceeded 1.5pu (520 kV) and wind turbines damage occurred.
6. Voltage continued to raise to ~2pu and series cap damage occurred.
7. Series cap was bypassed and oscillation was finally damped out after 1.5 seconds.



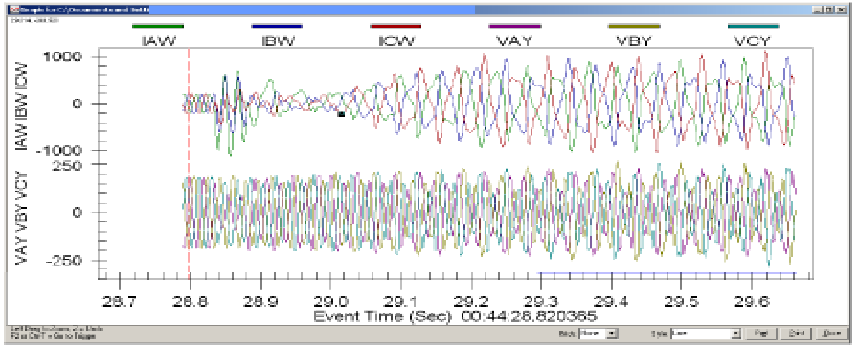
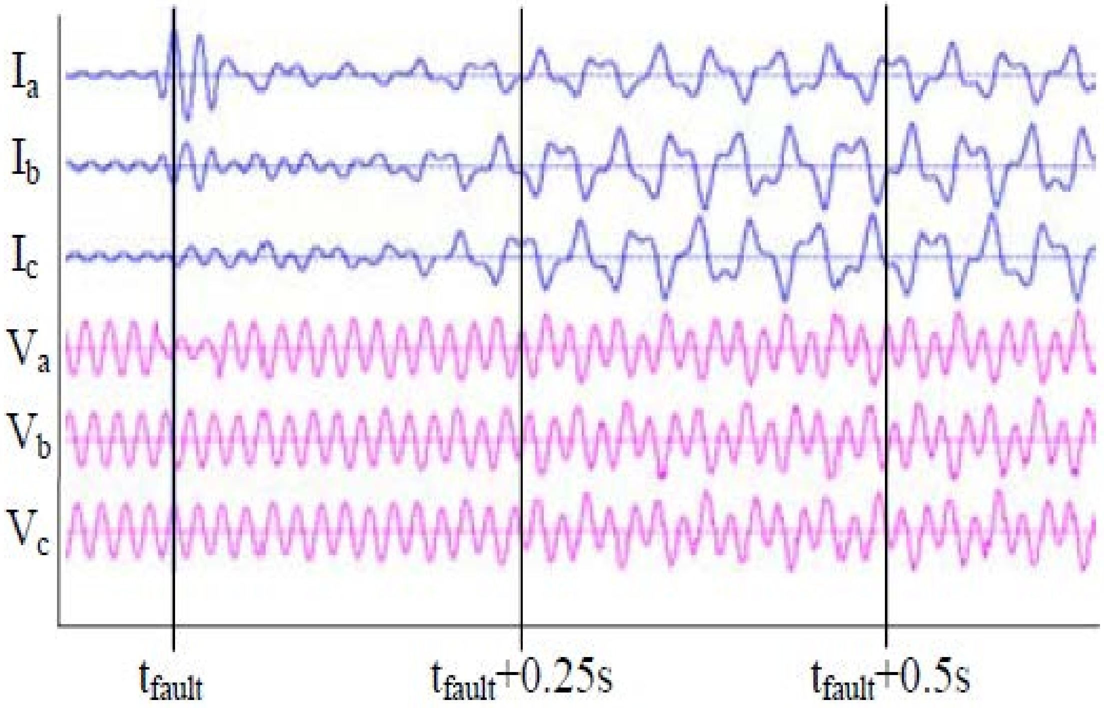


Figure 2: Oscillography Recorded at Wind System A during the Event.

EVENT – TYPE 3 WIND FARM SSCI



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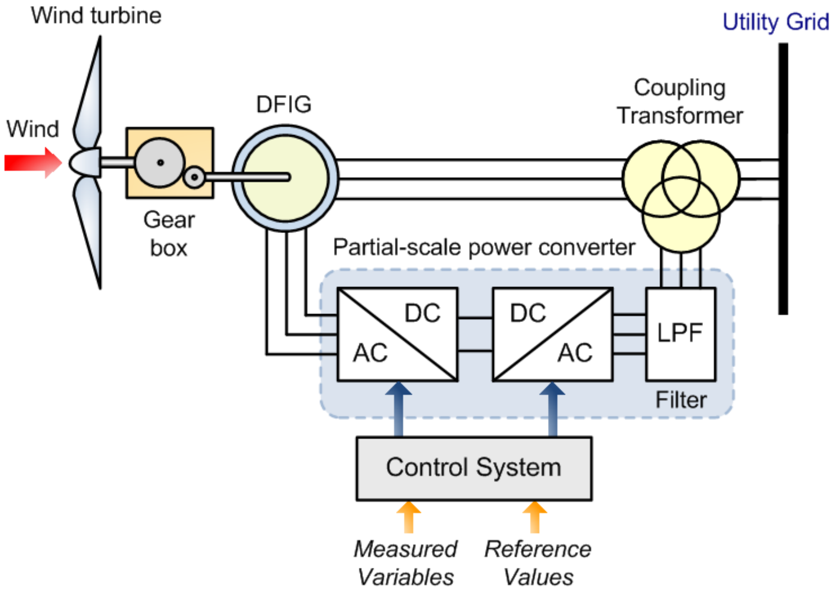
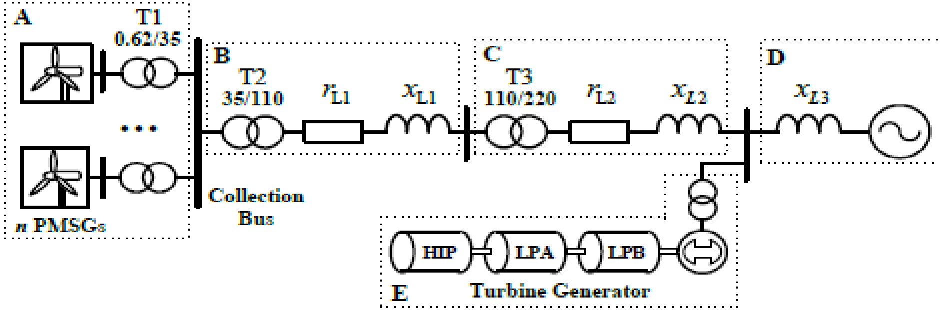
EVENT - TYPE 3 WIND FARM SSCI

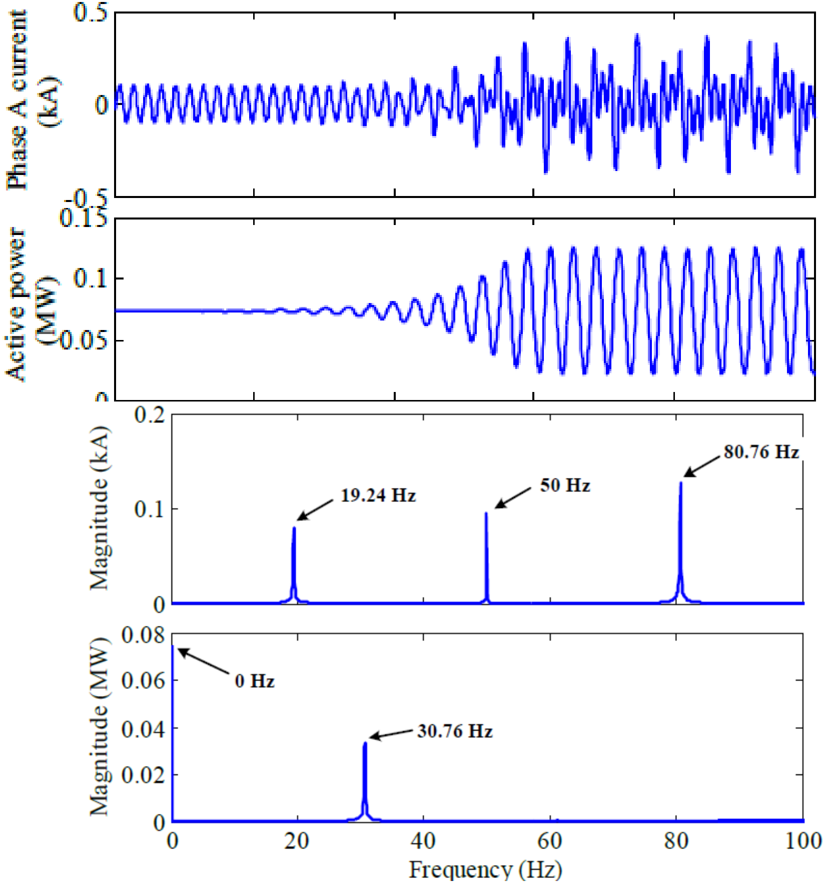
- SSCI involving Type 3 Wind Units
  - ✓ Large remote wind power facilities to be connected to load areas through series compensated transmission lines
  - ✓ Problem: DFIG controls act to ‘amplify’ sub synchronous currents entering the generator
  - ✓ Negative Damping by rotor side converter current controller



EVENT - TYPE 4 WIND FARM SSCI

- ✓ July 1st, 2015, Xinjiang, China. Response to ac system becomes weak due to line trip
- ✓ The SSO spread to the main grid and stimulated one torsional mode of turbine generators





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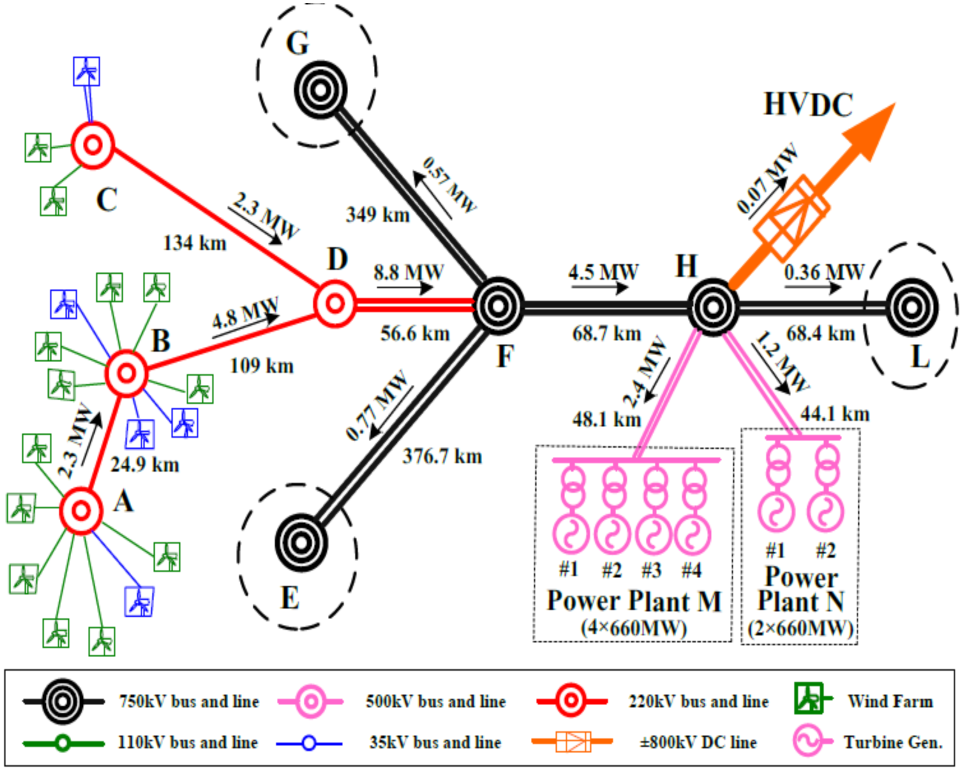
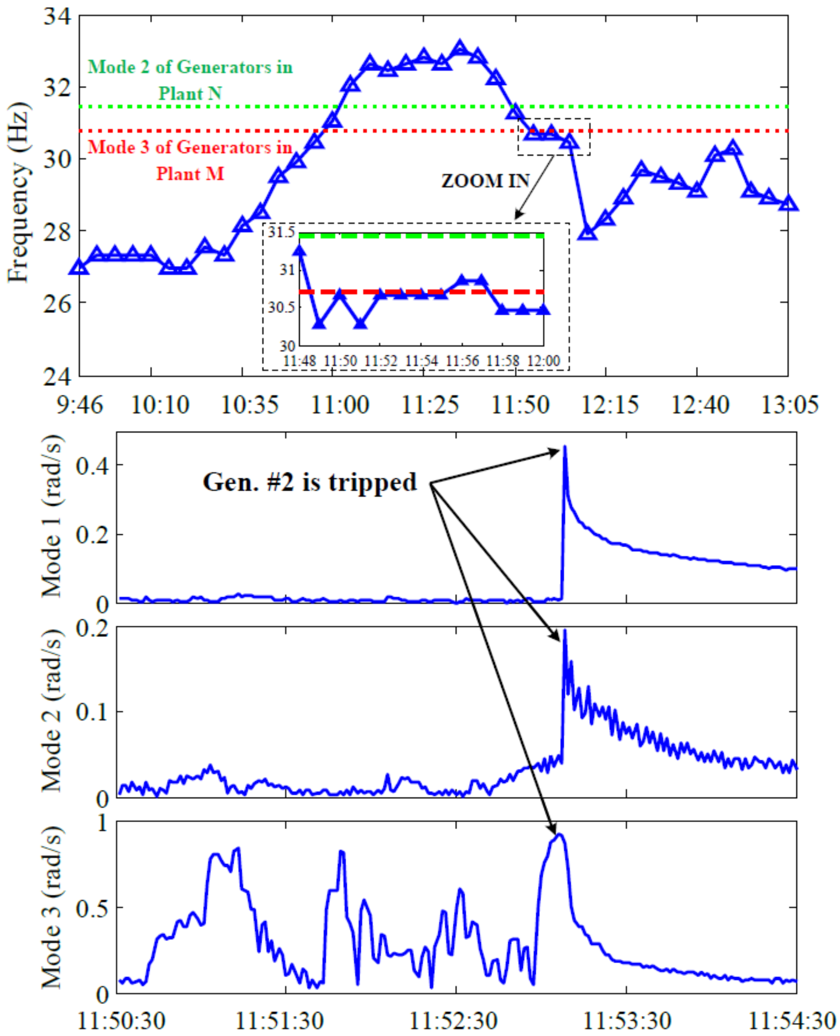
Huakun Liu, Xiaorong Xie, et al., "Subsynchronous Interaction between Direct-Drive PMSG Based Wind Farms and Weak AC Networks," IEEE Transactions on Power Systems, TPWRS.2017.2682197





TORSIONAL MODES

Generators	Mode 1	Mode 2	Mode 3
M: #1/#2/#3/#4	15.38 Hz	25.27 Hz	30.76 Hz
N: #1/#2	18.25 Hz	31.45 Hz	39.45 Hz

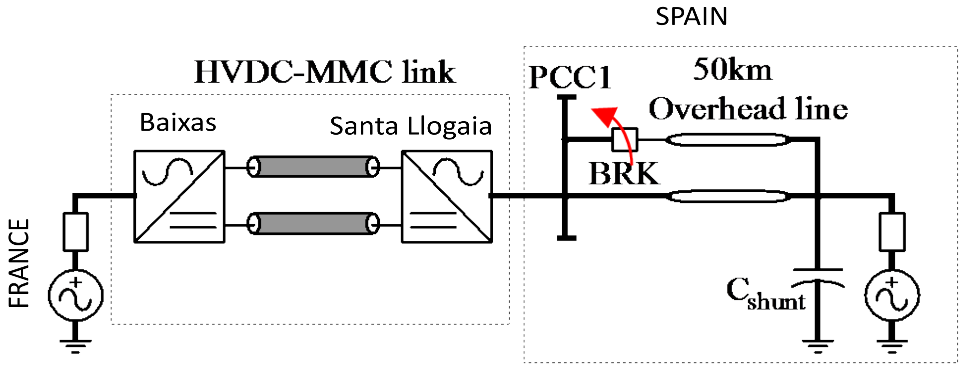
EVENT - TYPE 4 WIND FARM SSCI

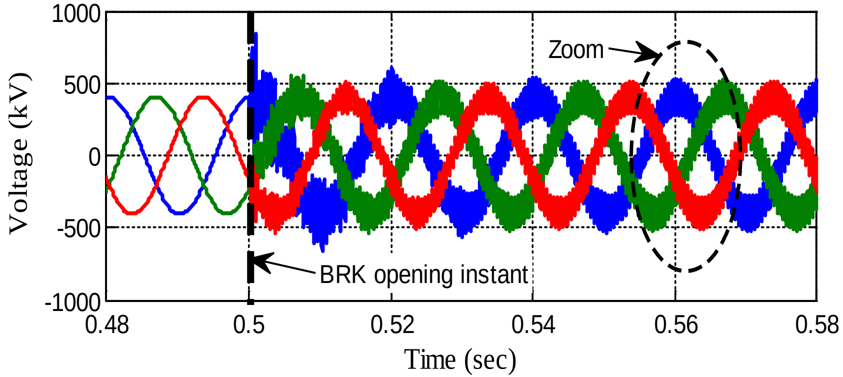
- ✓ With the installed capacity of these farms increasing, many sustained power oscillation events have occurred in these farms since June 2014.
- ✓ On July 1st, 2015, a severe SSI event occurred. The sustained power oscillation induced by these PMSG-based wind farms excited intense torsional vibration on shafts of power plant M.
- ✓ The SSI event lasted for about 3 hours and 20 minutes. The frequency varies in a wide range from 27 Hz to 33 Hz. Frequency at mode 3 lasted for about 360 s (see the zoomed-in curves). As a result, intense shaft torsional vibration at mode 3 was excited on generators in plant M.
- ✓ The torsional stress relays had to trip all the affected generators. The protection devices were installed originally to counteract the possible SSTI between units and HVDC.
- ✓ causing a total power loss of about 1280 MW and the frequency of this regional grid decrease from 50.05 Hz to 49.91 Hz.

Huakun Liu, Xiaorong Xie, et al., “Subsynchronous Interaction between Direct-Drive PMSG Based Wind Farms and Weak AC Networks,” IEEE Transactions on Power Systems, TPWRS.2017.2682197

EVENT – VSC HVDC CI

- CI – for grid-connected inverter
  - ✓ INELFE: Oscillations at harmonic frequency (1.7 kHz) observed on site after opening OHL breaker.





Harmonic control instability: VSC – INELFE – 2000 MW Commissioned in 2015

CIGRE TB B4.67 "AC side harmonics and appropriate harmonic limits for VSC"

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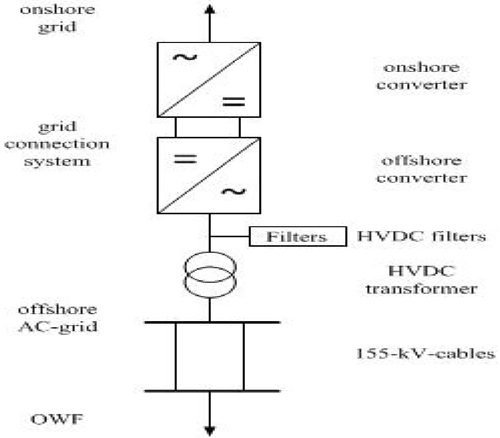
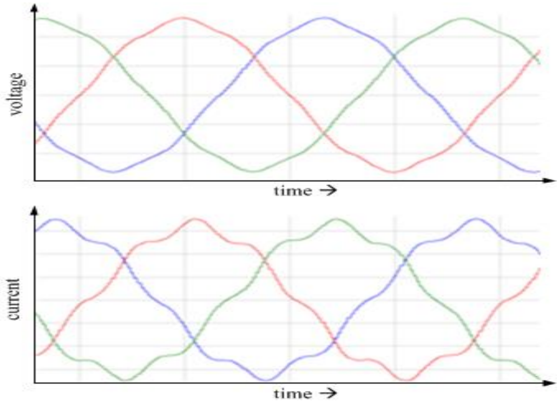
ACTIVE BEHAVIOR OF CONVERTERS – HARMONIC INSTABILIT

- ✓ The interaction is characterized by the natural frequencies of the network and the damping provided by the converter.
- ✓ Electromagnetic natural frequencies appearing within a region in which the converter presents ‘negative-resistive’ behavior may result in an instability if the network does not provide enough damping.
- ✓ The instability appears as an oscillatory component at harmonic frequencies with increasing amplitude and results in harmful effects such as the damage and ageing of assets or the trigger of the converter installation.
- ✓ Besides the extreme case of instability, resonances coinciding with this region may also result in sustained oscillations for several seconds with the respective over-voltages and adverse effects.

EVENT – OFFSHORE WIND GEN CI

- CI – for grid-connected offshore wind farm
  - ✓ BORWIN1: With slight 5th and 7th harmonics injected by the offshore wind turbines, phase voltages and currents become distorted during resonant grid scenarios.
  - ✓ Led to numerous outages of the HVDC system caused by thermal overload of its offshore AC filter.





CIGRE TB B4.67 “AC side harmonics and appropriate harmonic limits for VSC”

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EVENT – OFFSHORE WIND GEN CI

- ✓ BORWIN1: Commissioned in 2009. Within the offshore grid, all generation units and all loads are connected by power electronics. The whole connection system is optimized to have low losses and very little damping is provided in such an offshore grid
- ✓ From 2013 to 2015, as more offshore wind turbines were progressively commissioned, Borwin1 suffered harmonic instabilities. They led to numerous outages of the HVDC system caused by thermal overload of its offshore AC filter. As harmonics were often above allowed limits, capacitors of the filter were damaged over time.
- ✓ Instabilities were caused by the amplification of low order harmonics produced by wind turbines during particular offshore grid configurations presenting active resonances and were strengthened by the active behaviour of wind turbine VSC-converters at these frequencies.
- ✓ Their PLL (phase-locked-loop) and their current control loops were responsible for it.

CIGRE TB B4.67 "AC side harmonics and appropriate harmonic limits for VSC"

DEFINITION

DEFINITIONS OF SSI

- SSI: sub-synchronous interaction
  - ✓ (SSI) are a family of physical interactions which involve exchange of energy between a generator and a transmission system at AC frequencies below the system nominal frequency. They include SSR, SSTI, and SSCI.

DEFINITIONS OF SSR

- SSR: sub-synchronous resonance
  - ✓ Interaction between a series capacitor and the mechanical/torsional masses in a generator (or wind turbine) at sub-synchronous (SS) frequency
    - Induction generator effect (IGE)
    - Torsional interactions (TI)
    - Transient torques Amplification (TA)
  - ✓ Mainly to conventional synchronous machines with long turbine shaft systems

DEFINITIONS OF SSR

- Induction generator effect (IGE)
  - ✓ Purely electrical phenomenon
  - ✓ Self-excitation of SS oscillations
  - ✓ Negative SS resistance of generator rotor circuit exceeds the sum of:
    - Generator Armature/Stator circuit
    - System/Network resistances
  - ✓ Well understood, and it is less likely to pose an SSR concern in modern machines due to the ability of shaft system manufacturers to avoid torsional modes of oscillation at very low mechanical frequencies, where the effect is most pronounced.

DEFINITIONS OF SSR

- Torsional Interaction (TI)
  - ✓ Electrical resonance frequency (fe) of system caused by series capacitors close to compliment of natural torsional resonance frequency (fn) of mechanical system (turbine-generator unit) (TI).

    i.e., fe = fo - fn

  - ✓ Result in shaft fatigue & undesirable stress

DEFINITIONS OF SSR

- Transient Torsional Torque (TA)
  - ✓ Oscillations in the shaft torque immediately after a large disturbance
  - ✓ Could be sustained over long periods of time (and may even grow) in series compensated networks
  - ✓ Grid side reactance scans can provide good insight into transient torque issues
  - ✓ Reactance minimum with significant dip in vicinity of (60-fn)

DEFINITIONS OF SSTI

- 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…)
  - ✓ The power electronic controller can exhibit negative damping at sub-synchronous frequencies
  - ✓ This can also occur for wind turbine shaft systems, although the torsional modes are generally at low frequencies and are not a problem.
  - ✓ SSTI is easily mitigated through special damping controllers which may be integrated into the power electronic controller

DEFINITIONS OF SSCI

- SSCI: sub-synchronous control interaction
  - ✓ Interactions between a power electronic device (such as wind turbine, solar generators, FACTS, SVC, etc…) and a series compensated system.
  - ✓ Purely electrical phenomenon without shaft torsional dynamics being involved.
  - ✓ SSCI has no fixed frequency, since the frequency of the oscillations are based purely on the configuration of the controls and the configuration of the electrical transmission system
  - ✓ The oscillations grow very quickly as compared to mechanical SSR effects.
  - ✓ DFIG controls act to ‘amplify’ sub synchronous currents entering the generator. Negative damping by rotor side converter current controller

G. D. Irwin, et al., “Sub-synchronous control interactions between type 3 wind turbines and series compensated AC transmission systems”

DEFINITIONS OF CI

- CI: Harmonic control instability
  - ✓ Interaction between the grid-connected inverters for renewable energy sources integration
  - ✓ The inverters exhibit capacitive output impedance at harmonics and may resonate with the grid impedance.
  - ✓ Such resonances can be both sub and super synchronous.
  - ✓ The voltage source converter presents dynamics and control loops extended over a wider range of frequencies and up to considerably higher frequencies.

DEFINITIONS OF CI

- CI: Harmonic control instability
  - ✓ The interaction of the converter with the surrounding network differs and is affected by :
    - the massive penetration of power electronics based equipment,
    - the phase out of conventional generation, and
    - the extended tendency of obtaining more efficient assets and transmission equipment
  - ✓ Useful analysis tools to study active resonances include frequency sweeps of the parallel equivalent impedance between the converter and the AC network at the point of common coupling. Searching for phase impedance overshooting ±90 degrees correspond to searching for negative resistive impedances.
  - ✓ Time-domain simulation, is also an efficient tool as it allows to calculate resulting harmonic amplitudes and to verify if the converter trips under various conditions.

COMMON USED TOOLS AND TECHNIQUES

COMMON USED TOOLS AND TECHNIQUES

- Screening analysis
  - ✓ Unit Interaction Factor (UIF)
    - ➢ SSTI: phasor domain transient stability program
  - ✓ Impedance scan and Electrical damping analysis
    - ➢ SSR/SSCI/CI: frequency scanning program
      - Determine net system impedance (as seen from behind the generator equivalent impedance) as a function of frequency
      - Determines approximate frequency of electrical resonance
      - Impedance “dip” an approximate indicator of the likelihood of SS interactions (large dips indicate “closer to radial” connections – transition from positive to negative reactances)

COMMON USED TOOLS AND TECHNIQUES

- Perturbation electrical damping analysis
  - ✓ Perturbation analysis to determine electrical damping vs frequency
    - ➢ SSTI: EMT program

- Dynamic Impedance Scan
  - ✓ Advanced current/voltage injection techniques based frequency scanning to determine effective dynamic impedance of non-linear and active device
    - ➢ SSCI/CI: EMT program
      - The detailed time-domain representation of the wind turbine model, and will therefore include the representation of control systems and system non-linearities in full detail.
      - Uses a combination of Harmonic Impedance Scans (linear portion of a system) and Effective Dynamic Impedance Scan (non-linear and active device)

COMMON USED TOOLS AND TECHNIQUES

- Optional: Eigenvalue analysis
  - ✓ Eigenvalue analysis provides valuable insight into potential modes of oscillations at a given operating point.
  - ✓ These generic models do not represent several non-linearities which exist in practice including those associated with hard limiters in the turbine controller
  - ✓ The information provided by the eigenvalue analysis can also be captured by the combination of frequency scanning and electrical damping analyses which essentially determine the resonance frequency and electrical damping under various operating conditions.
  - ✓ The electrical damping analyses are based on a time-domain analysis which has a significantly higher accuracy than the eigenvalue approach which is based on the assumption of a linear system behavior.

COMMON USED TOOLS AND TECHNIQUES

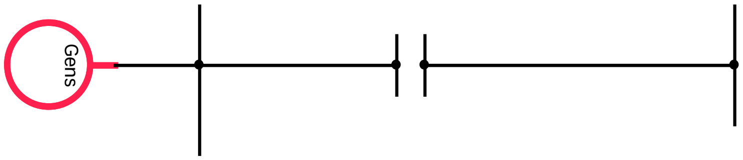
- Full time domain transient
  - ✓ SSR/SSTI/SSCI/CI: Uses fully detailed models of all devices in EMT program
    - Ultimate Simulation… Model the entire system including multi-mass shaft models, HVDC/SVC/Statcoms, wind farms etc…
    - Apply a small signal disturbance and measure log-decrement (quantify damping)
    - Apply faults and observe large signal disturbances (and watch for tripping/ride through)
    - Time consuming (varying loadflow conditions, contingencies, wind turbine combinations, two segment series capacitors…)
    - Used in conjunction with Screening Studies (to focus on most-concerning cases)

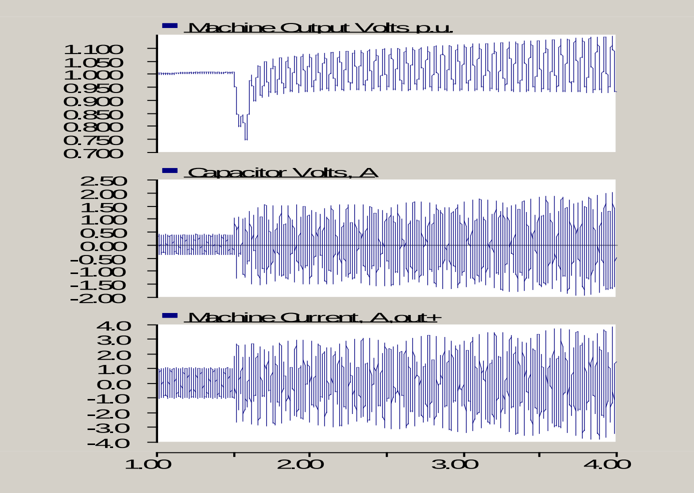
SSR FOR SERIES COMPENSATION

- SSR impedance scan: Z_{SSR}(=R_{SSR} +j X_{SSR}), as a function of frequency, seen when looking into the system from the neutral terminal of the generator
  - ✓ Frequency scans were performed for the base case, as well as system outages including single and multiple contingencies; variations in series compensation.
  - ✓ For each case and contingency, electrical “undamping” (negative damping) was calculated then compared to an estimate of mechanical positive damping to determine whether the mechanical mode was sufficiently damped.
  - ✓ A simple screening test for likely transient torque amplification problems is to find coincidences of mechanical modal frequencies with local minima in SSR reactance.

SSR FOR SERIES COMPENSATION

- Induction Generator Effect (IGE)
  - ✓ A negative value of RSSR at a series resonance frequency (XSSR=0) would be expected to result in self sustaining oscillations due to induction generator effect.
  - ✓ Purely electrical phenomenon
  - ✓ Self-excitation of Sub Synchronous Oscillations





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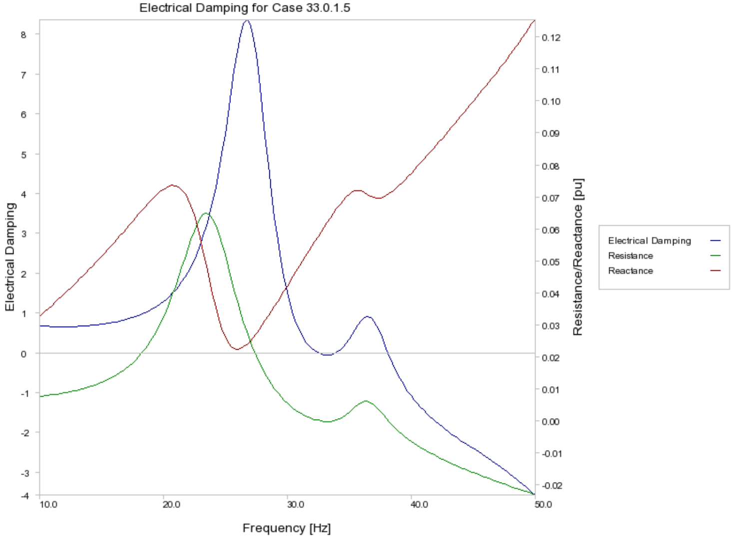
SSR FOR SERIES COMPENSATION

$$UDR = D_e/D_n$$

$$De = \frac{fe}{2 * fn} * \frac{R_{SSR}}{R^2_{SSR} + X^2_{SSR}}$$

$$Dn = 4 * Hn * \sigma_n$$

- Electrical damping analysis for Torsional Interaction (TI)
  - ✓ for UDR greater than unity (UDR>1) it is considered that the system would sustain self-excited oscillations
  - ✓ Electrical resonance frequency (fe) of system caused by series capacitors close to natural torsional resonance frequency (fn) of mechanical system (turbine-generator unit) i.e., fe = fo – fn (a range of ± 0. 5 Hz of fn as a criterion)
  - ✓ Result in shaft fatigue & undesirable stress, damage
  - ✓ Typical mechanical resonance frequencies (15 – 30 Hz)



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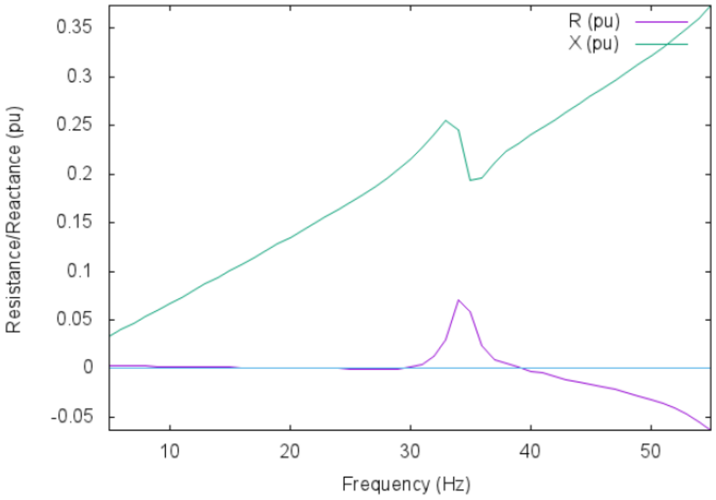
SSR FOR SERIES COMPENSATION

- Transient torques Amplification (TA)
  - ✓ A "reactance dip" of SSR impedance wherever a local minimum and a local maximum of SSR reactance occur within a specified frequency band near the modal frequency. (±3 Hz is used as a screening criterion.)
  - ✓ A reactance dip of greater than 5% which occurs near a modal frequency indicates that there may be transient torque problems related to that mode.

$$\frac{X_{SSR,MAX} - X_{SSR,MIN}}{X_{SSR,MAX}}.100\%$$



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SSR FOR SERIES COMPENSATION

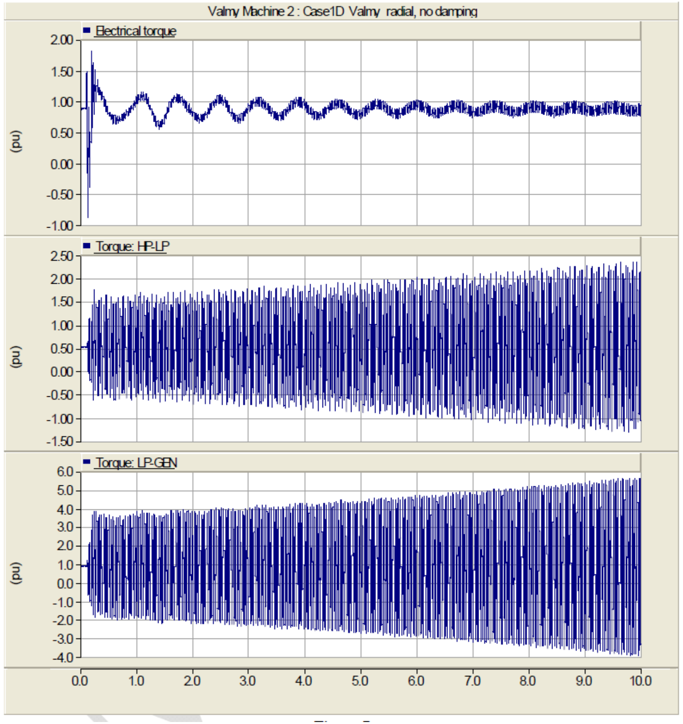
- Full time domain transient analysis

o The critical items that determines the level of severity are:

✓ Amplitude of the mechanical transient oscillations

✓ Decay of the oscillations (damping)

✓ Peak transient torque produced on each shaft segment can be used to determine the level of risk.



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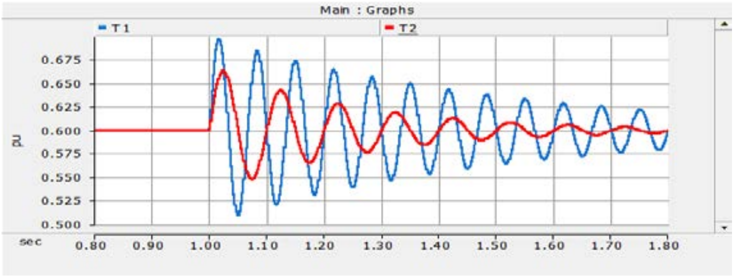
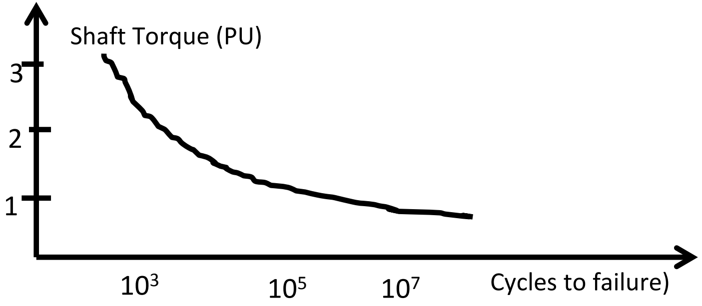
SSR FOR SERIES COMPENSATION

- Full time domain transient analysis
  - Machines are designed to withstand for “terminal short circuit” and the peak torque.
    - ✓ If the torque produced for an evet is larger than about 75% of the value for terminal short circuit, it is considered as in the zone of vulnerability.
    - ✓ Shaft oscillations following disturbances will result in shortening of the shaft life time due to material ‘fatigue’.
    - ✓ S-N curves (number of stress cycles as a function of stress amplitude before crack initiation).





Source: EPRI report: "*Torsional Interaction Between Electrical Network Phenomena and Turbine-Generator Shafts*"

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SSTI FOR HVDC

- UIF screen study
  - ✓ How close, electrically, the HVDC system is to the generating unit and the relative electrical coupling between two
  - ✓ The relative size of the HVDC as compared to the generating unit
- Perturbation electrical damping analysis
  - ✓ The total phase lag from a perturbation in the generator speed to the generator electrical torque, including the action of the HVDC controls
- Full time domain transient analysis

SSTI FOR HVDC

- Unit Interaction Factors
  - ✓ UIF > 0.1 is recommended for further analysis
  - ✓ UIF should be calculated for carefully selected (credible) N-x outage conditions

$$UIF_i = \frac{MVA_{HVdc}}{MVA_i}\left(1 - \frac{SC_i}{SC_{TOT}}\right)^2$$

- SC_{TOT} – Short circuit level at the HVDC terminal
- SC_i – Short circuit level at the HVDC terminal with the generator under SSTI investigation disconnected.

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SSTI FOR HVDC

- Unit Interaction Factors
  - ✓ It is only an indicator of the amount of electrical torque that might be applied to the machine (at sub-synchronous frequencies) as a consequence of converter operation.
  - ✓ Furthermore, UIF values are calculated at fundamental frequency only, and network impedance at sub-synchronous frequencies plays a role in determining the magnitude of the torque likely to be applied.

SSTI FOR HVDC

- Perturbation electrical damping analysis
  - ✓ Consider open loop transfer function from generator rotor speed to electrical torque…
  - ✓ Inject a small perturbation in the turbine speed
  - ✓ Measure the relative magnitude and angle between Te and Δω
  - ✓ Compute and store the damping coefficient De(ω)
  - ✓ plot damping vs frequency curves

$$\frac{\Delta T_E}{\Delta \omega_G}(j\omega) = D_e(j\omega) - j\left(\frac{\omega_o}{\omega}\right)K_e(j\omega)$$

where:

D_e = effective damping factor due to electrical system

K_e = effective synchronizing factor due to electrical system

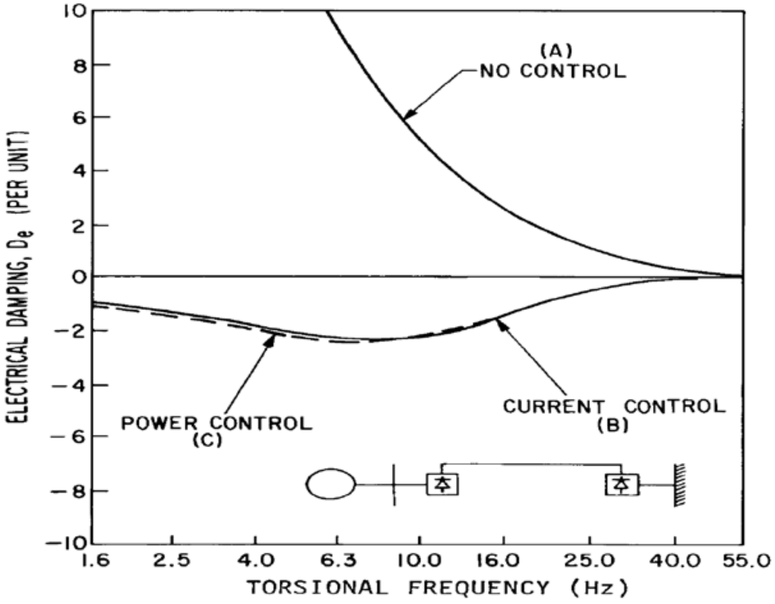
ω = frequency of oscillation

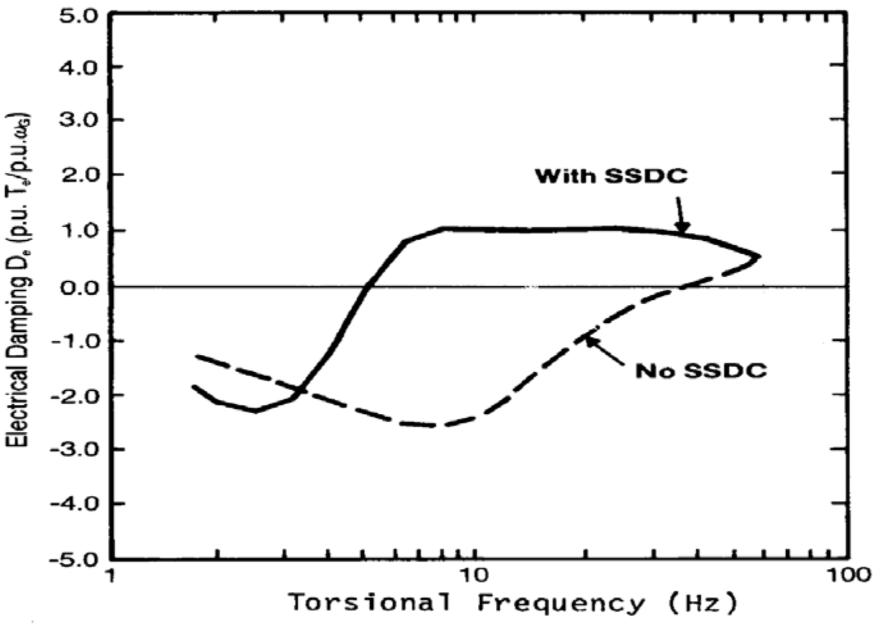
ω_o = system base frequency (60 Hz)

SSTI FOR HVDC

- Perturbation electrical damping analysis
  - ✓ The use of electrical damping alone is a conservative approach due to the neglect of the inherent mechanical damping of the turbine generator.
  - ✓ This process is repeated for all contingencies and generators that have been identified from UIF screening studies.
  - ✓ The frequency regions of negative damping can be compared to the mechanical modes of oscillation and mechanical damping levels for each generator of interest.
  - ✓ If there is overlap (i.e., a natural modal SSR frequency of a generator shows low or negative damping in the electrical system at this frequency), then undamped torsional oscillations are a concern for the generator under study.

SSTI FOR HVDC





EPRI, "HVDC System Control for Damping of Subsynchronous Oscillations," EPRI EL-2708, 1982

SSTI FOR HVDC

- Full time domain transient analysis
  - ✓ In addition to detailed SVC models, complex loads, generator exciters, governors, stabilizers, and the HVDC transmission in the perturbation analysis, a full time-domain study requires more detailed data for all nearby thermal generator units, in particular the shaft coefficients and the mass of each turbine/mass on the shaft.
  - ✓ A large signal disturbance following a nearby ac transmission fault.

SSCI FOR WIND FARM

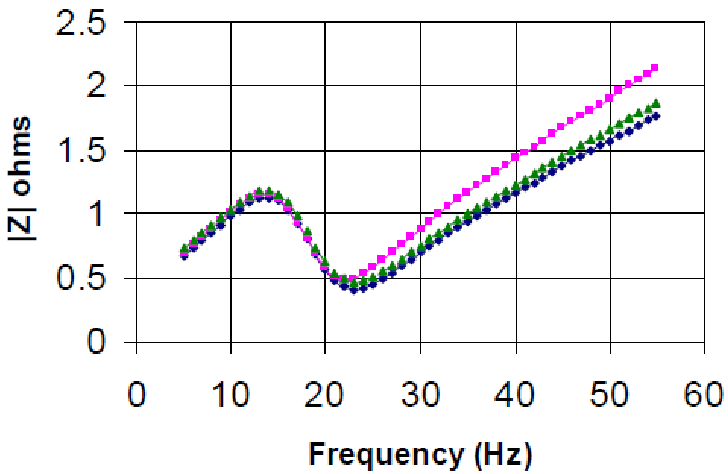
- System side frequency scans
  - ✓ Impedance “dip” an approximate indicator of the likelihood of SS interactions
- Turbine side dynamic frequency scans based on advanced current injection techniques
  - ✓ Any reactance crossovers on the turbine side that coincides with resonant conditions on the system side
  - ✓ Any resonant condition on the system side if the turbine resistance at that SS frequency is negative.
- Full time domain transient analysis

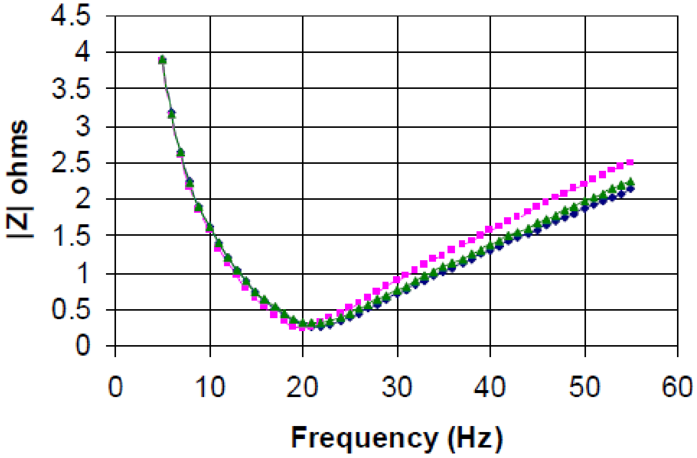
SSCI FOR WIND FARM

- System side frequency scans for credible & critical system conditions
  - Credible System Conditions
    - ✓ Planning contingencies/outages focused around WGR resulting in radial/near radial to series compensation
  - Critical System Conditions
    - ✓ Above and beyond the credible system conditions
    - ✓ Objective to identify outages that result in WGR being radial to the series compensation

SSCI FOR WIND FARM

- System side frequency scans : credible and critical system conditions





System side frequency scans for a nearly radial and radial system

B. Badrzadeh, et al., "General Methodology for Analysis of Sub-Synchronous Interaction in Wind Power Plants," IEEE Transaction on Power System, Vol. 28, pp. 1858-1869, 2013

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SSCI FOR WIND FARM

- Turbine side dynamic frequency scans
  - Passive network reduction methods do not lend themselves well to frequency scans for dynamic devices
    - ✓ Power electronic components and control system contributions
  - Current/Voltage injection technique utilized for turbine side scans

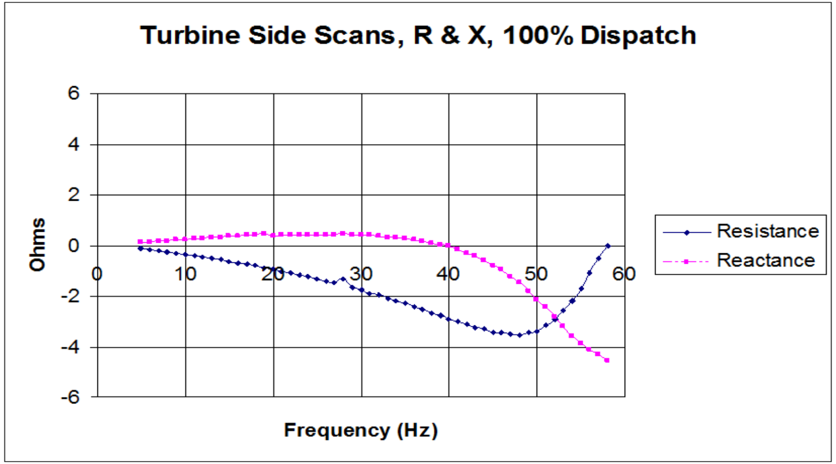
  Key aspects:

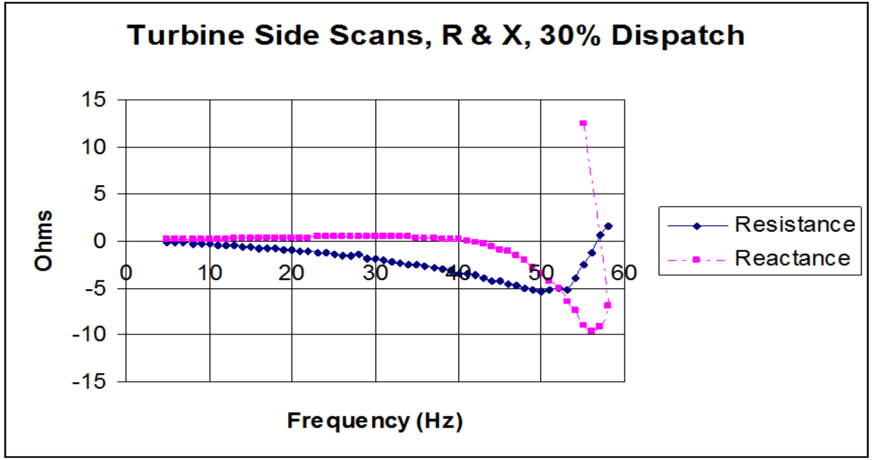
    - ✓ Ensure stable operation of the turbine following the signal injection
    - ✓ Wind turbine model should include all important details including control system details and set points
    - ✓ Transmission system details not necessary System side frequency scans

SSCI FOR WIND FARM

- Turbine side dynamic frequency scans
  - ✓ Superimpose a small input voltage signal which includes uniformly spaced sub-synchronous or even harmonic frequency component
  - ✓ Estimate the impedance seen from WTG terminal at different frequencies based on Fourier analysis.
  - ✓ Plot the harmonic impedance scanning results for both the resistive and reactive components

SSCI FOR WIND FARM





Turbine side frequency scan for nearly radial system

B. Badrzadeh, et al., "General Methodology for Analysis of Sub-Synchronous Interaction in Wind Power Plants," IEEE Transaction on Power System, Vol. 28, pp. 1858-1869, 2013

SSCI FOR WIND FARM

- Turbine side dynamic frequency scans
  - ✓ System side impedance resonance around 20-21 Hz which is indicative of a classical subsynchronous resonance issue. Turbine side reactance crosses over at around 40 Hz, which is very far from the network resonant frequency of around 20 Hz.
  - ✓ The turbine apparent resistance is negative across the entire subsynchronous frequency range; the higher the frequency the larger the negative resistance will be. The turbine apparent reactance is positive up to 40 Hz, and turns negative for the rest of sub-synchronous range.
  - ✓ This is most likely attributed to the active control of wind turbines whose behavior cannot be represented by passive R, L and C elements.

SSCI FOR WIND FARM

- Criteria to identify the conditions that require detailed EMT analysis
  - ✓ Any reactance crossovers on the turbine side that coincides with resonant conditions on the system side even if the resistance at the sub-synchronous frequency is positive
  - ✓ Any resonant condition on the system side if the turbine resistance at that SS frequency is negative. Even though the turbine reactance cross-over does not match the system

SSCI FOR WIND FARM

- Electromagnetic transient analysis
  - ✓ An EMT-type tool is the only possible tool when investigating interaction issues caused by large disturbances such as network faults.
  - ✓ Require data for all nearby power system including detailed HVDC, wind farm control system and generator mechanical shaft system.
  - ✓ Provide time-domain graph of the entire system response to the fault.

COMMONLY USED MITIGATION MEASURES

COMMONLY USED MITIGATION MEASURES

- To mitigate SSTI, a SSDC or POD can always be designed to provide positive damping from the converter. There are other mitigations which may be adopted as required:
  - ✓ Select other transmission or generator options (higher voltage AC lines etc…)
  - ✓ Use transfer trips to avoid trouble conditions
  - ✓ Add generator step up transformer filters
  - ✓ FACTS Devises (TCSC, SSSC, UPFC…)

COMMONLY USED MITIGATION MEASURES

- To mitigate SSCI, the primary is to design a SSCI damping controller. There are other mitigations which may be adopted as required:
  - ✓ Addition of bypass filters across series capacitor
  - ✓ Combination of wind turbine models
  - ✓ Install protection transfer trip the WTG or bypass the series capacitors
  - ✓ Install SSCI protection relays
  - ✓ Increasing the SCR for grid-connected inverter application
  - ✓ Use of grid-side power electronic controllers, such as auxiliary damping loops that can be implemented with FACTS controllers

REQUIREMENT OF RE-EXAMINE THE POSSIBILITY OF SSTI SSCI CI

REQUIREMENT OF RE-EXAMINE THE POSSIBILITY OF SSTI SSCI CI

- ✓ SSR and SSCI problems can develop anywhere if series capacitors used in the transmission system. System planners need to be aware of this potential and plan the system to minimize potential exposure to new and existing generators and power electronic equipment.
- ✓ System Operators must be aware of operating configurations that can increase exposure to SSR and SSCI when planning switching and operate accordingly.
- ✓ Sufficient studies should be performed that identify locations that are susceptible to isolation of generation or power electronic equipment with series compensated transmission lines.
- ✓ In addition, integration of wind farm and renewable energy into a system where the SCR is low (<5) should be identified as potential locations for SSCI. If the UIF of a particular generator is not considerably smaller than 0.1, SSTI between this generator and the HVDC converter need be examined.

REQUIREMENT OF RE-EXAMINE THE POSSIBILITY OF SSTI SSCI CI

- ✓ Major ac system change
- ✓ Major remedy scheme change
- ✓ New addition of HVDC system or HVDC control system replacement
- ✓ Replacement of turbine generator with renewable energy resources
- ✓ Changes in the ac grid configuration, such as commissioning of new series compensations, or new line or transformer
- ✓ Major operational practice change that would result in a weak grid integration or nearly radial connection to a series compensated line
- ✓ Change of the controller schemes of the wind generation and renewable energy resources
- ✓ Expansion of the renewable energy resources

DISCUSSIONS

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