MANITOBA HVDC RESEARCH CENTRE,
a Division of Manitoba Hydro International Ltd.

Sub Synchronous Oscillations – An Introduction

October 2016

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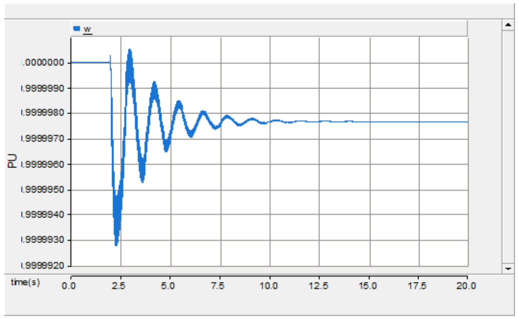
Presentation Outline

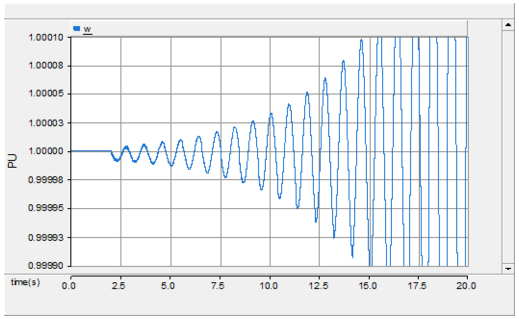
- General background
- AC Network characteristics
- Series compensation and impact on SSR
- Types/Classification of SSO
  - SSR
    - IG and SSTI
  - Transient Torques
  - HVDC – SSTI
  - SSCI – Wind
- Simulation examples

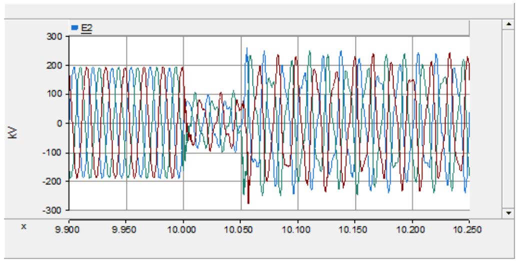
Introduction / Background

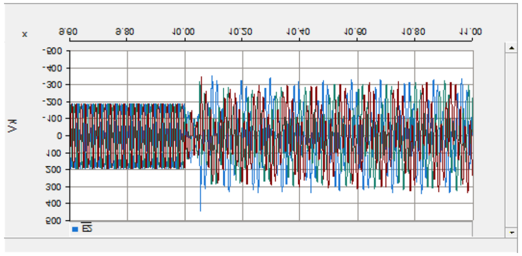
Transients in the Electric Network

- Transients following a system disturbance should damp out in a reasonable timeframe.





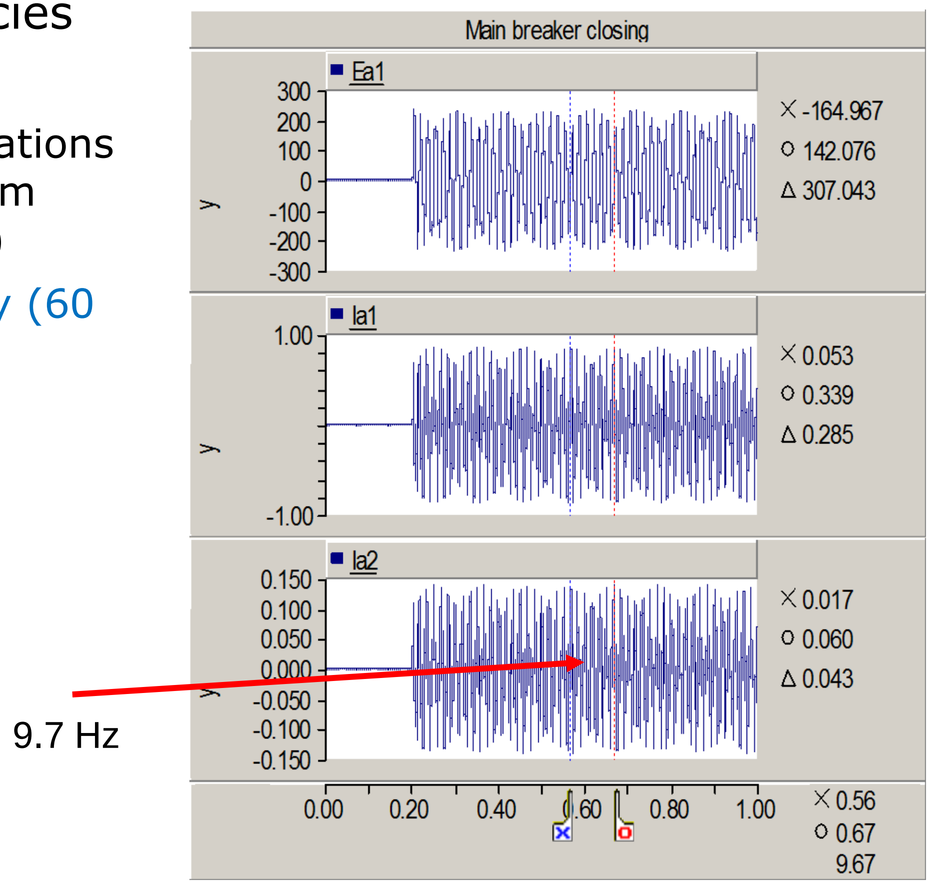




Transients in the Electric Network

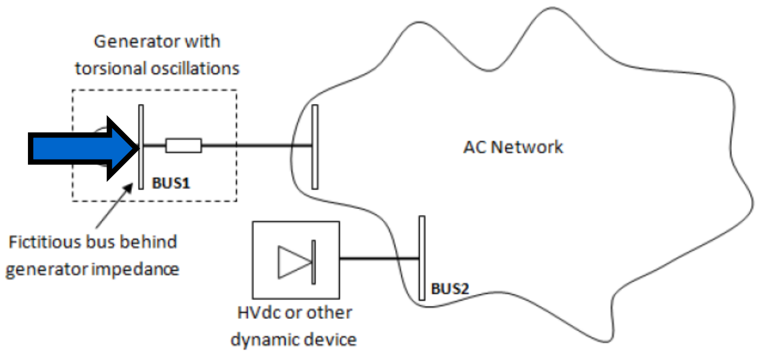
Voltage and current transient frequencies

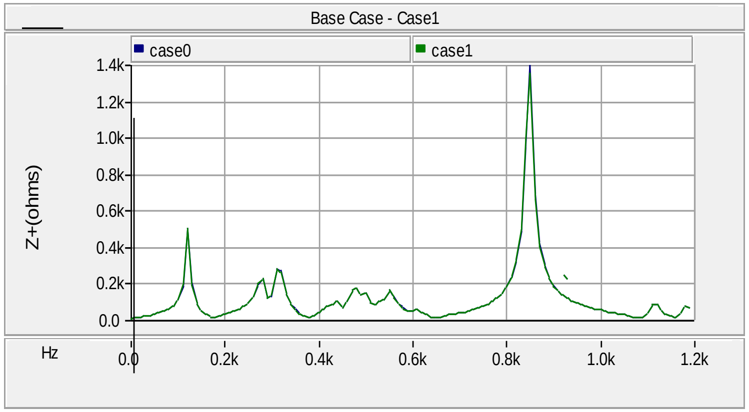
- High frequency transients
- 'Traditional' electromechanical oscillations (close to system frequency on system side, 0.1 – 5 Hz on mechanical side)
- Frequencies below system frequency (60 Hz)
  - Sub Synchronous Oscillations



Network Characteristics

System Impedance Vs Frequency Plots





A Typical frequency characteristic

Following a system disturbance currents (and voltages) corresponding to network resonance frequencies can flow in the system (and hence into generators stator windings).

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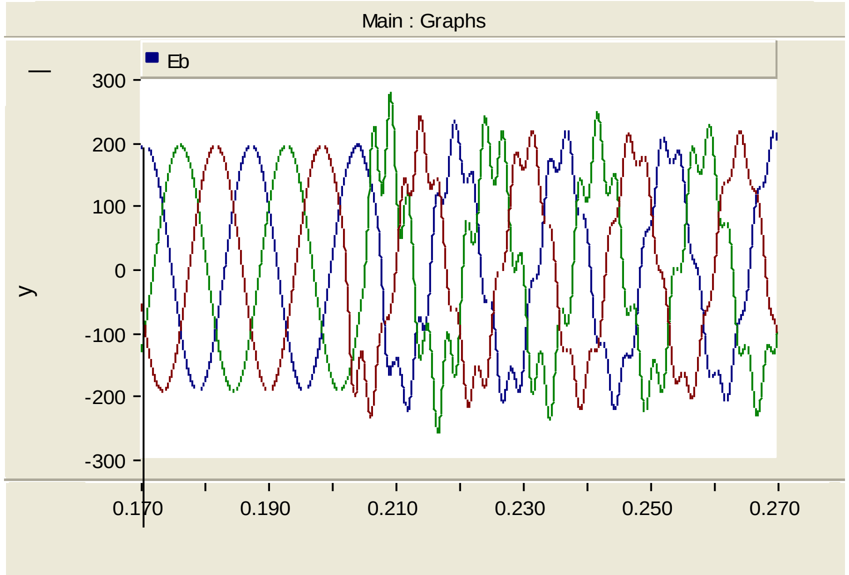
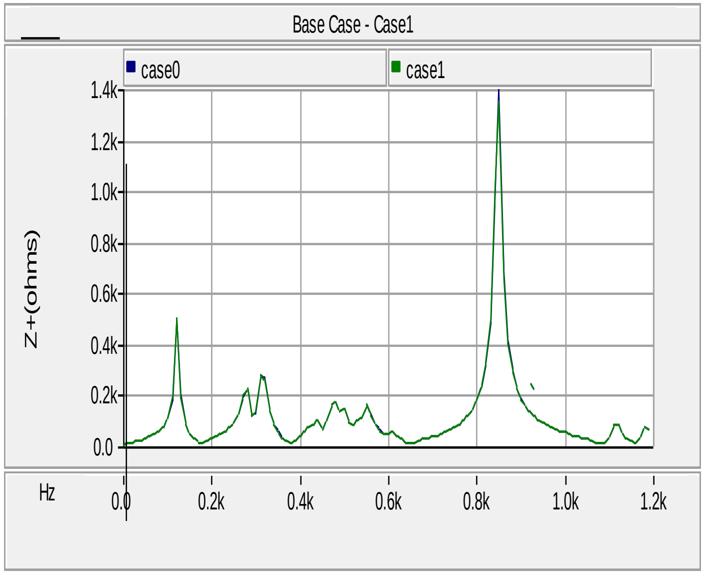
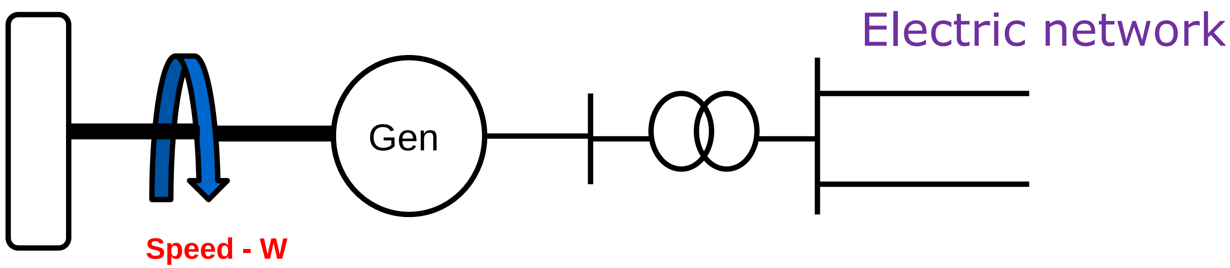
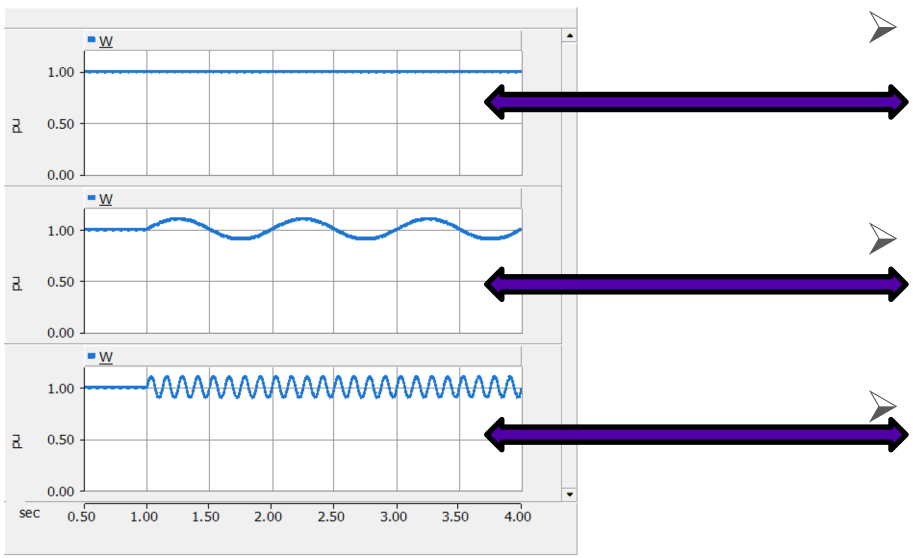




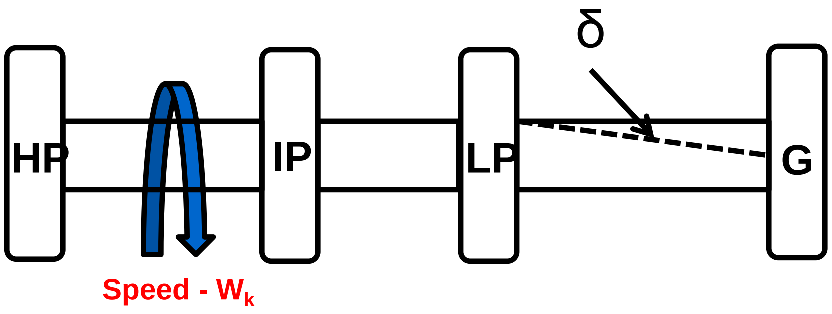
Mechanical Oscillations

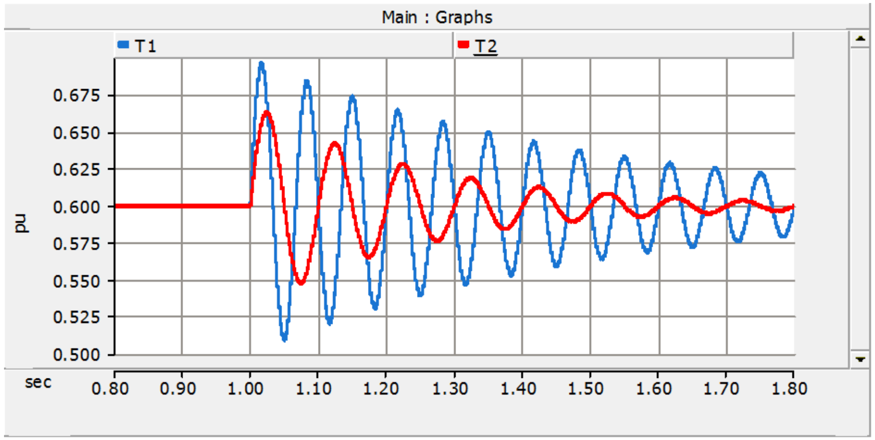




- Constant speed mechanical rotation => 60 Hz on electrical side
- 1 Hz mechanical oscillations => 59 Hz and 61 Hz
- 8 Hz mechanical oscillations => 52 Hz and 68 Hz
- f_m Hz mechanical oscillations => $(60-f_m)$ Hz and $(60 + f_m)$ Hz

Mechanical shaft-mass system

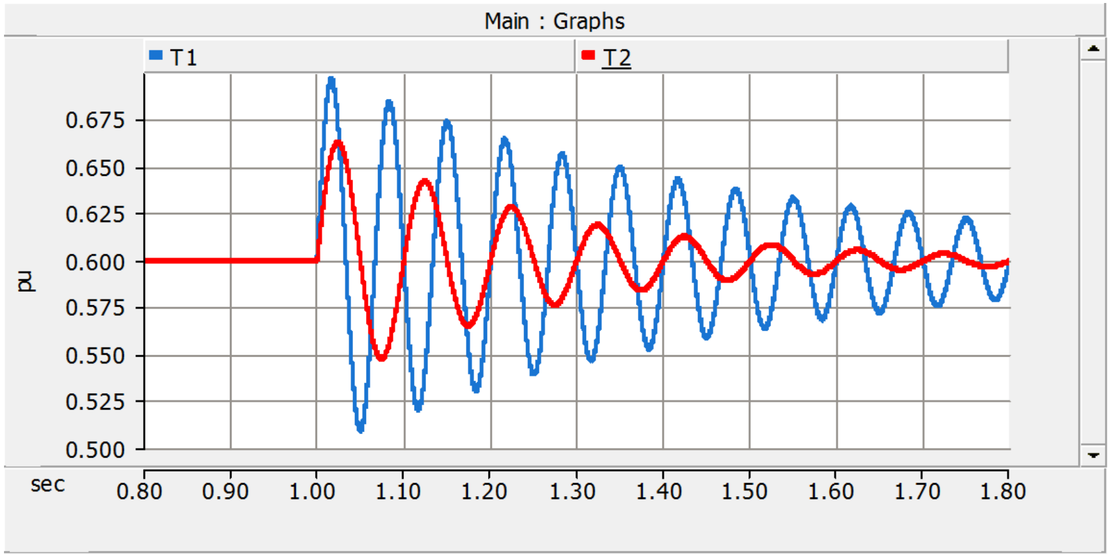




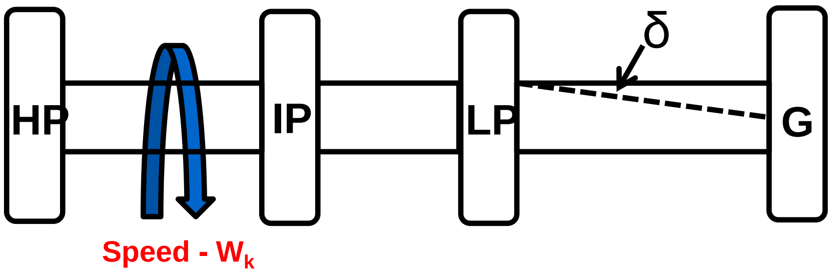
- In steady state (constant torque transmission) each shaft rotates at a constant speed and with a constant ‘twist’.
- Following a disturbance (network or mechanical system side), the shafts will go through a ‘transient’ period.
- The oscillation frequencies will correspond to ‘natural frequencies’ of the mass-shaft system.
- Damping associated with the mechanical system and the damping provided by the response of the electrical system will determine the nature of the oscillations.

Mechanical shaft-mass system

- Interaction between the mechanical and electrical system:
  - Damping associated with the mechanical system and the damping provided by the response of the electrical system will determine the nature of the oscillations.



Mechanical Resonance Frequencies



Mechanical modes can be calculated from shaft data:

- Inertias of individual masses (J)
- Shaft Spring Constant (K)

$$f_i = \frac{1}{2\pi}\sqrt{\frac{K_i.Wb}{2Hi}}$$

60Hz - 25 Hz => 35 Hz

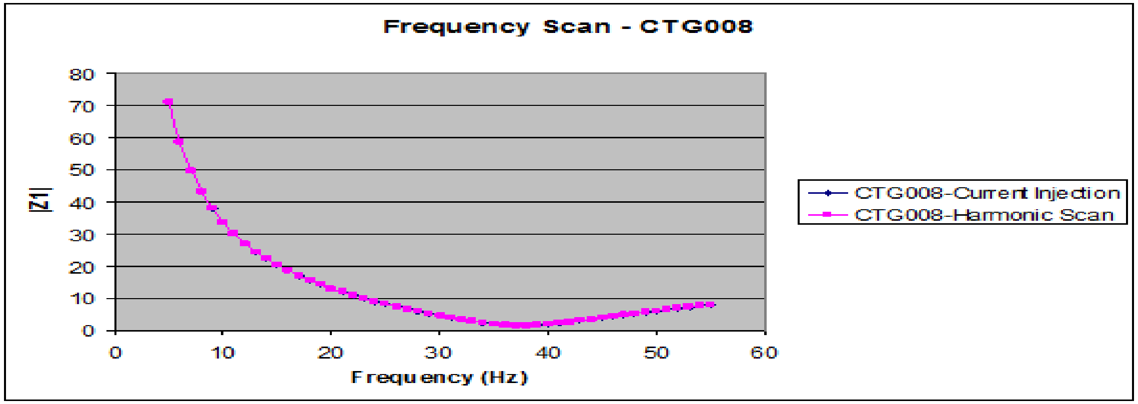
Typical resonant frequencies of Thermal Generator Turbine units are in the range of 15-25 Hz.

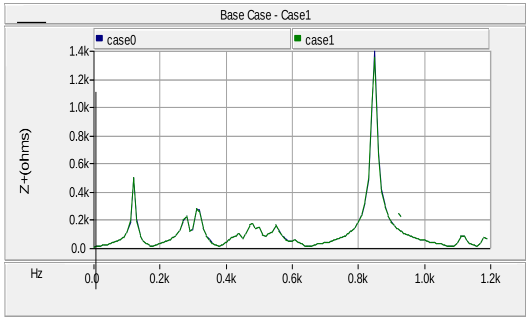
Series compensation and impact on SSR

Series compensation and impact on SSR

Impact on network characteristics (System Impedance Vs Frequency)

- 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
  - Increases potential risk of SSO related issues





Series compensation and impact on SSR

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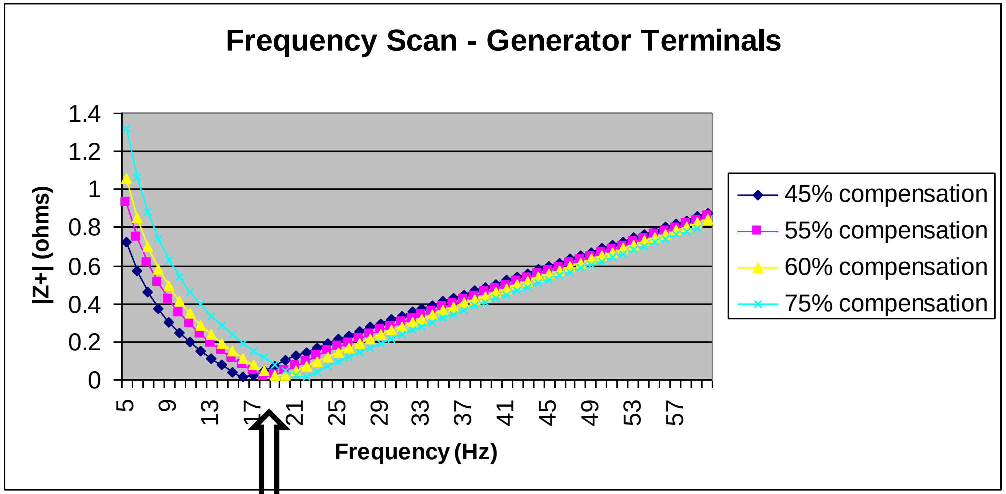
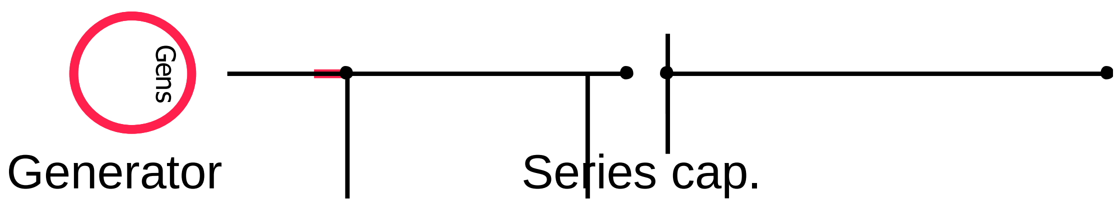


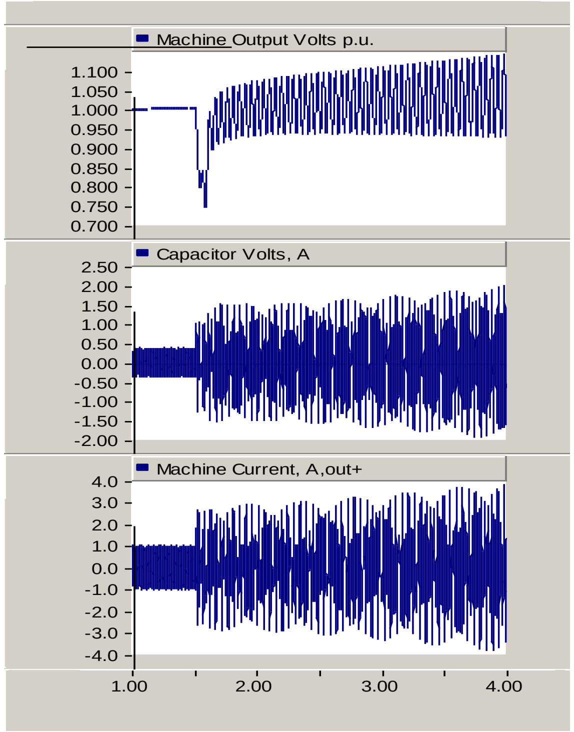
$$f_e = f_0\sqrt{\frac{X_c}{X_l}}$$

Types / Classification of SSO

1. Self Excitation (Induction generator effect)

- Purely electrical phenomenon
- Self-excitation of Sub Synchronous Oscillations
  - Generator 'acts' as a NEGATIVE resistance at the sub synchronous frequencies. If this effective negative resistance is greater in magnitude compared to the positive resistance as seen from the system, an unstable resonance condition can take place.

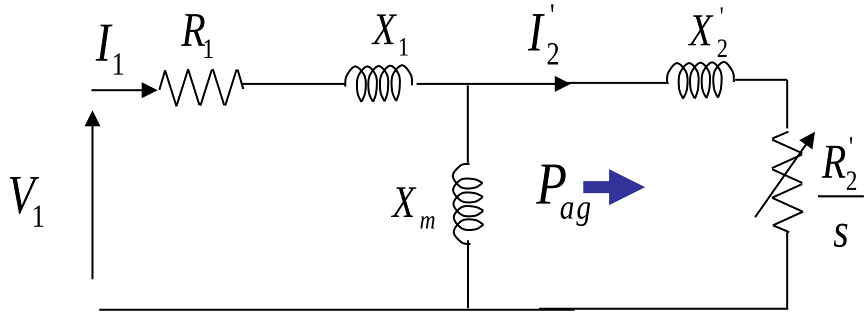


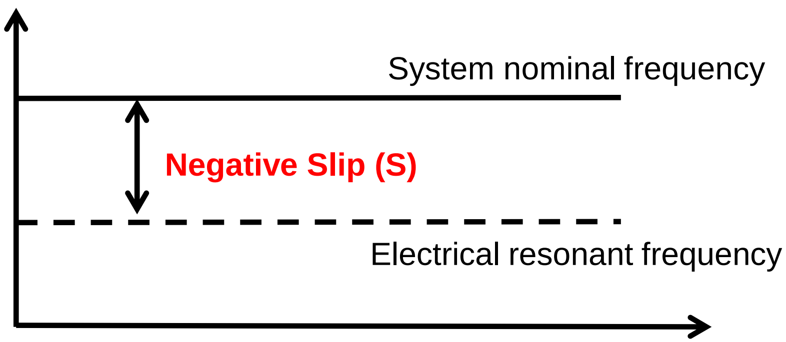


Types/Classification of SSO

1. Self Excitation (Induction generator effect)

- Synchronous generators as well as induction machines can contribute to this condition
- Easy to explain (in a 20 min introduction) using an induction machine example





$S \downarrow \Rightarrow \frac{R_2'}{s} \uparrow$ **Higher effective NEGATIVE resistance)**

1. Self Excitation (Induction generator effect)

Synchronous generators

- Field (and damper) winding characteristics contribute to IG
- At frequencies (w) below the system frequency (w_o), the effective resistance is negative.

$$R_s = -\frac{w(x-x')}{w_b}\frac{(w-w_0)T'_{d0}}{(1+[(w_0-w)T'_{do}]^2)}$$

2. Torsional Interaction

- Electrical resonance frequency (f_e) of system caused by series capacitors close to natural torsional resonance frequency (f_m) of mechanical system (turbine-generator unit)

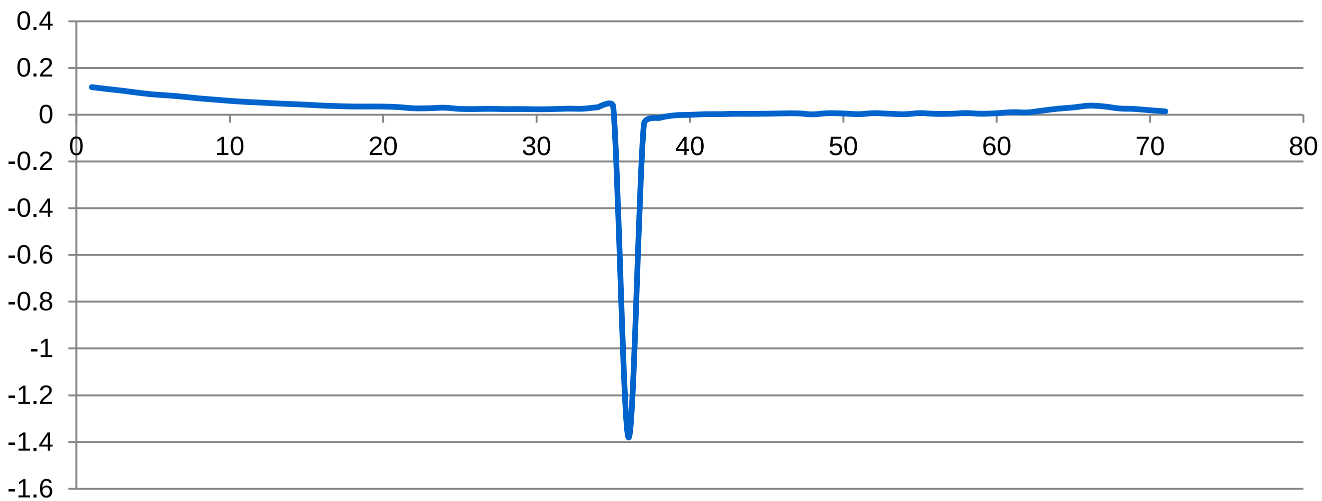
  Condition for SSR-TI Risk =>: $f_e \approx f_o - f_m$

  - Due to interaction between the electrical (generator/line series capacitor…) and mechanical systems (long shafts and masses of thermal units)
  - Result in shaft fatigue & undesirable stress, damage

- Typical mechanical resonance frequencies (15 – 30 Hz)
  - The risk is with higher Series Compensation (SC) levels
- This condition should be avoided through design considerations

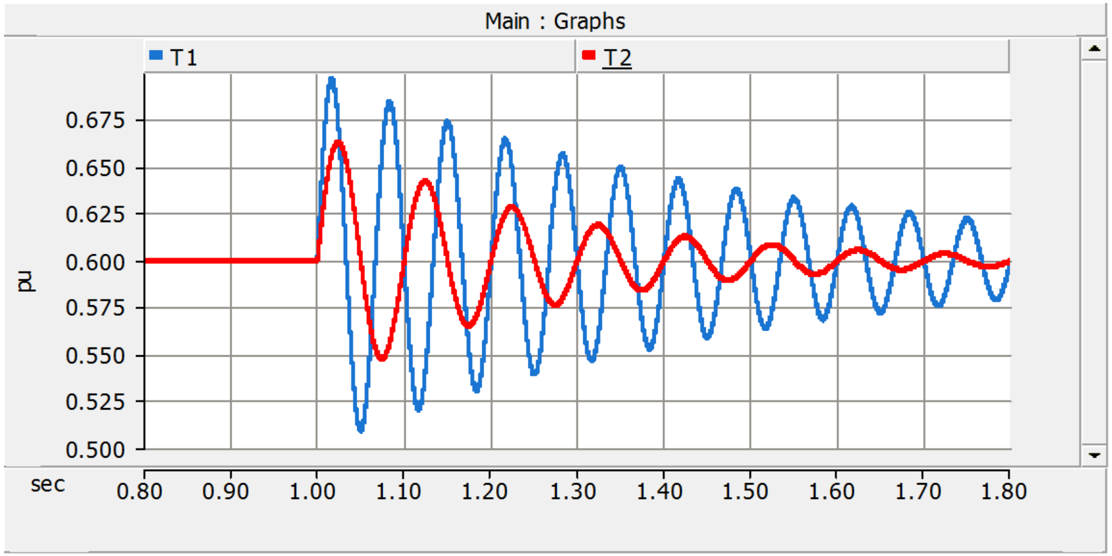
2. Torsional Interaction

Electrical damping from the machine/electric-network mechanical shaft oscillations – derived from EMT simulations (damping analysis using EMT simulations).



3.Transient Torques

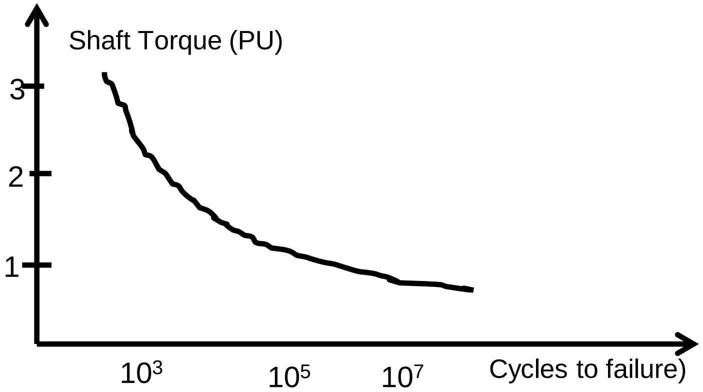
- Shaft oscillations following disturbances will result in shortening of the shaft life time due to material ‘fatigue’.
- The critical items that determines the level of severity are:
  - Amplitude of the mechanical transient oscillations
  - Decay of the oscillations (damping)



3.Transient Torques

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

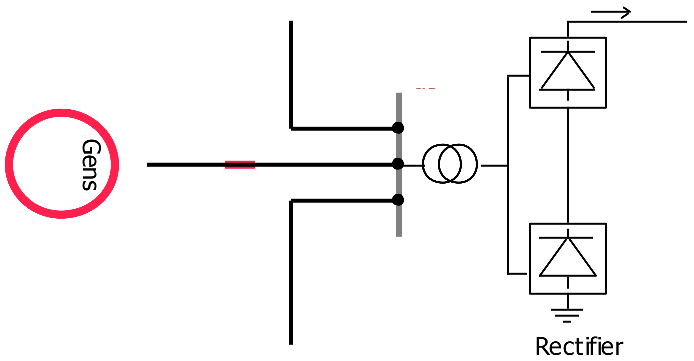
- Machines are designed to withstand for "terminal short circuit" and the peak torque produced for this event can be used as a reference.
  - If the torque produced for an evet is larger than about 75% of the value for terminal short circuit, it is considered as in the zone of vulnerability.
- S-N curves (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*"

4. Interaction with HVDC converter controls - SSTI

- An issue associated with conventional (LCC) HVDC schemes
- A parameter 'Unit interaction Factor' is used to determine the level of risk (a screening level indicator)
  - How close the generator is to the HVDC converter
  - Other parallel AC connections (improved damping)
    - Radial connection of a generator to the rectifier AC bus is the likely worst case.
    - Can be easily mitigated through proper design of HVDC control schemes and settings.



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4. Interaction with HVDC converter controls - SSTI

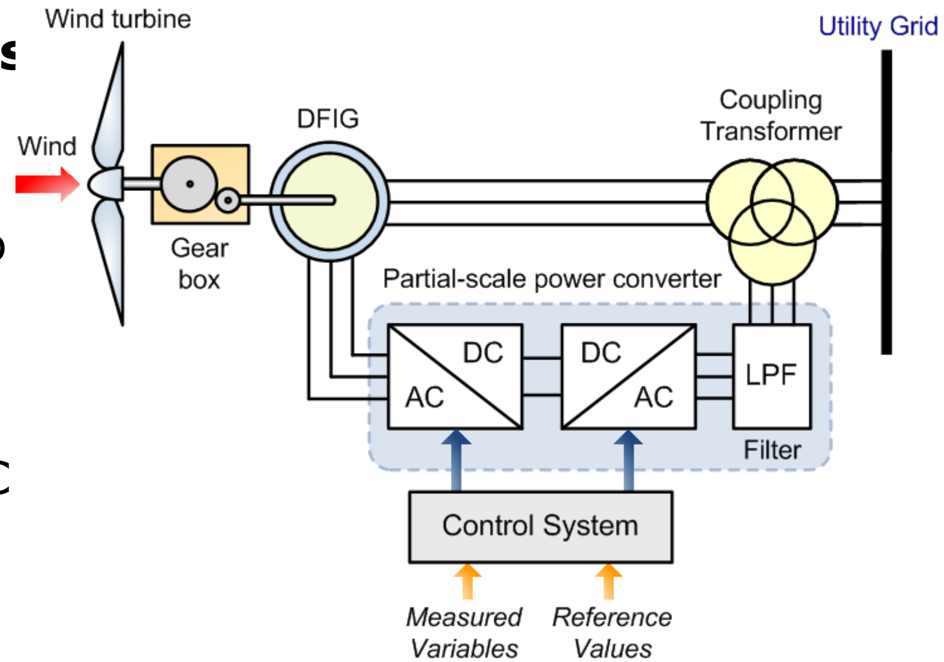
$$UIF_i = \frac{MVA_{HVdc}}{MVA_i}\left(1 - \frac{SC_i}{SC_{TOT}}\right)^2$$

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

Source: EPRI report: “Torsional Interaction Between Electrical Network Phenomena and Turbine-Generator Shafts”

Types/Classification of SSO

5. SSCI involving T3 Wind Units



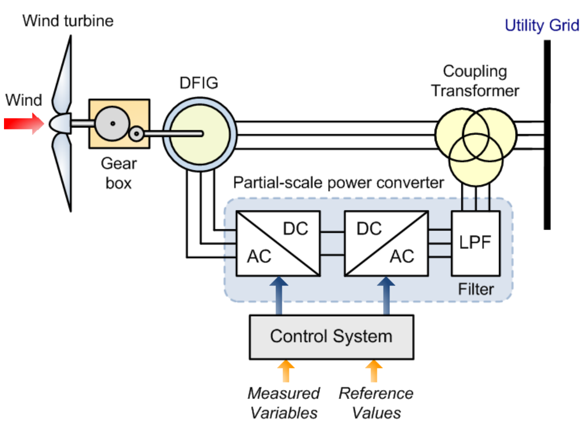
- Modern wind turbines use power electronic converters (connected to the generator) to improve performance

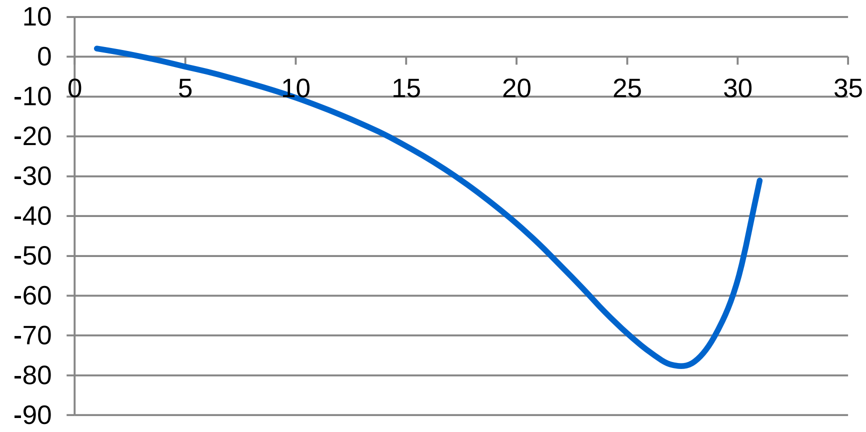
- Wind farms located far from the AC grid has necessitated 'Series Compensated (SC)' Transmission lines

- Problem: DFIG controls act to 'amplify' sub synchronous currents entering the generator
  - Negative Damping
  - Rotor side converter plays the dominant role

5. SSCI involving T3 Wind Units

Dynamic frequency scan to estimate damping provided by the DFIG to sub synchronous frequency transients





Do I need to perform studies?

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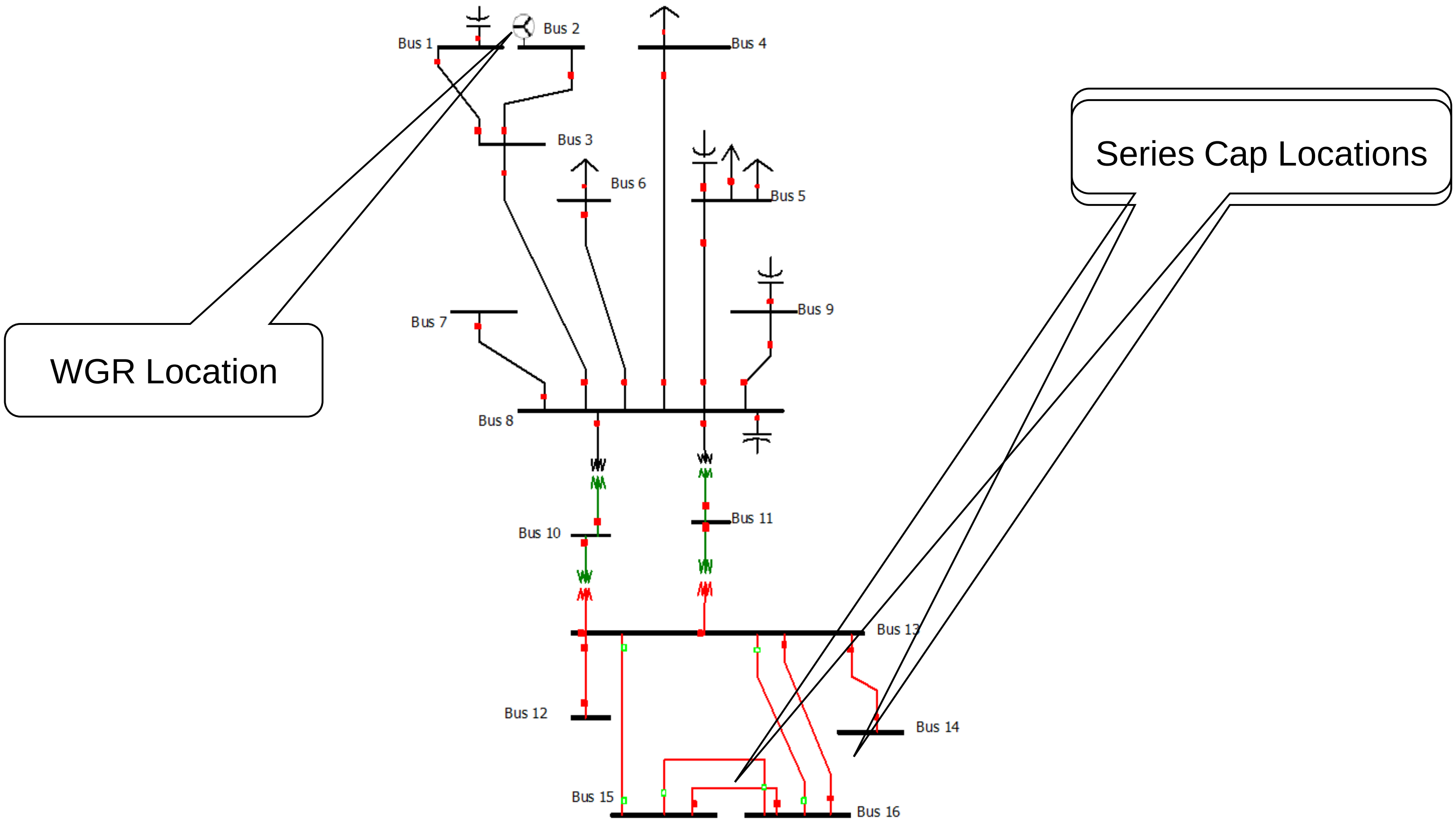
Identifying potential risks



Thank you