SUBSYNCHRONOUS OSCILLATIONS

Subsynchronous Oscillations

- In power system stability studies, turbine-generator rotor is assumed to be made up of a single mass
  - Accounts for oscillation of entire rotor
  - Frequency in the range of 0.2 to 2.0 Hz
- In reality, a steam turbine-generator rotor (may exceed 50 m in total length) has a very complex structure consisting of several predominant masses (rotors of turbine sections, generator, and exciter) connected by shafts of finite stiffness
- Such a rotor system has a large number of torsional vibration modes both above and below the rated frequency.

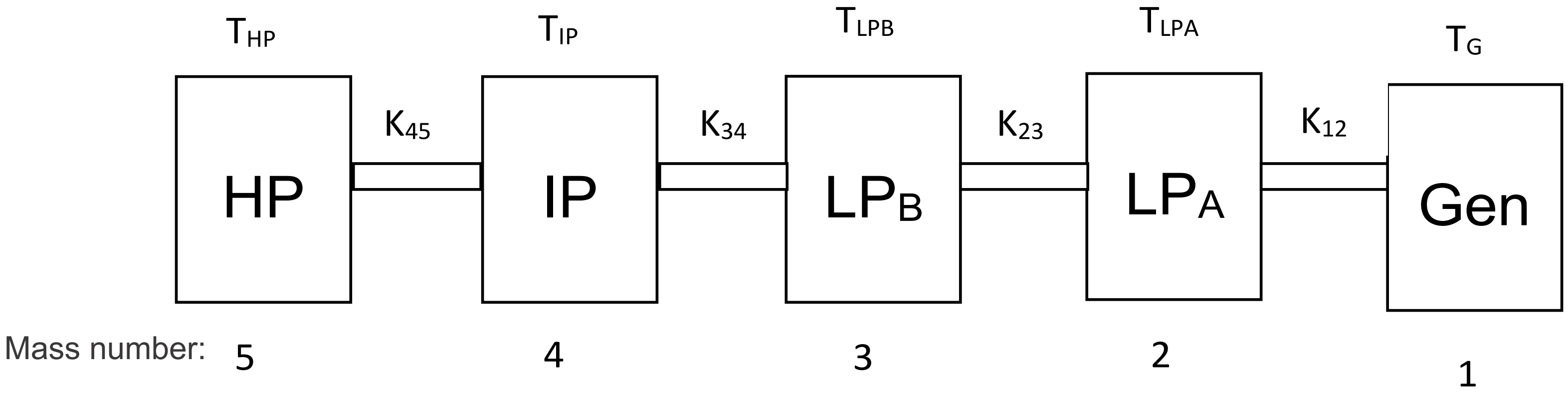
Sub-synchronous Oscillations

- The problem due to interaction between the electrical system and the rotor mechanical system is principally in the sub-synchronous frequency range.
  - When perturbed, torsional oscillations result between different sections of turbine-generator rotor

- Torsional oscillations in the sub-synchronous range could, under certain conditions, interact with the electrical system in an adverse manner:
  - Sub-synchronous resonance with series capacitor of compensated lines
  - Torsional interaction with power system controls

Shaft System Model

- The fact that torsional interaction between the electrical system and the rotor mechanical system is principally in the sub-synchronous frequency range allows the representation of the rotor system driven by a tandem compound reheat turbine by a simple lumped-mass model for each section

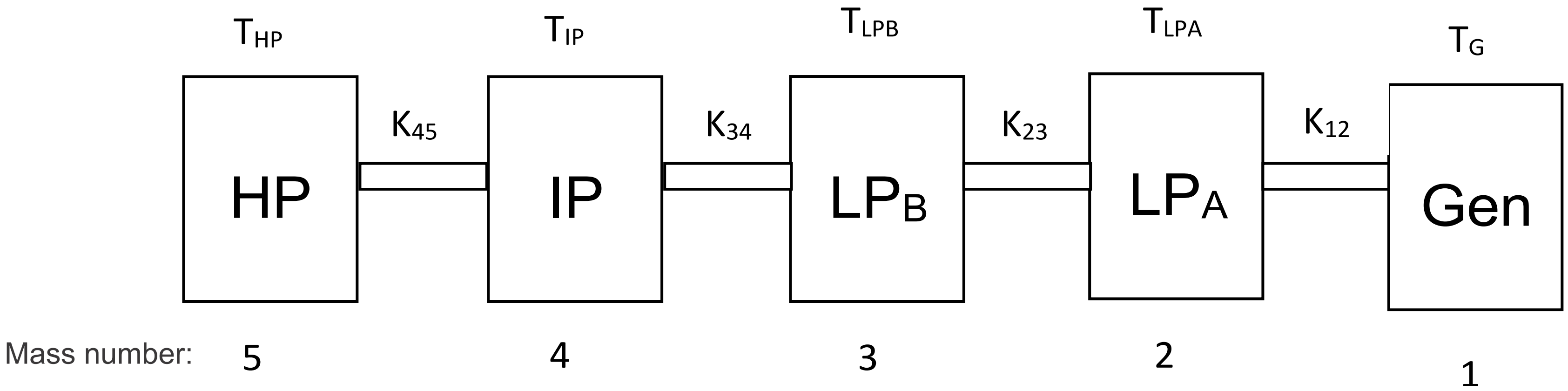


T_{HP} T_{IP} T_{LPB} T_{LPA} : mechanical torques developed by the respective turbine sections in p.u

T_G : generator air-gap torque in p.u.

Lumped-mass shaft system

- The five torsional masses represent the rotors of the generator, two low-pressure (LP) turbine sections, an intermediate-pressure (IP) turbine section, and a high-pressure(HP) turbine section.
- The generating unit is assumed to have a static exciter.
  - For a unit with a rotating exciter driven by the same shaft system, there will be an additional mass representing the exciter rotor.



Inertia constant H

- The inertia assigned to each rotor mass includes its share of shaft inertia. Turbine blades are assumed to be rigidly connected to the rotor. If the moment of inertia J of a rotor mass is in kg m^2, the per unit inertia constant H, is given by

$$H = \frac{1}{2}\frac{J\,\omega_{0m}^2}{S_{base}}$$

- It is also common to use the mechanical starting time Tm defined as the time needed to accelerate the rotor from standstill to rated speed by applying the accelerating torque of 1.0 p.u.

$$T_m = 2\,H$$

Damping coefficient / factor D

- There are a number of sources contributing to the damping of torsional oscillations:

  a. Steam forces on turbine blades

     The oscillation of the turbine blades in the steady-state steam flow introduces damping. As an approximation, this may be represented as being proportional to the speed deviation of the respective turbine section.

  b. Shaft material hysteresis

     When the interconnecting shaft sections twist, damping is introduced due to the mechanical hysteresis of the shaft material as it undergoes cyclic stress-strain variations.

  c. Electrical sources

     Generator, exciter, and transmission networks contribute to damping of oscillations.

Torsional stiffness K

- For a shaft of uniform cross-section undergoing elastic strain, the torsional stiffness or spring constant is given by:

$$K = \frac{G\,F}{l}$$

where

F : form factor which defines the geometric property

G : rigidity modulus of shaft material

K: stiffness, Nm/rad

l : length of shaft

- For a solid shaft of circular cross-section with diameter d,

$$F = \frac{\pi\, d^4}{32}$$

- The torsional stiffness defines the relationship between the torque transmitted and the angular twist between the two ends of the shaft:

$$T = K\,\boldsymbol{\delta}$$

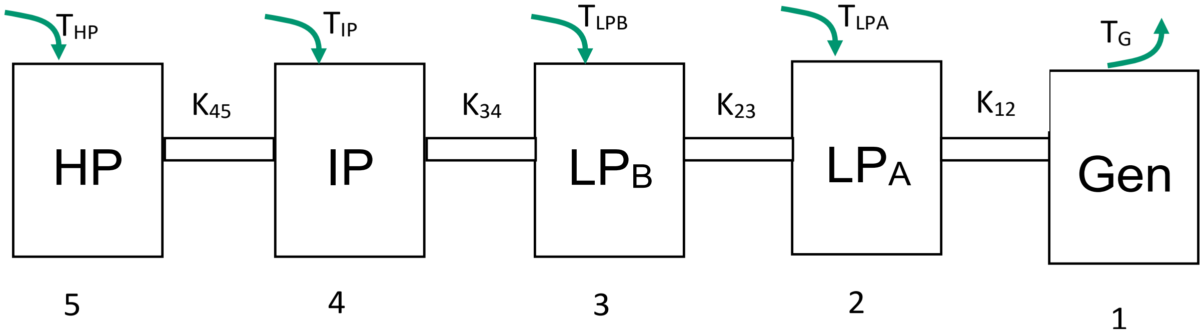
where *T* = torque, Nm **δ**= twist, rad

Torsional stiffness K

- In a turbine-generator rotor, each shaft span consists of several sections of different diameters.
- The torsional stiffness of each section is determined and then a single equivalent stiffness is computed as follows:

$$\frac{1}{K} = \frac{1}{\sum K_{indvidual-section}}$$

Shaft system equations



Gen: $2H_1 \frac{d(\Delta\omega_1)}{dt} = K_{12}(\delta_2 - \delta_1) - \boldsymbol{T_G} - D_1 \Delta\omega_1$ $\qquad \boldsymbol{\frac{d\delta_1}{dt} = \Delta\omega_1 \, \omega_0}$

LPA: $2H_2 \frac{d(\Delta\omega_2)}{dt} = T_{LPA} + K_{23}(\delta_3 - \delta_2) - K_{12}(\delta_2 - \delta_1) - D_2 \Delta\omega_2$ $\qquad \boldsymbol{\frac{d\delta_2}{dt} = \Delta\omega_2 \, \omega_0}$

LPB: $2H_3 \frac{d(\Delta\omega_3)}{dt} = T_{LPB} + K_{34}(\delta_4 - \delta_3) - K_{23}(\delta_3 - \delta_2) - D_3 \Delta\omega_3$ $\qquad \boldsymbol{\frac{d\delta_3}{dt} = \Delta\omega_3 \, \omega_0}$

IP: $2H_4 \frac{d(\Delta\omega_4)}{dt} = T_{IP} + K_{45}(\delta_5 - \delta_4) - K_{34}(\delta_2 - \delta_1) - D_4 \Delta\omega_2$ $\qquad \boldsymbol{\frac{d\delta_4}{dt} = \Delta\omega_4 \, \omega_0}$

HP: $2H_5 \frac{d(\Delta\omega_5)}{dt} = T_{HP} - K_{45}(\delta_5 - \delta_4) - D_5 \Delta\omega_5$ $\qquad \boldsymbol{\frac{d\delta_5}{dt} = \Delta\omega_5 \, \omega_0}$

Example of Torsional Characteristics

Example:

555 MVA, 3600 RPM fossil-fuel-fired generating unit with a static exciter (i.e. exciter mass not considered) (Example from Kundur)

H (MWs/MVA)	0.124	0.232	1.155	1.192	0.855
K (pu torque/rad)	21.8	48.4	75.6	62.3	1.98

K: torsional stiffness

- 1.67 Hz mode represents oscillation of the entire rotor against the power system. All five masses participate equally in this mode. This is the mode normally considered in rotor angle stability studies.
- 16.3 Hz mode is the first torsional mode. Has one polarity reversal in the mode shape, with the rotors of generator and LP_A oscillating against rotors of LP_B, IP and HP sections.
- 24.1 Hz is the second torsional mode. Its mode shape has two polarity reversals.
- 30.3 Hz and 44.0 Hz torsional modes have three and four polarity reversals, respectively

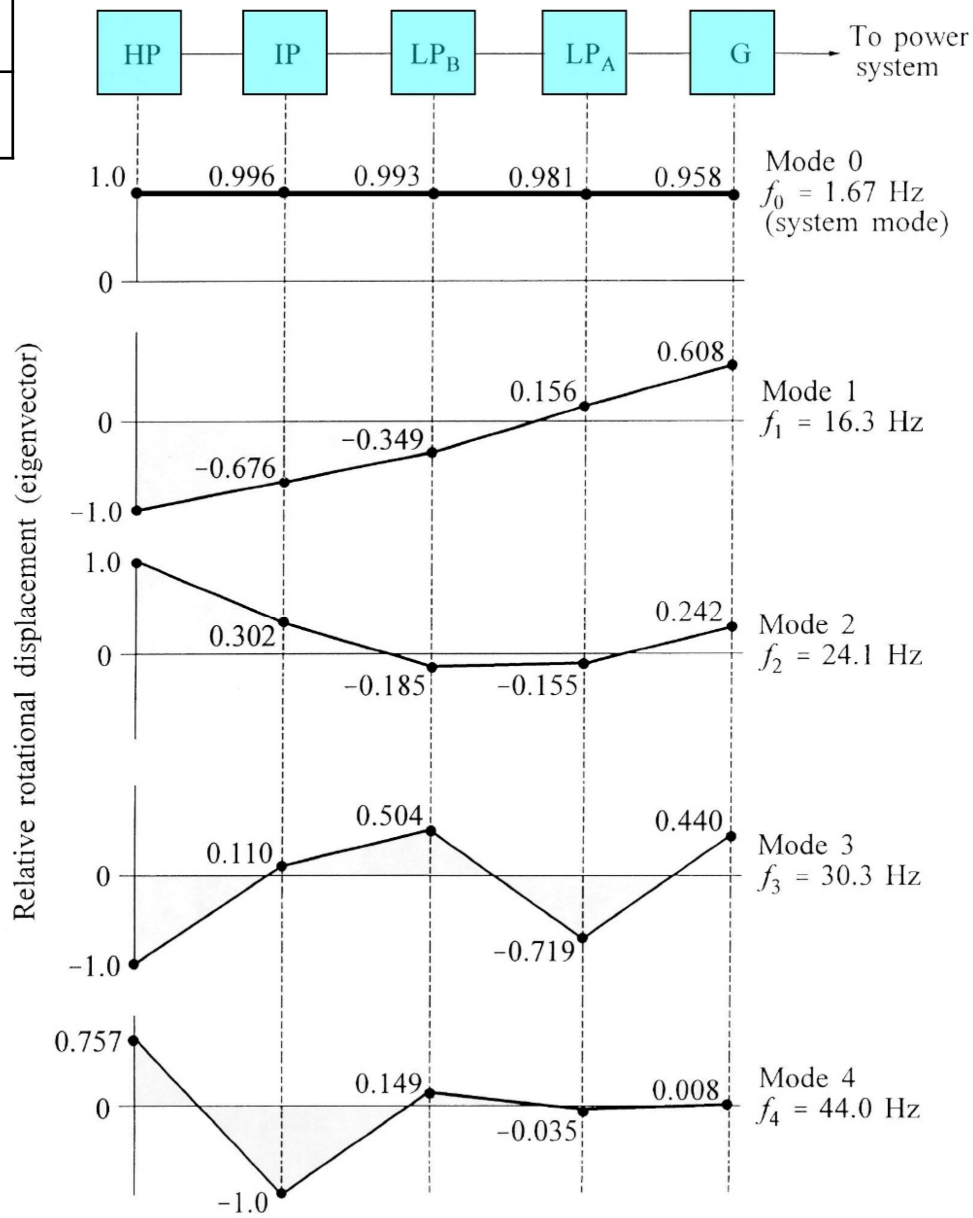


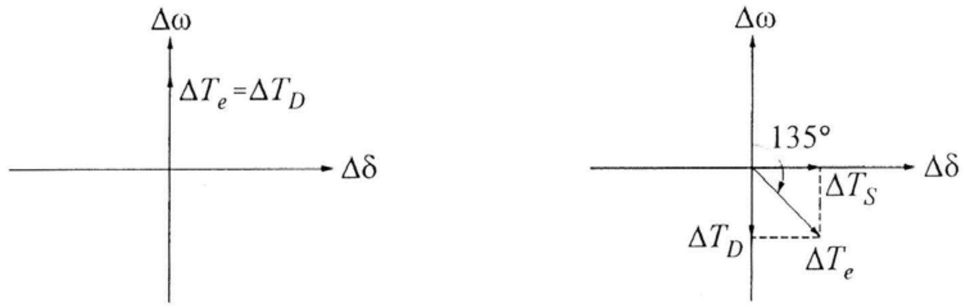
Figure 1 Rotor natural frequencies and mode shapes of a 555 MVA, 3,600 r/min steam turbine generator

Torsional Interaction with power System Controls

- Torsional oscillations are inherently lightly damped
- Normally, not affected by generating unit or network controls
- However, there have been several instances of instability of torsional modes due to interactions with
  - Generator excitation controls
  - Prime-mover controls
  - Controls of nearby HVDC converters

Interaction with Generator Excitation Controls

- Torsional mode destabilization by excitation control was first observed in 1969 while applying PSS at Lambton GS in Ontario, Canada (source: Kundur book)
  - PSS using speed signal at generator end of shaft excited lowest torsional mode
  - PSS transfer function designed to provide nearly zero phase shift at system mode frequency of 1.6 Hz and produce pure damping torque
  - At torsional frequency of 16 Hz, PSS results in 135° phase lag and hence, negative damping
- Problem solved by using torsional filter and <u>sensing speed</u> <u>between the two LP turbine sections</u>
  - Close to the "node" of 16 Hz torsional mode
  - Other torsional modes also have very low amplitude



(a) Pure damping torque at 1.67 Hz

(b) Negative damping torque and positive synchronizing torque at 16 Hz

Torsional Interaction with Power System Stabilizer

- Examine effect of PSS on torsional stability of a 889 MVA, 1,800 RPM generating unit with a tandem compound turbine and static exciter
- Each double flow LP turbine section is represented by two masses:

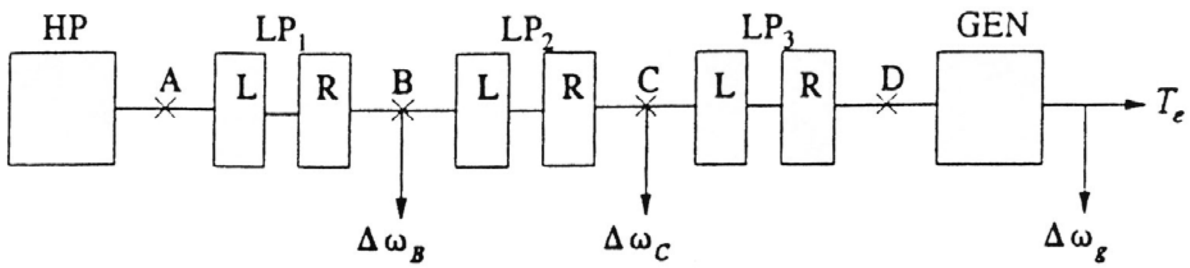
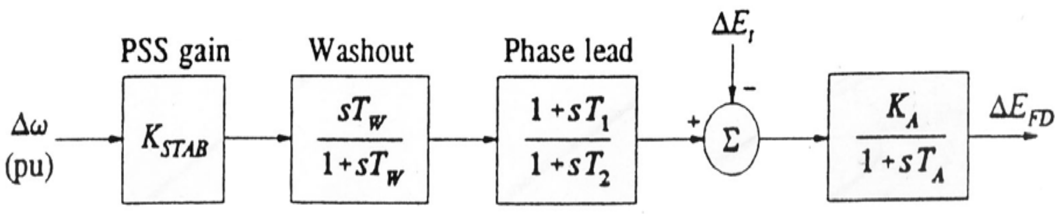


Figure 2 Shaft system representation

Delta-omega stabilizer

- Delta-omega stabilizer with shaft speed ($-\alpha$) as input signal with speed measured at
  - the generator end
  - at coupling B
  - coupling C
  - both couplings B and C
- Excitation system model



$K_A = 200$, $T_A = 0.005$ s, $T_1 = 0.3$ s, $T_2 = 0.06$ s, $T_W = 1.5$ s

Figure 3 Thyristor exciter with delta-omega stabilizer

Delta-omega stabilizer

- Speed signal at generator end causes instability or decreased damping of torsional modes while damping system mode
- Sensing at B adversely affects 23 Hz torsional mode
- Sensing at C adversely affects 9 Hz torsional mode
- No single speed sensing location suitable for all torsional modes
- Combination of B and C best for torsional modes
- System mode is insensitive to sensing location; depends only on gain
- Exciter mode is heavily damped in all cases

Table 1 Effect of delta-omega stabilization without a torsional filter circuit

K_{STAB}	Speed Sensing Location	Torsional Modes				System Mode	Exciter Mode
		9 Hz	17 Hz	23 Hz	24 Hz		
0.0	-	-0.05±j56.2	-0.07±j105.7	-0.10±j146.1	-0.17±j151.2	+0.23±j5.7	-
9.5	Generator	+0.31±j57.6	+0.20±j106.0	+0.24±j146.4	-0.06±j151.3	-0.73±j5.0	-13.7±j13.1
9.5	Coupl-B	-0.25±j55.3	-0.17±j105.6	-0.01±j146.2	-0.19±j151.2	-0.75±j5.0	-16.7±13.9
19.0	Coupl-B	-0.47±j54.3	-0.28±j105.5	+0.07±j146.3	-0.20±j151.2	-1.20±j4.2	-14.5±j19.7
9.5	Coupl-C	+0.06±j56.6	-0.26±j105.5	-0.21±j146.1	-0.18±j151.2	-0.74±j5.0	-15.5±j13.7
19.0	Coupl-C	+0.20±j57.0	-0.46±j105.3	-0.31±j146.1	-0.19 j151.2	-1.20±j4.2	-12.8±j18.5
9.5	Both B and C	-0.10±j56.0	-0.22±j105.5	-0.11±j146.1	-0.19±j151.2	-0.74±j5.0	-16.1±j13.8
19.0	Both B and C	-0.16±j55.7	-0.37±j105.4	-0.12±j146.1	-0.20±j151.2	-1.20±j4.2	-13.6±j19.1
28.5	Both B and C	-0.22±j55.5	-0.52±j105.2	-0.13±j146.1	-0.21±j151.2	-1.36±j3.6	-11.9±j22.9

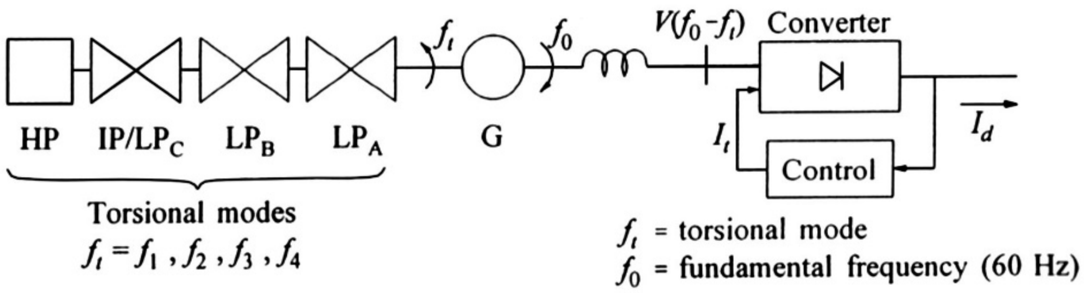
Interaction with Nearby HVDC Converters

- Problem first came to light on Square Butte HVDC system in North Dakota
  - Consists of 250 kV, 500 MW dc link
  - Rectifier station located adjacent to Milton Young GS with two units: 234 MW and 410 MW
- Converters employ equidistant firing system
  - Normal regulator control modes are constant current control at the rectifier and constant voltage at the inverter
  - In addition, a supplementary "frequency sensitive power controller" (FSPC) is provided for damping system oscillations
- Field tests showed that
  - The supplementary damping controller destabilized the first torsional mode (11.5 Hz) of 410 MW generating unit
  - Normal constant current control, without damping controller, could cause instability of 11.5 Hz torsional mode
- Problem solved by modifying converter controls

Interaction with HVDC Converters (cont'd)

Basic Phenomenon

- Torsional mode oscillations cause phase and amplitude modulation of generated voltage waveform
  - modulated voltage has frequency components equal to f_o-f_t
  - Modulated voltage impressed on the dc system commutating bus



- With equidistant firing angle control
  - a shift in voltage phase due to a torsional mode causes a similar shift in firing angle
  - results in corresponding changes in direct current, voltage and power

Sub-synchronous Resonance

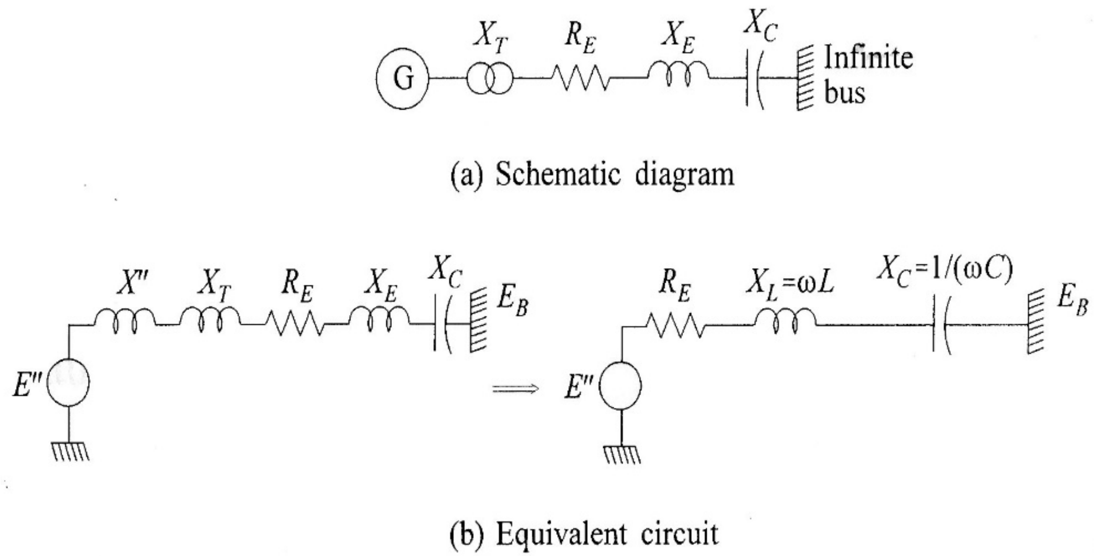
Subsynchronous Resonance (SSR)

- Occurs mainly in series capacitor compensated transmission systems

- First experienced in 1970 resulting in shaft failure of units at Mohave Plant in Southern California

  Not until the second failure in 1971 was the real cause of failure recognized as SSR

- Consider a simple radial system:



Radial series compensated system

Natural frequency of the network

Natural frequency f_n of the circuit inductance and capacitance:

$$\omega_n = \frac{1}{\sqrt{LC}} = \frac{\omega_0}{\sqrt{(\omega_0 L)(\omega_0 C)}} = \omega_0 \sqrt{\frac{X_C}{X_L}} \ \text{rad/s} \qquad f_n = f_0 \sqrt{\frac{X_C}{X_L}} \ \text{Hz}$$

In an uncompensated transmission system, faults and other disturbances result in dc offset components in generator stator windings:

- result in a component of air-gap torque at slip frequency equal to f_o
- necessary to avoid torsional frequencies very near the fundamental frequency f_o

- In a series capacitor compensated system, instead of the dc component, the offset transient current is an alternating current of frequency equal to the natural frequency f_n
  - induce rotor currents and torques of slip frequency $(f_o - f_n)$ Hz

Example

- Table below shows the natural and slip frequencies as a function of the degree of compensation (with $f_0 = 60$ Hz)

Table

Percent Compensation $(X_C/X_L) \times 100$ (%)	Natural Frequency f_n (Hz)	Slip Frequency $60-f_n$ (Hz)
10	18	42
25	30	30
30	32.6	27.4
40	38	22
50	42.4	17.6

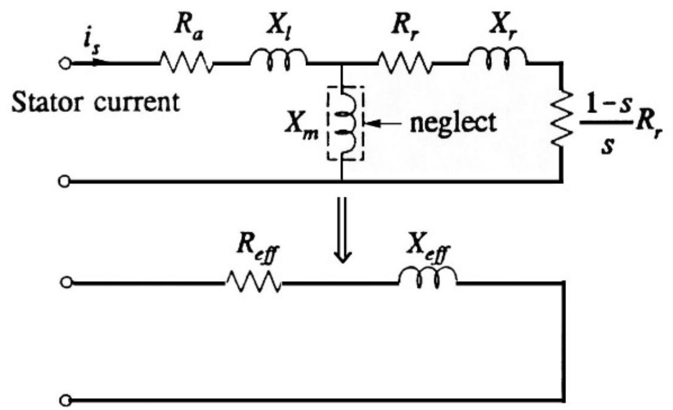
Series compensation

- Here we have considered a simple radial system. For a complex network, the frequency-dependent characteristic of the effective impedance seen by a generator may be determined by a frequency scanning program

- A series compensated network can cause sustained or negatively damped sub-synchronous oscillations by two distinctive mechanisms:
  a) Self-excitation due to induction generator effect
  b) Interactions with torsional oscillations (SSR)

- A shunt compensated transmission system normally has natural frequencies in the super-synchronous range
  - Sub-synchronous oscillations normally do not pose a problem
  - Exceptions are situations involving very long lines and a high degree of shunt compensation

Self-Excitation Due to Induction Generator Effect



Slip $s = \frac{f_n - f_0}{f_n}$

$R_{eff} = R_a + \frac{R_r}{s}$

- Since $f_n < f_0$, slip is negative.
  Depending on f_n, R_{eff} can be negative
- At high degrees of compensation, the apparent negative resistance of the generator may exceed the transmission network resistance,
  - Effectively results in an RLC circuit with <u>negative resistance</u>
- Will result in self-excitation causing electrical oscillations of intolerable levels
- Purely electrical phenomenon; not dependent on shaft torsionals

Interaction with Torsional Oscillations

- If the complement of f_n (i.e., $f_0 - f_n$) is close to one of the torsional frequencies, torsional oscillations are excited
  - Results in a strong "coupling" between electrical and mechanical systems
  - Condition referred to as "sub-synchronous resonance"
  - A small voltage induced by rotor oscillations can result in large sub-synchronous currents
  - Will produce torque whose phase is such that it enhances rotor oscillations
- Consequences of SSR can be dangerous
  - If oscillations build up, shaft will break
  - Even if oscillations not unstable, system disturbances can cause shaft torques of high magnitude and loss of shaft fatigue life
- Countermeasures to SSR:
  - Static filter
  - Dynamic filter
  - Dynamic stabilizer
  - Excitation system damper
  - Protective relays

Hydro Generator Torsional Characteristics

- Rotor of a hydraulic generating unit consists of a turbine runner and a generator rotor
  - If unit has a shaft-driven exciter, there is an additional rotor mass
  - There are at most two torsional modes of oscillation
- Inertia of generator rotor about 10 to 40 times that of turbine runner (waterwheel)
- No reported cases of adverse dynamic interaction with electrical network
- Principal reasons for absence of adverse interaction:

  a) High generator rotor inertia relative to turbine runner
    - effectively shields the rotor mechanical system from the electrical network

  b) Viscous waterwheel damping
    - torsional oscillations inherently highly damped

Summary

- Sub-synchronous Interaction – Two or more parts of the power system exchange energy at one or more frequencies below the fundamental frequency (50 Hz).
- Sub-synchronous Oscillation - A condition where the electric network exchanges energy with a turbine generator at one or more of the natural frequencies of the combined system below the synchronous frequency of the system following a disturbance from equilibrium.
- Sub-synchronous Resonance (SSR) – A type of SSI where the electric power system, most often a series compensated transmission line, exchanges energy with a turbo generator at one or more natural frequencies below the fundamental 50 Hz frequency (three types of SSR)

Summary

Types of Sub-synchronous Resonance (SSR)

a. Torsional Interaction (SSR-TI) – interaction between the mechanical system (turbo-generator) and a series compensated power system when small disturbances occur. This is the classic SSR condition.

b. Induction Generator Effect (IGE) – This is self-excitation of a series compensated power system. This is independent of the generator shaft torsional modes. Purely electric resonance condition.

c. Torque Amplification (TA) – amplification of turbo generator shaft system stress by transient torques on generator rotors caused by severe disturbances in a series compensated power system.

Sub-synchronous Control Interactions (SSCI) – A condition where a power electronic device (HVDC, SVC, STATCOM, Wind turbine control, etc) interacts with the electric power system containing nearby series compensated transmission .

Sub-synchronous Torsional Interaction (SSTI) – A condition where there is a control interaction between power electronic device and the mechanical mass system of a turbo generator. Does not interaction with series compensation.