ISSUES OF SYSTEM AND CONTROL INTERACTIONS IN ELECTRIC POWER SYSTEMS

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INTRODUCTION

- Electric Power Systems are very large, spread over a wide geographical area.
- They consist of several complex systems:
  Generation Systems
  Transmission Networks—primarily AC and few HVDC links
  Distribution Systems
  Protection and Control
INTRODUCTION

- Bulk Power Systems (Generation and Transmission) are operated to achieve economy with security constraints
- Distribution systems are operated to maximize utilization with Power Quality (PQ) constraints
- System Protection against blackouts
- System Control – to improve stability
System Stability Issues

- There are 4 major dynamic problems:
  - Loss of Synchronism (LOS)
  - Voltage Instability and Collapse
  - Low Frequency Oscillations (below 2 Hz)
  - Sub-synchronous frequency Oscillations (below system frequency) (SSO)
System Stability Issues

- LOS can occur due to a large disturbance (say fault followed by clearing). Growing low freq. oscillations can also result in LOS.
- Transient Stability can be improved by fast acting static excitation systems.
- However, it can aggravate low frequency oscillations which can be damped by Power System Stabilizers (PSS),
System Stability Issues

- PSS (unless limited in action) can cause LOS during backswings following a major disturbance
- SSO can be negatively damped by SSR (Sub-synchronous Resonance) (caused by interaction between the Generator and Transmission systems)
- PSS can also aggravate SSO
Objectives of this Lecture

- To present issues of System and Control Interactions that affect design and operation of power systems.
- Sub-Synchronous Resonance (SSR) interactions between turbo-generators and Transmission Networks (AC and DC)
- Harmonic Interactions between AC and DC Networks
Objectives (Contd)

- Control Interactions in Power Electronic Controllers (FACTS and HVDC) affected by Network Resonances
- Control Interactions in Damping Controllers (for damping swing modes) affected by Strong Resonance
SSR Interactions - Introduction

- Observed initially with Series Compensated AC lines where it is most severe
- In 1977, it was also observed with radially connected HVDC transmission (where it is not severe), but can be a problem that has to be tackled with modifications of converter control.
- Is a generic problem with FACTS controllers
SSR Interactions- Introduction

• In general, it can be said that the application of any high power electronic controller must consider SSR in its design.

• Interestingly, a TCSC can mitigate SSR without any additional controls.

• In general, an auxiliary Sub-Synchronous Damping Controller (SSDC) can overcome SSR problem.
Consider a turbine-generator supplying a series compensated system shown in Figure 10.1. The electrical system has a resonant frequency \( f_{er} \) given by

\[
f_{er} = f_o \sqrt{\frac{X_C}{X'' + X_T + X_E}}
\]  

(10.1)

where \( X'' \) is the subtransient reactance of the generator and \( X_T \) is the leakage reactance of the transformer. Since, in general, \( X_C < X_E \), \( f_{er} \) is less than the synchronous frequency \( f_o \). It is assumed that the reactances are calculated at the frequency \( f_o \).
SSR in Series Compensated AC Transmission

A balanced three phase set of armature currents of frequency $f_{er}$ produce a rotating magnetic field in the air gap, which rotates with same frequency in a direction determined by the sequence of currents. Positive sequence currents produce a field which rotates in the same direction as the rotor while negative sequence currents cause a field which rotates in the opposite direction. The frequency of the currents induced in the rotor windings is given by

$$f_r = f_{er} \pm f_o$$ (10.2)

The negative sign is associated with the positive sequence currents while positive sign is associated with the negative sequence currents. The induced rotor currents affect the rotor magnetic field and also result in subsynchronous frequency torques on the rotor (caused by interaction with steady magnetic field of the rotor).
When $f_r$, the frequency of induced voltage in the rotor windings and the torque component, is close to the frequency of a torsional mode, there is a possibility of instability due to SSR.

Torsional modes belong to the torsional system of rotors and shaft sections in a turbo-generator.
The turbo generators have several rotors corresponding to steam turbines (High Pressure, Intermediate Pressure and Low Pressure) in addition to the generator and rotating exciter (if any), all connected by elastic shafts which can be modeled as springs. Thus, the mechanical system of rotors and shaft sections is a lightly damped mass-spring system analogous to the electrical network of capacitors (analogous to rotor inertias) and inductors (analogous to the springs). This system has as many torsional modes as the number of rotors (masses), of frequencies ranging from 0 to 50 Hz (in the subsynchronous range). These frequencies are computed considering the mechanical system in isolation. The torsional mode corresponding to the zero frequency is termed as ‘mode zero’ in which all the rotors participate equally. (The eigenvector has
Torsional system with six masses

Figure 10.2: Torsional system with six masses
An Electrical Analogue

Figure 10.4: An electrical analogue for the torsional system of Fig. 10.2
Sub-Synchronous Resonance

- An IEEE Committee Report (1985) has defined SSR as follows: “subsynchronous resonance is an electric power system 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”. The two aspects of the SSR problem are:
  - 1. Self excitation (also called as steady state SSR)
  - 2. Transient torques (also called as transient SSR)
SSR-Self Excitation

- The self excitation problem includes (a) Induction Generator Effect (IGE). Here the mechanical system is not modeled. The subsynchronous frequency (positive sequence) armature currents produce a rotating mmf which moves slower than the generator rotor. The resistance of the rotor circuits appear to be negative (viewed from the armature terminals) due to the negative slip of the machine (corresponding to the subsynchronous frequency currents). If the net resistance is zero or negative, self excitation occurs. (b) Torsional Interaction (TI). This is due to the interplay between the electrical and mechanical system and is a much more serious problem compared to IGE. The problem was discovered accidentally after the shaft damage experienced at Mohave generating station in 1970 and 1971.
Analysis of SSR

1. Damping torque analysis based on frequency domain technique. This is a heuristic, simpler approach for checking for TI and gives reasonably accurate results.

2. Eigenvalue analysis based on the state space model of the linearized system equations. This gives accurate information about the stability of all the system modes including torsional modes.

The damping torque analysis can be used as a screening tool for fast evaluation of a host of system conditions for torsional interactions. Since IGE is not a major problem, it can be neglected. This permits the use of simple ‘classical model’ of the generator which simplifies the computation of the damping torque.
Analysis of SSR

The analysis of the transient torques requires detailed system simulation based on the nonlinear models. In the presence of FACTS controllers, three phase models considering switching action of the thyristor or other power semiconductor devices are most accurate. However, for SSR analysis, the modeling of a FACTS controller using D-Q variables (based on synchronously rotating reference frame) is found to be adequate. The use of D-Q variables implies that the harmonics generated by the FACTS devices have little effect on the SSR performance. It must be noted that unlike in the case of study of low frequency phenomena involving swing modes, the analysis of SSR requires representation of the network dynamics (by differential equations rather than algebraic equations involving phasors). Thus, it is not unusual to employ EMTP (Electromagnetic Transients Program) type software which was originally developed for the study of lightning and switching transients.
Analysis of SSR

- Following a disturbance, the turbine-generator rotors will oscillate relative to one another at one or more of the mechanical natural frequencies called ‘torsional mode frequencies’. The relative amplitude and phase of the individual rotors are fixed and are also called as ‘mode shapes’- of torsional motion. The mode shapes are also eigenvectors corresponding to the individual torsional modes. These modes are numbered sequentially according to mode frequency (and the numbers of phase reversals in the mode shape). In general, mode ‘n’ has a frequency above those corresponding to (n-1) modes and its mode shape has ‘n’ phase reversals. Note that mode zero mentioned earlier is not a torsional mode. The total number of torsional mode is (N-1) where N is the number of rotor masses.
Remarks

1. The mode zero corresponds to the frequency zero (determined from the analysis of the mechanical system alone). However interaction with electrical system results in a nonzero frequency (normally in the range of 0.2 to 2.0 Hz). The low frequency oscillations studied in the chapters 7 to 9 correspond to the mode zero. It is obvious from Eqs. (10.21) and (10.22) that, in the absence of torsional oscillations, only zeroth mode is present in which all rotors participate. As there is no relative motion among rotors (in the absence of torsional oscillations), it is in order to club all the turbine inertias together with the generator rotor. Thus the analysis of mode zero alone is accurately done in the previous chapters.

2. Some authors model the mechanical system in terms of modal parameters (inertias, damping and spring constants). One of the reasons for this is that the damping is normally known in terms of modal damping (determined from decrement tests). Also the ‘N’ second order equations (for N modes including mode zero) are all uncoupled.
Block diagram showing interaction of electrical and mechanical system
Analysis of the Combined System

The input variable for the (linearized) mechanical system is $\Delta T_e$ which is obtained from the electrical system equations. In Laplace domain, the electrical torque $\Delta T_e$ can be related to the generator rotor slip by

$$\frac{\Delta T_e(s)}{\Delta S_m(s)} = Y_e(s) \quad (10.39)$$

The combined system (mechanical and electrical) is represented (at the generator port) as shown in Fig. 10.9. The equations for this equivalent network is given by

![Figure 10.9: Combined system (mechanical and electrical)]
Analysis of the Combined System

\[ [Y_m(s) + Y_e(s)] \Delta S_m = 0 \]  \hspace{1cm} (10.40)

where

\[ Y_m(s) = Z_m^{-1}(s) \]

The system eigenvalues are the solutions of the scalar equations

\[ Y_m(s) + Y_e(s) = 0 \]  \hspace{1cm} (10.41)

For the eigenvalues corresponding to torsional modes, the following approximate equations are applicable

\[ Y_m(j\omega_k) + Y_e(j\omega_k) = 0 \]  \hspace{1cm} (10.42)

where \( \omega_k \) is the frequency of the \( k^{th} \) torsional mode. Actually,

\[ Y_e(j\omega_k) = T_{De}(\omega_k) - j \frac{T_{Se}(\omega_k)}{\omega_k} \frac{1}{\omega_B} \]  \hspace{1cm} (10.43)
Analysis of the Combined System

where $T_{De}$ and $T_{Se}$ are the damping and synchronizing torque coefficients (calculated from the analysis of the electrical torque). Similarly, one can define

$$Y_m(j\omega_k) = T_{Dm}(\omega_k) - j \frac{T_{Sm}(\omega_k)}{\omega_k} \omega_B$$  \hspace{1cm} (10.44)

Substituting (10.43) and (10.44) in (10.42), one gets

$$T_S(\omega_k) = T_{Sm}(\omega_k) + T_{Se}(\omega_k) = 0$$  \hspace{1cm} (10.45)

The above equation determines the oscillation frequencies. Variations of $T_{Sm}$ and $T_S$ for a typical case are shown in Fig. 10.10. This shows that $T_{Se}$ has very little effect on the zero crossing of $T_S$ (the determination of oscillation frequencies corresponding to torsional modes). The instability of a torsional mode ($\omega_k$) is determined from the criterion

$$T_D(\omega_k) = T_{Dm}(\omega_k) + T_{De}(\omega_k) < 0$$  \hspace{1cm} (10.46)
## Table 10.6 Modal Quantities

<table>
<thead>
<tr>
<th></th>
<th>Mode #1</th>
<th>Mode #2</th>
<th>Mode #3</th>
<th>Mode #4</th>
<th>Mode #5</th>
<th>Mode #0</th>
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<tr>
<td>Frequency (rad/sec)</td>
<td>98.7248</td>
<td>126.9921</td>
<td>160.5289</td>
<td>202.8517</td>
<td>298.1878</td>
<td>0.00</td>
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<td>Inertia ($H_i$)</td>
<td>2.70</td>
<td>27.80</td>
<td>6.92</td>
<td>3.92</td>
<td>11297</td>
<td>2.894</td>
</tr>
<tr>
<td>Spring constant ($K_i$)</td>
<td>139.627</td>
<td>2376.4</td>
<td>945.894</td>
<td>856.303</td>
<td>5328600</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Electrical Synchronizing Torque
Damping Torque with Classical (Simplified) Model of the generator
Damping Torque with Two-Axis (Detailed) Model of the Generator
Real part of Eigenvalue Corresponding to Torsional Modes as a function of % Series Compensation

Figure 10.22: Damping of torsional modes (Machine model 2.2)
Locus of Network Mode # 1

Figure 10.24: Locus of network mode #1 (machine model 2.2)
Comments

1. Due to Torsional Interaction (TI), the damping of each torsional mode (except mode zero) is significantly affected in the vicinity of a certain level of series compensation (which results in the frequency $f_{r}^{sub}$ coinciding with the torsional frequency). For mode 1, this occurs at the highest level of series compensation and for mode 4, this occurs at the lowest level of compensation.

4. The network mode #1 ($f_{r}^{sub}$) is affected both in frequency and damping as compensation level is increased. It is interesting to note that at compensation levels which cause SSR, the network mode has increased (positive) damping.
Harmonic Interaction in AC/DC Systems

- The converters in HVDC stations generate harmonics - both AC and DC. Some of these harmonics are called characteristic harmonics that will always be present even under ideal conditions, others are called non-characteristic (also called abnormal) harmonics which are caused by (i) firing angle errors, (ii) negative sequence components in the converter bus AC voltage, and (iii) unequal converter transformer leakage impedances.

- While AC (and DC) harmonic filters are employed, invariably, to filter out the characteristic harmonics, the cost considerations do not allow the provision of filters at other harmonic frequencies except under special circumstances. If AC harmonic currents (at, say, third harmonic) are injected into the AC system, they can cause harmonic distortion of the converter bus voltage due to resonances. If the distortion is severe, this can lead to operational difficulties such as higher incidence of commutation failure, etc.
Some of the major factors that affect the low order harmonic resonances are as follows:

1. Control system - generation of firing pulses
2. Saturation in converter transformers
3. The characteristics of system impedance (variation with frequency)
4. DC system characteristics - the impedance seen by the converter terminals
5. Induction effects.
Harmonic Interactions-AC/DC Systems

- The possible solutions to the problem are as follows:
  - 1. Modification of the control system
  - 2. Use of additional filters, say, at third harmonic. Also, provision of a C-type damped filter.

- Use of synchronous condensers, SVC or STATCOM at converter station.
Harmonic Instability due to Individual Phase Control (IPC) in HVDC Converters

• 1. The harmonic instability can be expected with systems having low SCR at the converter bus. The problem may be present even at moderate values of SCR if there is a resonance.

• 2. The firing control scheme has a major effect. The problem is worse with inverse cosine control scheme compared to the constant $\alpha$ control scheme (both schemes are based on IPC)
3. The performance with IPC schemes can be improved substantially using filters in the control system such that the commutation voltages derived from the bus voltage are free from the harmonics. However, there are certain problems with this method. The filters can cause errors and also slow down the response. Furthermore, the filtering may be ineffective due to the variation in the system frequency.

4. The problem of harmonic instability is substantially solved using the EPC scheme of firing pulse generation as this eliminates the firing angle errors that are caused by the shifting of the zero crossings of the commutation voltages (due to the harmonics).

In the cross-channel HVDC scheme, a third order, AC harmonic filter was provided to overcome the problem. In New Zealand scheme, a ninth harmonic filter was used.
Core Saturation Instability

- The major causes for this type of harmonic instability are due to (i) the DC system having series resonance at or near the fundamental frequency, (ii) low short circuit ratio at the converter bus. If there is a second harmonic voltage at the converter bus, this causes fundamental frequency voltage on the DC side. Due to series resonance in the DC line, there will be relatively large fundamental frequency components in the current through the converters. This, in turn, results in DC components in the currents flowing in valve windings of the converter transformers causing magnetic saturation of the cores. This will reinforce the original second harmonic component of the voltage present at the converter bus.
Core Saturation Instability

- The main feature of this instability is the presence of DC components in the magnetizing current of the converter transformers causing saturation. The harmonics generated due to the core saturation contain a large spectrum of even harmonics and if the system impedance has a large value at one of these frequencies (due to parallel resonance), the harmonic distortion in the bus voltage is aggravated. In the case of Kingsnorth scheme, the parallel resonance occurred at the 12th harmonic due to the presence of 11th and 13th harmonic (tuned) filters. In Nelson River scheme, the resonance occurred at the fourth harmonic.
Core Saturation Instability

- It is to be noted that the core saturation instability can occur even with EPC scheme. This type of instability cannot be predicted unless the finite nature of the DC system impedance and its variation with frequency is taken into consideration. In the earlier analysis [4], the DC current was assumed to be constant.

- The possible solutions to this instability are as follows:
  - 1. Selecting smoothing reactor values to avoid the resonance in the DC system at or near the fundamental frequency.
Solutions to Harmonic Instability

2. Modification of the controller by adding an additional dc flux control loop [5]. The control signal is derived from the measured DC magnetizing current or the second harmonic component. This is used to modulate the control signal that is normally generated from the converter controllers. The modulating signal is limited to a low amplitude so that its effect on the normal operation is negligible.

The DC component in the converter transformers may also be caused by the induction of fundamental frequency currents in the DC line caused by adjacent AC circuit on the same right of way [6].
Control Interactions with a Shunt FACTS Controller (SVC or STATCOM)

- A parallel (network) resonance of frequency below the second harmonic, can result in adverse interactions with the voltage regulator of the shunt FACTS controller.

- In James Bay system in Canada involving SVC in a 735 kV line, a 90 Hz resonance is critical and a notch filter is provided in the voltage measuring circuit.
The strong resonance can be thought of as the result of coupling between two oscillatory modes. The mode coupling arises from the similarity between eigenvectors. It is commonly observed that when there is mode coupling, the change in the damping of one mode is opposite in sign to the change in the damping of the other coupled mode when an important parameter is varied. For example, in subsynchronous resonance (SSR) analysis, when there is increase in the series compensation level, the damping of the network mode is increased while the torsional mode (with which it is coupled) is negatively damped and vice versa. The degree of mode coupling varies with the level of compensation [1].
Mode Coupling in the Presence of Damping Controllers

- It has been observed that mode coupling (between Swing Mode and the Exciter Mode) occurs when tuning Power System Stabilizers (PSS). There is also Strong Resonance in such a case.

- Recent studies show the presence of Strong Resonance in the presence of Supplementary Modulation Controller (SMC) of STATCOM (a shunt FACTS Controller).
A Case Study

- The SMC uses Thevenin voltage viewed from the STATCOM terminals.
- A three generator nine bus example is considered for the study.
- The mode coupling is between a swing mode and the exciter mode due to the generator located close to the STATCOM.
- Model reduction helps in the analysis of strong resonance.
Fig. 1. Block diagram of the supplementary modulation controller for the STATCOM.
A three machine system

Fig. 3. Three-machine system.
Root Loci showing interaction of two oscillatory modes

Fig. 4. Root loci showing interaction of two complex modes in three-machine system when $K_r$ is increasing.
Asymptotic Behaviour of Eigenvalues as Controller gain is Increased

Fig. 5. Asymptotic behavior of eigenvalues of reduced system when $K_p$ is increasing.
Asymptotic Behaviour of Eigenvalues as $X_{th}$ (a control parameter) is increased.

Fig. 6. Asymptotic behavior of eigenvalues of reduced system when $X_{dh}$ is increasing.
Root Loci of Swing and Exciter Mode as Controller gain is increased

Fig. 7. Root loci of three-machine system when $K_r$ is increasing when $\Delta X_{ef}$ is positive.
Root Loci for the reduced system as controller gain is increased

Fig. 8. Root loci of reduced system when $K_r$ is increasing when $\Delta X_{th}$ is positive.
Role of Emerging Technologies

- Wide Area Measurement System (WAMS) based on application of Phasor Measuring Units (PMU) using GPS technology is expected to provide a platform for the implementation of dynamic state estimation, system control and protection. The benefits include improved security of the system with optimal investments.
Role of Emerging Technologies

- Wireless sensor networks can be used to monitor the condition of transmission systems, provide for dynamic rating of lines based on weather conditions.
- Sensors can also be used for measurement of line flows, voltages and help prevent transition to emergency state from the normal state.
Role of Emerging Technologies

- The emerging technologies contribute to the development of ‘Smart Grids’ that can provide economic supply of electric energy maintaining Power Quality

Requirements: Need for the development of appropriate analytical tools for adaptive system control and protection
Conclusions-I

• In large, complex systems such as power systems there can be several interactions among subsystems which are often observed during system operation. These occur at different frequency spectrum.

• In power systems, interactions occur at low frequency (0.2-2 Hz), Subsynchronous freq (10-40Hz) and harmonic frequencies.
Conclusions-II

- Control interactions in complex systems require coordinated design of damping (stabilizing) controllers. This requires detailed knowledge of varying system models and their interconnections.

- It would be desirable to develop intelligent control that does not require knowledge of system interconnections.