

Mitigation of SSR Oscillations in Series Compensated Line using LCAP Subsynchronous Damping Controller

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Abstract

Subsynchronous Resonance (SSR) is a growing problem in power systems having series compensated transmission lines. Subsynchronous resonance with low frequency that surpasses aggregate fatigue threshold of the generator shaft frequently could significantly reduce the shaft service life, which is a new problem that emerges in recent years. Flexible AC transmission systems (FACTS) controllers are widely applied to alleviate subsynchronous resonance. A line current and active power (LCAP) supplementary subsynchronous damping controller (SSDC) is proposed to damp subsynchronous resonance caused by series capacitors. Both eigenvalue investigation and time-domain simulation results verify that the proposed control strategy can effectively damping power system oscillations of the power system with SVC and SSDC. Time domain simulations using the nonlinear system model are also carried out to demonstrate the effectiveness of the proposed damping controller. The recommended control approach has been accumulated with the IEEE first benchmark model for SSR study. The analysis indicates that SVC using the proposed control strategy has better alleviation effect and output characteristics. All the simulations are validated by using MATLAB/Simulink environment.

Keywords: FACTS devices, line current and active power (LCAP), sub synchronous resonance (SSR), supplementary controller damping controller (SSDC), eigenvalue investigation

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1. Introduction

The constantly growing demand for electric power necessitates the transmission of large amounts of power over long distances. An economically gorgeous solution to increase power transfer through long transmission lines, without building new parallel circuits is to install the series capacitors. It is known that series capacitor compensation benefits power systems in many ways, such as increasing power transfer capability, enhancing transient stability limits etc. it is also known that fixed series compensation may cause sub-synchronous resonance (SSR) in power systems, which can lead to the damage to machine shaft. Since the discovery in 1970 that SSR was the main cause of the shaft failures at the Mohave generating station (USA) extensive research and development efforts have been devoted to the development of effective SSR mitigation measures.

Flexible AC transmission systems (FACTS) devices are integrated in power systems to control power flow, increase transmission line stability limit and improve the security of transmission systems. FACTS controllers are used to enhance system flexibility and increase system loadability [1-2]. Many countermeasures to sub-synchronous resonance problem have been reported in the literature [3]. However sub-synchronous resonance control through FACTS controller is gaining importance. Based on the above considerations, some papers focused the attention on control of sub-synchronous resonance torques with FACTS controller such as SVC. SSR analysis with and without SVC is proposed. SSR analysis with SVC uses constant angle control method. These papers attempts to highlight the effectiveness of SVC control in stabilizing the critical torsional mode in addition to the enhancement of power transfer capability [4-6].

The use of series compensation may lead to sustained oscillations in generator-turbine shaft systems in thermal power stations closely connected to the compensated line. This phenomenon is known under the name subsynchronous resonance (SSR). The problem of SSR is related to the interaction between a series-compensated transmission line and the mechanical system into the generator unit. SSR can be divided into two main groups, steady-

state SSR [induction generator effect (IGE), and torsional interaction (TI)] and transient torques. IGE is considered a theoretical condition that unlikely can occur in a series-compensated power system, whereas SSR due to TI and TA are dangerous conditions that must be avoided [7-12]. The SVC is primarily installed to enhance power transfer capacity but with the proposed SSDC controller can additionally damp all subsynchronous oscillation modes. It is found that with the remote generator speed a simple subsynchronous damping controller (SSDC) can damp all the SSR modes with critical level of compensation [13-16].

The IEEE First Benchmark (FBM) model is considered for the analysis of SSR [17] and the complete simulation of the power system is performed in the MATLAB/Simulink environment. The study is carried out based on damping torque analysis, eigenvalue analysis, and transient simulation. The results show that the suggested controller is satisfactory for damping SSR. The remainder of this paper is organized as follows. Section 2 describes the modeling of power system. Section 4 explains the detailed eigenvalues analysis of study system for different operating conditions. Validation of the eigenvalue results through time domain simulation is also presented in section 4. Finally, Section 5 presents the major conclusion of the paper.

2. Study Power System Model

The study system, as shown in Figure 1, consists of a steam turbine driven synchronous generator supplying bulk power to an infinite bus over a long transmission line (IEEE first benchmark model) [17]. An SVC of switched capacitor and thyristor controlled reactor type is considered located at the central of the transmission line which provides continuously controllable reactive power at its terminals in response to line current and active power (LCAP) supplementary controller. The series compensation is applied at the sending end of the line [18-20].

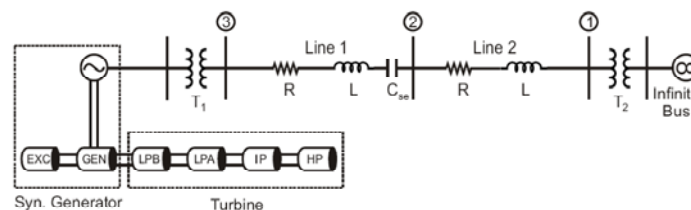


Figure 1. IEEE FBM of Study Power System

2.1. Modeling of Synchronous Generator

In the detailed machine model used in this paper, the stator is represented by a dependent current source parallel with the inductance. The generator model includes the field winding 'f' and a damper winding 'h' along d-axis and two damper windings 'g' and 'k' along q-axis. The IEEE type-1 excitation system is used for the generator [21-23].

The rotor flux linkages associated with different windings are defined by:

$$\begin{aligned}
 \dot{\psi}_f &= a_1\psi_f + a_2\psi_h + b_1V_f + b_2I_d \\
 \dot{\psi}_h &= a_3\psi_f + a_4\psi_h + b_3I_d \\
 \dot{\psi}_g &= a_5\psi_g + a_6\psi_k + b_5I_q \\
 \dot{\psi}_k &= a_7\psi_g + a_8\psi_h + b_6I_q
 \end{aligned} \tag{1}$$

Where V_f is the field excitation voltage. Constants a_1 to a_8 and b_1 to b_6 are defined in [24]. The i_d and i_q are d and q axis components of the machine terminal current respectively which are defined with respect to machine reference frame. To have a common axis of representation with

the network and SVC, these flux linkages are transformed to the synchronously rotating D-Q frame of reference using the following transformation:

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \cos \delta & -\sin \delta \\ \sin \delta & \cos \delta \end{bmatrix} \begin{bmatrix} i_D \\ i_Q \end{bmatrix} \quad (2)$$

Where i_D, i_Q are the respective machine current components along D and Q axis. δ is the angle by which d-axis leads the D-axis. Currents I_d and I_q , which are the components of the dependent current source along d and q axis respectively, are expressed as:

$$\begin{aligned} I_d &= C_1 \Psi_f + C_2 \Psi_h \\ I_q &= C_3 \Psi_g + C_4 \Psi_k \end{aligned} \quad (3)$$

Where constants c_1 - c_4 are defined in [20]. The above nonlinear differential equations are used in the power system modeling.

2.2. Modeling of Six Mass Mechanical System

In the mechanical model detailed shaft torque dynamics [2] has been considered for the analysis of torsional modes due to SSR. The mechanical system is described by the six spring-mass model as shown in Figure 2. This shows the electromechanical mass-spring damper system. It consists of exciter (EXC), generator (GEN), low pressure of two sections (LPA and LPB), intermediate pressure (IP) and high pressure (HP) turbine sections. Every section has its own angular momentum (M) and damping coefficient (D), and every two successive masses have their own shaft stiffness constant (K). All masses are mechanically connected to each other by elastic shafts [25]. The data for electrical and mechanical system are provided in appendix.

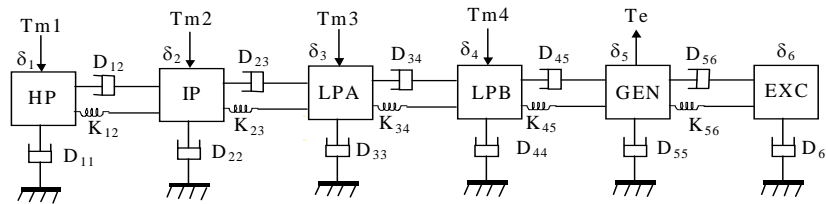


Figure 2. Six mass spring mechanical system (Typical SSR Studies) [18]

The leading equations and the state and output equations are given as follows:

$$\delta_i = \omega_i \quad i=1, 2, 3, 4, 5, 6$$

$$\frac{d}{dt} \omega_1 = \frac{1}{M_1} \left[-(D_{11} + D_{12}) \omega_1 + D_{12} \omega_2 - K_{12} (\delta_1 - \delta_2) + T_{M1} \right]$$

$$\frac{d}{dt} \omega_2 = \frac{1}{M_2} \left[D_{12} \omega_1 - (D_{12} + D_{22} + D_{23}) \omega_2 + D_{23} \omega_3 - K_{12} (\delta_2 - \delta_1) + T_{M2} \right]$$

$$\frac{d}{dt} \omega_3 = \frac{1}{M_3} \left[D_{23} \omega_2 - (D_{23} + D_{33} + D_{34}) \omega_3 + D_{34} \omega_4 - K_{23} (\delta_3 - \delta_2) - K_{34} (\delta_3 - \delta_4) + T_{M3} \right]$$

$$\frac{d}{dt} \omega_4 = \frac{1}{M_4} \left[D_{34} \omega_3 - (D_{34} + D_{44} + D_{45}) \omega_4 + D_{45} \omega_5 - K_{34} (\delta_4 - \delta_3) - K_{45} (\delta_4 - \delta_5) + T_{M4} \right]$$

$$\frac{d}{dt} \omega_5 = \frac{1}{M_5} \left[D_{45} \omega_4 - (D_{45} + D_{55} + D_{56}) \omega_5 + D_{56} \omega_6 - K_{45} (\delta_5 - \delta_4) - K_{56} (\delta_5 - \delta_6) - T_e \right]$$

$$\begin{aligned} \frac{d}{dt} \omega_6 &= \frac{1}{M_6} [D_{56} \omega_5 - (D_{56} + D_{66}) \omega_6 - K_{56} (\delta_6 - \delta_5)] \\ T_e &= -X_d'' (i_D I_Q - i_Q I_D) \end{aligned} \quad (4)$$

Where $\delta_1, \delta_2, \delta_3, \delta_4, \delta_5, \delta_6$ are the angular displacements and $\omega_1, \omega_2, \omega_3, \omega_4, \omega_5, \omega_6$ are the angular velocities of different shaft segments as shown in Figure 2.

2.3. Modeling of Excitation System

The IEEE type-1 excitation system [26] is described by the following equations:

$$\begin{aligned} \frac{d}{dt} V_f &= -\frac{(K_E + S_E)}{T_E} V_f + \frac{1}{T_E} V_r \\ \frac{d}{dt} V_S &= -\frac{K_F(K_E + S_E)}{T_E T_F} V_f - \frac{1}{T_E} V_S + \frac{K_F}{T_E T_F} V_r \\ \frac{d}{dt} V_r &= -\frac{K_A}{T_A} V_S - \frac{1}{T_A} V_r - \frac{K_A}{T_A} V_g + \frac{K_A}{T_A} V_{REF} \end{aligned} \quad (5)$$

2.4. Modeling of T Network

The ac transmission line in this study system is adapted from the IEEE first SSR benchmark system [17]. The transmission line is represented by standard lumped parameter T-circuit. The network has been represented by its α -axis equivalent circuit, which is identical with the positive sequence network. The governing equations of the α -axis, T-network representation is derived as follows:

$$\begin{aligned} \frac{di_{1\alpha}}{dt} &= -\frac{R}{L_2} i_{1\alpha} + \frac{1}{L_2} V_{2\alpha} - \frac{1}{L_2} V_{1\alpha} \\ \frac{di_{\alpha}}{dt} &= \frac{1}{L_1} V_{2\alpha} - \frac{R_1}{L_1} i_{\alpha} - \frac{L_d''}{L_1} \frac{di_{\alpha}}{dt} - \frac{1}{L_1} V_{4\alpha} \\ \frac{dV_{2\alpha}}{dt} &= -\frac{1}{C_n} i_{\alpha} - \frac{1}{C_n} i_{2\alpha} - \frac{1}{C_n} i_{1\alpha} \\ \frac{dV_{4\alpha}}{dt} &= \frac{1}{C_{se}} i_{\alpha} \end{aligned} \quad (6)$$

Where $C_n = C_T + C_{FC}$, $L_1 = L + L_A$, $L_2 = L + L_{T2}$, $L_A = L_{T1} + L_n''$ and $R_1 = R + R_a$

Similarly, the equations can be derived for the β - network. The α - β network equations are then transformed to D-Q frame of reference.

2.5. Modeling of Static VAR Compensator

The terminal voltage perturbation ΔV and the SVC incremental current weighted by the factor K_D representing current droop are fed to the reference junction. T_M represents the measurement time constant, which for simplicity is assumed to be equal for both voltage and current measurements. The voltage regulator is assumed to be a proportional- integral (PI) controller. Thyristor control action is represented by an average dead time T_D and a firing delay time T_s . ΔB is the variation in TCR susceptance. ΔV_F represents the incremental supplementary control controller [27].

The α - β axes currents entering TCR from the network are expressed as:

$$\begin{aligned} L_s \frac{di_{2\alpha}}{dt} + R_s i_{2\alpha} &= V_{2\alpha} \\ L_s \frac{di_{2\beta}}{dt} + R_s i_{2\beta} &= V_{2\beta} \end{aligned} \quad (7)$$

Where R_S , L_S represent TCR resistance and inductances respectively. The other equations describing the SVC model are:

$$\begin{aligned} Z_1 &= \Delta V_{ref} - Z_2 + \Delta V_F \\ \dot{Z}_2 &= \frac{1}{T_M} (\Delta V_2 - K_D \Delta i_2) - \frac{1}{T_M} Z_2 \\ \dot{Z}_3 &= -\frac{K_I}{T_3} Z_1 + \frac{K_P}{T_S} Z_2 - \frac{1}{T_S} Z_3 - \frac{K_P}{T_S} \Delta V_{ref} - \frac{K_P}{T_S} \Delta V_F \\ \Delta B &= (Z_3 - \Delta B) / T_D \end{aligned} \quad (8)$$

Where $\Delta V_2, \Delta i_2$ are incremental magnitudes of SVC voltage and current, respectively, obtained by linearizing.

$$V_2^2 = V_{2D}^2 + V_{2Q}^2, \quad i_2^2 = i_{2D}^2 + i_{2Q}^2$$

3. Design of Subsynchronous Damping Controller (SSDC)

The supplementary controller is implemented through a first order supplementary controller transfer function.

3.1. Line Current (LC) Supplementary Controller

The line current entering to SVC Bus from generator end bus is given by:

$$i_2^2 = i_{2D}^2 + i_{2Q}^2 \quad (9)$$

Linearizing (11) gives the deviation in line current:

$$\Delta i = \frac{i_{D0}}{i_0} \Delta i_D + \frac{i_{Q0}}{i_0} \Delta i_Q \quad (10)$$

Where '0' represents operating point or steady state values.

3.2. Active Power (AP) Supplementary Controller

The line active power entering to SVC bus from generator end is given by:

$$P_2 = V_{2D} i_D + V_{2Q} i_Q \quad (11)$$

Where V_{2D} and V_{2Q} are direct and quadrature axis SVC bus voltages & i_D and i_Q are direct and quadrature axis currents.

Linearizing above equation gives the deviation in active power ΔP_2 which is selected as supplementary control signal:

$$\Delta P_2 = V_{2D0} \Delta i_D + i_{D0} \Delta V_{2D} + V_{2Q0} \Delta i_Q + i_{Q0} \Delta V_{2Q} \quad (12)$$

Where '0' represents operating point or steady state values.

4. Results and Analysis

The study power system consists of 1110 MVA synchronous generator supplying power to an infinite bus over a 400 kV, 600 km long series compensated single circuit transmission line. The study system is as per the IEEE first bench mark model. The system data and torsional spring mass system data are given in appendix. The SVC rating for the line has been chosen to be 100 MVAR inductive to 300 MVAR capacitive. The 40% series compensation is used at the sending end of the transmission line [28-29].

4.1. Eigenvalue Investigation

The eigenvalue investigation has been carried using the linearized system modeling of power system. The natural system damping has been considered to be zero in order to simulate the weakest system conditions. Table 1 shows the eigenvalues without any supplementary controller incorporated in the SVC. Mode 0 is unstable at P=800 MW. Table 2 shows the system eigenvalues at P = 200, 500 and 800 MW with series compensated LCAP supplementary controller is stable. The supplementary controller parameters are selected based on an extensive root locus. All the electrical and electromechanical modes are found to be stable when the proposed supplementary controller is applied.

Table 1. System Eigenvalues of T Network without Supplementary Controller

Torsional Mode	P =200 MW	P =500 MW	P =800 MW
Mode # 5	-0.00±j298.1	-0.00±j298.1	-0.00±j298.1
Mode # 4	-0.22236±j202.88	-0.27157±j202.84	-0.3371±j202.78
Mode # 3	-0.010518±j160.52	-0.047052±j160.53	-0.09618±j160.52
Mode # 2	-0.005104±j126.97	-0.010512±j126.96	-0.01716±j126.95
Mode # 1	-0.026618±j98.757	-0.030093±j98.665	-0.02494±j98.517
Mode # 0	-0.33922±j4.0339	-0.098976±j4.2864	+0.079±j4.1284
	-13.132±j833.01	-13.133±j833	-13.133±j833
	-532.8±j3.3619i	-532.82±j4.4606	-532.83±j4.7221
	-12.767±j442.17	-12.769±j442.15	-12.769±j442.16
	-5.4252±j311.97	-5.4245±j311.97	-5.4245±j311.97
Other Modes	-34.282±j189.06	-35.515±j187.54	-35.498±j187.12
	-3.2239±j187.16	-3.2602±j188.75	-3.4007±j189.12
	-57.127±j86.317	-53.469±j85.459	-52.804±j85.669
	-25.634±j24.258	-25.689±j24.357	-25.744±j24.309
	-39.674	-40.643	-40.979
	-27.443	-31.073	-31.573
	-2.5406	-2.8919	-2.9457
	-0.5906±j0.74682	-0.5662±j0.79191	-0.6652±j0.84667

Note: Bold values represent unstable mode.

Table 2. System Eigenvalues of T Network with LCAP Supplementary Controller

Torsional Mode	P =200 MW	P =500 MW	P =800 MW
Mode # 5	-0.00±j298.1	-0.00±j298.1	-0.00±j298.1
Mode # 4	-0.2226±j202.88	-0.2717±j202.84	-0.3368±j202.78
Mode # 3	-0.0104±j160.52	-0.0469±j160.52	-0.0956±j160.52
Mode # 2	-0.0051±j126.97	-0.0105±j126.96	-0.0175±j126.95
Mode # 1	-0.0267±j98.757	-0.0302±j98.665	-0.0259±j98.514
Mode # 0	-0.3391±j4.0336	-0.0942±j4.3101	-0.8365±j3.7552
	-13.135±j833.01	-13.137±j833	-13.135±j833
	-532.8±j3.6968	-532.82±j4.9301	-532.84±j4.3843
	-12.763±j442.18	-12.763±j442.17	-12.773±j442.16
	-5.4251±j311.97	-5.4248±j311.97	-5.4199±j311.97
	-34.302±j189.15	-35.497±j187.66	-35.866±j187.04
Other Modes	-3.2247±j187.22	-3.2289±j188.8	-3.4121±j189.1
	-57.047±j85.892	-53.426±j84.979	-51.232±j85.518
	-25.629±j24.26	-25.687±j24.36	-25.767±j24.331
	-39.728	-40.74	-42.376
	-27.445	-31.076	-31.595
	-4.9466	-4.981	-5.0682
	-2.5451	-2.9035	-3.0897
	-0.58208±j0.73535	-0.5545±j0.77735	-0.26586±j1.6283
	-1.3895	-1.3909	-0.89987

4.2. Time Domain Simulations of SSR Study

Table 3. Supplementary controller parameters

SVC Supplementary Controller	K_{B1}	T_1	T_2
Line Current (LC)	-0.043	0.39	0.02
Active Power (AP)	-0.009	0.01	0.009

Table 4. Torsional spring-mass system data

Inertia H (sec)	Spring constant K (pu torque/rad.)
$H_1 = 0.1033586$	$K_{12} = 25.772$
$H_2 = 0.1731106$	$K_{23} = 46.635$
$H_3 = 0.9553691$	$K_{34} = 69.478$
$H_4 = 0.9837909$	$K_{45} = 94.605$
$H_5 = 0.9663006$	$K_{56} = 3.768$
$H_6 = 0.0380697$	

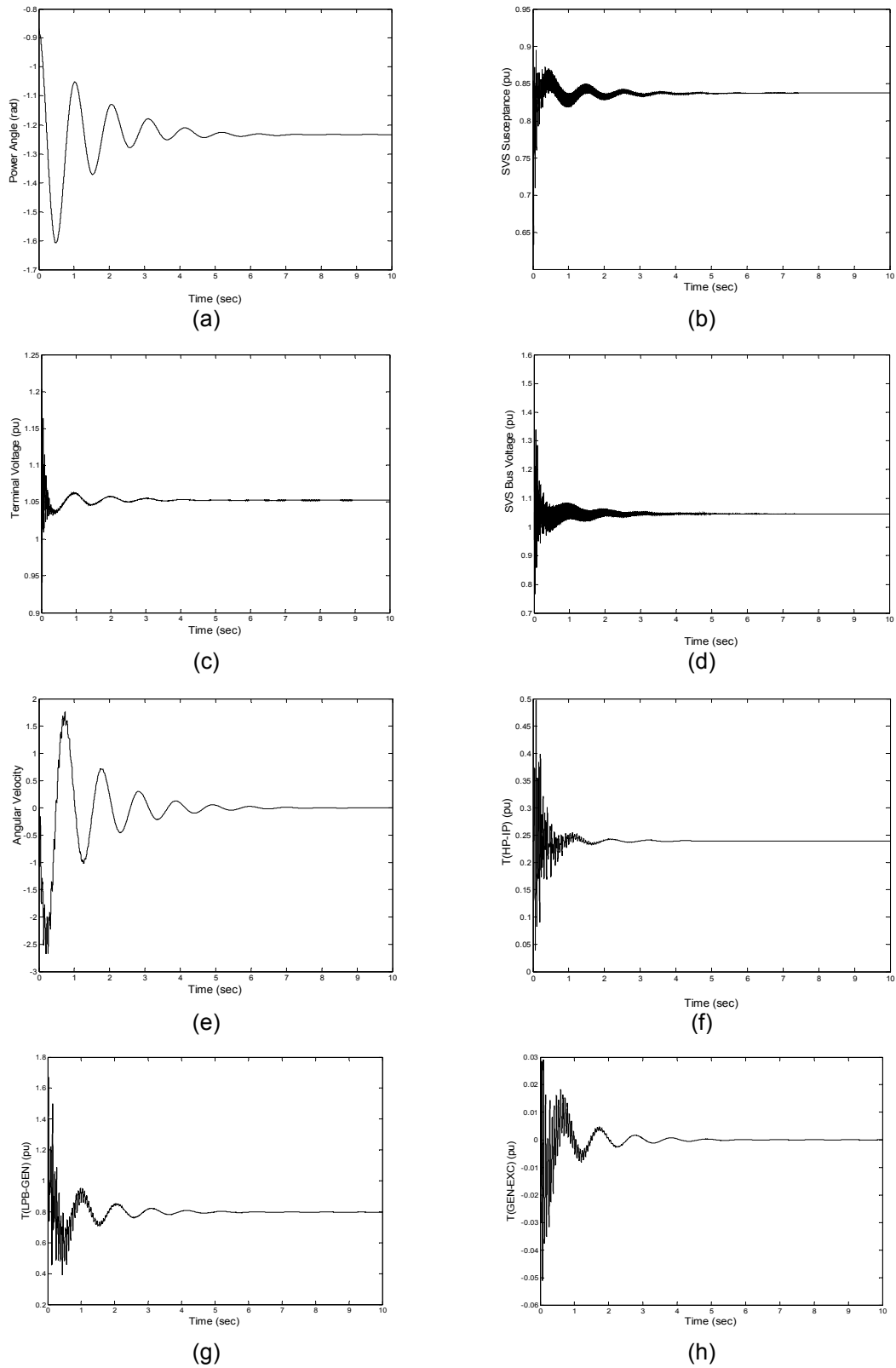


Figure 3. Variation of (a) Power Angle (b) SVC Susceptance (c) Terminal Voltage (d) SVC Bus Voltage (e) Angular Velocity (f) Torque (HP-IP) (g) Torque (LPB-GEN) (h) Torque (GEN-EXC) response with LCAP supplementary controller

A digital computer simulation study, using a nonlinear system model, has been carried out to validate the effectiveness of the LCAP supplementary controller under large disturbance conditions. Disturbance is simulated by 30% sudden increase in input torque for 0.1 s. The simulation study has been carried out at P=800MW. The natural damping of the mechanical subsystem is assumed to be zero in order to simulate the worst system conditions and to demonstrate the damping effectiveness of the proposed SVC controller alone without considering the already existing natural system damping [30-31]. Figure 3 shows the response curves of the terminal voltage, SVC bus voltage, SVC susceptance, power angle, angular velocity and torques of shaft sections with LCAP supplementary controller after the disturbance. It can be seen that there is tendency towards stability when LCAP supplementary controller is used in the SVC control system. The torsional oscillations are stabilized and the LCAP SVC supplementary controller attains a significant improvement in the transient performance of the series compensated power system. The supplementary controller parameters and torsional mass spring data are given in Appendix (Table 3 and Table 4). The control strategy is easily implemental as it utilizes the locally derived controllers from the SVC bus.

5. Conclusion

A supplementary subsynchronous damping controller (SSDC) for a static VAR compensator (SVC) has been designed for generator excitation system able to damp all unstable torsional modes. The IEEE first benchmark model is used to show the effectiveness of the controller. Eigenvalue investigation and time domain simulations using the nonlinear system model are carried out to investigate the performance of SVC SSDC. The analyzed results show that the proposed controllers can effectively stabilize the common mode torsional oscillations. The proposed LCAP supplementary controller with series compensated line uses an unsophisticated and easy to implement to cope with the SSR phenomenon. The scheme enhances the system performance considerably and torsional oscillations are damped out at all levels of series compensation and effective control of power flow is obtained. Extensive simulation results in MATLAB/Simulink show that an SVC installed in a transmission system with the primary objective of improving power transfer capability can also damp SSR with the supplementary controller.

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