A New SVS Control Strategy For Damping Torsional Oscillations In A Series Compensated Power System

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ABSTRACT

The paper presents a new SVS control strategy for damping torsional oscillations due to subsynchronous resonance (SSR) in a series compensated power system. The proposed SVS control strategy utilizes the effectiveness of combined reactive power and voltage angle (CRPVA) SVS auxiliary control signals. A digital computer simulation study, using a nonlinear system model, has been carried out to illustrate the performance of the proposed SVS controller under large disturbance. It is found that the torsional oscillations are effectively damped out and the transient performance of the series compensated power system is greatly improved.

KEYWORDS: Static VAR System (SVS), Combined reactive power and voltage angle (CRPVA), Subsynchronous resonance (SSR), Transient performance.

1. INTRODUCTION

Series compensation has been widely used to enhance the power transfer capability. However, series compensation gives rise to dynamic instability and sub synchronous resonance (SSR) problems. Many preventive measures to cope with these dynamic instability problems in series compensated lines have been reported in literature. Among these the application of SVS controller has gained importance in recent years [1].

In recent years static VAR system (SVS) has been employed to an increasing extent in the modern power systems [1] due to its capability to work as Var generation and absorption systems. Besides, voltage control and improvement of transmission capability, SVS in coordination with auxiliary controllers [2] can be used for damping of power system oscillations. Damping of power system oscillation plays an important role not only in increasing the power transmission capability but also for stabilization of power system conditions after critical faults, particularly in weakly coupled networks.

S.K. Gupta, Narendra Kumar [3,4] developed a double order SVS auxiliary controller in combination with continuously controllable series compensation and Induction machine damping unit (IMDU) for damping torsional modes in a series compensated power system. The proposed scheme was able to damp out the torsional modes at wide range of series compensation. However the control scheme was complex as it utilized three different controllers. G.N. Pillai and A. Ghosh et. al [6] designed a power flow controller proposing an integral state feedback controller which reduces the adverse effect of power flow controller on torsional interactions and compared the torsional characteristics of SSSC compensated power systems .

In this paper a new SVS control strategy for damping torsional oscillations due to subsynchronous resonance (SSR) in a series compensated power system has been developed. The proposed SVS control strategy utilizes the effectiveness of combined reactive power and voltage angle (CRPVA) SVS auxiliary control signals. A digital computer simulation study, using a nonlinear system model, has been carried out to illustrate the performance of the proposed SVS controller under large disturbance. It is found that the torsional oscillations are effectively damped out and the transient performance of the series compensated power system is greatly improved. The beauty of the proposed scheme is that it derives its control signals from the point of location of the SVS. The scheme can easily be implemented. SVS is considered located at the middle of transmission line due to its optimum performance.

2. SYSTEM MODEL

The study system (Fig.1) consists of a steam turbine driven synchronous generator supplying bulk power to an infinite bus over a long transmission line. An SVS of switched capacitor and thyristor controlled reactor type is considered located at the middle of the transmission line which provides continuously controllable reactive power at its terminals in response to bus voltage and combined reactive power and voltage angle (CRPVA) SVS auxiliary control signals. The series compensation is applied at the sending end side of SVS along the line.

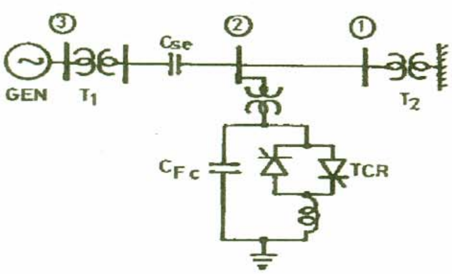


Fig. 1 Study System.

2.1 Generator

In the detailed machine model [2,7] used here, 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. In the mechanical model detailed shaft torque dynamics [2] has been considered for the analysis of torsional oscillations due to SSR. The rotor flux linkages 'ψ' associated with different windings of synchronous generator are defined by:

$$\dot{\psi}_f = a_1 \psi_f + a_2\psi_h + b_1 V_f + b_2 i_d$$

$$\dot{\psi}_h = a_3 \psi_f + a_4\psi_h + b_3 i_d$$

$$\dot{\psi}_g = a_5 \psi_g + a_6\psi_k + b_5 i_q \qquad (1)$$

$$\dot{\psi}_k = a_7 \psi_g + a_8\psi_k + b_6 i_q$$

where V_f is the field excitation voltage. Constants a_1 to a_8 and b_1 to b_6 are defined in [6]. i_d, 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 SVS, these flux linkages are transformed to the synchronously rotating D-Q frame of reference using the transformation:

$$i_d = i_D \cos\delta - i_Q \sin\delta$$

$$i_q = i_Q \sin\delta + i_Q \cos\delta \qquad (2)$$

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:

$$I_d = c_1 \psi_f + c_2 \psi_h$$
$$I_q = c_3 \psi_g + c_4 \psi_k \qquad (3)$$

where constants c_1- c_4 are defined in [7]. Substituting eqns.(2) and (3) in eqn.(1), the nonlinear set of differential eqns. governing the dynamics of the generator are finally obtained.

2.2 Mechanical System

The six spring mass model describes the mechanical system as shown in Fig.2. The governing nonlinear differential equations are given as follows:

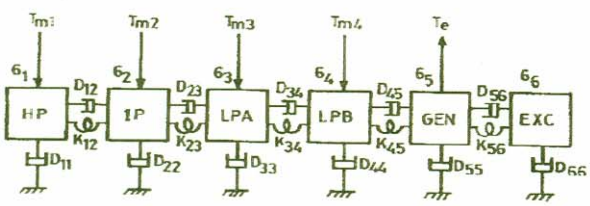


Fig. 2. Six – spring mass representation of the mechanical system

$$\dot{\delta}_i = \omega_i, \quad i = 1,2,3,4,5,6$$

$$\dot{\omega}_1 = [-(D_{11} + D_{12})\omega_1 + D_{12}\omega_2 - K_{12}(\delta_1 - \delta_2) + T_{m1}] / M_1$$

$$\dot{\omega}_2 = [(D_{12}\omega_1 - (D_{12} + D_{22} + D_{23})\omega_2 + D_{23}\omega_3 - K_{12}(\delta_2 - \delta_1) - K_{23}(\delta_2 - \delta_3) + T_{M2}] / M_2$$

$$\dot{\omega}_3 = [(D_{23}\omega_2 - (D_{23} + D_{33} + D_{34})\omega_3 + D_{34}\omega_4 - K_{23}(\delta_3 - \delta_2) - K_{34}(\delta_3 - \delta_4) + T_{M3}] / M_3 \qquad (4)$$

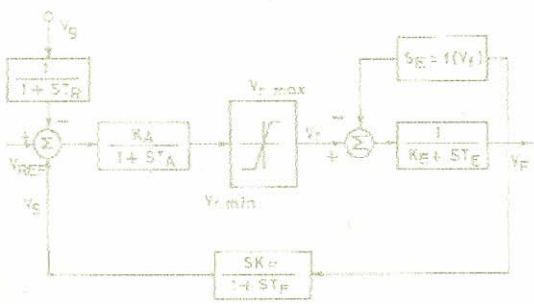
$$\dot{\omega}_4 = [(D_{34}\omega_3 - (D_{34} + D_{44} + D_{45})\omega_4 + D_{45}\omega_5 - K_{34}(\delta_4 - \delta_3) - K_{45}(\delta_4 - \delta_5) + T_{M4}] / M_4$$

$$\dot{\omega}_5 = [(D_{45}\omega_4 - (D_{45} + D_{55} + D_{56})\,\omega_5 + D_{56}\omega_6 - K_{45}(\delta_5 - \delta_4) - K_{56}(\delta_5 - \delta_6) + T_e] / M_5$$

$$\dot{\omega}_6 = [(D_{56}\omega_5 - (D_{56} + D_{66})\omega_6 - K_{56}(\delta_6 - \delta_5) + T_e] / M_6$$

2.3 Excitation System

The IEEE type-1 model as shown in Fig.3 represents the excitation system. V_g represents the generator terminal voltage and V_f is the field excitation voltage. S_E is the saturation function. The excitation system is described by the following nonlinear differential equations.



$$V_f = -(K_E+S_E)\, V_f / T_E + V_r / T_E$$

$$\dot{V}_S = -K_F\,(K_E+S_E)\, V_f / T_E\, T_F - V_S T_S + K_F\, V_r / T_E T_F \qquad (5)$$

$$\dot{V}_r = -K_A\, V_S / T_A - V_r / T_A - K_A\, V_g / T_A + K_A\, V_{REF} / T_A$$

2.4 Network

The transmission line is represented by lumped parameter π - circuit as shown in Fig.4. The network has been represented by its α–axis equivalent circuit, which is identical with the positive sequence network. The governing nonlinear differential equations of the network are derived as follows

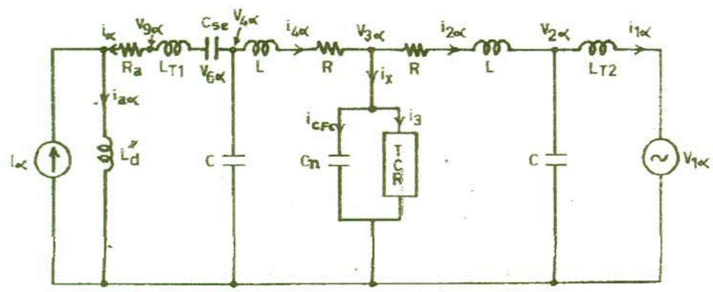


Fig.4. α-axis representation of network

$di_{1\alpha}/dt = (V_{2\alpha} - V_{1\alpha}) / L_{T2}$

$di_{2\alpha}/dt = (V_{3\alpha} - V_{2\alpha} - R\, i_{2\alpha})/L \qquad (6)$

$di_{4\alpha}/dt = (V_{4\alpha} - V_{3\alpha} - R\, i_{4\alpha})/L$

$di_{\alpha}/dt = (V_{4\alpha} - R_a\, i_\alpha - L_d''\, dI_\alpha/dt - V_{5\alpha})/L_A$

$dV_{2\alpha}/dt = (i_{2\alpha} - i_{1\alpha})/C$
$dV_{3\alpha}/dt = (i_{4\alpha} - i_{3\alpha} - i_{2\alpha})/C_n$
$dV_{4\alpha}/dt = (-i_{4\alpha} - i_{\alpha})/C$
$dV_{6\alpha}/dt = i_{\alpha}/C_{se}$

where $L_A = L_{T1} + L''_d$ and $C_n = 2C + C_{FC}$, and I_α is the current of the dependent current source. Similarly, the equations can be derived for the β- network. The α-β network equations are then transformed to the synchronously rotating D-Q frame of reference.

2.5 Static VAR System

Fig.5 shows a small signal model of a general SVS. The terminal voltage perturbations ΔV_3 and the SVS incremental current Δi_3 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 auxiliary control signal. The α, β axes currents entering TCR from the network are expressed as:

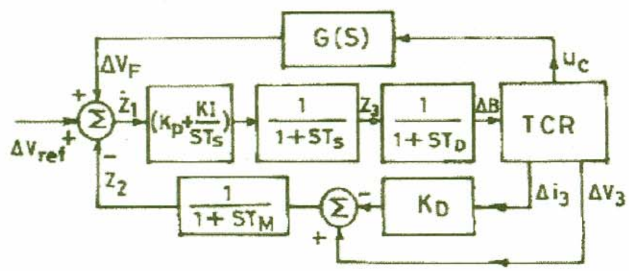


Fig. 5 SVS control system with auxiliary feedback

$di_{3\alpha}/dt = (V_{3\alpha} - R_S\, i_{i3\alpha})/L_S$

$di_{3\beta}/dt = (V_{3\beta} - R_S\, i_{3\beta})/L_S$ (7)

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

$\dot{z}_1 = V_{ref} - z_2 + \Delta V_F$

$\dot{z}_2 = (\Delta V_3 - K_D \Delta i_3)/T_M - z_2/T_M$

$\dot{z}_3 = (-K_I z_1 + K_P z_2 - z_3 - K_P \Delta V_{ref})/T_S$ (8)

$\Delta\dot{B} = (z_3 - \Delta B)/T_D$

Where ΔV_3, Δi_3 are incremental magnitudes of SVS voltage and current, respectively, obtained by linearising

$V_3 = \sqrt{(V^2_{3D} + V^2_{3Q})}$, and $i_3 = \sqrt{(i^2_{3D} + i^2_{3Q})}$

3. SVS CONTROL STRATEGY

In the proposed SVS control strategy, two auxiliary signals namely the reactive power and voltage angle deviations are used in combination in addition to the main voltage control loop of the SVS. This combination has been designated as combined reactive power and voltage angle (CRPVA) SVS auxiliary controller. This has been applied for damping power oscillations due to sub synchronous resonance (SSR) in a series compensated power system.

3.1 SVS Auxiliary Controller

The auxiliary signal U_C is implemented through a first order auxiliary controller transfer function G(s) as shown in fig.6, which is assumed to be:

$$G(s) = \Delta V_F / U_C = K_B (1 + sT_1) / (1 + sT_2) \tag{9}$$

This can be equivalently written as:

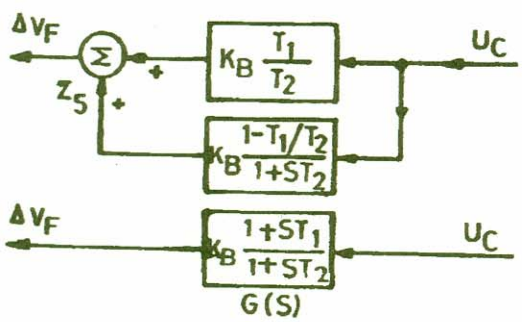


Fig. 6 General first-order auxiliary controller

$$G(s) = K_B T_1/ T_2 + K_B (1 - T_1 / T_2) / (1+sT_2) \tag{10}$$

Also, $Z_5/U_C = K_B (1 - T_1 / T_2) / (1+sT_2)$ (11)

From eqn. (11)

$$\dot{Z}_5 = (-1/T_2) Z_5 + [K_B/T_2(1-T_1/T_2)]Uc \tag{12}$$

or, $\dot{X}_c = A_C X_C + B_C U_C$, where, $X_C = Z_5$, $A_C = -1/T_2$, $B_C = K_B/T_2(1-T_1/T_2)$ (13)

$\Delta V_F = K_B(T_1/T_2)\, Uc + Z_5$

or, $\Delta V_F = [1]\, Z_5 + K_B(T_1/T_2)\, Uc$

or, $Y_C = C_c X_C + D_C U_C$ (14)

where, $C_c = 1$, and $D_C = K_B(T_1/T_2)$

3.2 Combined Reactive power and Voltage Angle (CRPVA) Auxiliary signal

The auxiliary controller signal in this case is the combination of the line reactive power and the voltage angle signals with the objective of utilizing the beneficial contribution of both signals towards improving the dynamic performance and transient performance of the system. The control scheme for the composite controller is illustrated in Fig.7. The auxiliary control signals U_{C1} and U_{C2} correspond, respectively, to the line reactive power and the voltage angle deviations, which are derived at the SVS bus.

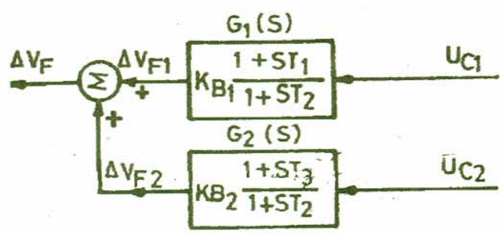


Fig. 7 Control scheme for C.R.P.V.A auxiliary controller

3.2.1 Reactive Power Auxiliary Signal

The auxiliary control signal is the deviation in the line reactive power entering the SVS bus. The reactive power entering the SVS bus can be expressed as:

$Q_3 = V_{3D}\, i_{4Q} - V_{3Q}\, i_{4D}$ (15)

Where i_{4D}, i_{4Q} and V_{3D}, V_{3Q} are the D-Q axis components of the line current i_4 and the SVS bus voltage V_3 respectively. Linearizing eqn. (15) gives the deviation in the reactive power ΔQ_3, which is taken as the auxiliary control signal, U_{C1}

$U_{C1} = \Delta Q_3$

$= V_{3Do}\Delta i_{4Q} + i_{Qo}\Delta V_{3D} - V_{3Qo}\Delta i_{4D} - i_{Do}\,\Delta V_{3Q}$ (16)

3.2.2 Voltage Angle Auxiliary Signal

The voltage angle is given as:

$\Delta\theta_3 = d/dt\,[\tan^{-1}(V_{3Q} / V_{3D})]$ (17)

Linearizing eqn. (17) gives the deviation in $\Delta\theta_3$ voltage angle which is taken as the auxiliary control signal (U_{C2}).

$U_{C2} = \Delta\theta_3$

$= (V_{3Do}/V_{3o}^2)\,\Delta V_{3Q} - (V_{3Qo}/V_{3o}^2)\,\Delta V_{3D}$ (18)

'o' represents operating point or steady state values.

The state and output equation for the C.R.P.V.A auxiliary controller are obtained as follows:

$\dot{X}_{c1} = A_{C1}X_{C1} + B_{C1}U_{C1}$

$\dot{X}_{c2} = A_{C2}X_{C2} + B_{C2}U_{C2}$

$Y_{C1} = C_{C1}\ X_{C1} + D_{C1}U_{C1}$

$Y_{C2} = C_{c2}X_{C2} + D_{C2}U_{C2}$

Where A_{C1}, B_{C1}, C_{C1} and D_{C1} are the coefficients, which correspond to the line reactive power auxiliary controller, and A_{C2}, B_{C2}, C_{C2} and D_{C2} are the coefficients, which correspond to the voltage angle auxiliary controller. The auxiliary control signals U_{C1} and U_{C2} as obtained from equations (16) and (18) are implemented as shown in Fig.7.

The overall nonlinear model of the system is obtained by combining the nonlinear differential equations of each constituent subsystem models developed above. The overall order of the system model is 35 with CRPVA SVS auxiliary controller, and 33 without auxiliary controller.

4. CASE STUDY

The IEEE first benchmark model [9] is considered for analysis. The study system consists of two synchronous generators, which are represented by a single equivalent unit of 1110 MVA, at 22 kV. The electrical power is supplied to an infinite bus over 400kV, 600 km long transmission line. The system data and torsional spring mass system data are given in Appendix. The SVS rating for the line has been chosen to be 100 MVAR inductive to 300 MVAR capacitive by performing the load flow study. About 40% series compensation is used at the sending end of the transmission line.

5. SIMULATION RESULTS

A digital time domain simulation of the system under large disturbance conditions has been carried out on the basis of nonlinear differential equations with all non-linearties and limits considered. The load flow study is carried out for calculating the operating point. The fourth order Runge-Kutta method has been used for solving the system non-linear differential equations. The natural damping of the system has been considered to be zero so that the effect of controlling-scheme can be examined exclusively. Disturbance is simulated by 30% sudden increase in input torque for 0.1 sec. The Fig. 8 shows the transient responses of the system without any auxiliary controller. It is seen that the oscillations are sustained and growing and the system is unstable. Fig. 9 shows the dynamic response curves when the proposed CRPVA SVS auxiliary controller is applied. It is seen that the torsional oscillations due subsynchronous resonance (SSR) are effectively damped out and the system becomes stable.

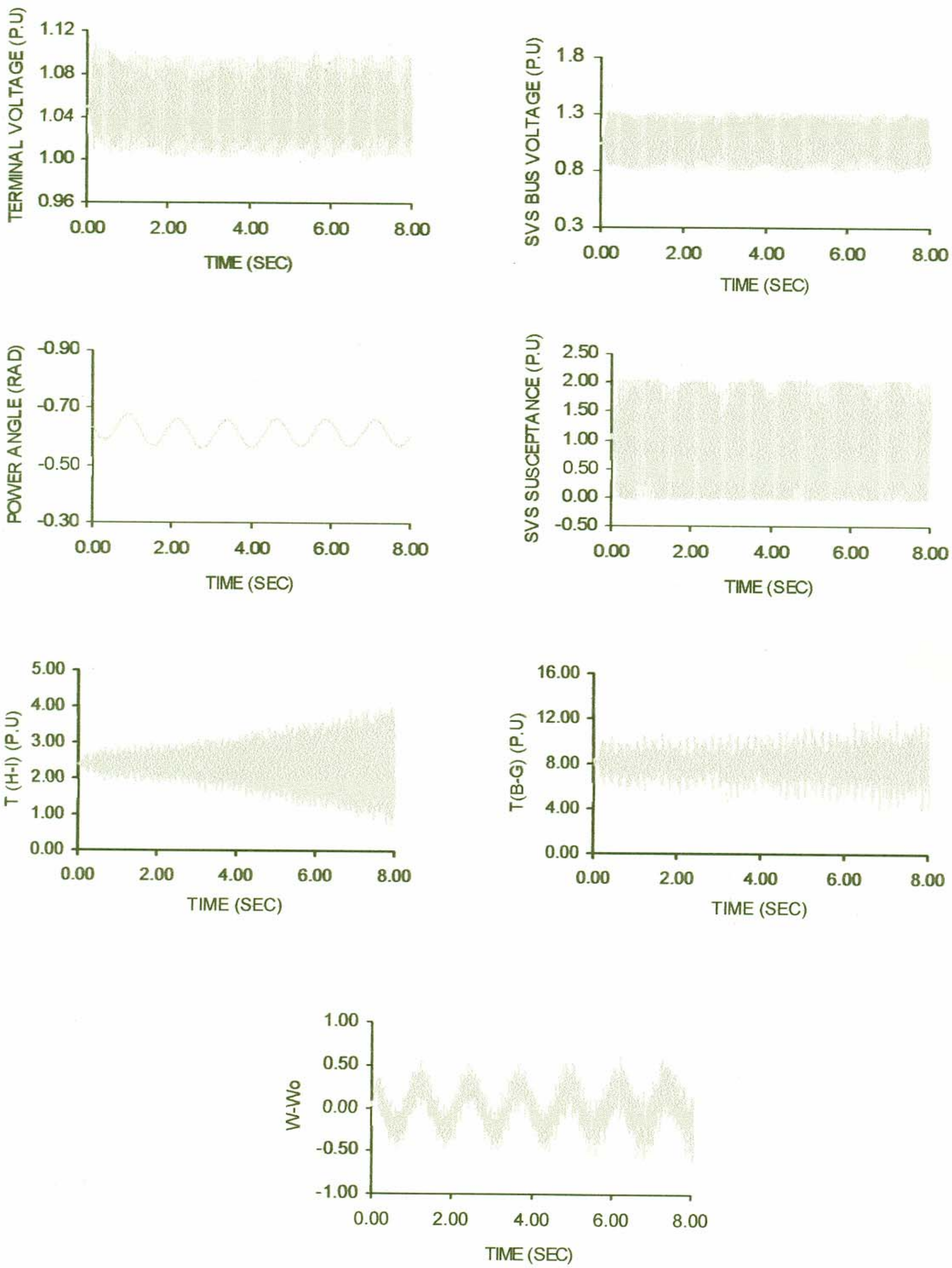


Fig . 8 Response curves without any auxiliary controller

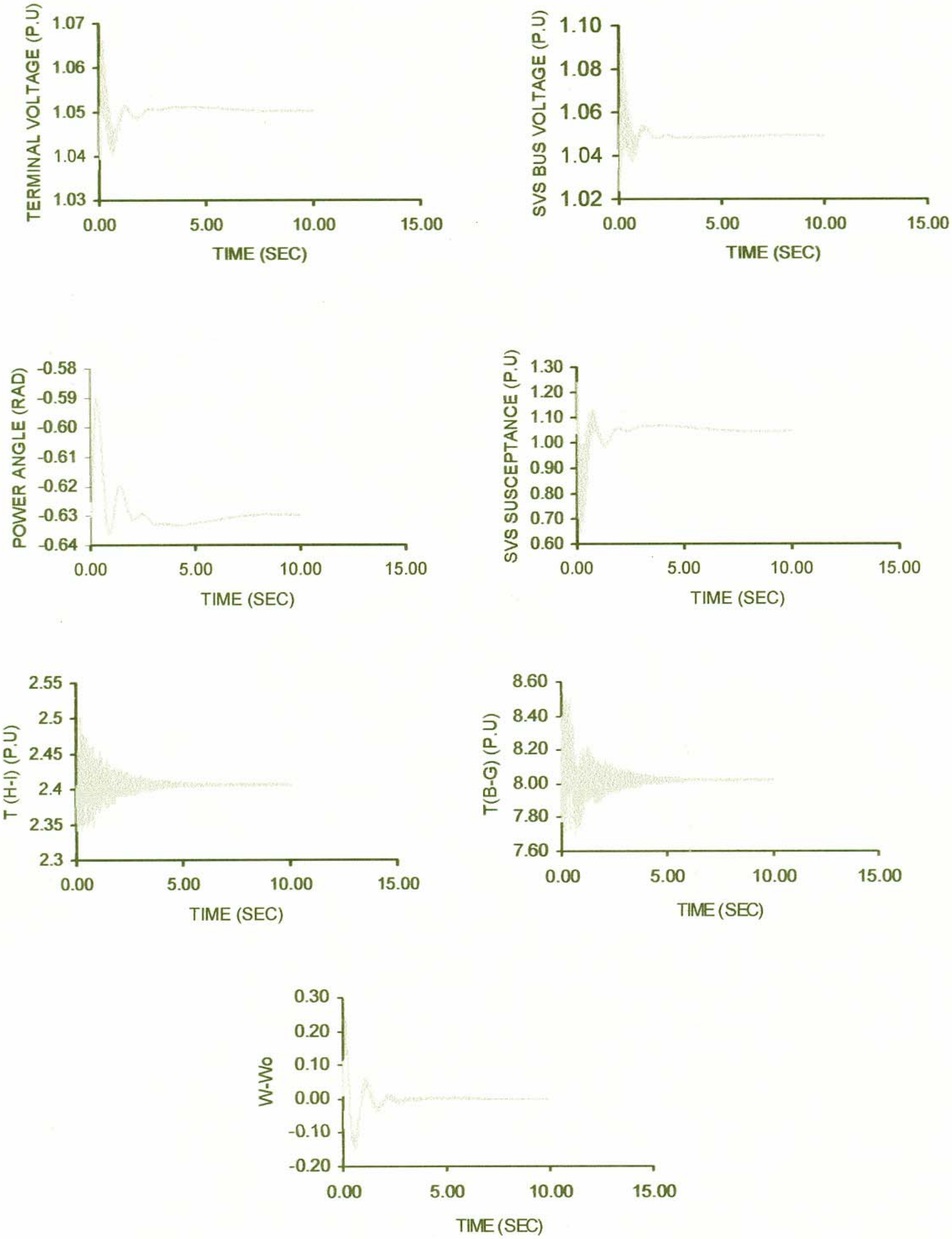


Fig (9) Response curves with (CRPVA) SVS auxiliary controller

CONCLUSION:

In this paper a new SVS control strategy for damping torsional oscillations due to subsynchronous resonance (SSR) in a series compensated power system has been developed. The proposed SVS control strategy utilizes the effectiveness of combined reactive power and voltage angle (CRPVA) SVS auxiliary control signals. The digital computer simulation study, using non-linear system model, has been carried out to illustrate the performance of the proposed SVS controller under large disturbance. It is found that the torsional oscillations due to SSR are effectively damped out and the transient performance of the series compensated power system is greatly improved. The proposed SVS controller can easily be implemented as it utilizes the signals derivable from the SVS bus itself. The SVS is considered located at the middle of the transmission line due to its optimal performance at this location.

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REFERENCES

1. Balda J.C. Eitelberg E. and Harley R.G., "Optimal output Feedback Design of Shunt Reactor Controller Damping Torsional Oscillations", Electric Power System research Vol. **10**, 25-33, 1986
2. Narendra Kumar, M.P. Dave, "Application of Auxiliary Controlled Static Var System for Damping Sub synchronous Resonance in Power Systems". Electric Power System Research **37** , 189 – 201, 1996
3. S.K. Gupta, Narendra Kumar et.al., "Controlled Series Compensation in Coordination with Double Order SVS Auxiliary Controller and Induction Machine for repressing the Torsional Oscillations in Power system". Electric Power System Research **62**, 93-103, 2002
4. S. K. Gupta, N. Kumar, "Damping Sub synchronous Resonance in Power Systems", IEE Proc. Gen. Trans. Distrib.Vol.149, No.6, pp 679-688.
5. G. N. Pillai, Arindam Gosh, A. Joshi, "Torsional Oscillation Studies in an SSSC Compensated Power System", Electric Power System research **55**, 57-64, 2000
6. Ning, Yang, Q. Liu, J. D. McCalley, "TCSC Controller Design for Damping Inter Area Oscillations", IEEE Trans. On Power System, 13(4) ,1304-1310, 1998.
7. R.S. Ramsaw, K.R. Padiyar, "Generalized System Model for Slip Ring Machines", IEEE Proc. 120 (6) 1973
8. K. R. Padiyar, R.K. Varma, "Damping Torque Analysis of Static Var System Controllers", IEEE Trans. on Power Systems, 6(2) ,458-465, 1991
9. IEEE Special Stability Control Working group, static var compensator models for power flow and dynamics performance simulation, IEEE Trans. Power Syst. **9** (1) 229-240, 1984

APPENDIX

Generator data: 1110MVA, 22kV, R_a= 0.0036, X_L = 0.21
T_{do}'=6.66, T_{qo}'=0.44, T_{do}''=0.032, T_{qo}''=0.057s
X_d = 1.933, X_q = 1.743, X_d' =0.467, X_q' = 1.144, X_d'' = 0.312, X_q'' = 0.312 p.u.

IEEE type 1 excitation system:
T_R=0, T_A=0.02, T_E=1.0, T_F=1.0s, K_A=400, K_E=1.0; K_F=0.06 p.u.
V_{fmax}=3.9, V_{fmin}=0, V_{rmax}=7.3, V_{rmin}= -7.3

Transformer data:
R_T=0, X_T=0.15 p.u. (Generator base)

Transmission line data:
Voltage 400kV, Length 600km, Resistance R=0.034Ω / km, Reactance X=0.325 Ω / km
Susceptance B_c=3.7μ mho / km

SVS data:

Six-pulse operation:
T_M = 2.4, T_S=5, T_D = 1.667ms, K_I = 1200, K_P = 0.5, K_D = 0.01

Torsional spring-mass system data

Mass	shaft	Inertia H (s)	Spring constant K (p.u. Torque/rad)
HP		0.1033586	
	HP-IP		25.772
IP		0.1731106	
	IP-LPA		46.635
LPA		0.9553691	
	LPA-LPB		69.478
LPB		0.9837909	
	LPB-GEN		94.605
GEN		0.9663006	
	GEN-EXC		3.768
EXC		0.0380697	

All self and mutual damping constants are assumed to zero.