Colloquium on Role of HVDC , FACTS and Emerging Technologies in Evolving Power Systems
23-24 September, 2005, Bangalore, India

Transient performance enhancement of a series compensated power system using a new SVS control strategy

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Abstract The paper presents a new SVS control strategy to improve the transient performance of 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 performed to illustrate the performance of the proposed SVS controller under large disturbance conditions. It is found that the transient performance of the series compensated power system is greatly improved. SVS is assumed to be located at the middle of transmission line in order to optimize the power transfer capability.

Keywords : Static Var System, Combined reactive power and voltage angle (CRPVA), Auxiliary control, Transient performance.

INTRODUCTION

In recent years 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 transmission capability but also for stabilization of power system conditions after critical faults, particularly in weakly coupled networks.

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 this dynamic instability problem in series compensated lines have been reported in literature. Among these the application of SVS controller has gained importance in recent years [3,4].

A linearized discrete time model of a series compensated transmission line was presented by A. Ghosh and G. Ledwhich[5]. In their study thyristor controlled reactor was used as compensating device and dynamics of transmission lines was governed by the change in line reactance. G. N. Pillai and A. Gosh 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 system with that of fixed series capacitor compensated system. Ning Yan et. al. [7] showed the design of controller that could modulate the impedance of line for enhancing the damping of oscillations. But the result shows that the controller is not able to damp out all the unstable modes

This paper presents a new SVS control strategy to improve the dynamic and transient performance of 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 performed to illustrate the performance of the proposed SVS controller under large disturbance conditions. It is found that the transient performance of the series compensated power system is greatly improved

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 of the line.

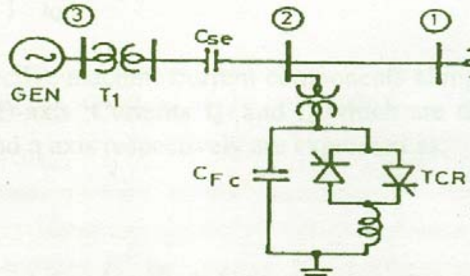

Fig. 1 : Study system.

GENERATOR

In the detailed machine model [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. The rotor flux linkages 'ψ' associated with different windings are defined by:

$$\psi_f = a_1 \psi_f + a_2 \psi_h + b_1 V_f + b_2 i_d$$

$$\psi_h = a_3\,\psi_f + a_4\psi_h + b_3\, i_d \quad ...(1)$$

$$\psi_g = a_5\,\psi_g + a_6\psi_k + b_5\, i_q$$

$$\psi_k = a_7\,\psi_g + a_8\psi_k + b_6\, i_q$$

V_f is the field excitation voltage. Constants a_1 to a_8 and b_1 to b_6 are defined in [7]. 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 following transformation:

$$\begin{vmatrix} i_d \\ i_q \end{vmatrix} = \begin{vmatrix} \cos\delta & -\sin\delta \\ \sin\delta & \cos\delta \end{vmatrix} \begin{vmatrix} i_D \\ i_Q \end{vmatrix} \quad ...(2)$$

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:

$$I_d = c_1\,\psi_f + c_2\,\psi_h$$

$$I_q = c_3\,\psi_g + c_4\,\psi_k \quad ...(3)$$

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.

Mechanical System

The mechanical system is described by the following equations:

$$\dot{\delta} = (\omega - \omega_o)$$

$$\dot{\omega} = \omega_o/2H[-D\omega + T_m + X''_d(i_D I_Q - i_Q I_D)]$$

where H is inertia constant of the generator, X''_d the generator subtransient reactance, D is the damping torque coefficient, T_m mechanical torque.

Excitation System

The IEEE type-1 model as shown in Fig.2 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 equations.

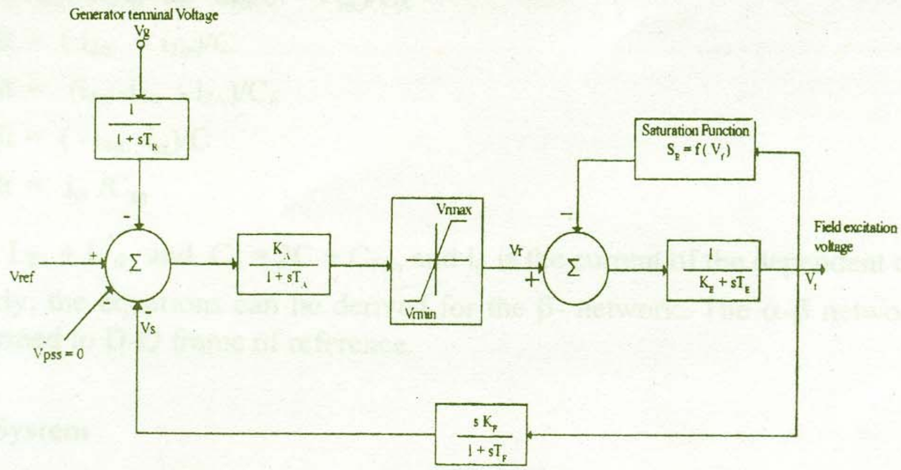

Fig. 2. IEEE Type-1 excitation system

$$\dot{V}_f = -(K_E+S_E)\, V_f \,/\, T_E + V_r / T_E$$

$$\dot{V}_S = -K_F\,(K_E+S_E)\, V_f \,/\, T_E\, T_F \;-\; V_S T_S + K_F\, V_r \,/ T_E T_F \qquad \ldots (4)$$

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

Network

The transmission line is represented by lumped parameter π - circuit. The network has been represented by its α–axis equivalent circuit (Fig.3), which is identical with the positive sequence network. The governing equations of the α-axis, π -network representation are derived as follows:

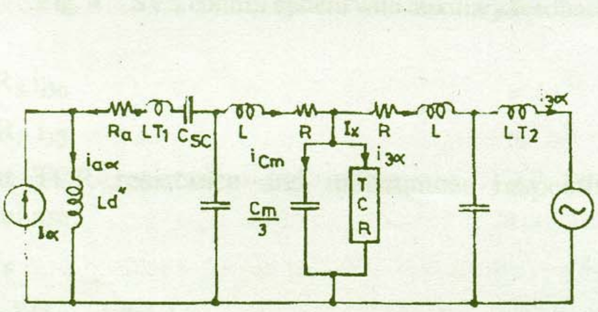

Fig. 3. α-axis representation of network

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

$$di_{2\alpha}/dt = (V_{3\alpha} - V_{2\alpha} - R\, i_{2\alpha})/L \qquad \ldots (5)$$

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

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

$dV_{2\alpha}/dt = (i_{2\alpha} - i_{1\alpha})/C$

$dV_{3\alpha}/dt = (i_{4\alpha} - i_{3\alpha} - i_{2\alpha})/C_n$

$dV_{4\alpha}/dt = (-i_{4\alpha} - i_\alpha)/C$

$dV_{5\alpha}/dt = i_\alpha / C_{se}$

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 D-Q frame of reference.

Static Var System

Fig. 4 shows a small signal model of a general SVS. The terminal voltage perturbation ΔV and the SVS 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. ΔVF represents the incremental auxiliary control signal. The α, β axes currents entering TCR from the network are expressed as:

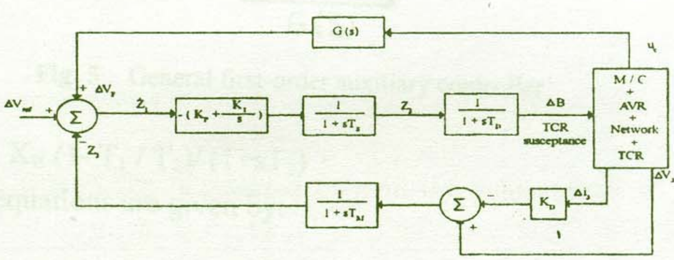

Fig. 4 : SVS control system with auxiliary feedback

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

$L_S \, di_{3\beta}/dt = V_{3\beta} - R_S i_{3\beta}$ ...(6)

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

$z_1 = V_{ref} - z_2 + \Delta V_F$

$z_2 = (\Delta V_3 - K_D \Delta i_3)/T_M - z_2/T_M$ ...(7)

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

$\Delta B = (z_3 - \Delta B)/T_D$

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

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

DEVELOPMENT OF THE NEW SVS CONTROL STRATEGY

In this damping scheme, two controllers namely the combined reactive power and voltage angle (CRPVA) SVS auxiliary controller has been developed and applied in combination for improving the transient performance of a series compensated power system.

SVS Auxiliary Controller

The auxiliary signal U_C is implemented through a first order auxiliary controller transfer function G(s) as shown in Fig.5 which is assumed to be:

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

This can be equivalently written as:

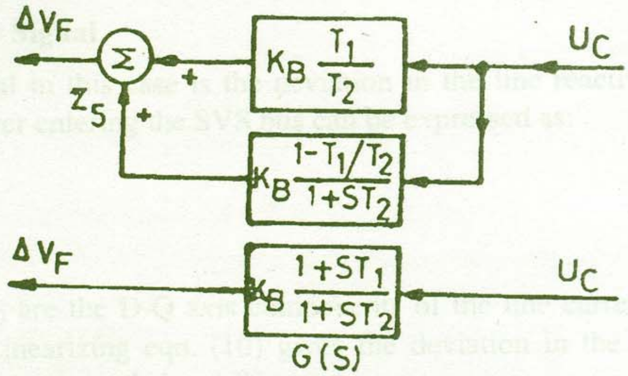

Fig. 5 : General first-order auxiliary controller

$$G(s) = K_B T_1/T_2 + K_B(1 - T_1/T_2)/(1 + sT_2) \quad ...(8)$$

The state and output equations are given by:

$$X_C = [A_C]X_C + [B_C]U_C$$

$$Y_C = [C_C]X_C + [D_C]U_C \quad ...(9)$$

where

$X_c = Z_5$, $Y_C = \Delta V_F$, $A_C = -1/T_2$

$B_C = K_B/T_2(1 - T_1/T_2)$, $C_C = 1$, $D_C = K_B T_1/T_2$

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 transient performance of the system. The control scheme for the composite controller is illustrated in Fig.6. 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.

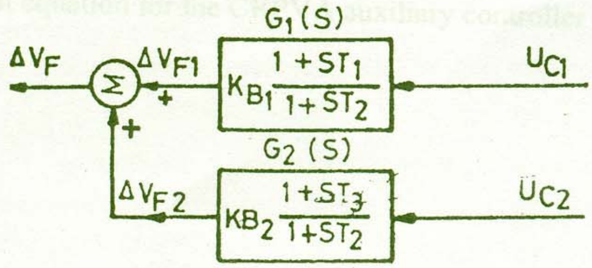

Fig. 6: Control scheme for CRPVA auxiliary controller

Reactive Power Auxiliary Signal

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

$$Q_3 = V_{3D}\, i_Q - V_{3Q}\, i_D \qquad \text{...(10)}$$

where i_D, i_Q and V_{3D}, V_{3Q} are the D-Q axis components of the line current i_3 and the SVS bus voltage V_3 respectively. Linearizing eqn. (10) gives the deviation in the reactive power ΔQ_3, which is taken as the auxiliary control signal (U_{C1}).

$$U_{C1} = \Delta Q_3$$

$$= V_{3Do}\Delta i_Q + i_{Qo}\Delta V_{3D} - V_{3Qo}\Delta i_D - i_{Do}\,\Delta V_{3Q} \qquad \text{...(11)}$$

Voltage Angle Auxiliary Signal

The voltage angle is given as:

$$\theta_3 = d/dt\,[\tan^{-1}(V_{3Q} / V_{3D})] \qquad \text{...(12)}$$

Linearizing eqn. (12) gives the deviation in voltage angle, $\Delta\theta_3$, which is taken as the auxiliary control signal (U_{C2}).

$$U_{C2} = \Delta\theta_3$$

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

'o' represents operating point or steady state values.

The state and output equation for the CRPVA auxiliary controller are obtained as follows:

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

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

or

$$\begin{bmatrix} X_{C1} \\ X_{C2} \end{bmatrix} = \begin{bmatrix} A_{C1} & 0 \\ 0 & A_{C2} \end{bmatrix} \begin{bmatrix} X_{C1} \\ X_{C2} \end{bmatrix} + \begin{bmatrix} B_{C1} & 0 \\ 0 & B_{C2} \end{bmatrix} \begin{bmatrix} U_{C1} \\ U_{C2} \end{bmatrix}$$

$$[Y_C] = [C_{C1}\ C_{C2}] \begin{bmatrix} X_{C1} \\ X_{C2} \end{bmatrix} + [D_{C1}\ \ D_{C2}] \begin{bmatrix} U_{C1} \\ U_{C2} \end{bmatrix} \qquad ...(13)$$

where A_{C1}, B_{C1}, C_{C1} and D_{C1} are the matrices of the reactive power auxiliary controller and A_{C2}, B_{C2}, C_{C2} and D_{C2} are the matrices of the voltage angle auxiliary controller.

The non linear differential equations and algebraic equations of various subsystems are combined to achieve the overall system model. The order of the system is 35 with CRPVA SVS auxiliary controller, and 33 without auxiliary controller.

CASE STUDY

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 400 kV, 600 km long transmission line. The SVS rating for the line has been chosen to be 100 MVAR inductive to 300 MVAR capacitive. About 40% series compensation is applied on the sending end of the transmission line.

SIMULATION RESULTS

A digital time domain simulation of the system under large disturbances has been carried out on the basis of non linear differential equations with all non-linearities 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 non-linear differential equations. System's natural damping is considered to be equal to 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 dynamic responses of the system without and with CRPVA SVS auxiliary controller are shown in Fig 7. It is seen that the oscillations are unstable when no SVS auxiliary controller is applied. The oscillations are effectively damped out when the proposed controller is used.

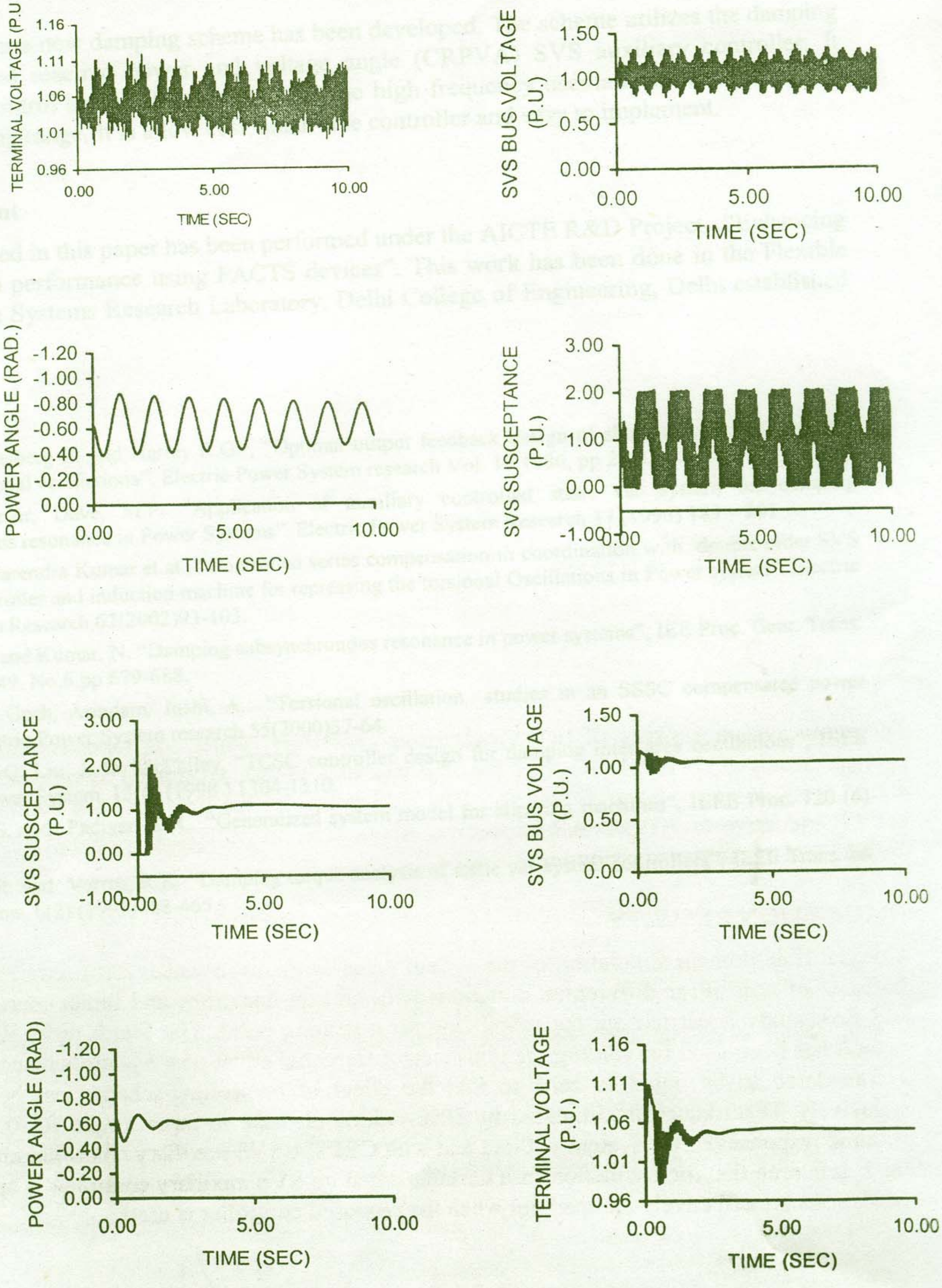

Fig 7: System responses without and with auxiliary controller for 30% torque disturbance for 0.1 sec at 40% compensation of line.

CONCLUSIONS

In the present paper a new damping scheme has been developed. The scheme utilizes the damping effect of combined reactive power and voltage angle (CRPVA) SVS auxiliary controller. It provides robust control and is able to damp out the high frequency oscillations very effectively over wide operating range. It is a low cost, small size controller and easy to implement.

Acknowledgement

The work presented in this paper has been performed under the AICTE R&D Project , "Enhancing the power system performance using FACTS devices". This work has been done in the Flexible AC Transmission Systems Research Laboratory, Delhi College of Engineering, Delhi established under the project

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