COMBINED REACTIVE POWER AND DERIVED MACHINE FREQUENCY SVS AUXILIARY CONTROLLER FOR DAMPING SSR IN A SERIES COMPENSATED POWER SYSTEM

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ABSTRACT

In this paper a controller, namely, combined reactive power and derived machine frequency (CRPDMF) auxiliary controller has been developed and incorporated in the SVS control system located at the middle of a series compensated long transmission line. Damping performance of CRPDMF auxiliary controller is analyzed for a system having a similar spread of the torsional modes as the first IEEE benchmark model. The proposed controller stabilizes all the unstable system modes over a wide operating range. It is seen from the eigenvalue analysis study that the torsional modes due to SSR are effectively damped out.

KEY WORDS: Static Var System, CRPDMF, Eigenvalue analysis, Subsynchronous resonance (SSR)

Introduction

One of the most promising task in power utility is to suppress the low frequency oscillations in power system. These oscillations which are associated with the generator rotor swings exhibit poor damping when the power transfer level in the transmission network is high. With the advent of fast acting power electronics based FACTS controllers like static var system (SVS), thyristor controlled series compensator (TCSC), static synchronous series compensator (SSSC), static synchronous compensator (STATCOM), and unified power flow controller (UPFC) it has been feasible to enhance the damping of power system oscillations. The selection of an effective location and feedback signal is an important aspect to employ these devices. In recent years SVS has been employed to an increasing extent in 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 effectively. The auxiliary signals may be deviation in voltage, current frequency, active power, reactive power, power angle and derived machine frequency etc. The derived machine frequency involves the computation of internal voltage frequency of the remotely stationed generator utilizing locally measurable SVS bus voltage, line current and the total inductance between the generator internal voltage and SVS terminals.

Series compensation has been widely used to enhance the power transfer capability. However series compensation gives rise to dynamic instability and subsynchronous resonance (SSR) problem. Many preventive measures to cope with the dynamic instability problem in series compensated lines have been reported in the literature. Among these the application of SVS controller has gained importance in recent years[3,4]. Ning Yang *etal.*[5] showed the design of controller that could modulate the impedance of the line for enhancing the damping of oscillations. But the result showed that the controller was not able to damp out all the unstable

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modes. S.K. Gupta and Narendra Kumar[3] 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 scheme is able to damp out the torsional modes at wide range of series compensation. However, the control scheme is complex and the difficult to implement.

The present paper investigates a new scheme which utilizes the damping effect of combined reactive power and derived machine frequency (CRPDMF) SVS auxiliary controller for suppressing torisonal modes in a series compensated power system. The scheme is able to stabilize all the torisonal modes over a wide operating range of power transfer. The proposed scheme is simple, economical, and easy to implement.

System Model

The study system consists of a steam turbine driven synchronous generator (a six-mass model) 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 derived machine frequency and reactive power (CRPDMF) auxiliary control signals. The series compensation is located on the generator side of the SVS.

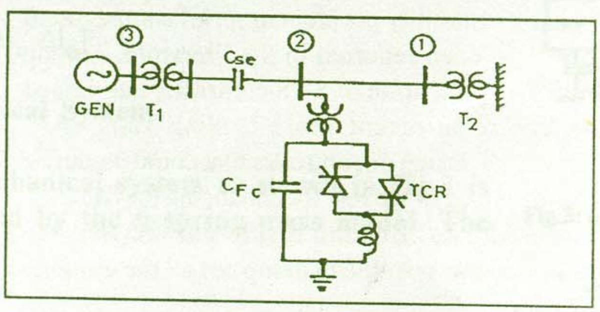

Fig. 1: Study System

Generator

In the detailed machine model[6] 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 as shown in Figure 2. The IEEE type-1 excitation system is used for the generator. In the mechanical model detailed shaft torque dynamics has been considered for the analysis of torsional modes due to SSR. The natural system damping has been considered to be zero. The rotor flux linkages 'ψ' associated with different windings are defined by:

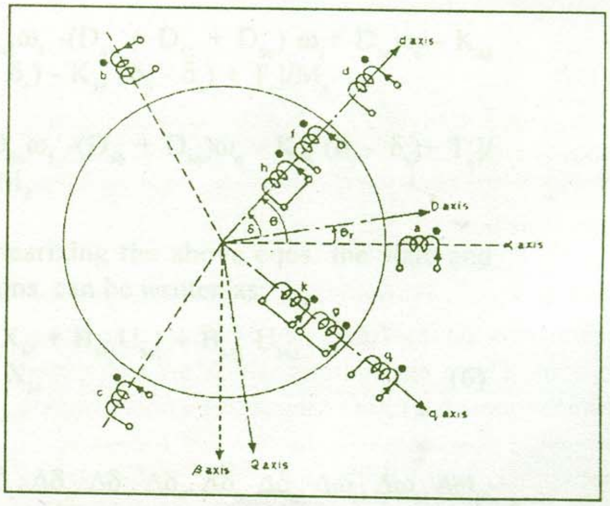

Fig. 2: Schematic layout of windings of synchronous machine and their two axis representation.

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

$$\psi_h = a_3 \psi_f + a_4\psi_h + b_3 i_d$$

$$\psi_g = a_5 \psi_g + a_6\psi_k + b_5 i_q \qquad (1)$$

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

Where v_f is the field excitation voltage. Constants a_1 to a_8 and b_1 to b_6 are defined in Eq. (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 following transformation:

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

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 [6]. Substituting eqn.(2) in eqn.(1) and linearizing gives the state and output equation of the rotor circuit as:

$$X_R = A_R\,X_R + B_{R1}\,U_{R1} + B_{R2}\,U_{R2} + B_{R3}\,U_{R3}$$
$$Y_{R1} = C_{R1}\,X_R + D_{R1}\,U_{R1} \qquad (4)$$
$$Y_{R2} = C_{R2}\,X_R + D_{R2}\,U_{R1} + D_{R3}\,U_{R2} + D_{R4}\,U_{R3}$$

Where

$X_R = [\Delta\psi_f\ \Delta\psi_h\ \Delta\psi_g\ \Delta\psi_k]^t$, $U_{R1} = [\,\Delta\delta\ \Delta\omega]^t$,

$U_{R2} = \Delta V_f$, $U_{R3} = [\Delta i_D\ \Delta i_Q]^t$, $Y_{R1} = [\Delta I_D\ \ \Delta I_Q]^t$,

$Y_{R2} = [\Delta I_D\ \Delta I_Q]^t$

Mechanical System

The mechanical system as shown in Fig.3 is described by the 6-spring mass model. The governing equations and the state and output equations are given as follows:

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

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

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

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

$$\omega_4 = [(D_{34}\omega_2 - (D_{34} + D_{44} + D_{45})\,\omega_4 + D_{45}\omega_5 - K_{34}\,(\delta_4 - \delta_3) - K_{45}\,(\delta_4 - \delta_5) + T_{M4}]/M_4 \qquad (5)$$

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

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

After linearizing the above eqns. the state and output eqns. can be written as:

$$X_M = A_M X_M + B_{M1} U_{M1} + B_{M2}\,U_{M2}$$
$$Y_M = C_M\,X_M \qquad (6)$$

Where

$X_M = [\Delta\delta_1, \Delta\delta_2, \Delta\delta_3, \Delta\delta_4, \Delta\delta_5, \Delta\delta_6, \Delta\omega_1, \Delta\omega_2, \Delta\omega_3, \Delta\omega_4, \Delta\omega_5, \Delta\omega_6]^t$

$Y_M = [\Delta\delta_5, \Delta\omega_5]^t$ $U_{M1} = [\Delta I_D, \Delta I_Q]^t$ $U_{M2} = [\Delta i_D,$

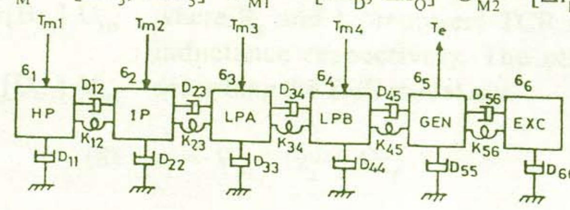

Fig.3: 6- Spring mass representation of the mechanical system

Network

The transmission line is represented by lumped parameter π-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, π-network

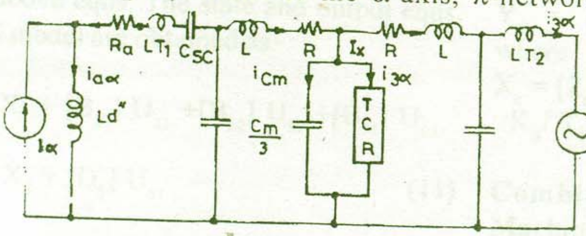

Fig. 4: α-axis representation of network

$$
\begin{aligned}
(L+L_{T2})\, di_{1\alpha}/dt &= V_{2\alpha} - V_{1\alpha} \\
L\, di_{\alpha}/dt &= V_{3\alpha} - V_{2\alpha} - R\, i_{2\alpha} - V_{5\alpha} \\
L\, di_{4\alpha}/dt &= V_{4\alpha} - V_{3\alpha} - R\, i_{4\alpha} \\
L_A\, di_{\alpha}/dt &= V_{4\alpha} - R_a i_{\alpha} - L_d''\, dI_{\alpha}/dt \qquad (7)\\
C_n\, dV_{2\alpha}/dt &= i_{2\alpha} - i_{1\alpha} \\
C_n\, dV_{3\alpha}/dt &= V_{4\alpha} - i_{3\alpha} - i_{2\alpha} \\
C\, dV_{4\alpha}/dt &= - i_{4\alpha} - i_{\alpha} \\
C_{se}\, dV_{5\alpha}/dt &= i_{\alpha}
\end{aligned}
$$

Where $L_A = L_{T1} + L''_d$ and $C_n = C + C_{FC}$

Similarly, the equations can be derived for the β-network. The α–β network equations are then transformed to D-Q frame of reference and subsequently linearised. The state and output equations for the network model are finally obtained as:

$$X_N = [A_N]\, X_N + [B_{N1}] U_{N1} + [B_{N2}] U_{N2} + [B_{N3}]\, U_{N3}$$

$$Y_{N1} = [C_{N1}] X_N + [D_{N1}]\, U_{N1} + [D_{N2}] U_{N2} + [D_{N3}]\, U_{N3}$$

$$Y_{N2} = [C_{N2}]\, XN,\; Y_{N3} = [C_{N3}]\, X_N \qquad (8)$$

Where,

$X_N = [\Delta i_{1D}\ \Delta i_{2D}\ \Delta i_{4D}\ \Delta i_D\ \Delta v_{2D}\ \Delta v_{3D}\ \Delta v_{4D}\ \Delta v_{5D}\ \nabla i_{1Q}$
$\Delta i_{2Q}\ \Delta i_{4Q}\ \Delta_{iQ}\ \Delta v_{2Q}\ \Delta v_{3Q}\ \Delta v_{4Q}\ \Delta v_{5Q}]^t$

$U_{N1} = [\Delta i_{3D}\ \Delta i_{3Q}]^t$, $U_{N2} = [\Delta I_D\ \Delta I_Q]^t$, $U_{N3} = [\Delta I_D\ \Delta I_Q]^t$

$Y_{N1} = [\Delta V_{gD}\ \Delta V_{gQ}]^t$, $Y_{N2} = [\Delta i_D\ \Delta i_Q]^t$, $Y_{N3} = [\Delta V_{3D}\ \Delta V3_Q]^t$

Static Var System

Fig. 5 shows a small signal model of a general SVS. The terminal voltage perturbations ΔV and 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. ΔV_F represents the incremental auxiliary control signal. The α, β axes currents

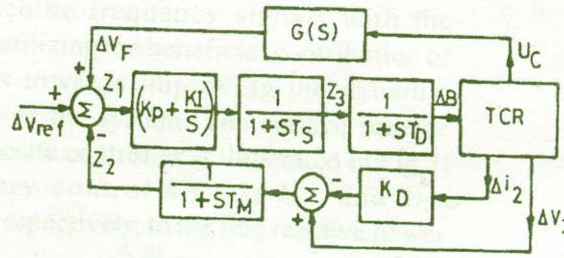

Fig. 5: SVS control system with auxiliary feedback

$$L_S\, di_{3\alpha}/dt = V_{3\alpha} - RS\, i_{i3\alpha}$$
$$L_S\, di_{3\beta}/dt = V_{3\beta} - R_S\, i_{3\beta} \qquad (9)$$

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

$$z_1 = V_{ref} - z_2 + \Delta V_F$$
$$z_2 = (\Delta V_3 - K_D \Delta i_3)/T_M - z_2/T_M \qquad (10)$$
$$z_3 = (-K_I z_1 + K_P z_2 - z_3 - K_P \Delta V_{ref})/T_S$$

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

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

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

From the above eqns. The state and output eqns. of the SVS model are obtained as:

$$X_S = [A_S]\, X_S + [B_{S1}]\, U_{S1} + [B_{S2}]\, U_{S2} + [B_{S3}]\, U_{S3}$$

$$Y_S = [C_S]\, X_S + [D_S]\, U_{S1} \quad (11)$$

where

$X_S = [i_{3D}\ i_{3Q}\ z_1\ z_3\ z_3\ \Delta B]^t$,

$U_{S1} = [\Delta V_{3D}\ \Delta V_{3Q}]^t$, $U_{S2} = \Delta V_{ref}$,

$U_{S3} = \Delta V_F$

$Y_S = [\Delta i_{3D}\ \Delta i_{3Q}]^t$

Development of 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:

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

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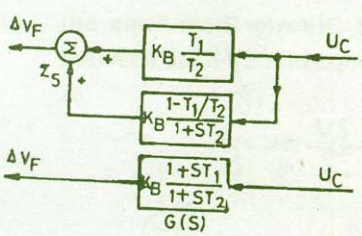

Fig. 6: General first-order auxiliary controller

$$G(s) = = K_B\, T_1/T_2 + K_B\,(1 - T_1/T_2)/(1 + sT_2) \quad (12)$$

The state and output equations are given by

$$X_C = [A_C]\, X_C + [B_C]\, U_C$$
$$Y_C = [C_C]\, X_C + [D_C]\, U_C \quad (13)$$

where

$X_c = [Z_C]$, $Y_C = \Delta V_F$, matrices $[A_C] = -1/T_2$, $[B_C] = K_B/T_2\,(1 - T_1/T_2)$, $[C_C] = 1$, $[D_C] = K_B\, T_1/T_2$

Combined Reactive Power and Derived Machine Frequency (CRPDMF) SVS

The auxiliary controller signal in this case is the combination of the line reactive power and the derived machine frequency signals with the objective of utilizing the beneficial contribution of both signals towards improving the dynamic 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 deri ns which are derivec

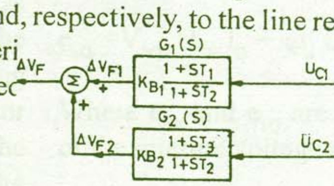

Fig. 7: Control scheme for C.R.P.D.M.F. auxiliary controller

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:

$$Q_3 = V_{3D}\, i_{4Q} - V_{3Q}\, i_{4D} \quad (14)$$

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. (14) gives the deviation in the reactive power ΔQ_3 which is taken as the auxiliary control signal (U_{C1}).

$$U_{C1}=\Delta Q_3 \quad (15)$$

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

Derived Machine Frequency Auxiliary Signal

The derived machine frequency (DMF) control signal has been drived from the generation source frequency which has a more beneficial influence on the high frequency torosional oscillations. As it is not feasible to obtain this signal by measurement as the generating station and the SVS are located far apart from each other. Therefore, it is attempted to derive the proposed signal in terms of parameters which are available at the SVS bus. The parameters utilized for the signal are bus voltage, transmission line current at the SVS bus and the reactance between the generator and SVS terminals. The study system is simplified for the D.M.F. signal as shown in figure. Only the section between the generator and SVS is considered. The line charging capacitances and the resistances of the generator stator and the transmission line are neglected. The dependent current source representing the generator is transformed to an equivalent voltage source behind the subtransient inductance. From the equivalent circuit, the total inductance L_E between the SVS and equivalent source e_1 is given as:

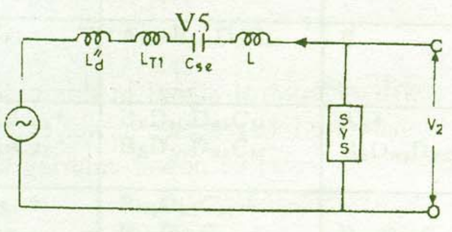

Fig. 8: α-axis Representation of simplified study system for D.M.F signal

$$L_E = L_d'' + L_{T1} + (X_L - X_C)/\omega_o$$

Where L_d'' and L_{T1} are the subtransient inductance of the generator and inductance of the sending end transformer respectively. X_L and X_C are the inductive reactance of the transmission segment between sending end transformer and SVS and reactance of the series capacitor respectively.

The α, β axis component of the internal voltage e_1 are expressed as:

$$e_{1\alpha} = V_{2\alpha} + L_E \frac{di_\alpha}{dt} - V_{5\alpha} \quad (16)$$

$$e_{1\beta} = V_{2\beta} + L_E \frac{d\, i\beta}{dt} \; V_{5\beta} \quad (17)$$

The above equations are transformed to D-Q frame of reference:

$$e_{1D} = V_{2D} + L_E\, i_D + \omega_o L_E\, i_Q - V_{5D} \quad (17)$$

$$e_{1Q} = V_{2Q} + L_E\, i_Q + \omega_o L_E\, i_D - V_{5Q}$$

Where e_{1D} and e_{1Q} are the D-Q axis components of the internal voltage e_1

The angle δ_1 of the internal voltage is given by

$$\delta_1 = \tan^1 (e_{1Q} / e_{1D}) \quad (18)$$

Linearzing Eqn. (18)

$$\Delta\delta_1 = \frac{e_{1Do}}{e_{1o}^2}\Delta e_{1Q} - \frac{e_{1Qo}}{e_{1o}^2} e_{1D} \quad (19)$$

The derived machine frequency is obtained by differentiating Eqn. (19)

$$\Delta\omega_1 = d/dt(\Delta\delta_1) = \frac{e_{1Do}}{e_{1o}^2}\Delta e_{1Q} \; \frac{e_{1Qo}}{e_{1o}^2}\Delta e_{1D} \quad (20)$$

Linearzing eqn.(17) and substituting in eqn.(19)

$$\Delta\delta_1 = \frac{e_{1Do}}{e_{10}^2}\left[\Delta V_{2Q} + L_E\,\Delta i_Q - \omega_o\,L_E\,\Delta i_D - \Delta V_{5Q}\right]$$

$$\frac{e_{1Do}}{e_{1o}^2}\left[\Delta V_{2D} + L_E\,\Delta i_D - \omega_o\,L_E\,\Delta i_Q - \Delta V_{5D}\right] \qquad (21)$$

or $\Delta\delta_1 = [F_1]\,X_T + [F_2]\,X_T$ (22)

Where, $X_T = [X_R\ \ X_M\ \ X_E\ \ X_N\ \ X_S]^t$

F_1 =(1x41) vector having non-zero elements as follows:

$$F_1(1,23) = -\frac{e_{1Do}}{e_{10}^2}\,\omega_o\,L_E,\quad F_1(1,31) = -\frac{e_{1Qo}}{e_{10}^2}\,\omega_o\,L_E,$$

$$F_1(1,25) = -\frac{e_{1Qo}}{e_{1o}^2},\quad F_1(1,33) = -\frac{e_{1Do}}{e_{1o}^2}$$

$$F_2(1,23) = -\frac{e_{1Qo}}{e_{1o}^2}\,LE,\quad F_2(1,31) = -\frac{e_{1Do}}{e_{1o}^2}\,L_E,$$

Substituting $X_T = A\,X_T + BU_{S3}$ in eqn. (22)

$$\Delta\delta_1 = F_1\,X_r + F_2\,[AX_r + BU_{S3}]$$

or $\Delta\delta_1 = [F_3]\,X_T$ (23)

Where: $F_3 = [F_1 + F_2A]$, and $F_2B = 0$

Differentiating Eqn.(23) the derived machine frequency signal is given by

$$\Delta\omega_1 = [F_3]\ X_T \qquad (24)$$

Again substituting X_T in Eqn. (24) results in

$$\Delta\omega_1 = [F_3]\,[AX_T + BU_{s3}] \qquad (25)$$

or $\Delta\omega_1 = [F_4]\,X_T$

Where: $F_4 = F_3A$ and $F_3B = 0$

Now, Eqn. (25) can be written in expanded form as

$$U_{C2} = [F_{CR}]X_R + [F_{CM}]X_M + [F_{CE}]X_E + [F_{CN}]\,X_N + [F_{CS}]X_S$$

Where, $U_{C2} = \Delta\omega_1$ (26)

The state and output equation for the C.R.P.D.M.F. auxiliary controller are obtained as follows:

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

$$[\,Y_C\,] = [C_{C1}\ C_{C2}] \begin{bmatrix} X_{C1} \\ X_{C2} \end{bmatrix} + [\,D_{C1}\ D_{C2}] \begin{bmatrix} U_{C1} \\ U_{C2} \end{bmatrix} \qquad (27)$$

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 derived machine frequency auxiliary controller.

[A] =

A_R	$B_{R1}\,C_M$	$B_{R2}C_E$	$B_{R3}C_{N2}$	0	
$B_{M1}C_{R1}$	$A_M+B_{M1}D_RC_M$	0	$B_{M2}C_{N2}$	0	0
$B_ED_{N2}C_{R1}+$ $B_ED_{N3}C_{R2}$	$B_ED_{N2}D_{R1}C_M+$ $B_ED_{N3}D_{R2}C_M$	A_E+ $B_ED_{N3}D_{R3}C_E$	$B_EC_{N1}+$ $B_ED_{N1}D_SC_{N3}+$ $B_ED_{N3}D_{R4}C_{N2}$	0	0
$B_{N2}C_{R1}+$ $B_{N3}C_{R2}$	$B_{N2}D_{R1}C_M+$ $B_{N3}D_{R2}C_M$	$B_{N3}D_{R3}C_E$	$A_N+B_{N1}D_SC_N+$ $B_{N3}D_{R4}C_{N2}$	$B_{N1}C_S$	0
$B_{S3}D_CF_{CR}$	$B_{S3}D_CF_{CM}$	0	$B_{S1}C_{N3}+$ $B_{S3}D_CF_{CN}$	A_S+ $B_{S3}D_CF_{CS}$	$B_{S3}C_C$
B_CF_{CR}	B_CF_{CM}	0	B_CF_{CN}	B_CF_{CS}	A_C

The overall dimension of the system matrix is 43.

The state and output equations of the different constituent subsystems along with the auxiliary controller are combined to result in the linearised state equations of overall system as:

$$X_T = [A] X_T \quad (18)$$

Where,

$$X_T = [X_R \quad X_M \quad X_E \quad X_N \quad X_S \quad X_C]^t$$

Case Study—Dynamic Performance

The study 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 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. Series compensation is used towards the generator side of SVS along the transmission line. The eigenvalues have been computed for the system with and without the C.R.P.M.D.F. auxiliary controller. It can be seen from table 2 that above auxiliary controller stabilizes all the torsional modes at P_G=200MW, 500MW & 800MW. At P_G=200MW the electrical mode (frequency 212.16 rad./sec) becomes unstable. Its damping improves on increasing the generator power. The damping of torsional modes 3,1,0 improves on increasing the generator power. The damping of these modes is highest at P_G=800MW. Table1 presents the eigenvalues for the system at generator power P_G=200, 500, and 800 MW without any control scheme. It is seen that four unstable

Table 1: System Eigenvalues without any controller

	P_g = 200 MW	P_g = 500 MW	P_g = 800MW
Mode 5	.0000±j298.1006	.0000±j298.1006	.000±j298.10
Mode 4	.043±j202.7	.058±j202.7	.087±202.7
Mode 3	.0013±j160.5	.0007±j160.500	-.0004±j160.5
Mode 2	-.0007±j126.9	-.001 ± j126.9	-.0027±j126.9
Mode 1	-.016±j98.87	-.0006 ±j98.83	-.004±j98.74
Mode 0	-.4096±j4.47	-.16±j4.93	.0178+j4.97
	-28.2	-.32.28	-33.23
	-2.421	-2.83	-3.044
	-.9822+j.8262	-..817+j.8537	-.885+j.9192
	-37.2539	-37.72	-38.61
	-25.7±j23.62	-.25.65±j23.91	-25.24±j24.1
Elect	-9.29±j186.6	-9.88±j188.09	-10.49±j198.84
mode	-3.43±j3507.33	-.3.44±j3507.60	-.3.27±j3499
	-3.43±j2879.33	-3.44±j2879.6	-3.27±j2871.08
	-13..35±j2523.9	-13.3± j2524.62	-13.22±j2495.3
	-14.92± j1895.9	-14.92±j1896.6	-14.92±j1867.3
	-11.74±j1314	-13.99±j1307.8	-12.69±j1137.8
	-15.20±j686.93	-15.58±j680.64	-18.90±j510.94
	-12.46 ± j446.83	-12.64.±j445.78	-12.92±j443.94
	-545.89±j81.5	- 545.9±j81.57	-545.29±j74.4
	-55.82±j71.21	- 53.23±j69.84	-49.9±j74.74
	-7.22±j311.75	- 6.32±j311.66	-5.08.±j311.45

Table 2: Sytems Eigen Values with C.R.P.I.F. Auxillary Controllers

	P_g = 200 MW	P_g = 500 MW	P_g = 800MW
Mode 5	-.0±j289.1	-.0±j298.1	-.0±j298.1
Mode 4	-.0087±j202.8	-.0017±j202.9	-.008±j202.8
Mode 3	-.0005±j160.5	-.0003±j160.5	-.0014±j160.5
Mode 2	-.0001±j126.9	-.0002±j126.9	-.0001±j126.9
Mode 1	-.0018±j98.8	-.0027±j98.8	-.018±j98.7
Mode 0	-.4587±j4.47	-.6312.±j4.98	-1.13±j5.504
E.Mode	.731±j212.16	-.506.±j208.9	-7.9±j195.5
	-.772±j.813	-.571+j.797	-.6+j.872
	-29.10	-32.35	-32.99
	-2.5766	-2.797	-2.986
	-.10.10	-8.35	-6.39
	-.7722+j.813	-.571±j.797	-.6±-j.872
	-3.43±j13507.33	-3.43±j3507.61	-3.23±j3499.08
	-3.43±j2879.33	-3.433±j2879.60	-3.27±j2871.08
	-13.873±j2524.5	-13.663±j2525.0	-13.16±j2495.3
	-14.24±j1895.0	-14.40±j1896.0	-15.08.±j1867.5
	-4.69±j1310.76	-7.72±1304.71	-14.76±j1138.6
	-35.12±j692.79	-29.5±j683.9	-11.87.±j1516.25
	-14.86±j447.54	-13.43±j447.15	-.9.95±j445.07
	-49.57	-68.98	-74.38
	-169.47	-143.93	-130.06
	-7.75±j312.8	-6.49±j312.37	-.4.73±j312.4
	-.46±j23.99	-1.88±j25.99	-.5.4±j33.42
	-543.5±j88.47	-543.38±j87.95	-.547.5

Table 3: Auxiliary Controllers Parameter

	KB	T1	T2
B.F.	-.015	.002	.1
D.M.F	-0.024	.002	.1

modes 5 , 4 , 1 and 0 are investigated in the system at P_G= 800 MW. At P_G= 500 and 200 MW, three torisonal modes 5, 4, and 3 are unstable.

Conclusion

In this paper the effect of combined reactive power and derived machine frequency SVS auxiliary signals has been evaluated for damping subsynchronous resonance in a series compensated power system over a wide operating range. The following conclusion can be drawn from the eigen values study and digital time simulation for the system

1. Under large disturbance conditions, the proposed scheme damps out the sub-synchronous Resonance (SSR) modes in the series compensated power system over a wide operating range of power transfer. Hence, increase of power transfer capability of transmission line by series compensation becomes feasible without the fear of SSR.
2. The C.R.P.D.M.F. auxiliary controller stabilizes all the unstable torsional modes due to SSR for wide range of power transfer.
3. The electrical mode is not stabilized at low power level but its damping increases with increase in generator power.

4. The damping of torsional modes 3,1,0 improves on increasing the generator power.

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Appendix

Generator data: 1110MVA, 22kV, Ra= 0.0036, XL = 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=0.034 Ω/ km. Reactance X=0.325 Ω/ km. Susceptance B_c=3.7μ mho / km

SVS data: 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)	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.

Parameters of IMDU R_2' = 3.6x 10^{-4}, p.u., X_2' = 0.32646 p.u.