Damping subsynchronous resonance in power systems

S.K. Gupta, A.K. Gupta and N. Kumar

Abstract: An idea is presented for damping SSR in power systems using a double-order SVS auxiliary controller in combination with continuous controlled series compensation (CCSC) and an induction machine damping unit (IMDU) coupled with the T–G shaft. A linearised dynamic model of continuous controlled series compensation has been derived and incorporated. The eigenvalue analysis using the linearised model for continuous operation of CSC in combination with an induction machine damping unit (IMDU) and a double-order SVS auxiliary controller (DOAC) has been applied. It is seen that all the unstable torsional modes of various frequencies are stabilised effectively. A time-domain modulation study has also been performed using the nonlinear model to demonstrate the effectiveness of the proposed scheme under large disturbance conditions. 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.

List of principal symbols

ω_0	normal angular velocity
ω_i	angular velocity of *i*th inertia
δ_{Mi}	angular position of *i*th mass
T_{m1}	mechanical torque HP turbine
T_{im1}	mechanical torque of induction motor
P_E	electrical power output from generator
P_M	net mechanical power input to system
$X_c = X_{cbase}$	capacitive reactance of compensating capacitor
X_r	controlled reactance
X_{se1}	net series compensation

1 Introduction

Power transmitted through a power system network is influenced by three parameters namely voltage, impedance and phase difference. Development of high voltage and high current power semiconductor devices has led to flexible AC transmission systems (FACTS). Power electronics based systems and other static equipment which control one or more AC transmission system parameters are called FACTS devices [1]. Series compensator and static VAr systems (SVS) are used as the FACTS devices in power systems to accommodate changes in operating conditions of an electric transmission system while maintaining sufficient steady-state and transient stability margins. Series compensation of a transmission line gives rise to the problem of subsynchronous resonance (SSR) in the system which has two distinctive effects, namely the induction generator effect and torsional interactions effect. Because of torsional oscillations the shaft of the T–G set may break with disastrous consequences [2]. A.H. Othman and L. Angquist [3] developed an analytical model of thyristor controlled series compensation (TCSC) to investigate subsynchronous torsional interaction between the TCSC and turbine generator shaft, and to evaluate control interactions between the TCSC and other devices in the power systems such as SVC (static VAr compensation) and excitation systems. J.V. Milanovic and I.A. Hiskens [4] proposed the robust tuning of SVC, but results showed that the interarea mode is less damped when one load had uncertain parameters. From an exhaustive survey of the literature [1–9], it is observed that there are no controllers or schemes that can effectively dampout all the SSR modes at different levels of series compensation, over a very light load to overload conditions for different types of severe fault (without considering the natural damping of the system). To handle the problem of SSR and enhance the performance of the power transmission system, the following three different types of controllers are developed:

- Double-order SVS auxiliary controller (DOAC)
- Induction machine damping unit (IMDU)
- Continuous controlled series compensation (CCSC).

The effectiveness of the proposed scheme has been demonstrated for the IEEE first benchmark model of power systems. The controller effectively damps out the power system oscillations at different levels of series compensation.

2 System model

The system under consideration consists of a steam turbine synchronous generator set (a six-mass representation) [8] connected to the infinite bus through a long transmission line as shown in Fig. 1. An SVS [9] comprises a fixed capacitor and an inductor whose inductance is varied by adjusting the conduction angle of thyristors according to the variations in terminal voltage. An auxiliary signal is also incorporated in the static VAr system for enhancing the power system damping. The series compensation is applied at the sending-end bus. IEEE type-1 excitation [10] is used

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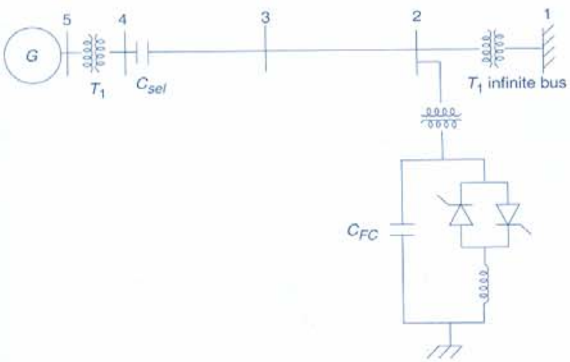

Fig. 1 *Schematic diagram of system under study*

The state and output equations of different constituent subsystems are combined together to form the state equations of the overall system. Fig. 2 shows the interconnections of different subsystems including the network transients. For the testing and implementing of series compensation and the mentioned control scheme, the transient performance of the system has been studied using a nonlinear system model under large disturbance conditions, and the dynamic performance of the system has been evaluated by performing eigenvalue analysis using a linearized system model.

3 Controller development

In this Section the three controllers' namely double-order SVS auxiliary controller (DOAC), induction machine damping unit (IMDU) and continuous controlled series compensator (CCSC) are developed and applied in combination for damping the subsynchronous resonance. Their linearised models are also derived to study dynamic analysis.

3.1 Double-order SVS auxiliary controller

The auxiliary controller transfer function $G(S)$ should have an appropriate phase compensation circuit to compensate for the phase lag between the SVS input and output susceptances. The phase lag occurs because of the delay associated with the SVS controller and measurement units. To make the SVS system more effective the derivative of reactive power (Q_3) at the SVS bus is used as an auxiliary input signal, as shown in Fig. 3. The linear block, comprising constants x, G, α and ω_d, is expected to offer the required phase lead to the selected stabilising signal. The values of constants, x, G, α and ω_d, as given in Table 1, are optimally found from the locus of the results obtained by the recursive technique. In Fig. 3,

$$y = (\alpha^2 + \omega_d^2)/x \tag{1}$$

$$p = ((x-\alpha)^2 + \omega_d^2)/(y-x) \tag{2}$$

$$q = ((y-\alpha)^2 + \omega_d^2)/(x+y) \tag{3}$$

The differential equations obtained are as

$$\begin{aligned} U_C &= \Delta Q_3 \\ &= V_{3D}(\Delta i_{4Q}) + i_{4Q}(\Delta V_{3D}) - V_{3Q}(\Delta i_{4D}) \\ &\quad - i_{4D}(\Delta V_{3Q}) \end{aligned} \tag{4}$$

$$\Delta V_F = G(U_C + Z_1 + Z_2) \tag{5}$$

$$dZ_{C1}/dt = -xZ_{C1} + pU_C \tag{6}$$

$$dZ_{C2}/dt = -yZ_{C2} + qU_C \tag{7}$$

The equations are linearsied around the operating point as

$$\begin{bmatrix} \dot{Z}_{C1} \\ \dot{Z}_{C2} \end{bmatrix} = \begin{bmatrix} -x & 0 \\ 0 & -y \end{bmatrix} \begin{bmatrix} Z_{C1} \\ Z_{C2} \end{bmatrix} + \begin{bmatrix} p \\ q \end{bmatrix} U_C$$

$$\dot{X}_C = [A_C]X_C + [B_C]U_C \tag{8}$$

$$\Delta V_F = G.[1 \quad 1] \begin{bmatrix} Z_{C1} \\ Z_{C2} \end{bmatrix} + G\,U_C$$

$$Y_C = [C_C]X_C + [D_C]U_C \tag{9}$$

where $U_C = [F_{CN}]X_N$.

3.2 Induction machine damping unit

The problem of torsional oscillations occurs because of active power imbalance (a difference between turbine input and generator output) during rotor swing, but no work has

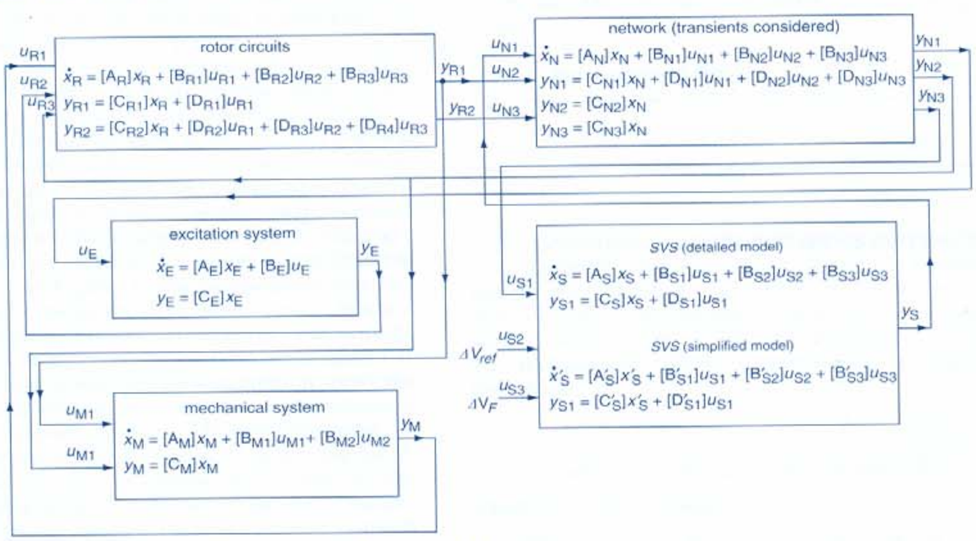

Fig. 2 *Interconnection of various subsystems in overall system model*

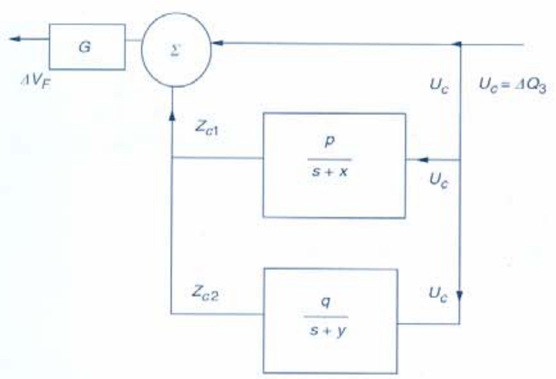

Fig. 3 *Auxiliary controller block diagram*

Table 1: Double-order auxiliary controller parameter

Compensation, %	X	G	α	ω_d
0	5.05	−0.161046	0.2	0.1
10	5.05	−0.121046	0.2	0.0
25	5.05	−0.121046	0.2	0.0
40	5.05	−0.121046	0.2	0.0
55	5.05	−0.121046	0.2	0.0
70	5.05	−0.081046	0.2	0.0

been reported for handling this problem through active power control.

The property of an induction machine to act either as a generator or motor is utilised to absorb mechanical power if there is excess and to release it when there is a deficiency. High pressure (HP) and other turbines produce torque in the direction of rotation (forward direction) and the generator produces the electromagnetic torque in the opposite direction. The T–G set has a long shaft and consequently the turbine and generator torques produce an angular twist in the shaft. The twist angle is dependent on load, and during steady-state operation it is constant. However, during the torsional oscillating state the angle varies periodically. If the system has negative damping, the amplitude of the torsional oscillations will grow exponentially which may damage the shaft. If an induction machine is connected to the HP turbine on its left side as shown in Fig. 4 and the speed of the machine exceeds the synchronous speed (mechanical input is greater than electrical output of generator) the machine acts as an induction generator. Torque produced by it is in the reverse direction as indicated, in this Figure. It can be visualised that this torque will tend to reduce the twist angle $(\delta_1 - \delta_5)$, hence it reduces the amplitude of torsional oscillation. Alternatively, it can be said that it increases the damping of the system. If the speed of the shaft is less than the synchronous speed, the induction machine will act as a motor and it produces a torque in the forward direction. In this operation, it supports the turbine torque and helps to restore the speed. So in any case it tries to oppose the change in the synchronous speed of the shaft. It can be said that it reduces the oscillations in the rotating mass around the nominal speed, or that the damping of the system is increased.

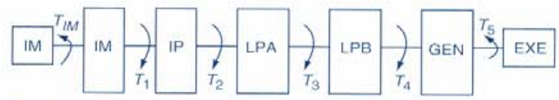

Fig. 4 *Direction of torques for above synchronous speed*

Since this machine comes into operation during transients only, it is designed for very high short-term rating and very small continuous rating; consequently the machine has low inertia, low power, small size and low cost. Because of its small mass and tight coupling with the high pressure turbine it has been considered a single mass unit with the HP turbine. Electrically it is connected to the generator bus. The per-unit torque for induction machine (T_{im1}) is given by

$$T_{im1} = \frac{3s}{\omega_0 r'_2[1 + (sx'_2/r'_2)^2]} \tag{10}$$

$$s(\omega_0 - \omega_1)/\omega_0 \tag{11}$$

The mechanical system equation of HP turbine-induction machine unit is then given by

$$M_1\dot{\omega}_1 = -(D_{11} + D_{12})\omega_1 + D_{12}\,\omega_2 - K_{12}(\delta_1 - \delta_2) + T_{m1} + T_{im1} \tag{12}$$

Linearising the equations we get

$$\Delta T_{im1} = (3/(\omega_0, r'_2))\frac{[(1 + (sx'_2/r'_2)^2) - s(x'_2/r'_2)^2]\Delta s}{[1 + (sx'_2/r'_2)^2]^2} \tag{13}$$

where $\Delta s = -\Delta\omega_1/\omega_0$. At normal operating point $s = 0$, hence $\Delta T_{im1} = 3\,\Delta s/\omega_0 r'_2 = -3\Delta\omega_1/\Delta\omega_0^2 r'_2$. From these equations

$$M_1\Delta\dot{\omega}_1 = -(D_{11} + D_{12}).\Delta\omega_1 - 3\Delta\omega_1/\omega_0^2.r'_2 + D_{12}\omega_2 - K_{12}(\Delta\delta_1 - \Delta\delta_2) \tag{14}$$

The damping of the mechanical system $[-(D_{11} + D_{12})/M_1]$ is thus modified to $[-(D_{11} + D_{12})/M_1 - 3/\omega_0^2 r'_2]$ on application of the induction machine. it indicates the enhancement of mechanical system damping only during a disturbance. Higher sensitivity $(dT_{im}/ds = 3/\omega_0^2 r'_2)$ is desirable to improve the damping. To maximise the slope or sensitivity of the characteristics, the r_2/x_2 ratio should be minimised. The parameters of IMDU selected are given in Table 2.

Table 2: Parameters of IMDU

r'_2	3.6×10^{-4} pu
x'_2	0.32646 pu

3.3 Continuous controlled series compensation

To consider the dynamic effect of CSC it is important to present the change in the line reactance as one of the state variables. The appropriate control action in controlled series compensation is initiated to reduce a function P_D (defined as follows) progressively, following the disturbance.

$$P_D = (P_E - P_M)^2/2 \tag{15}$$

$$dP_D/dt = (dP_D/dP_E)(dP_E/dX_s)(dX_s/dt) \tag{16}$$

where $P_D = (V_0V_1/X_s)\sin\delta$.

$$dP_D/dt = (P_M - P_E)(V_s.V_1/X_s^2)\sin\,\delta(dX_s/dt) \tag{17}$$

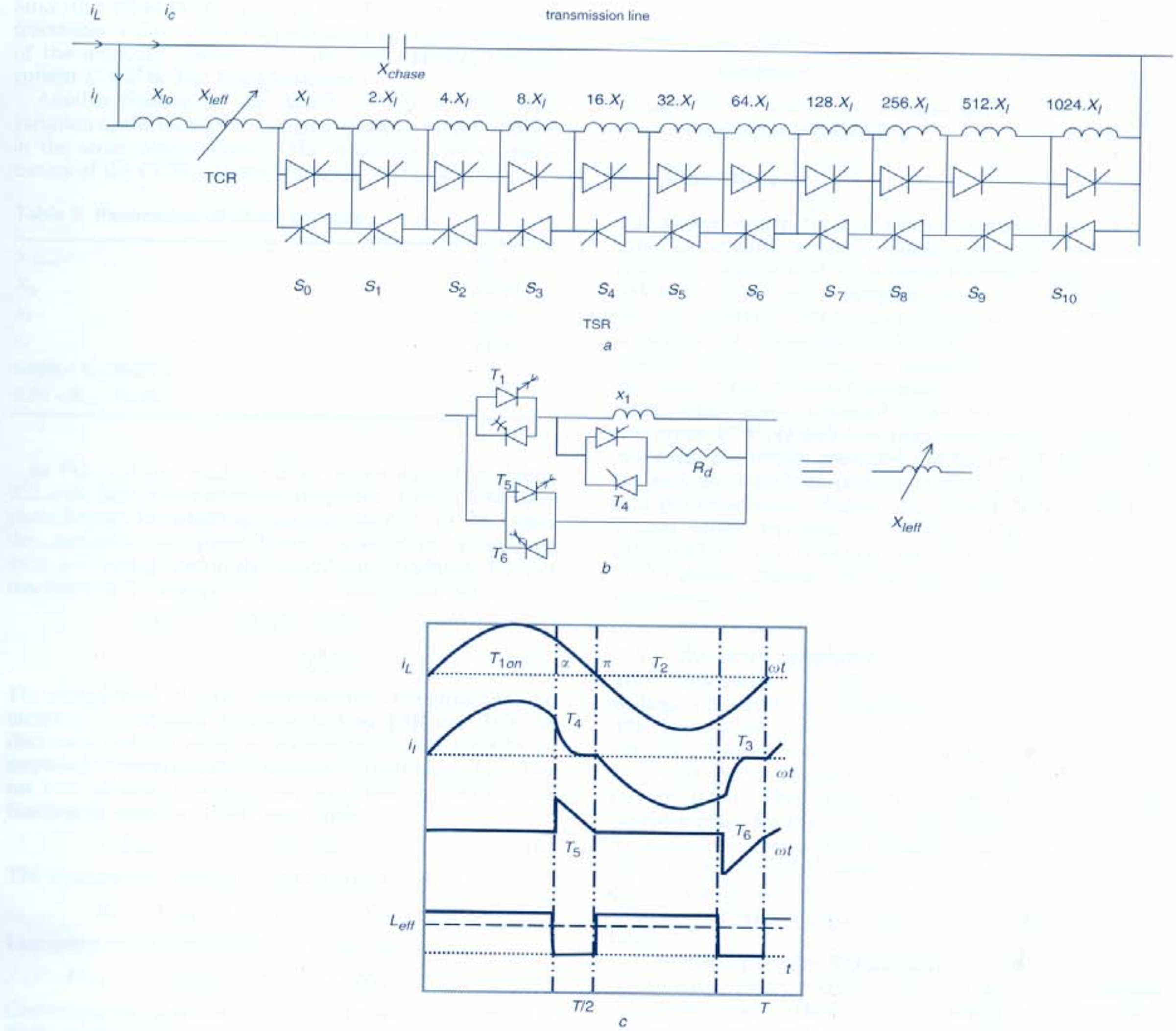

Fig. 5 *a Continuous control series compensation scheme; b TCR control of lower part of inductive reactance; c Waveforms for circuit of Fig. 5b*

Substituting the condition ($P_M > P_E$) in the equations we find the relation $dP_D/dX_s > 0$. It is obvious that dX_s/dt should be less than zero which means X_s should reduce with time and *vice versa*. Conventional series compensation introduces harmonics owing to the chopping action of TCR. This scheme eliminates the introduction of harmonics in a power system which would otherwise have an adverse effect on its performance. A parallel L, C tank is used for controlled series compensation. It has a fixed capacitance, 11 thyristor switched inductive reactances (TSR), and a constant inductive reactance ($X_{lo} > X_{chase}$) to limit the maximum level of series compensation, as shown in Fig. 5*a*. The thyristor-switched reactor changes the reactance in steps (multiples of X_1), where the value of X_1 is 0.01% of the total reactance of transmission line. The required inductive reactors, ranging from X_1 to $1024X_1$ as shown in Fig. 5*a*, are switched in or out of the circuit by the appropriate group of thyristors. For example, if $510X_1$ reactance is to be inducted into the circuit switches S_0, S_9 and S_{10} are switched on, as a result the reactors X_{lo}, $512X_1$ and $1024X_1$ are bypassed. Since other switches are in the off state, the remaining eight reactors come into circuit and $510X_1$ reactance appears across the fixed capacitance.

Also an inductance of lowest value is used in the TCR section to provide fine variation; its detailed circuit is shown in Fig. 5*b*. The working of the TCR is explained as follows: T_1 (GTO) conducts from 0° to α [Fig. 5*c*], as a result X_1 is connected in the series with X_{lo}. At $\omega t = \alpha$, T_1 (GTO) is turned off and T_5 is turned on, consequently inductive current i_1 is diverted to T_5. At the same time T_4 is turned on, which freewheels the current through X_1 and R_d, and the stored inductive energy is quickly dissipated (in R_d). Thus the reactance appears in circuit from 0° to α, and is bypassed by T_5 from α to π. A similar operation takes place in negative half-cycle. By varying the conduction period of T_1 (and T_2), the effective value of x_{leff} can be controlled.

Since the value of X_1 is much smaller than other series reactances, a chopping action will cause negligible distortion of the inductive current i_l of the tank. Hence, the line current i_L will be free from harmonics.

Another feature of the circuit is that a very small variation in the inductive reactance causes a large variation in the series compensation. The values of various parameters of the CCSC scheme are given in Table 3.

Table 3: Parameters of CCSC scheme

X_{cbase}	5%
X_{lo}	5.35%
X_1	0.01%
r_d	2.8 kΩ
$5.35\% < X_r < 25.81\%$	
$6.2\% < X_{sel} < 75.4\%$	

In Fig. 5, $X_{leff} = T_{on}X_1/(T/2)$ or $X_{leff} = T_{on}\omega_0 X_1/\pi$. Here, $T/2$ is the half period of power frequency. Energy loss takes place through freewheeling resistance R_D (α to π). And since this operation takes place during transients (5 to 6 s) only, there is no energy loss at the steady-state condition. The net reactance of the compensation of transmission line is

$$-jX_{sel} = (-jX_c jX_r)/(jX_r - jX_c)$$
$$= -j(X_c + X_c^2/(X_r - X_c)) \qquad (18)$$

The overall level of series compensation therefore may be increased by reducing X_r (controlled by TSR and TCR as discussed) and *vice versa*. As a disturbance occurs CCSC is employed to minimise the deviation of shaft angle δ_{M5}. The net level of series compensation described as follows is a function of generator shaft twist angle:

$$X_{sel} = X_{sel0}(1 + \sin(\delta_{M5} - \delta_{M50})) \qquad (19)$$

The equation for voltage (α-axis) across CCSC is

$$\dot{V}_{6\alpha} = X_{sel0} \cdot [1 + \sin(\delta_{M5} - \delta_{M50})] i_\alpha \omega_0 \qquad (20)$$

Linearsing around the operating point, we get

$$\Delta \dot{V}_{6\alpha} = -(i_{\alpha 0}/C_{sel0})\Delta\delta_{M5} + (1/C_{sel0})\Delta i_\alpha \qquad (21)$$

Converting this equation (along with its β-axis) into the d–q frame of reference

$$\begin{bmatrix}\Delta\dot{v}_{6D}\\ \Delta\dot{v}_{6Q}\end{bmatrix} = \begin{bmatrix}0 & -\omega_0\\ -\omega_0 & 0\end{bmatrix}\begin{bmatrix}\Delta v_{6D}\\ \Delta v_{6Q}\end{bmatrix} + \begin{bmatrix}1/C_{sel0} & 0\\ 0 & 1/C_{sel0}\end{bmatrix}\begin{bmatrix}\Delta i_D\\ \Delta i_Q\end{bmatrix} + \begin{bmatrix}i_{D0}/C_{sel0}\\ i_{Q0}/C_{sel0}\end{bmatrix}\Delta\delta_{M5} \qquad (22)$$

The first two terms, on the right-hand side of the equation, are already included in transmission line model equations ($\dot{X}_N$). The third term is represented and included in the model in the form

$$\text{third term} = [B_{N4}]Y_M = [B_{N4}][C_M]X_M \qquad (23)$$

$[B_{N4}]$ is 18×2 matrix, the nonzero elements of which are given in the Appendix (Section 7.1).

4 Case study

The power system used to study the performance of the proposed control strategies consists of two synchronous generators represented by a single equivalent unit of 1110 MVA, at 22 kV and supplying power to an infinite bus through a 400 kV, 600 km long transmission line. The SVS is capable of delivering 650 MVAR reactive power. The system's natural damping is assumed to be zero so that the effect of the controller exclusively can be examined. The main information obtained from the load-flow study comprises P, V, Q and δ at operating point on each bus. Although the results presented are for an 800 MVA load, the analyses have been performed for a wide range of load and the conclusions drawn are general. Initial values of system states, required in the eigenvalues analysis, are calculated from the results of load-flow studies with the help of the phasor diagram of the synchronous generator and transmission line.

4.1 Dynamic analysis

The dimensions of the system matrix with and without a controller are found to be 45 and 43, respectively. The eigenvalues, so obtained from the system matrix, are the familiar modes of response for the system. The real parts of eigenvalues are called decremental factors (DF). They must be in the left half of the complex plane for the system to be stable. The frequencies of modes (imaginary parts of eigenvalues) are found as in [9]. The DF for the system at various levels of series compensation are calculated and presented in Tables 4–11 without and with various controllers and their combinations.

It is seen from the Tables that no single controller or combination of any two controllers are effective in damping of all the modes. However, a combination of all three controllers has been found to be perfectly effective in damping all the modes. It is therefore reasonable to apply three controllers.

4.2 Time-domain analysis

Digital time-domain analysis, for the system under large disturbances, has been done on the basis of nonlinear differential equations with all nonlinearities and limits. A fourth-order Runga Kutta method has been used for solving the nonlinear differential equations. Disturbance is

Table 4: DFs for system without any auxiliary controller

Compensation, %	Mode 0	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Other modes
00.000	1.1008	−0.0004	0.0001	0.0008	0.0026	−0.0001	stable
10.000	0.7293	0.0028	0.0005	0.0036	0.0251	0.0000	stable
25.000	0.3493	0.0105	0.0021	0.0345	0.0156	−0.0001	stable
40.000	0.1279	0.0330	0.0127	0.0382	−0.0009	0.0000	stable
55.000	−0.0303	0.1578	0.0312	0.0028	−0.0023	0.0000	stable
70.000	−0.1687	0.8486	0.0029	−0.0008	−0.0027	0.0000	stable

Table 5: DFs of system with DOAC alone

Compensation, %	Mode 0	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Other modes
00.00	**−0.1931**	0.0157	0.0007	0.0012	0.0016	0.0001	stable
10.00	**−0.8634**	0.0160	0.0009	0.0036	0.0184	0.0001	stable
25.00	**−2.0002**	0.0234	0.0024	0.0258	0.0227	−0.0001	stable
40.00	**−1.6629**	0.0457	0.0101	0.0606	0.0011	0.000	stable
55.00	**−1.5413**	0.1413	0.0371	0.0079	−0.0011	0.000	stable
70.00	**−0.7712**	0.5628	0.0064	0.0012	0.0024	0.000	stable

Table 6: DFs of system with IMDU controller separately

Compensation, %	Mode 0	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Other modes
00.00	**1.0916**	−0.0672	−0.0494	−0.2055	−0.0169	−0.1080	stable
10.00	**0.7179**	−0.0642	−0.0490	−0.2026	**0.0056**	−0.1083	stable
25.00	**0.3356**	−0.0565	−0.0475	−0.1715	−0.0044	−0.1082	stable
40.00	**0.1143**	−0.0340	−0.0370	−0.1689	−0.0202	−0.1083	stable
55.00	−0.0447	**0.0980**	−0.0181	−0.2036	−0.0220	−0.0182	stable
70.00	−0.1836	**0.7874**	−0.0466	−0.2069	−0.0223	−0.1083	stable

Table 7: DFs of system with CCSC alone

Compensation, %	Mode 0	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Other modes
00.00	0.9828	**−0.0001**	0.0001	0.0007	0.0026	0.0001	stable
10.00	0.7696	0.0064	0.0008	0.0055	0.0217	0.0000	stable
25.00	0.5602	0.0145	0.0023	0.0167	**−0.0392**	0.0001	stable
40.00	0.4332	0.0208	0.0035	**−0.0316**	**−0.0150**	0.0001	stable
55.00	0.3575	0.0146	**−0.0100**	**−0.0089**	**−0.0072**	0.000	stable
70.00	0.3458	**−0.1552**	**−0.0012**	**−0.0018**	**−0.0016**	0.000	stable

Table 8: DFs for system with DOAC and IMDU

Compensation, %	Mode 0	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Other modes
00.000	−0.0876	−0.0507	−0.0488	−0.2049	−0.0278	−0.1083	stable
10.000	−0.6443	−0.0502	−0.0485	−0.2025	−0.0010	−0.1083	stable
25.000	−2.3559	−0.0425	−0.0471	−0.1802	**0.0031**	−0.1082	stable
40.000	−1.8600	−0.0201	−0.0395	−0.1459	−0.0187	−0.1083	stable
55.000	−1.6891	**0.0758**	−0.0122	−0.1987	−0.0206	−0.1083	stable
70.000	−0.8130	**0.4985**	−0.0431	−0.2053	−0.0217	−0.1083	stable

simulated by a 33% sudden increase in input torque for 0.6 s. The responses of the system without and with the proposed scheme are plotted in Fig. 6. Further, the three-phase open-circuit fault has also been considered to occur at point F as shown in Fig. 7. The net level of series compensation considered is 40% and both the parallel lines are identical. The controller performance for this transient fault is demonstrated in Fig. 8.

Table 9: DFs system with CCSC in combination with DOAC only

Compensation, %	Mode 0	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Other modes
00.00	**−0.1931**	0.0157	0.0007	0.0012	0.0016	0.0001	stable
10.00	**−0.4522**	0.0173	0.0012	0.0048	0.0157	0.0000	stable
25.00	**−2.2029**	0.0196	0.0018	0.0096	**−0.0416**	0.0001	stable
40.00	**−1.5799**	0.0154	0.0010	**−0.0356**	**−0.0138**	0.0000	stable
55.00	**−0.7891**	**−0.0140**	**−0.0104**	**−0.0087**	**−0.0061**	**−0.0001**	stable
70.00	**−0.0925**	**−0.1229**	**−0.0014**	**−0.0012**	**−0.0009**	0.0000	stable

Table 10: DFs of system with CCSC in combination with IMDU only

Compensation, %	Mode 0	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Other modes
00.00	**0.9725**	−0.0670	−0.0494	−0.2095	−0.0170	−0.1082	stable
10.00	**0.7586**	−0.0604	−0.0486	−0.2009	**0.0023**	−0.1082	stable
25.00	**0.5497**	−0.0524	−0.0473	−0.1895	−0.0585	−0.1083	stable
40.00	**0.4206**	−0.0460	−0.0459	−0.2380	−0.0346	−0.1082	stable
55.00	**0.3445**	−0.0520	−0.0595	−0.2159	−0.0266	−0.1082	stable
70.00	**0.3323**	−0.2030	−0.0507	−0.2078	−0.0211	−0.1083	stable

Table 11: DF for system with DOAC in combination with IMDU and CSC

Compensation, %	Mode 0	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Other modes
00.00	−0.0876	−0.0507	−0.0488	−0.2049	−0.0178	−0.1083	stable
10.00	−0.3005	−0.0485	−0.0482	−0.2011	−0.0024	−0.1082	stable
25.00	−0.8426	−0.0456	−0.0476	−0.1957	−0.0649	−0.1083	stable
40.00	−1.7398	−0.0496	−0.0483	−0.2464	−0.0350	−0.1082	stable
55.00	−0.8495	−0.0809	−0.0614	−0.2162	−0.0267	−0.1082	stable
70.00	−0.0837	−0.2100	−0.0515	−0.2080	−0.0210	−0.1082	stable

5 Conclusions

An active controller, called an induction machine damping unit (IMDU), has been developed and implemented in combination with a double-order SVS auxiliary controller (DOAC). A scheme of continuous control of series compensation has been proposed which does not introduce harmonics in the system. A linearised model of continuous control of series compensations has been presented. The feasibility of the application of controlled series compensation in combination with DOAC and IMDU has been proposed for the effective damping of all SSR modes.

• The steady-state stability of the compensated line is considerably enhanced.

• Mode 0 is responsible for the dynamic interaction of the generator and transmission line. The magnitude of the real part of the eigenvalue of this mode improves considerably on application of double-order SVS auxiliary controller.

• As a consequence of the previous point, transmission system oscillations are greatly suppressed. This is verified by time-domain analysis which shows the fast recovery of transmission system states after the disturbance.

• The IMDU has significant damping effect on all the SSR modes except mode 0. And the combination of DOAC and IMDU very effectively damps out almost all the torsional modes at different levels of series compensation. Transient analysis of the power system using this combination shows excellent performance under a large disturbance.

• A scheme of controlled series compensation has been developed with a continuous mode of operation. The proposed CCSC scheme does not introduce any harmonic into the system and when applied alone it is seen that the

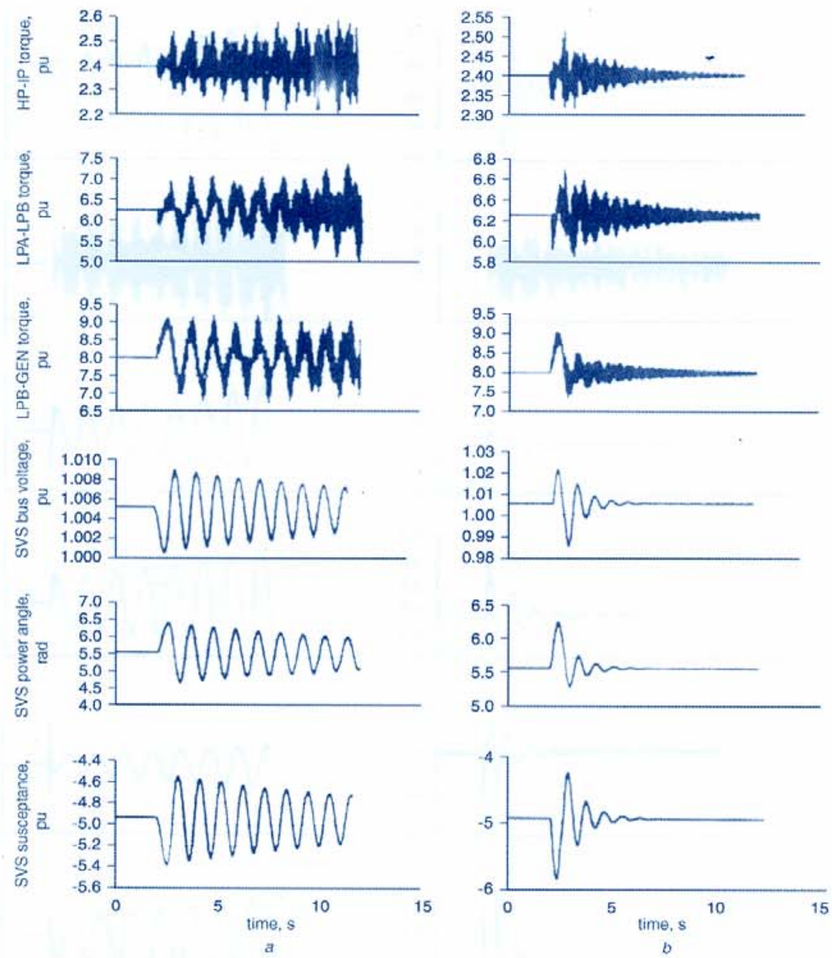

Fig. 6 *System response for torque disturbance with and without proposed scheme*
a without scheme
b with proposed scheme

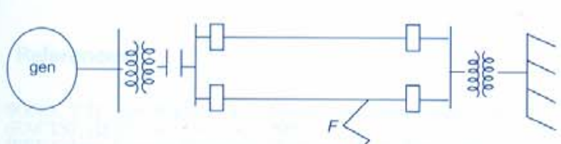

Fig. 7 *Test power system for open-circuit*

effect of CSC is more prominent at higher levels of series compensation. When CCSC is used in combination with DOAC and IMDU the unstable SSR modes are shifted to the stable region. To illustrate the performance of the proposed combination under a large disturbance and severe fault conditions, a digital modulation study was carried out using a nonlinear system model. The proposed combination works very effectively, and torsional oscillations and the other SSR oscillations are effectively damped out and better transient performance of the system is obtained.

- Damping of SSR is achieved at various levels (10 to 70%) of series compensation over a wide range of power demand.
- The proposed strategy is tested for torque disturbance of a magnitude as high as nearly 50% of full load torque and for open circuit fault.
- All the controllers developed work in close co-operation with one another and their net effect is additive towards a common goal of damping subsynchronous resonance in power systems.
- Increase of the power transfer capability of transmission line by series compensation becomes feasible.
- Overall performance of the power system is improved.

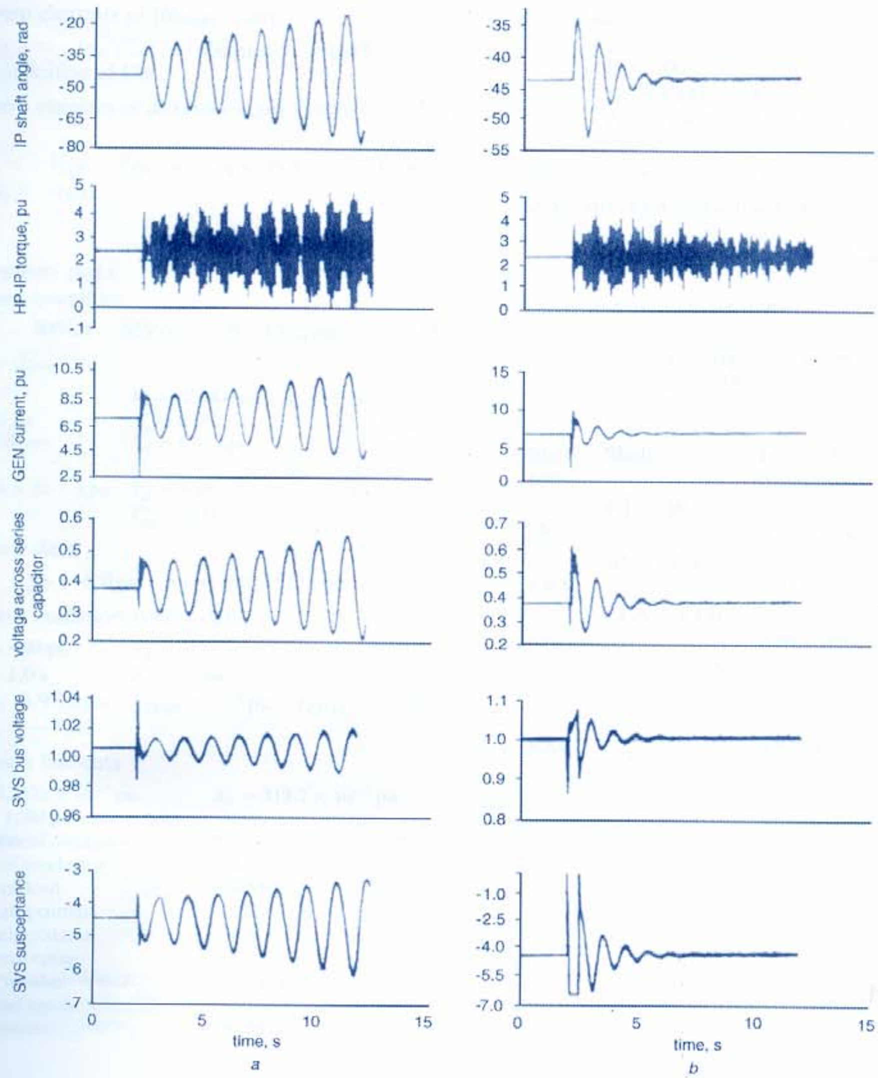

Fig. 8 *System responses for open-circuit fault with and without proposed scheme*
a without scheme
b with proposed scheme

6 References

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7 Appendix

7.1 Nonzero elements of matrix

Dimensions and elements of all the matrices of subsystems (other than mentioned) are given in [8, 9].

$$A_{M(7,1)} = -(D_{11} + D_{12})/M_1, \quad \text{(without IMDU)}$$

The nonzero elements of $[B_{N4}]_{18\times 2}$ are

$$B_{N4(9,1)} = -i_{D0}/C_{sel0}, \quad B_{N4(18,1)} = -i_{Q0}/C_{sel0}$$
(on application of CSC)

The nonzero elements of auxiliary-system matrix $[F_{CN}]_{1\times 18}$ are

$$F_{CN(1,3)} = -V_{3Q0}, \quad F_{CN(1,6)} = i_{4Q0}, \; F_{CN(1,12)} = V_{2D0}, \; F_{CN(1,15)} = -i_{4D0}$$

7.2 System data

System base quantities

Voltage = 400 kV   MVA = 100   Frequency = 50 Hz

Generator data

$S_n = 11.1$	$V_n = 22/400$ pu	$R_a = 3.243.10^{-4}$
$X'_d = 0.042$ pu	$X'_q = 0.103$ pu	$X''_d = X''_q = 0.0281$ pu
$X_1 = 0.01889$ pu	$X_d = 0.174$ pu	$X_q = 0.157$ pu
$F_0 = 50$	$D = 0$	$T''_{do} = 0.032$ s
$R_a = 3.243 \times 10 - 4$ pu	$T'_{do} = 6.66$ s	$T''_{qo} = 0.057$ s
$H = 3.22$	$T'_{qo} = 0.44$	

Transformer data

$$R_T = 0.0 \text{ pu} \quad X_T = 0.0135135 \text{ pu}$$

IEEE type-1 excitation system data

$K_A = 400$ pu	$T_A = 0.02$ s	$K_E = 1.0$ pu
$T_E = 1.0$ s	$K_F = 0.06$	$T_F = 1.0$ s
$V_{RMAX} = 9.75$ pu	$V_{RMIN} = -7$ pu	$V_{FMAX} = 5$ pu
$V_{FMIN} = -7$ pu		

Transmission line data

$R = 12.525 \times 10^{-3}$ pu	$X_L = 119.7 \times 10^{-3}$ pu
$B_c = 1.784$ pu on both sides	
Number of conductors	2
Area of conductor	0.4 in^2
Natural load	540 MW
Charging current	0.845 A/phase/km
Surge impedance	296 Ω
Thermal rating:	
Cold weather ($< 40°F$)	1100 MVA
Normal weather ($40 - 65°F$)	900 MVA
Hot weather ($> 65°F$)	790 MVA

SVS data

$$Q = 100$$
$$K_I = 1200 \quad K_p = -1 \quad K_D = 0.01 \text{ pu}$$
$$T_M = 2.4 \text{ ms} \quad T_s = 5 \text{ ms} \quad T_D = 1.667 \text{ ms}$$

Mechanical system data (at generator base)
Generator as a single mass unit

Inertia (H) 3.22 s

Generator as six-mass units

$$Dii = 0 \text{ for } i = 1 \text{ to } 6$$
$$Dij = 0 \text{ for } i = 1 \text{ to } 6, j = 1 \text{ to } 6$$

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	