A New Scheme for Damping Torsional Modes in a Series Compensated Power System

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***Abstract*—In the present paper, a new scheme for damping torsional modes in a series compensated power system has been developed. The proposed scheme, utilizes the effectiveness of combined active power and frequency (C.A.P.F.) SVS auxiliary controller in co-ordination with an induction machine damping unit coupled to the T-G shaft. Studies are conducted on the first IEEE benchmark model. The damping scheme stabilizes all the torsional modes over a wide operating range of power transfer. SVS is installed at the middle of transmission line to optimize the power transfer capability. Also the optimal location of IMDU along the T-G shaft has been determined by using eigenvalue analysis. It is found that locating IMDU after the IP turbine yields the maximum damping effect.**

Index Terms— **Static Var System, C.A.P.F., Induction machine damping unit (IMDU), Torsional modes**

I. INTRODUCTION

In recent years SVS has been employed to an increasing extent in modern power system [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.Series compensation has been widely used to enhance the power transfer capability. However series compensation gives rise to dynamic instability and SSR problems. Many preventive measures to cope with this 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 [3,4]. Ning Yan et. al. [8] showed the design of controller that can 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.Massimo Bongiorno et. al[11] presented a scheme using SSSC for damping subsynchronous resonance by controlling the subsynchronopus component of grid to zero. K.R. Padiyar and Nagesh Prabhu [12] used an auxiliary controller using STATCOM bus voltage and reactive current signals for damping subsynchronous resonance. Naotokakimoto and Anan Phongphanee [13] used TCSCfor subsynchronous resonance damping by oscillating the firing angle in phase with that of rotor angle. Mojtaba Noroojian et. al.[14] developed control laws for TCSC and SVS using local input signals for damping electromechanical power oscillations The damping scheme is robust with respect to loading conditions, fault location and network structure. 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 active power and frequency (CAPF) SVS auxiliary controller in coordination with induction machine damping unit (IMDU) for repressing torsional modes in a series compensated power system. C.A.P.F. auxiliary controller with IMDU is able to stabilize all the torsional modes over a wide operating range of power transfer.

II. 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 active power and frequency (CAPF) auxiliary control signals. The series compensation is applied at the sending end of the line. IEEE type –1 excitation system is used.

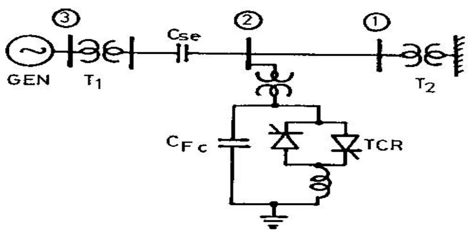

Figure1: Study System

A. Generator

In the detailed machine model [9] 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 [10] has been considered for the analysis of torsional modes due to SSR. The linearized state and output equation of the rotor circuit are as:

$$\dot{X}_R = A_R X_R + B_{R1} U_{R1} + B_{R2} U_{R2} + B_{R3} U_{R3}$$
$$Y_{R1} = C_{R1} X_R + D_{R1} U_{R1} \quad (1)$$
$$Y_{R2} = C_{R2} X_R + D_{R2} U_{R1} + D_{R3} U_{R2} + D_{R4} U_{R3}$$

where

$$X_R = \lfloor \Delta\psi_f \quad \Delta\psi_h \quad \Delta\psi_g \quad \psi_k \rfloor,\ U_{R1} = \lfloor \Delta\delta \quad \Delta\omega \rfloor,$$
$$U_{R2} = \Delta V_f,\ U_{R3} = \lfloor \Delta i_D \quad \Delta i_Q \rfloor,\ Y_{R1} = [\Delta I_D \quad \Delta I_Q]$$

B. Mechanical System

The mechanical system (Fig.2) is described by the six spring mass model. The state and output equations are given as follows:

$$\dot{X}_M = A_M X_M + B_{M1} U_{M1} + B_{M2} U_{M2},\ Y_M = C_M X_M$$
$$X_M = \begin{bmatrix} \Delta\delta_1, \Delta\delta_2, \Delta\delta_3, \Delta\delta_4, \Delta\delta_5, \Delta\delta_6, \\ \Delta\omega_1, \Delta\omega_2, \Delta\omega_3, \Delta\omega_4, \Delta\omega_5, \Delta\omega_6 \end{bmatrix}^t$$
$$Y_M = \lfloor \Delta\delta_5, \Delta\omega_5 \rfloor^t,\ U_{M1} = \lfloor \Delta I_D, \Delta I_Q \rfloor^t$$
$$U_{M2} = \lfloor \Delta i_D, \Delta i_Q \rfloor^t \quad (2)$$

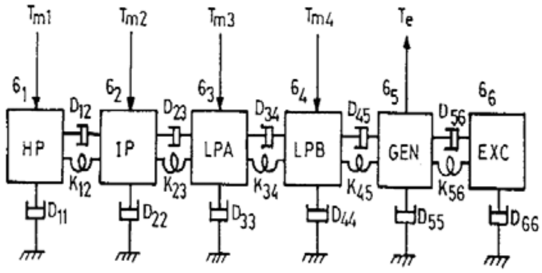

Figure:2 Six–Spring mass representation of the mechanical system

C. Network

The transmission line is represented by lumped parameter T- circuit. The network has been represented by its α–axis equivalent circuit which is identical with the positive sequence network as shown in Fig.3.

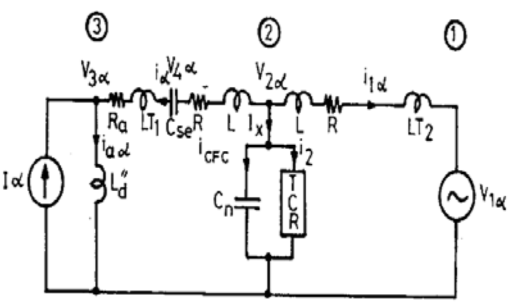

Figure 3. α – axis representation of the network

The state and output equations for the network model are obtained as:

$$\dot{X}_N = [A_N] X_N + [B_{N1}] U_{N1} + [B_{N2}] U_{N2} + [B_{N3}] U_{N3}$$
$$Y_{N1} = [C_{N1}] X_N + [D_{N1}] U_{N1} + [D_{N2}] U_{N2} + [D_{N3}] U_{N3}$$
$$Y_{N2} = [C_{N2}] X_N,\ Y_{N3} = [C_{N3}] X_N \quad (3)$$

where

$$X_N = \lfloor \Delta i_{1D} \ \Delta i_D \ \Delta v_{2D} \ \Delta v_{4D} \ \Delta i_{1Q} \ \Delta i_Q \ \Delta v_{2Q} \ \Delta v_{4Q} \rfloor^t$$
$$,U_{N1} = \lfloor \Delta i_{2D} \ \Delta i_{2Q} \rfloor^t,\ U_{N2} = \lfloor \Delta\dot{I}_D \ \Delta\dot{I}_Q \rfloor^t$$
$$U_{N3} = \lfloor \Delta I_D \ \Delta I_Q \rfloor^t,\ Y_{N1} = [\Delta V_{gD} \ \Delta V_{gQ}]^t$$
$$Y_{N2} = [\Delta i_D \ \Delta i_Q]^t,\ Y_{N3} = [\Delta V_{2D} \quad \Delta V_{2Q}]^t$$

D. Static Var System

Fig. 4 shows a small signal model of a general SVS.

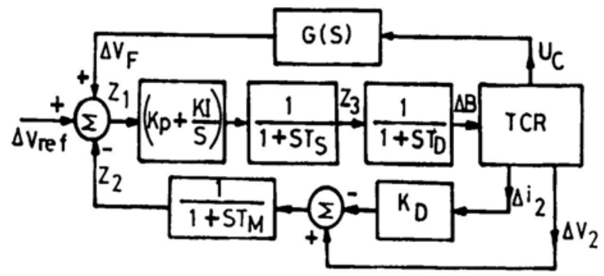

Figure 4. SVS control system with auxiliary feedback

The equations describing SVS system are as:

$$\dot{z}_1 = V_{ref} - z_2 + \Delta V_F \quad (4)$$
$$\dot{z}_2 = \frac{(\Delta V_2 - K_D \Delta i_2)}{T_M} - \frac{z_2}{T_M}$$
$$\dot{z}_3 = \frac{(-K_I z_1 + K_P z_2 - z_3 - K_P \Delta V_{ref})}{T_s}$$
$$\Delta\dot{B} = \frac{(z_3 - \Delta B)}{T_D}$$

Where ΔV_2, Δi_2 are incremental magnitudes of SVS voltage and current, respectively, obtained by linearising

$$V_2 = \sqrt{(V_{2D}^2 + V_{2Q}^2)}\ ,\ i_2 = \sqrt{(i_{2D}^2 + i_{2Q}^2)} \quad (5)$$

The state and output equations of the SVS model are obtained as:

$$\dot{X}_S = [A_S] X_S + [B_{S1}] U_{S1} + [B_{S2}] U_{S2} + [B_{S3}] U_{S3}$$
$$Y_S = [C_S] X_S + [D_S] U_{S1} \quad (6)$$

where

$$X_S = \lfloor i_{2D} \quad i_{2Q} \quad Z_1 \quad Z_2 \quad Z_3 \quad \Delta B \rfloor^t,$$
$$U_{S1} = [\Delta V_{2D} \quad \Delta V_{2Q}]^t,\ U_{S2} = \Delta V_{REF},\ U_{S3} = \Delta V_F$$
$$Y_S = [\Delta i_{2D} \quad \Delta i_{2Q}]^t$$

III. COMBINED ACTIVE POWER AND FREQUENCY (CAPF) AUXILIARY SIGNAL

The auxiliary controller signal in this case is the combination of the line active power and the bus 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.6. The auxiliary control signals U_{C1} and U_{C2} correspond,

respectively, to the line active power and the bus frequency deviations which are derived at the SVS bus.
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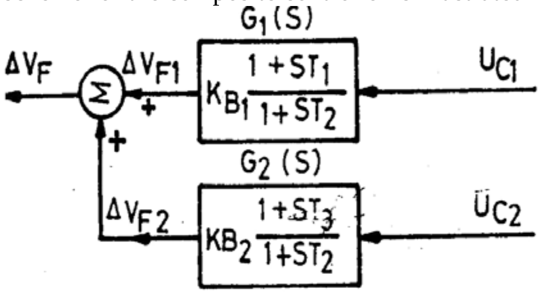

Figure 5.Control scheme for C.A.P.F. auxiliary controller

A. Active Power Auxiliary Signal

The active power entering the SVS bus can be expressed as:

$$P_2 = V_{2D} i_D + V_{2Q} i_Q \tag{7}$$

where i_D, i_Q and V_{2D}, V_{2Q} are the D-Q axis components of the line current i and the SVS bus voltage V_2 respectively. Linearizing eqn. (7) gives the deviation in the reactive power ΔQ_2 which is taken as the auxiliary control signal (U_{C1}).

$$U_{C1} = \Delta Q_2 = V_{2D_o}\Delta i_Q + i_{Q_o}\Delta V_{2D} + V_{2Q_o}\Delta i_D + i_{D_o}\Delta V_{2Q} \tag{8}$$

B. Bus Frequency Auxiliary Signal

The SVS bus frequency is given as:

$$f_{SVS} = \frac{d}{dt}\left[\tan^{-1}\frac{V_{2Q}}{V_{2D}}\right] \tag{9}$$

Linearizing eqn. () gives the deviation in bus frequency, Δf_{SVS} which is taken as the auxiliary control signal (U_{C2}).

$$U_{C2} = \Delta f_{SVS} = \left(\frac{V_{2Do}}{V_{2o}{}^2}\right)\Delta V_{2Q} - \left(\frac{V_{2Qo}}{V_{2o}{}^2}\right)\Delta V_{2D} \tag{10}$$

where, 'o' represents operating point or steady state values.

The state and output equation for the C.A.P.F auxiliary controller is obtained as follows:

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

$$Y_C = [C_{C1} \quad C_{C2}]\begin{bmatrix}X_{C1}\\ X_{C2}\end{bmatrix} + [D_{C1} \quad D_{C2}]\begin{bmatrix}U_{C1}\\ U_{C2}\end{bmatrix} \tag{11}$$

Where A_{C1}, B_{C1}, C_{C1} and D_{C1} are the matrices of the Active power auxiliary controller and A_{C2}, B_{C2}, C_{C2} and D_{C2} are the matrices of the bus frequency auxiliary controller.

IV. INDUCTION MACHINE DAMPING UNIT (IMDU)

The property of induction machine to act as a generator or motor is utilized to absorb the mechanical power when there is excess and to release it when there is a deficiency. Since the 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 it small mass and tight coupling with the intermediate pressure turbine it has been considered as a single mass unit with IP turbine. Electrically it is connected to the generator bus. The per unit torque (T_{iml}) is given by:

$$T_{im1} = \frac{3s}{\left[(\omega_0 r_2').\left(1+\left(\frac{s.x_2'}{r_2'}\right)^2\right)\right]} \text{ and}$$

$$\text{slip } s = \frac{(\omega_0 - \omega_1)}{\omega_0} \tag{12}$$

Hence by considering eqn. (12 the mechanical system model is modified as below:

$$\dot{\omega}_3 = \frac{\left[\begin{array}{l}(D_{23}\omega_2 - (D_{23} + D_{33} + D_{34})\omega_3 + D_{34}\omega_4 - \\ K_{23}(\delta_3 - \delta_2) - K_{34}(\delta_4 - \delta_3)) + T_{m3} + T_{im1}\end{array}\right]}{M_3}$$

$$\Delta T_{im1} = \frac{3\left[\left(1+\left(\frac{s.x_2'}{r_2'}\right)^2\right)\Delta s - 2s\left(\frac{s.x_2'}{r_2'}\right)\right]}{\left[(\omega_0 r_2').\left(1+\left(\frac{s.x_2'}{r_2'}\right)^2\right)^2\right]}$$

$$\text{As deviation in slip, } \Delta s = \frac{-\Delta\omega_1}{\omega_0} \tag{13}$$

At normal operating point s = 0,

$$\text{Hence, } T_{im1} = \frac{3\Delta s}{\omega_0 r_2'} = \frac{-3\Delta\omega_3}{\omega_0^2 r_2'}$$

$$\Delta\dot{\omega}_3 = \frac{\left[\begin{array}{l}\left(D_{23}\Delta\omega_2 - (D_{23} + D_{33} + D_{34} + \frac{3}{\omega_0^2 r_2'}\right)\Delta\omega_3 \\ + D_{34}\Delta\omega_4 - K_{23}(\delta_3 - \delta_2) - K_{34}(\delta_4 - \delta_3))\end{array}\right]}{M_3}$$

The damping coefficient term - ($D_{23} + D_{33} + D_{34}$) of intermediate pressure turbine is thus modified to -($D_{23} + D_{33} + D_{34} + 3/\omega_0^2 r_2'$) on application of IMDU, similarly other mechanical equations can be modified to account the damping effect of IMDU for its different locations on the TG shaft. 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:

$\dot{X}_T = [A]X$, where,

$X_T = [X_R \quad X_M \quad X_E \quad X_N \quad X_S \quad X_C]^t$ (14)

The dimension of the system matrix is 35.

V. 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 A. The SVS rating for the line has been chosen to be 100 MVAR inductive to 300 MVAR capacitive. 40% Series compensation is used at the sending end of the transmission line. The eigen values have been computed for the system with and without C.A.P.F. auxiliary controller in-corporated in SVS control system and IMDU for wide range of power transfer. Table1 presents the eigen values for the system at generator power P_G=200,500 and 800 MW without any auxiliary controller. When no auxiliary controller is incorporated, five unstable modes 5, 4, 3, 1 and 0 are investigated in the system at P_G= 800 MW. At P_G= 500 and 200 MW, three torsional modes 5, 4 and 3 are unstable Table 2 shows the eigen values for P_G=800 MW for different locations of IMDU on T-G shaft. When IMDU is located after IP turbine, only two modes 4 and 0 are unstable. Hence it is found that the most effective location of IMDU is when it is located after IP turbine. Table 3 shows the system eigen values at P_G= 200, 500 and 800 MW using combination of C.A.P.F. and IMDU. This combination stabilizes the entire torsional mode at wide operating range of power transfer.

CONCLUSION

In this paper the effectiveness of CAPF auxiliary controller in combination with IMDU has been evaluated for damping torsional modes for a series compensated power system. Also the most effective location of IMDU has been determined. The following conclusions can be drawn from the eigen values study performed:

(i) The location of IMDU after IP turbine is most effective for damping torsional modes.

(ii) CAPF auxiliary controller in combination with I.M.D.U. is able to stabilize all the system torsional modes, for high intermediate and low power level.

(iii) Damping of torsional mode 0 is excellent. Damping of mode 1 decrease with increase in power by using C.A.P.F. along with I.M.D.U.

(iv) Damping of mode 0 which interacts with the whole system is excellent.

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APPENDIX A

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, $V_{R\,min}$=-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_1= 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
$R_2 = 3.6\text{x } 10^{-4}$, p.u., X_2 = 0.32646 p.u

Table.1 System Eigen Values Without Auxiliary Controller

MODE	P_G = 200 MW	P_G = 500 MW	P_G = 800 MW
Mode 5	**.0000±j298.1006**	**.0000±j298.1006**	**.0000±j298.1006**
Mode 4	**.0593±j202.7368**	**.0681±j202.7265**	**.1118±j202.7264**
Mode 3	**.0111±j160.5519**	**.0050±j160.5464**	**-.0089±j160.5241**
Mode 2	-.0008±j126.9794	-.0017±j126.9764	-.0032±j126.9691
Mode 1	-.0167±j98.8784	-.0090±j98.8381	**.0100±j98.7327**
Mode 0	-.3969±j4.7451	-.1985±j5.0264	**.0153±j4.9871**

Table. 2 System Eigen Values with IMDU at Different Locations on T-G Shaft (PG=800mw)

Mode	**Before HP turbine**	**After HP turbine**	**After IP turbine**	**After LPA turbine**	**After LPB turbine**
MODE 5	-.0108 ±j298.1006	-.0291 ±j298.1009	-.0021 ±j298.1007	.0000 ±j298.1009	.0000 ±j298.1008
MODE 4	.1096 ±j202.7258	.1119 ±j202.7260	.1060 ±j202.7257	.0874 ±j202.7261	.1024 ±j202.7267
MODE 3	-.0295 ±j160.5243	-.0130 ±j160.5242	-.0190 ±j160.5241	-.0107 ±j160.5242	-.0142 ±j160.5240
MODE 2	-.0045 ±j126.9690	-.0040 ±j126.9690	-.0034 ±j126.9692	-.0048 ±j126.9691	-.0046 ±j126.9690
MODE 1	.0037 ±j98.7329	.0041 ±j98.7329	-.0011 ±j98.7328	.0089 ±j98.7327	-.0036 ±j98.7328
MODE 0	.0140 ±j4.9872	.0129 ±j4.9872	.0026 ±j4.9873	.0022 ±j4.9873	.0026 ±j4.9874

Table3. System Eigen Values with Combined Active Power & Frequency Auxiliary Controller with IMDU

MODE	**PG=200MW** K_{B1}=-0.00018,T_1=0.011,T_2=0.01 K_{B2}=- 0.002, T_3=0.18 T_4=0.02	**PG=500MW** K_{B1}=-0.001, T_1=0.025, T_2=0.01 K_{B2}=- 0.002, T_3=0.18, T_4=0.02	**PG=800MW** K_{B1}=-.001, T_1=0.003, T_2=0.3 K_{B2}=-0 .001, T_3=0.1, T_4=0.3
MODE 5	-.0005±j298.1006	-.0007±j298.1005	-.0008±j298.1006
MODE 4	-.0012±j202.7389	-.1991±j202.6952	-.1381±j202.7251
MODE 3	-.0071±j160.5377	-.0028±j160.5378	-.0258±j160.5248
MODE 2	-.0098±j126.9775	-.0139±j126.9767	-.0185±j126.9690
MODE 1	-.0182±j98.8629	-.0063±j98.8442	-.0002±j98.7302
MODE 0	-.5163±j4.7826	-.3370±j5.0221	-.3721±j3.3605