A novel method of coordinating PSSs and FACTS Devices in Power System Stability Enhancement

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Abstract— this paper shows the effect of power system Stabilizers (PSS) and Flexible AC Transmission Systems (FACTS devices) based stabilizers containing Thyristor controlled Series Compensator (TCSC), Static var compensators (SVC), Thyristor Controlled and phase shifter (TCPS) on stability of power systems. Moreover this paper presents a novel approach for designing coordinated controllers of PSS and FACTS such as coordination of PSS with SVC, PSS with TCSC and PSS with TCPS for enhancing small disturbance stability. The coordinated control problem is formulated as a constrained optimization with eigenvalue-based objective function .The proposed approach employs genetic algorithm (GA) for optimization. To study the effectiveness of the proposed controllers, three different loading conditions including light, normal and heavy loading conditions are considered. Moreover in order to determine effect of proposed design, three case studies are considered too. These include: 1-without compensation (base case), 2-single compensation and 3-coordinated compensation.

Simulation results show that the controller design approach is able to provide better damping and stability performance.

Index Terms- Power system stabilizer, PSS, FACTS devices, SVC, TCSC, TCPS, Optimization, coordinated design, small disturbance stability.

I.INTRODUCTION

The line impedance, the receiving and sending ends voltages, and phase angle between these voltages determine the rate of electrical power transmission over an electric line. Hence, controlling, one or few of the transmitted power factors; it is possible to control the active as well as the reactive power flow over a line.

Series and shunt capacitor, and phase shifter are different approaches to increase the power transmission capacity of lines. Even traditionally used but all these were relatively slow but very useful in a steady state operation of power systems. From a dynamical point of view, their time response is too slow to effectively damp transient oscillations. If mechanically controlled systems were made to respond faster, power system security would be significantly improved, allowing the full utilization of system capability while maintaining adequate levels of stability. This concept and advances in the field of power electronics led to a new approach introduced by the Electric Power Research Institute (EPRI) in the late 1980. Called Flexible AC Transmission Systems or simply FACTS, it was an answer to a call for a more efficient use of already existing resources of power systems while maintaining and even improving power system stability.

Damping of electromechanical oscillations among interconnected synchronous generators is necessary for secure system operation. Power system stabilizer (PSS) has been used for many years to damp out the oscillations [1]. With this way of increasing transmission line loading over

long distances, then use of PSS in some cases may not provide sufficient damping for inter-area oscillations. In such cases, in addition to PSS, other effective alternatives are needed.

In particular, FACTS device stabilizers have been proposed to augment the main control systems for the purpose of damping the rotor modes or inter-area modes of oscillation.

However, to achieve an optimal small-disturbance performance and transient state stability improvement, the co-ordination between PSSs and FACTS devices controllers is necessary.

A procedure was previously reported for simultaneous co-ordination of PSSs and FACTS devices to enhance the damping of the rotor modes [2], [4]. The procedure [2] determines only the stabilizer gains based on the approximation that ‘the shift in the rotor mode eigenvalue is linearly related to the increments in stabilizer gains’. In that paper [2], a systematic and optimal control coordinate design procedure between PSSs and FACTS devices such as static VAR compensator (SVC) is developed. The controllers design problem is transformed into a constrained optimization problem (i.e. search for optimal settings of controller parameters). The design is based on the minimization of the real parts of eigenvalues, including those of the rotor modes, and eigenvalues of the state matrix of the power system to enhance its small disturbance stability. The alternative design is based on the minimization of stabilizer gains with constraints imposed on selected eigenvalues.

But in this paper for increment of damping of electromechanical mode and to improve small disturbance stability, a lead-lag controller is also used. This controller is shown in figs.1-4. In these controllers, in addition to stabilizer gains, time constants including T_1, T_2, T_3 and T_4 optimized using genetic algorithm. To study the effectiveness of the proposed controllers, three different loading conditions including light, normal and heavy loading conditions are considered.

In order to determine the effectiveness of proposed design three case studies are considered: 1-without compensation (base case), 2-single compensation and 3-coordinated compensation.

Simulation results show that the controller design approach is able to provide better damping and stability performance.

II.MODEL OF POWER SYSTEM ELEMENTS

A. Generator model

The generator is represented by the 3rd order model consisting of the swing equation and the generator internal voltage equation. The swing equation can be written as [5]:

$$\dot{\delta} = \omega_b(\omega - 1) \tag{1}$$

$$\dot{\omega} = (P_m - P_e - D(\omega - 1))/M \tag{2}$$

The internal voltage, *Eq'*, is given by

$$\dot{E}_q = (E_{fd} - (x_d - x'_d)i_d - E_q)/T_{do} \tag{3}$$

B. Excitation system model

$$\dot{E}_{fd} = (K_A(V_{ref} - v + u_{pss}) - E_{fd})/T_A \tag{4}$$

$$v = (v_d^2 + v_q^2)^{1/2} \tag{5}$$

$$v_d = x_q i_q \tag{6}$$

$$v_q = E_q - x'_d i_d v_q = E_q - x'_d i_d \tag{7}$$

Where V_{ref} is the reference voltage, v is the terminal voltage, and *id, iq* are d- and q-axis armature current *and vd, vq* are d- and q-axis terminal voltage *xd' is* d-axis transient reactance and *xq is* Generator q-axis reactance.

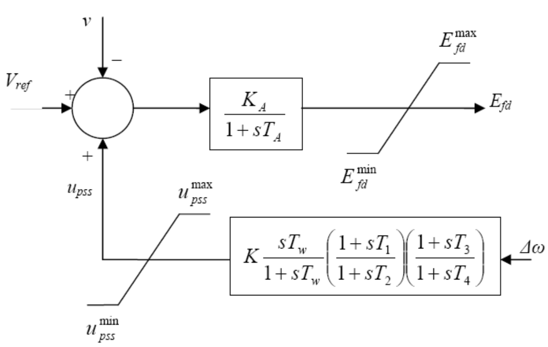

Fig.1:typeST1 excitation system with PSS. [6]

C. Damping Controller Model of PSS

A conventional lead-lag PSS is installed in the feedback loop to generate a supplementary stabilizing signal u_{pss}, see Fig. 1. The PSS input is the change in the machine speed.

D. Damping Controller Model of TCS

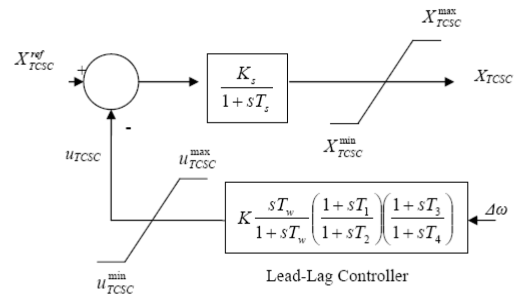

Fig. 2: TCSC with lead-lag controller.[6]

The complete TCSC controller structure is shown in Fig. 2. The output signal of the TCSC is the desired capacitive/inductive compensation signal, noted as XTCSC. The structure shown in Fig. 2is expressed as:

$$\dot{X}_{TCSC} = (k_s(X_{TCSC}^{ref} - U_{TCSC}) - X_{TSCS})/T_s \tag{8}$$

E. Damping Controller Model of SVC

The SVC damping controller structure is shown in Fig. 3. The susceptance of the SVC, *BSVC*, could be expressed as:

$$\dot{B}_{SVC} = (K_S(B_{SVC}^{ref} - U_{SVC}) - B_{SVC})/T_S \tag{9}$$

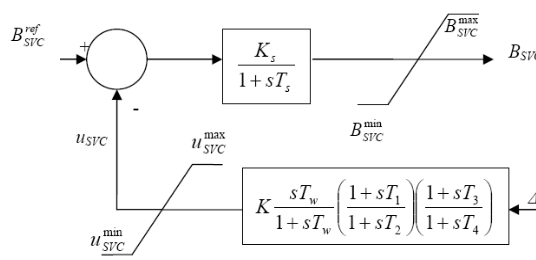

Fig. 3: SVC with lead-lag controller. [6]

F. Damping Controller Model of TCPS

Similarly, Fig. 4 shows a TCPS equipped with a lead-lag stabilizer. The TCPS phase angle is expressed as:

$$\dot{\Phi}_{TCPS} = (K_s(\Phi_{TCPS}^{ref} - U_{TCPS}) - \Phi_{TCPS})/T_s \tag{10}$$

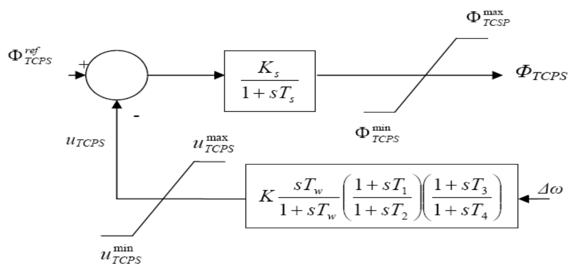

Fig. 4: TCPS with lead-lag controller. [6]

III.SINGLE MACHINE INFINITE BUS (SMIB) POWER SYSTEM

A. Phillips-Heffron model of SMIB system installed with PSS and FACTS Devices

Usually, the linearized incremental model around a nominal operating point is employed in design of electromechanical mode damping controllers. The SMIB system is shown in Fig. 5. (Detailed system data is shown in Appendix.)

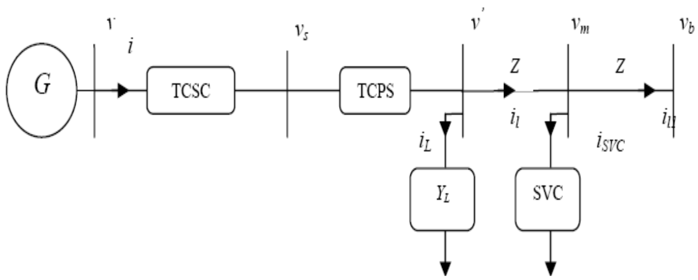

Fig. 5: SMIB with FACTS Devices and PSS

Referring to Fig. 5, the *d* and *q* components of the machine current *i* and terminal voltage *v* can be written as:

$$i = i_d + ji_q \tag{12}$$

$$v = v_d + jv_q \tag{13}$$

The voltage *vs* can be written as:

$$v_s = v - jX_{TCSC}\, i$$

where *i* is the generator armature current.
The *d* and *q* components of *vs* can be written as:

$$v_{sd} = x_{qs} i_q \tag{14}$$

$$v_{sq} = E_q - x'_{ds} i_d \tag{15}$$

Where

$$x_{qs} = x_q + X_{TCSC} \tag{16}$$

$$x'_{ds} = x'_d + X_{TCSC} \tag{17}$$

The voltage v' can be written as:

$$v' = \frac{V_s}{\bar{K}} = \frac{V_s}{K \prec \Phi_{TCPS}} \tag{18}$$

The *d* and *q* components of v' can be written as

$$v'_d = \frac{1}{V}\left[V_{sd}\, COS\ \Phi + V_{sq} \sin \Phi\right] \tag{19}$$

$$v'_q = \frac{1}{K}\left[V_{sq} \cos \Phi - V_{sd} \sin \Phi\right] \tag{20}$$

The load current

$$i_L = v' Y_L, \tag{21}$$

Where the load admittance Y_L is given as:

$$Y_L = g + jb \tag{22}$$

The *d* and *q* components of i_L can be written as:

$$i_{Ld} = gv'_d - bv'_q \tag{23}$$

$$i_{Lq} = gv'_q + bv'_d \tag{24}$$

Then, the line current is:

$$i_l = i - i_L \tag{25}$$

The *d* and *q* components of i_l can be written as:

$$i_{ld} = i_d - i_{Ld} \tag{26}$$

$$i_{1q} = i_q - i_{Lq} \tag{27}$$

The midpoint voltage is

$$v_m = v' - i_1 Z \tag{28}$$

Hence, the d and q components of v_m can be written as:

$$v_{md} = c_1 v'_d - c_2 v'_q - Ri_d + Xi_q \tag{29}$$

$$v_{mq} = c_2 v'_d + c_1 v'_q - Xi_d - Ri_q \tag{30}$$

Where

$$c_1 = 1 + Rg - Xb \tag{31}$$

$$c_2 = Rb + Xg \tag{32}$$

The SVC current can be given as

$$i_{SVC} = v_m Y_{svc} \tag{33}$$

Then the line current in this section i_{l1} is given as

$$i_{l1} = i_1 - i_{SVC} \tag{34}$$

The voltage of infinite bus is

$$v_b = v_m - i_{l1} Z \tag{35}$$

And the components of v_b can be written as:

$$v_{bd} = v_b \sin\delta = v_{md} - Ri_{d1} + Xi_{q1} \tag{36}$$

$$v_{bd} = v_b \cos\delta = v_{mq} - Xi_{d1} - Ri_{q1} \tag{37}$$

Substituting (14)-(35) into (36) and (37), the following two equations can be obtained

$$c_3 i_d + c_4 i_q = v_b \sin\delta + c_7 E_q \tag{38}$$

$$c_5 i_d + c_6 i_q = v_b \cos\delta + c_8 E_q \tag{39}$$

Solving (38) and (39) simultaneously, *id* and *iq* expressions can be obtained.

Linearizing (38) and (39) at the nominal loading condition, Δi_d and Δi_q can be expressed in terms of $\Delta\Phi_{TcPs}$, $\Delta X_{T\,\mathrm{csc}}$, ΔB_{svc}, ΔEq and $\Delta\delta$ as following:

$$c_3 \Delta i_d + c_4 \Delta i_q = v_b \cos\delta\Delta\delta + c_7 \Delta E_q + c_9 \Delta B_{svc} + c_{11} \Delta X_{TCSC} + c_{13} \Delta\Phi_{TCPS} \tag{40}$$

$$c_5 \Delta i_d + c_6 \Delta i_q = -v_b \sin\delta\Delta\delta - c_8 \Delta E_q + c_{10} \Delta B_{SVC} + c_{12} \Delta X_{TCSC} + c_{14} \Delta\Phi_{TCPS} \tag{41}$$

Solving (40) and (41) simultaneously, Δid and $\Delta\, iq$ can be expressed as:

$$\Delta i_d = c_{15}\Delta\delta + c_{17}\Delta E_q + c_{19}\Delta B_{SVC} + c_{21}\Delta X_{TCSC} + c_{23}\Delta\Phi_{TCPS} \tag{42}$$

$$\Delta i_q = c_{16}\Delta\delta + c_{18}\Delta E_q + c_{20}\Delta B_{SVC} + c_{22}\Delta X_{TCSC} + c_{24}\Delta\Phi_{TCPS} \tag{43}$$

The constants $c1$-$c24$ are expressions of:

$$Z, Y_L, x'_d, x_q, i_{q0}, i_{d0}, E_{q0}, B_{svc}, X_{TCSCO}, \Phi_{TCPSO}$$

The linearized form of vd and vq can be written as:

$$\Delta v_d = x_q \Delta i_q \tag{44}$$

$$\Delta v_q = \Delta E_q - x'_d \Delta i_d \tag{45}$$

Using Equations (42) and (43), the following expressions can be easily obtained

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E_q + K_{PB}\Delta B_{SVC} + K_{px}\Delta X_{TCSC} + K_{p\Phi}\Delta\Phi_{TCPS} \tag{46}$$

$$(K_3 + sT_{do})\Delta E_q = \Delta E_{fd} - K_4\Delta\delta - K_{qB}\Delta B_{SVC} - K_{qX}\Delta X_{TCSC} - K_{q\Phi}\Delta\Phi_{TCPS} \tag{47}$$

$$\Delta v = K_5\Delta\delta + K_6\Delta E_q + K_{vB}\Delta B_{SVC} + K_{vx}\Delta X_{TCSC} + K_{v\Phi}\Delta\Phi_{TCPS} \tag{48}$$

where the constants K_1-K_6, K_{pB}, K_{pX}, $K_{p\Phi}$, K_{qB}, K_{qX}, $K_{q\Phi}$, K_{vB}, K_{vX}, and $K_{v\Phi}$ are expressions of c_1-c_{24}.

The above linearizing procedure yields the following linearized power system model:

$$\begin{bmatrix} \dot{\Delta\delta} \\ \dot{\Delta\omega} \\ \dot{\Delta E}_q \\ \dot{\Delta E}_{fd} \end{bmatrix} = \begin{bmatrix} 0 & 377 & 0 & 0 \\ \frac{k_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 \\ -\frac{K_4}{T_{do}} & 0 & -\frac{K_3}{T_{do}} & \frac{1}{T_{do}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \end{bmatrix}$$

$$+ \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & -\frac{K_{PB}}{M} & -\frac{K_{PX}}{M} & -\frac{K_{P\Phi}}{M} \\ 0 & -\frac{K_{qB}}{T_{do}} & -\frac{K_{qX}}{T_{do}} & -\frac{K_{q\Phi}}{T_{do}} \\ \frac{K_A}{T_A} & -\frac{K_A K_{vB}}{T_A} & -\frac{K_A K_{vX}}{T_A} & -\frac{K_A K_{v\Phi}}{T_A} \end{bmatrix} \begin{bmatrix} u_{pss} \\ \Delta B_{SVC} \\ \Delta X_{TCSC} \\ \Delta\Phi_{TCPS} \end{bmatrix} \quad (49)$$

IV. Objective Function

The state-space equation of a power system installed with PSSs and FACTS devices, linearized about a selected operating point, can be compactly written as following:

$$P\Delta x = A\Delta x + B\Delta u \quad (50)$$

Where x is state vector; u is the vector of input reference signals; and A is the state matrix which is the function of controller parameters.

The dynamic characteristics of the system are influenced by the locations of eigenvalues of matrix A. Hence, in order to have a good dynamic characteristic (i.e. good damping), it is necessary to shift eigenvalues associated with poorly-damped modes to positions in the complex plane with good damping characteristics. This is called as tuning.

The objective of the tuning problem is to find a set of appropriate controller parameters to improve the system damping. However, the objective function used to be maximized with respect to controller parameters in the single and coordinated control design is:

$$f(K, \lambda_1, \lambda_2, \ldots, \lambda_m, , z_1, z_2 ,, \ldots, ,z_m) = \sum (\mathrm{Re}\ l(\lambda i))^2 \quad (51)$$

where:

K= controller parameters to be optimized
λ_i = the ith eigenvalue to be placed
z_i = the eigenvector associated with the ith eigenvalue;
m = number of selected eigenvalues

The related eigenvalues and eigenvectors are nonlinear functions of parameter vector K. The maximization of the objective function is subject to equality constraints formed from the eigenvalue-eigenvector equations and inequality constraints which represent the bounds required on the selected eigenvalues and controller parameters.

V. Optimization Problem Formulation

In this study, the proposed objective function is optimized individually. The problem constraints are the stabilizer optimized parameter bounds. Therefore, the design problem can be formulated as the following optimization problem.

Maximize f
Subject to
$K_i \min \le K_i \le K_i \max$
$T_{1i} \min \le T_{1i} \le T_{1i} \max$
$T_{2i} \min \le T_{2i} \le T_{2i} \max$
$T_{3i} \min \le T_{3i} \le T_{3i} \max$
$T_{4i} \min \le T_{4i} \le T_{4i} \max$

Genetic algorithm (GA) is employed to solve this optimization problem. Searching is done for optimal set of the stabilizer parameters, i.e. Ki, T_{1i}, T_{2i}, T_{3i}, T_{4i} where i is the Number of stabilizers considered.

VI. Stabilizer Tuning and Simulation Results

To study the effectiveness of the proposed controllers, three different loading conditions are considered for eigenvalue analysis. These conditions are as following:

1. Light loading (Pe, Qe) = (0.25, 0.02) p.u.
2. Normal loading (Pe, Qe) = (1.0, 0.02) pu.
3. Heavy loading (Pe, Qe) = (1.5, 0.45) pu.

VII .Case studies

Case 1: without compensation (base case)

In this case, the power system is not equipped with any compensator. Eigenvalues and damping factors of electromechanical mode, in different loading conditions, are as following:

Table1. Eigenvalues of light, normal and heavy loading conditions, Base case (without installation of PSS&FACTS Devices)

Light	Normal	Heavy
-.009±j4.85	.1754±j4.9563	.3652±j3.98

Table2. Damping of electromechanical mode in light, normal and heavy loading conditions, Base case (without installation of PSS&FACTS Devices)

Light	Normal	Heavy
.0019	-.0357	-.0671

Simulated results in this case are shown in figs. 6-8. These figures shown Step response of deviation of generator speed in normal, light and heavy loading conditions, without compensation,

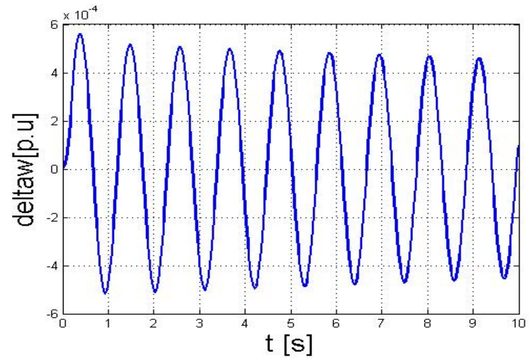

Fig 6: Step response of deviation of generator speed in light loading condition, without compensation

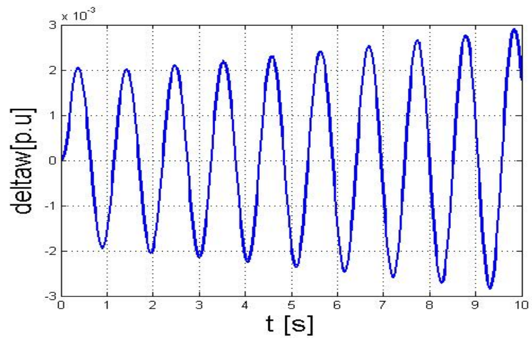

Fig 7: Step response of deviation of generator speed in heavy loading condition, without compensation

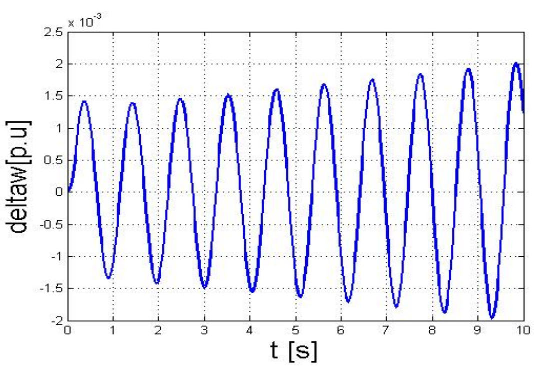

Fig 8: Step response of deviation of generator speed in normal loading condition, without compensation

Case 2: Single compensation Design Approach

In this case the power system is equipped by PSS or FACTS devices alone. The state matrix of power system equipped by PSS and FACTS devices are following:

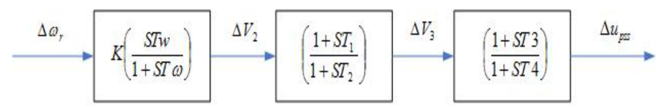

Fig 9: PSS Lead-Lag controller

$$\begin{bmatrix}\dot{\Delta\delta}\\ \dot{\Delta\omega}\\ \dot{\Delta Eq}\\ \dot{\Delta Efd}\\ \dot{\Delta v2}\\ \dot{\Delta v3}\\ \dot{\Delta upss}\end{bmatrix}=\begin{bmatrix}0 & 377 & 0 & 0 & 0 & 0 & 0\\ \frac{-K1}{M} & \frac{-D}{M} & \frac{-K2}{M} & 0 & 0 & 0 & 0\\ \frac{-K4}{Td0} & 0 & \frac{-K3}{Td0} & \frac{-1}{Td0} & 0 & 0 & 0\\ \frac{-KAK5}{TA} & 0 & \frac{-KAK6}{TA} & \frac{-1}{TA} & 0 & 0 & \frac{KA}{TA}\\ \frac{-K1}{M}K & \frac{-D}{2}K & \frac{-K2}{M}K & 0 & \frac{-1}{T\omega} & 0 & 0\\ \frac{-K1KT1}{M\ T2} & \frac{-DKT1}{2\ T2} & \frac{-K2KT1}{M\ T2} & 0 & \left(\frac{-T1+T\omega}{T2T\omega}\right) & \frac{-1}{T2} & 0\\ \frac{-T1T3\ \ K1K}{T2T4M} & \frac{-DKT1T3}{2\ T2T4} & \frac{-K2KT1T3}{MT2T4} & 0 & \frac{(T\omega-T1)T3}{T2T4\ T\omega} & \frac{T2-T3}{T2T4} & \frac{-1}{T4}\end{bmatrix}\times\begin{bmatrix}\Delta\delta\\ \Delta\omega\\ \Delta Eq\\ \Delta Efd\\ \Delta v2\\ \Delta v3\\ \Delta upss\end{bmatrix} \quad (52)$$

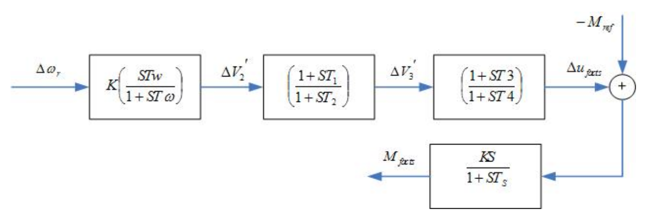

Fig 10: FACTS devices with lead-lag controller

$$\begin{bmatrix}\dot{\Delta\delta}\\ \dot{\Delta\omega}\\ \dot{\Delta Eq}\\ \dot{\Delta Efd}\\ \dot{\Delta v2'}\\ \dot{\Delta v3'}\\ \dot{\Delta ufacts}\\ \Delta Mfacts\end{bmatrix}=\begin{bmatrix}0 & 377 & 0 & 0 & 0 & 0 & 0 & 0\\ \frac{-K1}{M} & \frac{-D}{M} & \frac{-K2}{M} & 0 & 0 & 0 & 0 & 0\\ \frac{-K4}{Td0} & 0 & \frac{-K3}{Td0} & \frac{-1}{Td0} & 0 & 0 & 0 & 0\\ \frac{-KAK5}{TA} & 0 & \frac{-KAK6}{TA} & \frac{-1}{TA} & 0 & 0 & \frac{KA}{TA} & 0\\ \frac{-K1}{M}K & \frac{-D}{2}K & \frac{-K2}{M}K & 0 & \frac{-1}{T\omega} & 0 & 0 & 0\\ \frac{-K1KT1}{M\ T2} & \frac{-DKT1}{2\ T2} & \frac{-K2KT1}{M\ T2} & 0 & \left(\frac{-T1+T\omega}{T2T\omega}\right) & \frac{-1}{T2} & 0 & 0\\ \frac{-T1T3\ \ K1K}{T2T4M} & \frac{-D\,KT1T3}{2\ T2T4} & \frac{-K2KT1T3}{M\,T2T4} & 0 & \frac{(T\omega-T1)T3}{T2T4\ T\omega} & \frac{T2-T3}{T2T4} & \frac{-1}{T4} & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{-KS}{TS} & \frac{-1}{TS}\end{bmatrix}\times\begin{bmatrix}\Delta\delta\\ \Delta\omega\\ \Delta Eq\\ \Delta Efd\\ \Delta v2\\ \Delta v3\\ \Delta ufacts\\ \Delta Mfacts\end{bmatrix} \quad (53)$$

Equations (52) and (53) show the linearized power system model equipped by PSS and FACTS devices respectively. GA has been applied to optimize the settings of the proposed stabilizers. The final settings of the optimized parameters, eigenvalues and damping factors of electromechanical mode for the proposed stabilizers in light loading condition are given in Tables 3-5:

Table3. Optimum parameters of Stabilizer in light loading condition, single design (with installation of PSS or FACTS Devices)

Optimum parameter	PSS	TCSC	TCPS	SVC
T1	.1178	.0476	.0576	1
T2	.1000	.1000	.1000	.3100
T3	.1645	.0398	.0317	.0120
T4	.1000	.1000	.1000	.3000
K	19.2467	95.7300	90.870	89.94

Table4. System eigenvalues in light loading condition, Single design (with installation of PSS or FACTS Devices)

PSS	TCSC	TCPS	SVC
-.87±j5.06	-.82±j5.1	-4.5±j6.6	-.68±j4.7
-6.98±j5.5	-9.9±j3.8	-9.3±j3.4	-7.04±j2.08
-16.77	-19.53	-17.37	-19.9
-7.7	-10.72	-10.76	-9.93
-.2	-8.43	-4.33	-2.55
	-.203	-.212	-.199

Table5. Damping of system electromechanical mode in light loading condition, single design (with installation of PSS or FACTS Devices)

PSS	TCSC	TCPS	SVC
.2548	.2631	.5802	.1516

Simulated results in this case are shown in figs. 11-12. These figures show effect of PSSs and FACTS devices on Step response of deviation of generator speed and step response of generator power angle in light loading condition.

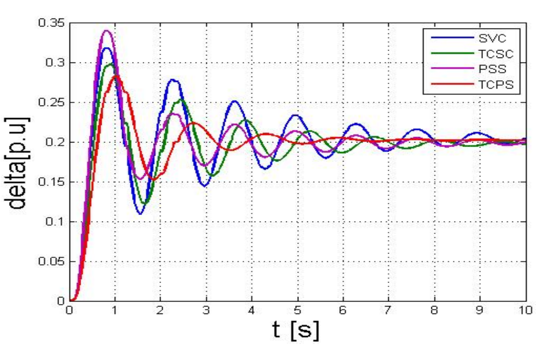

Fig11:step response generator power angle in light loading condition, single design

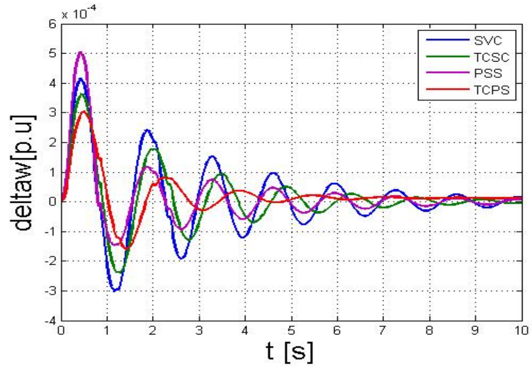

Fig12: step response deviation of generator speed in light loading condition, single design

The final settings of the optimized parameters, eigenvalues and damping factors of electromechanical mode for the proposed stabilizers in normal loading condition are given in Tables 6-8:

Table6. Optimal parameters of Stabilizer in normal loading condition, single design

Optimal Parameter	PSS	TCSC	TCPS	SVC
T1	.1478	.0751	.0790	1
T2	.1000	.1000	.1000	.3000
T3	.1741	.0765	.0754	.0110
T4	.1000	.1000	.1000	.3000
K	21.2467	98.000	100.000	93.9870

Table7. System eigenvalues in normal loading condition, Single design (with installation of PSS or FACTS Devices)

PSS	TCSC	TCPS	SVC
-3.24±j5.6	-3.5±j4.1	-3.1±j3.5	-2.26±j4.6
-3.39±j5.9	-5.7±j6.7	-7.1±j7.9	-2.49±j5.07
-19.497	-11.4±j1.2	-11.04±j.83	-20.45
-7.414	-18.67	-10.76	-14.26
-.2055	-.2	-17.8	-2.63
		-.2099	-.2

Table8. Damping of electromechanical mode in normal loading condition (with installation of PSS or FACTS Devices)

PSS	TCSC	TCPS	SVC
.4716	.6384	.651	.3143

Simulated results in this case are shown in figs. 13-14. These figures show effect of PSSs and FACTS devices on Step response of deviation of generator speed and step response of generator power angle in normal loading condition.

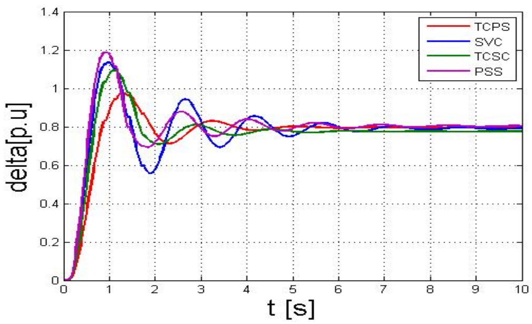

Fig13:step response of generator power angle in normal loading condition, single design.

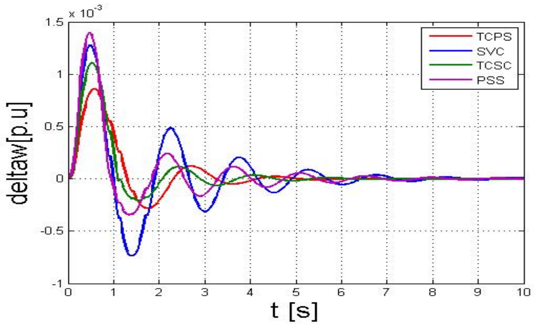

Fig 14: step response of deviation of generator speed in normal loading condition, single design.

The final settings of the optimized parameters, eigenvalues and damping factors of electromechanical mode for the proposed stabilizers in heavy loading condition are given in Tables 9-11:

Table9. Optimal parameters of Stabilizer in heavy loading condition, single design

Optimum .parameter	PSS	TCSC	TCPS	SVC
T1	.1918	.018	.1388	.01
T2	.1000	.1000	.1000	.3100
T3	.2016	.2741	.0489	.01
T4	.1000	.1000	.1000	.3000
K	26.23	100	99.987	100

Table10. System eigenvalues in heavy loading condition, Single design (with installation of PSS or FACTS Devices)

PSS	TCSC	TCPS	SVC
-1.4±j3.58 -5.11±j7.1 -19.62 -7.23 -.2094	-5.8±j7.58 -10.3±j.76 -18.05 -7.463 -2.342 -.2275	-7.651±j8.5 -2.92±j1.17 -10.8±j.862 -17.198 -.221	-2.81±j5.25 -1.48±j2.67 -20.9455 -13.1445 -4.1267 -.2037

Table11. Damping of system electromechanical mode in heavy loading condition (with installation of PSS or FACTS Devices)

PSS	TCSC	TCPS	SVC
.4105	.6014	.8712	.4948

Simulated results in this case are shown in figs. 15-16. These figures show effect of PSSs and FACTS devices on Step response of deviation of generator speed and step response of generator power angle in heavy loading condition.

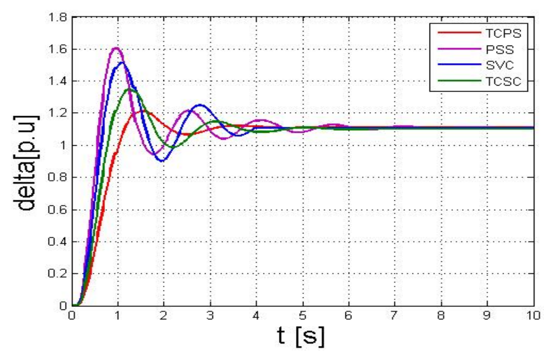

Fig 15: step response of generator power angle in heavy loading condition, single design.

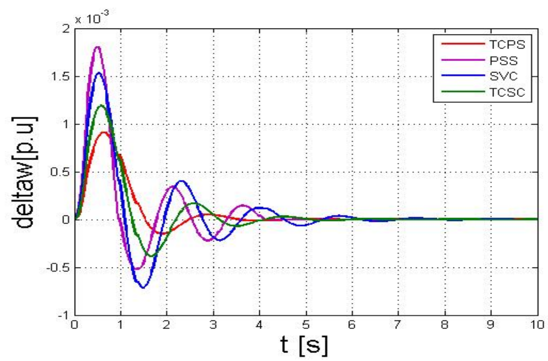

Fig 16: step response of deviation of generator speed in heavy loading condition, single design

CASE 3: Coordinated Compensation

In this case FACTS devices and PSS are coordinated and state matrix of power system is following:

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E}q \\ \Delta\dot{E}fd \\ \Delta\dot{v}2 \\ \Delta\dot{v}3 \\ \Delta\dot{u}pss \\ \Delta\dot{v}2' \\ \Delta\dot{v}3' \\ \Delta\dot{u}facts \\ \Delta Mfacts \end{bmatrix} = \begin{bmatrix} 0 & 377 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-K1}{M} & \frac{-D}{M} & \frac{-K2}{M} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-K4}{Td0} & 0 & \frac{-K3}{Td0} & \frac{-1}{Td0} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-KAK5}{TA} & 0 & \frac{-KAK6}{TA} & \frac{-1}{TA} & 0 & 0 & \frac{KA}{TA} & 0 & 0 & 0 & 0 \\ \frac{-K1}{M}K & \frac{-D}{2}K & \frac{-K2}{M}K & 0 & \frac{-1}{T\omega} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-K1KT1}{M\,T2} & \frac{-DKT1}{2\,T2} & \frac{-K2KT1}{M\,T2} & 0 & \left(\frac{-T1+T\omega}{T2T\omega}\right) & \frac{-1}{T2} & 0 & 0 & 0 & 0 & 0 \\ \frac{-T1T3\ K1K}{T2T4M} & \frac{-DKT1T3}{2\,T2T4} & \frac{-K2KT1T3}{MT2T4} & 0 & \frac{(T\omega-T1)T3}{T2T4\,T\omega} & \frac{T2-T3}{T2T4} & \frac{-1}{T4} & 0 & 0 & 0 & 0 \\ \frac{-K1}{M}K & \frac{-D}{2}K & \frac{-K2}{M}K & 0 & \frac{-1}{T\omega} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-K1KT1}{M\,T2} & \frac{-DKT1}{2\,T2} & \frac{-K2KT1}{M\,T2} & 0 & \left(\frac{-T1+T\omega}{T2T\omega}\right) & \frac{-1}{T2} & 0 & 0 & 0 & 0 & 0 \\ \frac{-T1T3K1K}{T2T4M} & \frac{-DKT1T3}{2\,T2T4} & \frac{-K2KT1T3}{MT2T4} & 0 & \frac{(T\omega-T1)T3}{T2T4\,T\omega} & \frac{T2-T3}{T2T4} & \frac{-1}{T4} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-KS}{TS} & \frac{-1}{TS} \end{bmatrix} \times \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta Eq \\ \Delta Efd \\ \Delta v2 \\ \Delta v3 \\ \Delta upss \\ \Delta v2' \\ \Delta v3' \\ \Delta ufacts \\ \Delta Mfacts \end{bmatrix} \quad (54)$$

A. Coordinated Design [PSS & SVC]

According to tables.7,9 and 11, because that Damping of system electromechanical mode equipped by SVC and PSS at all loading conditions is smaller than another devices .Therefore, In this stage the coordinated design of PSS and SVC-based stabilizer is done at whole of loding conditions.

Both stabilizers PSS & SVC are simultaneously tuned by PSO search for the optimum controllers parameter settings.

System eigenvalues for different loading conditions in this case are following:

Table12. System eigenvalues in light loading condition, coordinated design

single design		coordinated design
PSS	SVC	PSS&SVC
-.87±j5.06 -6.98±j5.5 -16.77 -7.7 -.2	-.48±j4.7 -7.04±j2.08 -19.9 -9.93 -2.55 -.199	-.95±j5.56 -10.1±j3.32 -20.3 -8.11 -2.98 -.205 -.19

Table13. System eigenvalues in normal loading condition, coordinated design

single design		coordinated design
PSS	SVC	PSS&SVC
-3.24±j5.6 -3.39±j5.9 -19.497 -7.414 -.2055	-2.26±j4.6 -2.49±j5.07 -20.45 -14.26 -2.63 -.2	-6.4321±j6.045 -6.0321±j5.668 -13.8±j14.07 -17.26 -2.48 -.213 -.197 -.209

Table14. System eigenvalues in heavy loading condition, Coordinated design

single design		coordinated design
PSS	SVC	PSS&SVC
-1.4±j3.58 -5.11±j7.1 -19.62 -7.23 -.2094	-2.81±j5.25 -1.48±j2.67 -20.9455 -13.1445 -4.1267 -.2037	-7.22±j7.75 -8.67±j3.64 -2.4±j.503 -16.88±j11.54 -.228 -.2 -2.67

Table15. Damping of system electromechanical mode in all of loading conditions, single and coordinated design

	single design		coordinated design
Loading	PSS	SVC	PSS&SVC
Light	.2548	.1516	.2685
Normal	.4716	.3143	.6984
Heavy	.3141	.4948	.6821

Simulated results in this case are shown in figs. 17-18. These figures show effect of coordination of PSSs and SVC on Step response of deviation of generator speed and step response of generator power angle in normal loading condition.

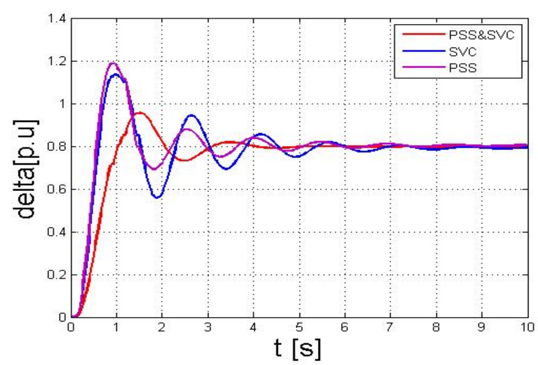

fig 17: step response of generator power angle in normal loading condition, coordinated design

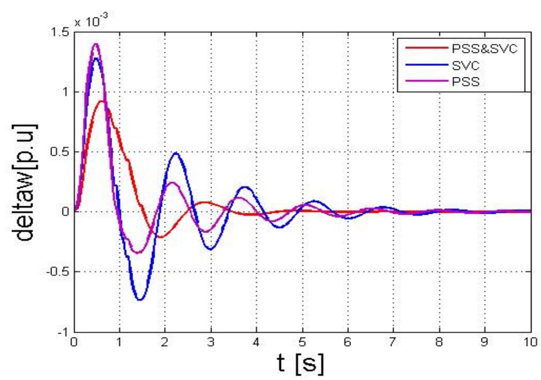

fig 18: step response of deviation of generator speed in normal loading condition, coordinated design.

B. Coordinated Design [PSS & TCSC]

According to tables 1 because that Damping of system electromechanical mode in coordinated design of PSS with SVC-based stabilizer at light loading conditions is smaller than another condition. Therefore, in this stage the coordinated design of PSS and TCSC-based stabilizer is done at this loading condition. Eigenvalues and damping of electromechanical mode are in tables 17 and 18 respectively.

Table16. System eigenvalues in light loading condition, coordinated design

single design		coordinated design
PSS	TCSC	PSS&TCSC
-.87±j5.06 -6.98±j5.5 -16.77 -7.7 -.2	-.82±j5.1 -9.9±j3.8 -19.53 -10.72 -8.43 -.203	-1.53±j5.26 -7.33±j3.54 -16.22±j2.6 -10 -.205 -.2

Table17. Damping of system electromechanical mode in light loading condition, single and coordinated design

single design		coordinated design
PSS	TCSC	PSS&TCSC
.2548	.2631	.4203

Table18. Controller optimal parameters in light loading condition for single and coordinated design.

Controller optimal parameter	*single design*		*coordinated design*	
	PSS	TCSC	PSS	TCSC
T1	.178	.0476	.305	.2053
T2	.09	.1	.11	.1
T3	.645	.0398	.4085	.1624
T4	.1	.108	.1	.1
K	19.546	95.73	30.6035	55.137

Table19. Damping of system electromechanical mode in light loading condition, single and coordinated designs

single design		*coordinated design*
PSS	TCSC	PSS&TCSC
.2548	.2631	.4203

Table20. System eigenvalues in light loading condition,single and coordinated designs.

Single design		*coordinated design*
PSS	TCSC	PSS&TCSC
-.87±j5.06 -6.98±j5.5 -16.77 -7.7 -.2	-.82±j5.1 -9.9±j3.8 -19.53 -10.72 -8.43 -.203	-1.53±j5.26 -7.33±j3.54 -14.22±j2.6 -10±j5.65 -5.86 -.205 -.2

Simulated results in this case are shown in figs. 19-20. These figures show effect of coordination of PSSs and TCSC on Step response of deviation of generator speed and step response of generator power angle in light loading condition.

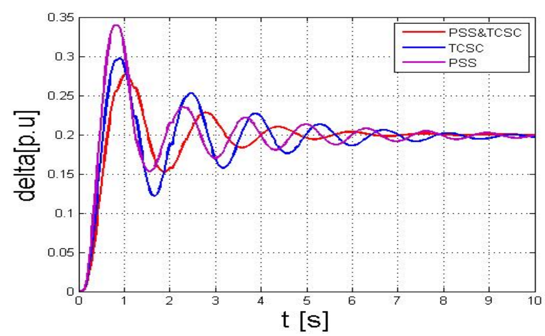

Fig19: step response of generator power angle in light loading condition, coordinated design.

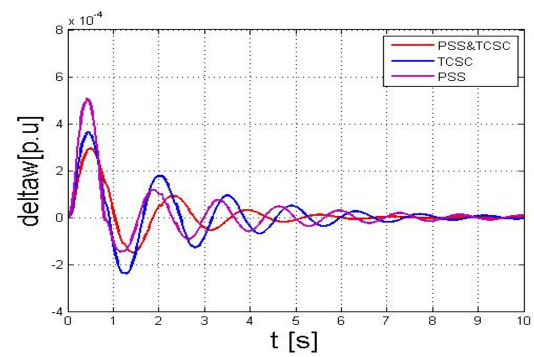

Fig 20: step response of deviation of generator speed in light loading condition, coordinated design.

C. Coordinated Design [PSS & TCPS]

The above results of eigenvalues analysis shows that, the maximum effect on damping of electromechanical mode is related to TCPS, in this stage for increment of damping of electromechanical mode in heavy loading condition, PSS is coordinated with TCPS.

Table21. Controller optimal parameters in heavy loading,single and coordinated design.

Controller optimal parameter	*Single design*		*coordinated design*	
	PSS	TCPS	PSS	TCPS
T1	.1918	.1388	.321	.543
T2	.1	.1	.098	.1201
T3	.2016	.0489	.142	.1629
T4	.1	.1	.1	.0871
K	26.23	99.987	43.165	87.197

Table22. System eigenvalues in heavy loading condition, single and coordinated design.

Single design		*coordinated design*
PSS	TCPS	PSS&TCPS
-1.4±j3.58 -5.11±j7.1 -19.62 -7.23 -.2094	-7.651±j4.7 -2.92±j1.17 -11.8±j.862 -17.198 -.221	-8.243±j4.05 -4.87±j2.14 -10.5±j1.453 -14.432±j12.6 -4.65 -.218 -.187

Table23. Damping of system electromechanical mode in heavy loading condition, single and coordinated design

Single design		*coordinated design*
PSS	TCPS	PSS&TCPS
.4105	.8712	.9603

Simulated results in this case are shown in figs. 21-22. These figures show effect of coordination of PSSs and TCPS on Step response of deviation of generator speed and step response of generator power angle in heavy loading condition.

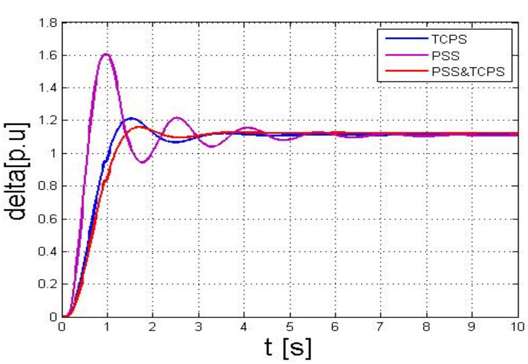

Fig 21: step response of generator power angle in heavy loading condition, coordinated design.

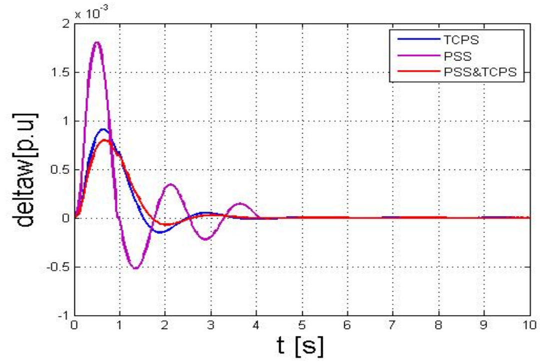

Fig 22: step response of deviation of generator speed in heavy loading condition, coordinated design.

VIII. Eigenvalue and Simulation results Analys*is*

According to above design and simulation results the following observations could be derived:

1) Damping of electromechanical mode by TCPS depends on the loading conditions. (The damping is increased as the load increases)

2) At light loading conditions, the operation of PSS, SVC, and TCSC to control the electromechanical mode are considerably lower compared to that of TCPS.

3) The electromechanical mode controllability of the PSS and SVC is approximately the same in the different range of loading conditions.

4) The electromechanical mode of TCSC and TCPS is more controllable in comparison to that of PSS and SVC.

5) The electromechanical mode controllability by TCPS changes almost linearly with the practical system loading.

6) The electromechanical mode at heavy loading is most controllable by TCPS.

7) With taking in account of all loading conditions, the electromechanical mode is most controllable by coordinated design.

X. Conclusion

An optimization method for single and coordinated designs of PSSs, FACTS devices such as TCSC, SVC and TCPS controllers in a single machine infinite bus (SMIB) power system is developed. The optimization technique has been successfully applied to a test system. The performance of the proposed technique in solving the problem has also been verified through eigenvalue analysis. It is found that system damping can be improved by the PSS, and the FACTS devices. Controllers can further improve the damping when the controllers' parameters are properly tuned coordinately. These results show the importance of the control coordination of PSS and FACTS controllers and the effectiveness of the proposed technique.

In this paper a SMIB power system has been simulation study. It is proposed to apply the proposed method to a large multi-machine system for more investigation.

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