International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

September 2012 | Issue 12 | Volume 4 | Number 3 | Pages 133-140

A COMPARISON OF DESIGN AND OPERATION OF SINGLE AND COORDINATED PSS CONTROLLERS WITH SVC AND STATCOM FOR DAMPING POWER SYSTEM OSCILLATIONS

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Abstract- To damp power system oscillations, the commonly-used method is to arrange multiple decentralized stabilizers, such as Power System Stabilizer (PSS) and Flexible AC Transmission Systems (FACTS) controllers. This paper is mainly concerned with comparison of design and operation of single and coordinated Power System Stabilizer (PSS) controllers with Static VAR Compensator (SVC) and Static Synchronous Compensator (STATCOM) for improvement power system stability using Genetic Algorithm (GA). The eigenvalue analysis and the nonlinear simulation results are used for small signal stability of Single Machine Infinite Bus (SMIB) system installed with PSS and FACTS controllers. It is worth mentioning that the PSS and FACTS-based controllers help in damping power system oscillations after a disturbance so as to improve the power system stability. Finally, this analysis results reveal that coordinated design of PSS and STATCOM-based controllers has significant performance to promote the damping power system oscillations compared with SVC-Based controllers.

Keywords: PSS, SVC, STATCOM, Damping Controller, Genetic Algorithm, Power System Stability.

I. INTRODUCTION

Small signal stability of power systems is an important issue in long increasing power transmission line. Due to continuously growing power demand, Small signal stability is characterized by synchronizing power and damping power. The synchronizing power is defined as the component of real power in phase with the rotor angle deviation, while the damping power is defined as the component of the real power in phase with the rotor speed deviation. However, lack of damping power causes oscillatory instability, while lack of synchronizing power causes a periodic instability. Such lack of synchronizing power and damping power occurs particularly in power systems with long transmission line.

To enhance system damping, the generators are equipped with power system stabilizers (PSSs) that provide supplementary feedback stabilizing signals in the excitation systems. PSSs extend the power system stability limit by enhancing the system damping of low frequency oscillations associated with the electromechanical modes [1-4].

Despite the potential of modern control techniques with different structures, power system utilities still prefer the conventional lead-lag power system stabilizer (CPSS) structure [5-7]. Kundur et al. [7] have presented a comprehensive analysis of the effects of the different CPSS parameters on the overall dynamic performance of the power system. It is shown that the appropriate selection of CPSS parameters results in satisfactory performance during system upsets. The advent of high-power electronic equipment to improve utilization of transmission capacity, as envisaged in the concept of flexible alternating current transmission systems (FACTS) controllers, provides a system planner with additional leverage to improve the stability of a system. FACTS controllers like static VAR compensator (SVC), thyristor controlled series compensator (TCSC), static synchronous compensator (STATCOM), static synchronous series compensator (SSSC), and unified power flow controller (UPFC) can provide variable shunt and/or series compensation [8].

Recently, to improve overall system performance, many researches were made on the coordination between FACTS controllers and PSS on damping power system oscillation [9-14]. Barati et al. [15] presented a coordinated PSS, SVC and TCSC control for a synchronous generator. Nonlinear optimization algorithm was presented to coordinate parameters adjustment for a TCSC, a SVC and a PSS in a power system [16].

In [17], a gain adjustment approach for a TCSC, a SVC and a PSS was introduced and the effect of gain tuning on oscillation modes and on overall power system performance are investigated. The availability of high power gate-turn-off thyristors has led to the development of a STATCOM which is one of the FACTS devices connected in shunt and to improve transmission stability and to dampen power oscillations. The Phillips-Heffron model of the single machine infinite bus(SMIB) power system with FACTS devices is obtained by linearizing non-linear equations around a nominal operating point of the power system [18, 19].

The design problem is transformed into an optimization problem and GA optimization techniques are employed to search for the optimal PSS and FACTS controller's parameters. In this paper the eigenvalue analysis and the nonlinear simulation results are used for small signal stability of single machine infinite bus (SMIB) system installed with PSS and FACTS controllers. This analysis shows that coordinated design of PSS and STATCOM-based controllers has significant performance to promote the damping power system oscillations compared with SVC-Based controllers.

II. SYSTEM MODEL

A. Generator Model

The power system is represented by a single machine infinite-bus (SMIB) with FACTS devices is shown in Figure1. The generator is equipped with a PSS. The generator has a local load of admittance $Y_L = g + jb$. The transmission line has impedances of $Z = R + jX$. The SVC and STATCOM are used at the middle point in transmission line for power oscillations damping. The system is modeled for low frequency oscillations studies and the linearized power System model is used for this purpose. The generator is represented by the 3rd order model consisting of the electromechanical swing equation and the generator internal voltage equation. The dynamics of rotor angle δ and velocity ω is described by the so called swing equations:

$$\begin{aligned}
&\dot{\delta} = \omega_b(\omega - 1)\\
&\dot{\omega} = \left(P_m - P_e - D(\omega - 1)\right)/M\\
&\dot{E}'_q = \left(E_{fd} - (x_d - x'_d)i_d - E'_q\right)/T'_{do}\\
&\dot{E}_{fd} = (K_A(V_{ref} - V + U) - E_{fd})/T_A
\end{aligned} \quad (1)$$

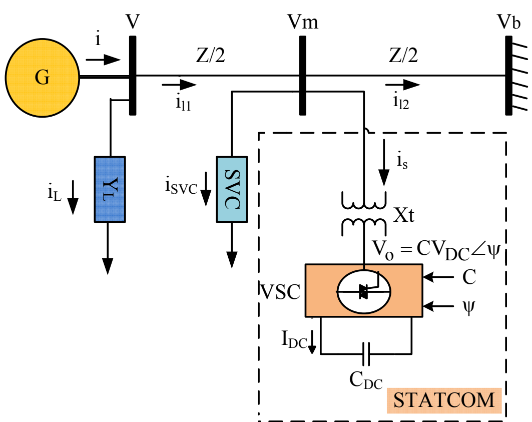

Figure 1. SMIB with PSS and FACTS devices

B. Exciter and PSS

Figure 2 shows the IEEE Type-ST1 excitation system is considered in this work. It can be described as:

$$\dot{E}_{fd} = \left(K_A\left(V_{ref} - V + u_{pss}\right) - E_{fd}\right)/T_A \quad (2)$$

The inputs to the excitation system are the terminal voltage V and reference voltage V_{ref}. The K_A and T_A are represented the gain and time constants of the excitation system, respectively. In Equations (1) and (2), the P_e and V are related by the following equations:

$$P_e = V_d i_d + V_q i_q \quad (3)$$

$$V = \left(V_d^2 + V_q^2\right)^{1/2} \to \begin{cases} V_d = x_q i_q \\ V_q = E'_q - x'_d i_d \end{cases} \quad (4)$$

where x_q is the q-axis reactance of the generator. Moreover, Figure 2 shows the transfer function of the PSS. It consists of an amplification block, a wash out block and two lead-lag blocks [1]. The objective of the washout block is to act as a high pass filter that eliminates DC offset. The lead-lag blocks provide the appropriate phase-lead characteristic to compensate for the phase lag between the exciter input and the generator electrical torque. The output of the PSS is limited to guarantee that the PSS does not counteract the voltage regulator action of the AVR.

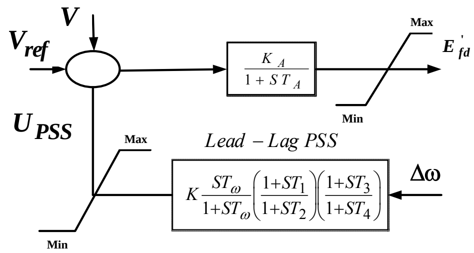

Figure 2. IEEE type-ST1 excitation system with PSS

C. SVC-Based Stabilizer

The complete SVC controller structure with a lead-lag compensator is shown in Figure 3. The susceptance of the SVC, B, could be expressed as:

$$\dot{B}_{SVC} = \left(K_S\left(B_{SVC}^{REF} - U_{SVC}\right) - B_{SVC}\right)/T_S \quad (5)$$

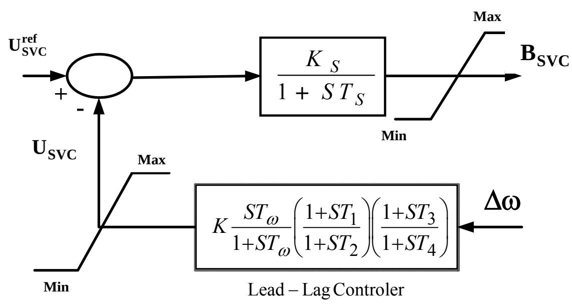

Figure 3. SVC with lead-lag controller

Referring to Figure 1, the d and q components of machine current i and terminal voltage V are as the following:

$$i = i_d + ji_q \tag{6}$$

$$V = V_d + jV_q \tag{7}$$

By linearizing Equations (1) and (2) it is possible to obtain:

$$\begin{aligned}
&\Delta \dot{\delta} = \omega_b \Delta\omega \\
&\Delta \dot{\omega} = \left(-\Delta P_e - D\Delta\omega\right)/M \\
&\Delta \dot{E}'_q = \left(\Delta E_{fd} - \left(x_d - x'_d\right)\Delta i_d - \Delta E'_q\right)/T'_{do} \\
&\Delta \dot{E}_{fd} = (-\Delta E_{fd} - K_A \Delta V)/T_A
\end{aligned} \tag{8}$$

where,

$$\begin{aligned}
&\Delta P_e = K_1\Delta\delta + K_2\Delta E'_q + K_{PB}\Delta B_{SVC} \\
&\left(K_3 + sT_{do}\right)\Delta E'_q = \Delta E_{fd} - K_4\Delta\delta - K_{qB}\Delta B_{SVC} \\
&\Delta V = K_5\Delta\delta + K_6\Delta E'_q + K_{vB}\Delta B_{SVC}
\end{aligned} \tag{9}$$

where, K_1-K_6, K_{PB}, K_{qB} and K_{vB} are linearization constants. substituting Equation (9) into Equation (8) one can obtain the linearized model of the power system installed with the SVC as [15]:

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E}'_q \\ \Delta\dot{E}_{fd} \end{bmatrix} = \begin{bmatrix} 0 & 377 & 0 & 0 \\ \frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 \\ -\frac{K_4}{T'_{do}} & 0 & -\frac{K_3}{T'_{do}} & \frac{1}{T'_{do}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & -\frac{K_{PB}}{M} \\ 0 & -\frac{K_{qB}}{T'_{do}} \\ \frac{K_A}{T_A} & -\frac{K_A K_{vB}}{T_A} \end{bmatrix} \begin{bmatrix} U_{pss} \\ \Delta B_{SVC} \end{bmatrix} \tag{10}$$

In short expression:

$$P\Delta x = A\Delta x + B\Delta u \tag{11}$$

where, the state vector X is $\left[\Delta\delta, \Delta\omega, \Delta E'_q, \Delta E_{fd}\right]^T$, and the control vector U is $[U_{PSS}, \Delta B]^T$, and K_1-K_6, K_p, K_q and K_v are linearization constant.

D. STATCOM-Based Stabilizers

As shown in Figure 1, the STATCOM consists of a three phase gate turn-off (GTO) based voltage source converter (VSC) and a DC capacitor. The STATCOM model used in this study is founded well enough for the low frequency oscillation stability problem. The STATCOM is installed through a step-down transformer with a leakage reactance of X_t. The voltage difference across the reactance produces active and reactive power exchange between the STATCOM and the transmission network.

The STATCOM resembles in many respects a synchronous compensator, but without the inertia. The STATCOM is one of the important FACTS devices and can be used for damping electromechanical oscillations in a power system to provide stability improvement. This study examines the application of STATCOM for damping electromechanical oscillations in a power system. The VSC generates a controllable AC voltage source $CV_{DC}\angle\psi$ behind the leakage reactance. The voltage difference between the STATCOM-bus AC voltage $V_m(t)$ and $V_o(t)$ produces active and reactive power exchange between the STATCOM and the power system, which can be controlled by adjusting the magnitude $CV_{DC}\angle\psi$ and the phase ψ. In Figure 1, we have [20]:

$$\begin{aligned}
&V_o = CV_{DC}\angle\psi = CV_{DC}(\cos\psi + j\sin\psi) \\
&I_s = I_{sd} + jI_{sq} \\
&\frac{dV_{DC}}{dt} = \frac{I_{DC}}{C_{DC}} = \frac{C}{C_{DC}}(I_{sd}\cos\psi + I_{sq}\sin\psi)
\end{aligned} \tag{12}$$

where $C = mk$, k is the ratio between the AC and DC voltage depending on the converter structure, m is the modulation ratio defined by pulse width modulation (PWM), V_{DC} is the DC voltage, and ψ is the phase defined by PWM. Furthermore, C_{DC} is the DC capacitor value and I_{DC} is the capacitor current while I_{sd} and I_{sq} are the d and q components of the FACTS current I_s, respectively. Figure 4 illustrates the block diagram of STATCOM AC/DC voltage PI controller with a damping stabilizer. The proportional and integral gains are K_{ACP}, K_{ACI} and K_{DCP}, K_{DCP} for AC and DC voltages, respectively. The STATCOM damping stabilizers are lead-lag structure where K_C and K_ψ are the stabilizer gains, Tw is the washout time constant, and T_{1C}, T_{2C}, T_{3C}, T_{4C}, $T_{1\psi}$, $T_{2\psi}$, $T_{3\psi}$, and $T_{4\psi}$ are the stabilizer time constants.

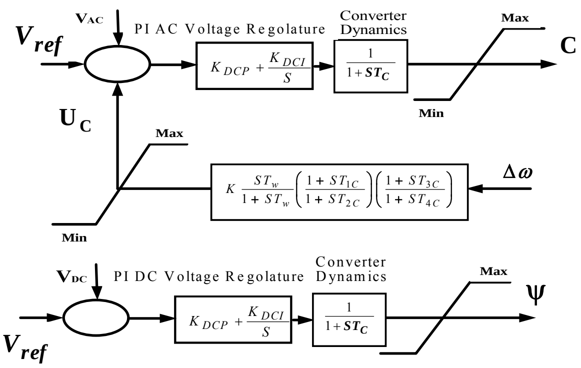

Figure 4. STATCOM AC/DC voltage regulator with supplementary damping control in the AC control loop

E. Linearizing Model STATCOM

In electromechanical mode damping stabilizers analysis, the linearized incremental model around a nominal operating point is usually employed [21]. Linearizing the expressions of i_d and i_q and substituting into the linear form of (1)-(4), (6)-(8) and (12) yield the following linearized expressions.

The I_s is the current flow from STATCOM, and the d-q axis measure is:

$$C_7 i_d + C_8 i_q = V_b\sin\delta + C_{11}E'_q + CV_{DC}\cos\psi \tag{13}$$

$$C_9 i_d + C_{10} i_q = V_b\cos\delta + C_{12}E'_q + CV_{DC}\sin\psi \tag{14}$$

Solving (13) and (14) simultaneously, i_d and i_q expressions can be obtained.

$$C_7\Delta i_d + C_8\Delta i_q = V_b\cos\delta\Delta\delta + C_{11}\Delta E'_q + \\ +C\cos\psi\Delta V_{DC} + V_{DC}\cos\psi\Delta C - CV_{DC}\sin\psi\Delta\psi \tag{15}$$

$$C_9\Delta i_d + C_{10}\Delta i_q = V_b\sin\delta\Delta\delta + C_{12}\Delta E'_q + \\ +C\sin\psi\Delta V_{DC} + V_{DC}\sin\psi\Delta C + CV_{DC}\cos\psi\Delta\psi \tag{16}$$

Solving (15) and (16) simultaneously, Δi_d and Δi_q can be expressed as:

$$\Delta i_d = C_{19}\Delta\delta + C_{21}\Delta E'_q + C_{23}\Delta V_{DC} + C_{25}\Delta\psi + C_{27}\Delta C \tag{17}$$

$$\Delta i_q = C_{20}\Delta\delta + C_{22}\Delta E'_q + C_{24}\Delta V_{DC} + C_{26}\Delta\psi + C_{28}\Delta C \tag{18}$$

The constants C_7-C_{28} are expressions of:

$$Z, Y_L, x'_d, x_q, i_{q0}, i_{d0}, E'_{q0}, C_0, \Psi_0$$

The linearized form of V_d and V_q can be written as:

$$\Delta v_d = x_q\Delta i_q \tag{19}$$

$$\Delta v_q = \Delta E'_q - x'_d\Delta i_d \tag{20}$$

Using Equations (ΔI_d) and (ΔI_q), the following expressions can be easily obtained:

$$\begin{aligned} &\Delta P_e = K_1\Delta\delta + K_2\Delta E'_q + K_{pDC}\Delta V_{DC} + K_{pC}\Delta C + \\ &+K_{p\psi}\Delta\psi + (K_3 + sT'_{do})\Delta E'_q = \Delta E_{fd} - K_4\Delta\delta - \\ &-K_{qDC}\Delta V_{DC} - K_{qC}\Delta C - K_{q\psi}\Delta\psi \\ &\Delta v = K_5\Delta\delta + K_6\Delta E'_q + K_{vDC}\Delta V_{DC} + \\ &+K_{vC}\Delta C + K_{v\psi}\Delta\psi \\ &\Delta V_{DC} = K_7\Delta\delta + K_8\Delta E'_q + K_{DC}\Delta V_{DC} + \\ &+K_{\Delta C}\Delta C + K_{\Delta\psi}\Delta\psi \end{aligned} \tag{21}$$

where K_1-K_8, K_{DCP}, K_{PC}, $K_{p\psi}$, K_{qDC}, K_{qC}, $K_{q\psi}$, K_{vDC}, K_{vC}, $K_{v\psi}$, K_{DC}, $K_{\Delta C}$, and $K_{\Delta\psi}$ are linearization constants. The above linearizing procedure yields the following linearized power system model:

$$\begin{bmatrix} \dot{\Delta\delta} \\ \dot{\Delta\omega} \\ \dot{\Delta E'_q} \\ \dot{\Delta E}_{fd} \\ \dot{\Delta V}_{DC} \end{bmatrix} = \begin{bmatrix} 0 & 377 & 0 & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 & \frac{-K_{pDC}}{M} \\ -\frac{K_4}{T'_{do}} & 0 & -\frac{K_3}{T'_{do}} & T'_{do} & \frac{-K_{qDC}}{T'_{do}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & \frac{-K_A K_{vDC}}{T_A} \\ K_7 & 0 & K_8 & 0 & K_9 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \\ \Delta V_{DC} \end{bmatrix} + \tag{22}$$

$$+ \begin{bmatrix} 0 & 0 & 0 \\ 0 & -\frac{K_{pC}}{M} & -\frac{K_{P\psi}}{M} \\ 0 & -\frac{K_{qC}}{T'_{do}} & -\frac{K_{q\psi}}{T'_{do}} \\ \frac{K_A}{T_A} & -\frac{K_A K_{vC}}{T_A} & -\frac{K_A K_{v\Psi}}{T_A} \\ 0 & K_{\Delta C} & K_{\Delta\Psi} \end{bmatrix} \begin{bmatrix} u_{PSS} \\ \Delta C \\ \Delta\psi \end{bmatrix}$$

Using vector representation, the above equation can be written as:

$$P\Delta x = A\Delta x + B\Delta u \tag{23}$$

where, the state vector X is $\left[\Delta\delta, \Delta\omega, \Delta E'_q, \Delta E_{fd}, \Delta V_{DC}\right]^T$ and the control vector U is $[U_{PSS}, \Delta C, \Delta\psi]^T$. The K_1-K_9, K_p, K_q, K_v and K_Δ are linearization constant.

III. PROBLEM FORMULATION

A. Stabilizer Structure

The commonly used lead-lag structure is chosen in this study. The transfer function of the stabilizer is:

$$u = K\left(\frac{sT_w}{1+sT_w}\right)\left(\frac{1+sT_1}{1+sT_2}\right)\left(\frac{1+sT_3}{1+sT_4}\right)y \tag{24}$$

where u and y are the stabilizer output and input signals, respectively, K is the stabilizer gain, T_w is the washout time constant, and T_1, T_2, T_3, and T_4 are the stabilizer time constants. From the viewpoint of the washout function, the value of T_W is not critical and may be in the range of 1-20 s [21]. In the lead-lag structured controllers, the washout time constants T_w is usually prespecified [15, 22]. In the present study a washout time constant T_w=10 s is used. The controller gain K and time constants T_1, T_2, T_3 and T_4 are to be determined.

Furthermore, in the design of a robust damping controller, selection of the appropriate input signal is a main issue. Input signal must give correct control actions when a disturbance occurs in the power system. Both local and remote signals can be used as control. However, local control signals, although easy to get, may not contain the desired oscillation modes. For local input signals, line active power, line reactive power, line current magnitude and bus voltage magnitudes are all candidates to be considered in the selection of input signals for the FACTS power oscillation damping controller [23].

Similarly, generator rotor angle and speed deviation can be used as remote signals. However, rotor speed seems to be a better alternative as input signal for FACTS-based controller [24]. In this study, the input signal of the proposed damping stabilizers is the speed deviation, $\Delta\omega$.

B. Objective Function

A widely used conventional lead-lag structure for both PSS and FACTS-based stabilizers, shown in Figures 2-5, is considered. In this structure, the washout time constant T_w is usually prespecified. It is worth mentioning that the damping controller is designed to minimize the electromechanical mode oscillation while the internal PI controllers are designed to minimize the variations in ac and dc voltages of the STATCOM. Therefore, the following weighted-sum multiobjective function is proposed in order to coordinate among the damping stabilizers and the internal ac and dc PI controllers. Therefore, to increase the system damping to electromechanical modes, an objective function J defined below is proposed.

$$J = \int_0^{t=t_{sim}} t\left(|\Delta\omega| + \alpha|\Delta V_{AC}| + \beta|\Delta V_{DC}|\right)dt \tag{25}$$

In the above equations t_{sim} is the simulation time, α and β are weighting factors, $\Delta\omega$ is the generator speed deviation, ΔV_{AC} is the STATCOM AC voltage deviation, and ΔV_{DC} is DC voltage deviation, where for SVC weighting factors α and β are zero. It is aimed to minimize this objective function in order to improve the system response in terms of the settling time and overshoots.

C. Optimization Problem

In this study, it is aimed to minimize the proposed objective function J. The problem constraints are the PSS and FACTS controller parameter bounds. Therefore, the design problem can be formulated as the following optimization problem.

minimize J subject to:

$$T_1^{\min} \le T_1 \le T_1^{\max}\ ,\ T_2^{\min} \le T_2 \le T_2^{\max}$$

$$T_3^{\min} \le T_3 \le T_3^{\max}\ ,\ T_4^{\min} \le T_4 \le T_4^{\max}$$

$$K_{PSS}^{\min} \le K_{PSS} \le K_{PSS}^{\max}\ ,\ K_{ACP}^{\min} \le K_{ACP} \le K_{ACP}^{\max}$$

$$K_{ACI}^{\min} \le K_{ACI} \le K_{ACI}^{\max}\ ,\ K_{DCI}^{\min} \le K_{DCI} \le K_{DCI}^{\max}$$

$$K_{DCP}^{\min} \le K_{DCP} \le K_{DCP}^{\max}\ ,\ K_C^{\min} \le \kappa_C \le K_C^{\max}$$

$$K_{\psi}^{\min} \le K_{\psi} \le K_{\psi}^{\max}$$

The proposed approach employs Genetic Algorithm (GA) [15] to solve this optimization problem and search for optimal set of the controller parameters. Based on the linearized power system model, genetic algorithm has been applied to the above optimization problem to search for optimal settings of the proposed stabilizer. In this study, PSS and FACTS-based damping controllers as discussed in the following combination cases:

Case 1: without compensation (base case)

Case 2: Single and coordinated compensation Design Approach (PSS and SVC)

Case 4: STATCOM internal AC and DC PI voltage controllers with PSS and C-based damping stabilizer.

Case 5: STATCOM internal AC and DC PI voltage controllers with PSS and ψ-based damping stabilizer.

IV. SIMULATION RESULTS

Simulations on the SMIB system (shown in Figure 1) are performed to evaluate the effectiveness of the PSS and FACTS controllers to damping power system oscillations and its design by the methods proposed using GA in the paper are demonstrated by example power systems. The relevant parameters of the power system are given in Appendix. To validate the effectiveness of the proposed controllers, two different operating conditions (Normal & Heavy) as given in Table 1 are considered. Parameters for proposed stabilizers are given in Table 2.

Table 1. Different Loading Conditions

Loading	P_e (pu)	Q_e (pu)
Normal	1.0	0.015
Heavy	1.1	0.4

A. Eigenvalues Analysis

The system eigenvalues and their damping ratio with and without PSS, SVC and STATCOM (single and coordinated design) for nominal and heavy loading conditions are given in Tables 3-5, respectively. The eigenvalue analysis reveals the effectiveness of GA based single and coordinated of PSS and FACTS-based controllers to damping power system oscillations and power system stability enhancement.

Table 2. Optimal parameter setting of the proposed stabilizers

Controller optimal parameter	Single design		Coordinated design			
	PSS	SVC	PSS	SVC	*C*-based Stabilizer	*ψ*-based Stabilizer
T_1	0.561	0.2801	0.1894	0.795	0.4910	0.0081
T_2	0.1000	0.3000	0.1000	0.3000	0.5000	0.5000
T_3	0.267	0.0124	0.1372	0.5186	0.7016	0.140
T_4	0.1000	0.3000	0.1000	0.3000	0.5000	0.5000
K	16.021	310	1.45	87.18	41.650	55.72
K_{PAC}	--	--	--	--	523.12	340.3
K_{IAC}	--	--	--	--	30.190	798.0
K_{PDC}	--	--	--	--	290	171.06
K_{IDC}	--	--	--	--	934.18	830.40

Table 3. System eigenvalues in nominal loading condition, single and coordinated design

	Single Design			Coordinated Design		
No Control	PSS	SVC	STATCOM only	PSS & SVC	*C*-based stabilizer	*ψ*-based stabilizer
-0.3±j4.96	-1.93±j3.55	-0.72±j5.98	-1.0835± j2.651	-2.045±j1.740	-1.141± j1.289	-3.07± j0.861

Table 4. System eigenvalues in heavy loading condition, single and coordinated design

	Single Design			Coordinated Design		
No Control	PSS	SVC	STATCOM only	PSS & SVC	*C*-based Stabilizer	*ψ*-based Stabilizer
-0.49±j3.69	-1.02±j2.40	-0.539±j5.54	-0.717± j1.8546	-3.212±j3.95	-1.602± j2.501	-2.731± j2.304

Table 5. Damping of system electromechanical mode in both of loading conditions, single and coordinated

		Single Design			Coordinated Design		
Loading	No Control	PSS only	SVC only	STATCOM only	PSS & SVC	*C*-based Stabilizer	*ψ*-based Stabilizer
Normal	-0.0600	0.4776	0.1195	0.3783	0.7616	0.66282	0.9628
Heavy	-0.1310	0.3911	0.0968	0.308	0.6309	0.53937	0.7643

B. Non Linear Time Domain Simulation

To assess the effectiveness of the proposed PSS and FACTS devices to improve the stability of SMIB power system shown in Figure 1 is considered for nonlinear simulation studies. 6-cycle 3-φ fault on the infinite bus was created, at both loading conditions given in Table 1, to study the performance of the proposed controller. The system data is given in the appendix. Figures 5-7 show the rotor angle response with above mentioned disturbance at nominal and heavy loading conditions respectively. The response with coordinated design is much faster, with less overshoot and settling time compared to CPSS and single design. It can be observed from the figures that, the coordinated design approach provides the best damping characteristic and enhance greatly the first swing stability at two loading conditions. Response when CPSS and designed individually and in coordinated manner at nominal and heavy loading conditions are compared and show in Figures 5-7, respectively. It is clear that the control effort is greatly reduced with the coordinated design approach.

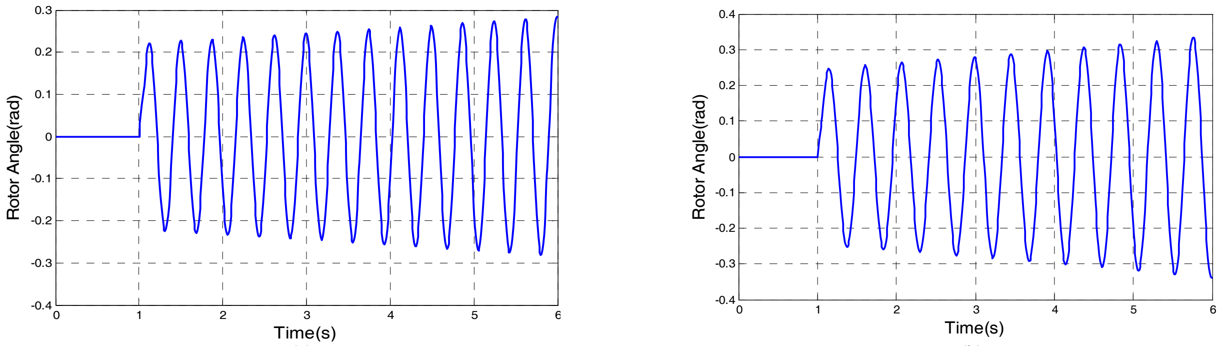

Figure 5. Machine rotor angle response for a six cycles fault with nominal (a) and heavy (b) loading conditions

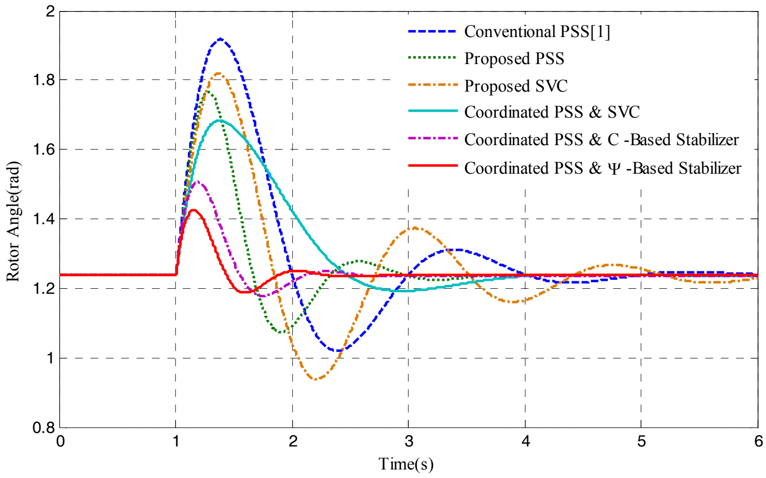

Figure 6. Machine rotor angle response for a six cycles fault with nominal loading condition

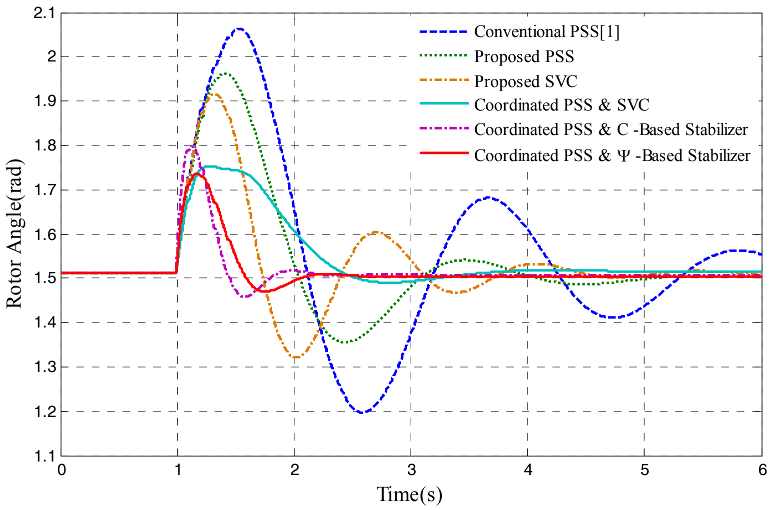

Figure 7. Machine rotor angle for a six cycles fault with heavy loading condition

V. CONCLUSIONS

In this study, the power system stability enhancement via PSS and FACTS device are presented and discussed. Genetic Algorithms (GA) is employed to coordinately tune the parameters of the PSS and FACTS controller. The coordination between the FACTS controller and the PSS is taken into consideration to improve the damping power system oscillations. The electromechanical mode is more controllable through based stabilizers. The proposed stabilizers have been applied and tested on Single Machine Infinite Bus (SMIB) power system under severe disturbance and different loading conditions. In this paper the eigenvalue analysis and the nonlinear simulation results are used for small signal stability of single machine infinite bus system installed with PSS and FACTS device. Finally, this analysis results reveal that coordinated design of PSS and STATCOM-based controllers has significant performance to promote the damping power system oscillations compared with SVC-Based controllers. Moreover it can be seen that the coordinated PSS and ψ-based stabilizer provide better damping characteristics and enhances the first swing stability greatly compared to the coordinated PSS and C-based stabilizer case.

APPENDIX

Power System Data in Per Unit Value

M=9.26, T_{do}=7.76, D=0, x=0.973, x_d=0.19, x_q=0.55
R=0.234, X=0.997, g=0.249, b=0.262, K_c=1.0, T_c=0.05
$|E_{fd}|\leq$ 7.3 pu, V_{dc}=1, K_A=20, T_A=0.01

NOMENCLATURES

Z, X, R : Transmission line impedance and resistance
Y_L : Local load admittance, $Y_L = g + jb$
g, b : Load inductance and susceptance
Δ : Rotor angle
ω : Rotor speed
ω_b : Synchronous speed
P_m : Mechanical input power of the generator
P_e : Electrical output power of the generator
M : Inertia constant
D : Damping constant of the generator
T'_{do} : Open-circuit field time constant
x_d, x'_d : d-axis reactance and d-axis transient
x_q : q-axis reactance of the generator
V : Terminal voltage of the generator
V_d, V_q : d- and q-axis terminal voltage
V_{ref} : Reference voltage
V_b : Infinite bus voltage
E'_q, E_{fd} : Generator internal and field voltages
K_A, T_A : Gain and time constant of the excitation system
U_{PSS} : PSS control signal
K_s, T_s : FACTS gain and time constant
i_{SVC}, i_L : SVC and load currents
B_{SVC} : SVC equivalent susceptance
X_{TCSC} : TCSC equivalent reactance
X_t : Leakage reactance of transformer (STATCOM)
V_m : STATCOM bus voltage
C_{dc} : Capacitance of dc capacitor
C, ψ : Modulation index, phase of STATCOM voltage

ACKNOWLEDGEMENTS

Funding support of this research was provided by the Ramhormoz Branch, Islamic Azad University, Ramhormoz, Khoozestan, Iran. Moreover, this paper was derived from a plan named "A Novel Approach to Comparison Effect of PSS and Series FACTS-Based Stabilizer for Enhance Power System Stability".

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