ROBUST COORDINATED DESIGN OF PSS & STATCOM CONTROLLERS FOR DAMPING POWER SYSTEM OSCILLATION

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Abstract - The main objective of this paper is to investigate the enhancement of damping the power system oscillation via coordinated design of the Power System Stabilizer (PSS) and STATic COMpensator (STATCOM) controllers. The design problem of PSS and STATCOM controllers are formulated as an optimization problem. Using the developed linearized model of a power system equipped with STATCOM-based stabilizer & PSS, the particle swarm optimization (PSO) algorithm is employed to search for optimal controllers parameters. In addition, the paper presents a singular value decomposition (SVD) based approach to asses and measures the controllability of the poorly damped electromechanical modes by different controllers' inputs. The proposed controllers are evaluated on a single machine infinite bus power system with STATCOM installed. The nonlinear time domain simulation and eigenvalue analysis results show the effectiveness of the coordinated design in damping the power system oscillation.

1. INTRODUCTION

Damping of a power system oscillation is one of the main concerns in the power system operation since many years [1-2]. Nowadays, the conventional power system stabilizer (CPSS) is widely used by power utilities.

Generally, it is important to recognize that machine parameters change with loading making the machine behavior quite different at different operating conditions. Hence, PSSs should provide some degree of robustness to the variations in system parameters, loading conditions, and configurations.

H_∞ optimization techniques [3] have been applied to robust PSS design problem. However, the order of the H_∞ based stabilizer is as high as that of the plant. This gives rise to complex structure of such stabilizers as reduces their applicability.

A comprehensive analysis of the effects of the different CPSS parameters on the dynamic performance of the power system was presented in [4]. It is shown that the CPSS provide satisfactory damping over a wide range of system loading conditions [5].

Although PSSs provide supplementary feedback stabilizing signals, they suffer a drawback of being liable to cause great variations in the voltage profile.

The recent advances in power electronics have led to the development of the flexible alternating current transmission systems (FACTS). Utilities are beginning to install FACTS devices in their transmission networks due to the increase in the power system requirements. It is well recognized that FACTS devices, in addition to their primary function, have the capability of enhancing the system damping [6].

STATic COMpensator (STATCOM) is a second generation's shunt connected FACTS devices based on a voltage source converter (VSC) using GTOs. STATCOM maintains the bus voltage by supplying the required reactive power even at low bus voltages and improves the power swing damping. STATCOM has several advantages over the conventional Static Var Compensation (SVC).

An extensive attention has been directed for investigating the effect of STATCOM-based stabilizer on power system stability [7-11]. Assessment study of STATCOM & SVC on stability enhancement has been introduced in [7]. It was verified that STATCOM-based stabilizer has a better performance compared to that of SVC-based stabilizer in damping power oscillations and fast voltage recovery. STATCOM model has been incorporated in to the Phillips-Heffron model and its AC/DC voltage regulators controllers' interaction has been studied [8]. Several approaches based on modern control theory have been applied to STATCOM-based controllers design such as variable structure controller [9], robust controller using H_∞ technique, and loop-shaping technique [10]. Damping improvement of power system oscillation using STATCOM has been studied in [11]; however the robust controller design approach and coordination with PSS were not taken in to consideration in the design process.

In this paper, a comprehensive assessment of the effects of robust controller design of the Excitation and STATCOM-based controllers when they applied independently and also through coordinated application has been carried out. The design problem is transformed into an optimization problem where the particle swarm optimization (PSO) algorithm is employed to search for the optimal settings of stabilizers' parameters. A controllability measure based on singular value decomposition (SVD) is used to identify the effectiveness of each controller input. For completeness, the eigenvalue analysis and nonlinear simulation results are carried out to demonstrate the effectiveness and robustness of the proposed stabilizers to enhance system stability.

2. POWER SYSTEM MODEL

In this study, a single machine infinite bus system with STATCOM at the midpoint of the line connected through a step-down transformer shown in Fig. 1 is considered.

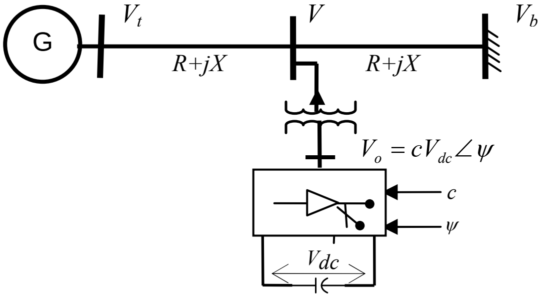

Figure 1: Single machine with STATCOM

2.1 Generator Model

In this study, the generator will be presented by the third-order model comprising of the electromechanical swing equation and the generator internal voltage equation.

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

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

$$\dot{E}'_q = (E_{fd} - (x_d - x'_d)i_d - E'_q)/T'_{do} \tag{3}$$

$$T_e = v_q i_q + v_d i_d \tag{4}$$

Where, T_m and T_e are input and output power of the generator respectively; M and D are the inertia constant and damping coefficient respectively; δ and ω are rotor angle and speed respectively; E_{fd} is the field voltage; T'_{do} is the open circuit field time constant, x_d and x'_d are the d-axis reactance and d-axis transient reactance of the generator respectively.

2.2 Exciter and PSS

The IEEE Type-ST1 excitation system shown in Fig. 2 is considered. It can be described as

$$\dot{E}_{fd} = \left(K_A\left(V_{ref} - v + u_{PSS}\right) - E_{fd}\right)/T_A \tag{5}$$

Where, K_A and T_A are the gain and time constant of the excitation system respectively; V_{ref} is the reference voltage. As shown in Fig. 2, a conventional lead-lag PSS is installed in the feedback loop to generate a stabilizing signal u_{PSS}.

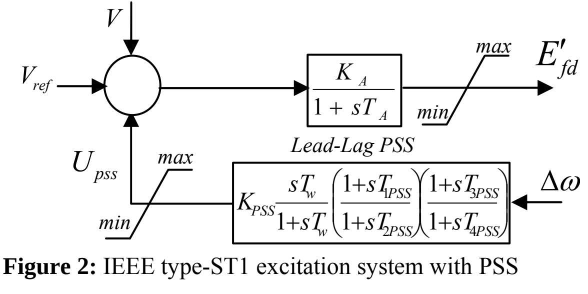

Figure 2: IEEE type-ST1 excitation system with PSS

2.3 STATCOM Model

The STATCOM is modeled as a voltage-sourced converter behind a step down transformer as shown in Fig.1. The STATCOM generates a controllable AC-voltage source $V_{out}(t) = V_o \sin(\omega t - \psi)$ behind the leakage reactance. The voltage difference between the STATCOM bus AC voltage and $V_{out}(t)$ produces active and reactive power exchange between the STATCOM and the system grid.

$$V_o = cV_{DC}(\cos\psi + i\sin\psi) = cV_{DC}\angle\psi \;\ldots\ldots\ldots\ldots\ldots \tag{6}$$

$$\frac{dV_{DC}}{dt} = \frac{c}{C_{DC}}(I_{LD}\cos\psi + I_{LQ}\sin\psi) \;\ldots\ldots\ldots\ldots\ldots \tag{7}$$

Where, for the PWM inverter, $c = mk$ and k is the ratio between AC and DC voltage; m is the modulation ratio defined by PWM, and ψ is defined by the PWM.

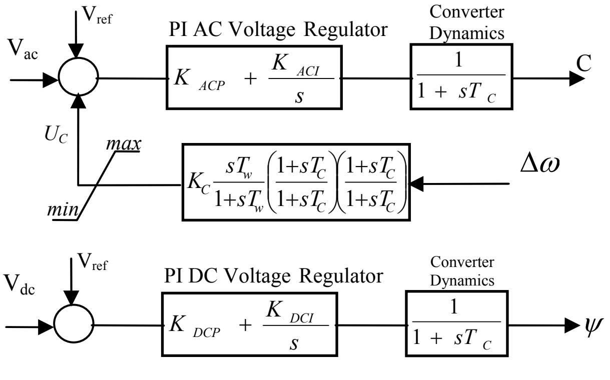

Figure 3: STATCOM AC/DC Voltage Regulator with supplementary damping control in the AC control loop

There are two basic controllers implemented in STATCOM, an AC voltage regulation and a DC voltage regulation shown in Fig. 3. The AC voltage controller regulates the reactive power exchange while the DC controller regulates the active power exchange with the power system. The DC voltage across the DC capacitor of the STATCOM is controlled to be constant for normal operation of the PWM inverter.

Installing both PI DC and PI AC voltage regulators lead to system instability, if they are designed independently, because of the interaction of the two controllers. Coordination design of the two controllers is necessary to avoid negative damping to the power system [8].

2.4 Linearized Model

In the design of electromechanical mode damping controllers, the linearized incremental model around a nominal operation point is usually employed [1].

The complete linearized system model is shown in equation (8) where K_1-K_9, K_{PDC}, K_{qDC}, K_{VDC}, K_{PC}, K_{qC}, K_{vC}, K_{dC}, $K_{P\psi}$, $K_{q\psi}$, $K_{v\psi}$, and $K_{d\psi}$ are linearization constants.

In short, $\dot{X} = AX + HU$, 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 $\left[\Delta u_{PSS}, \Delta C, \Delta\psi\right]$.

$$\begin{bmatrix} \dot{\Delta\delta} \\ \dot{\Delta\omega} \\ \dot{\Delta E_q'} \\ \dot{\Delta E_{fd}} \\ \dot{\Delta V_{DC}} \end{bmatrix} = \begin{bmatrix} 0 & 377 & 0 & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 & -\frac{K_{PDC}}{M} \\ -\frac{K_4}{T_{do}'} & 0 & -\frac{K_3}{T_{do}'} & \frac{1}{T_{do}'} & \frac{K_{qDC}}{T_{do}'} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vDC}}{T_A} \\ K_7 & 0 & K_8 & 0 & K_9 \end{bmatrix}$$

$$\times \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E_q' \\ \Delta E_{fd} \\ \Delta V_{dc} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & -\frac{K_{PC}}{M} & -\frac{K_{P\psi}}{M} \\ 0 & \frac{K_{qC}}{T_{do}'} & \frac{K_{q\psi}}{T_{do}'} \\ \frac{K_A}{T_A} & -\frac{K_A K_{vC}}{T_A} & -\frac{K_A K_{v\psi}}{T_A} \\ 0 & K_{dc} & K_{d\psi} \end{bmatrix} \times \begin{bmatrix} \Delta u_{PSS} \\ \Delta C \\ \Delta\psi \end{bmatrix} \qquad (8)$$

3. THE PROPOSED APPROACH

3.1 Electromechanical Mode Identification

The state equations of the linearized model can be used to determine the eigenvalues of the system matrix A. Out of these eigenvalues; there is a mode of oscillations related to machine inertia. For the stabilizers to be effective, it is extremely important to identify the eigenvalue associated with the electromechanical mode. In this study, the participation factors method [12] is used.

3.2 Controllability Measurement

To measure the controllability of the electromechanical mode by a given input, the singular value decomposition (SVD) is employed in this study. Mathematically, if G is an m×n complex matrix then there exist unitary matrices W and V with dimensions of m×m and n×n respectively such that G can be written as

$$G = W \Sigma V^H \qquad (9)$$

where

$$\Sigma = \begin{bmatrix} \Sigma_1 & 0 \\ 0 & 0 \end{bmatrix}, \quad \begin{aligned} &\Sigma_1 = diag(\sigma_1, \ldots\ldots, \sigma_r) \\ &\text{with } \sigma_1 \geq \ldots \geq \sigma_r \geq 0 \end{aligned} \qquad (10)$$

Where $r = min\ \{m, n\}$ and $\sigma_1,\ldots,\sigma_r$ are the singular values of G.

The minimum singular value σ_r represents the distance of the matrix G from the all matrices with a rank of r–1. This property can be utilized to quantify modal controllability. In this study, the matrix H can be written as $H = [h_1, h2, h3]$ where h_i is the column of matrix H corresponding to the *i-th* input. The minimum singular value, $\sigma_{\min}$, of the matrix $[\lambda I - A\ h_i]$ indicates the capability of the *i-th* input to control the mode associated with the eigenvalue λ. As a matter of fact, the higher the $\sigma_{\min}$, the higher the controllability of this mode by the input considered. Having been identified, the controllability of the electromechanical mode can be examined with all inputs in order to identify the most effective one to control that mode.

3.3 Electromechanical Mode Controllability Measurement

With each input signals of STATCOM-based stabilizer (ψ & C) and PSS in the linearized model, the minimum singular value $\sigma_{\min}$ has been estimated to measure the controllability of the electromechanical mode from that input. The minimum singular value has been estimated for each input signal over a wide range of operating conditions. Specifically, for a range of 84 loading conditions specified by P = [0.05 - 1.0] *pu* with a step of 0.05 *pu* and Q = [-0.4 - 0.4] *pu* with a step of 0.4 *pu*, $\sigma_{\min}$ has been estimated. At each loading condition in the specified range, the system model is linearized, the electromechanical mode is identified, and the SVD-based controllability measure is implemented.

The capabilities of ψ, C & u_{PSS} to control the electromechanical modes over the specified range of operating conditions are given in Figs 4.

It can be seen that the controllability of the electromechanical mode with the ψ, C and u_{PSS} increases with loading at lagging and leading power factor. However, the controllability of the electromechanical mode with the ψ is higher in all aspect and this has been confirmed in [11].

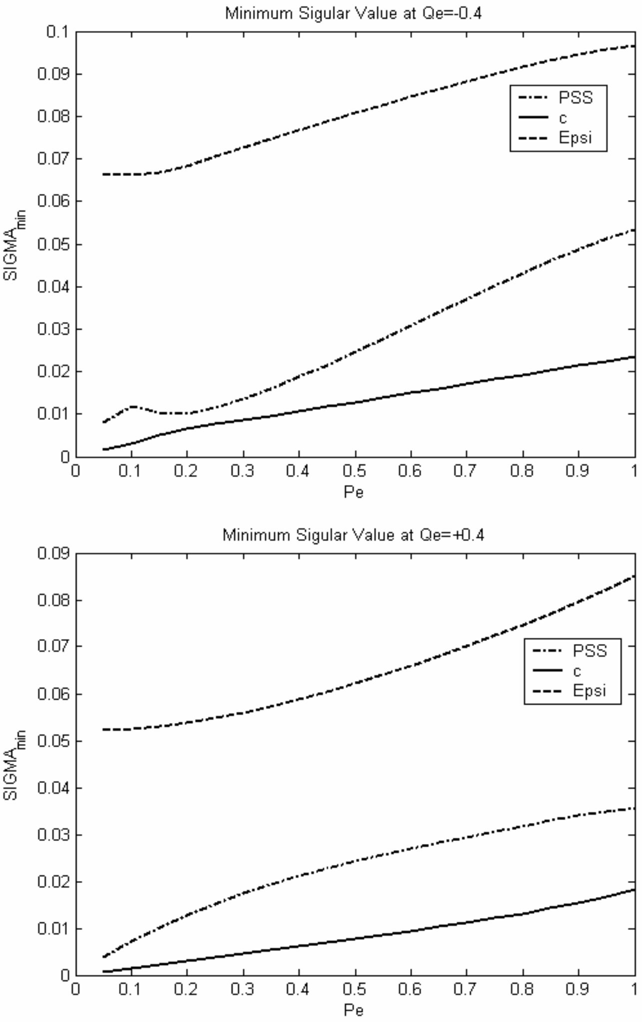

Figure 4: Minimum singular value with all inputs at leading & lagging power factor

3.4 *Stabilizer Design*

Because both of AC and DC STATCOM voltage regulators controllers are not designed for power oscillation damping (POD) duty, an auxiliary conventional lead-lag structure damping controller on the AC voltage control loop of the STATCOM as shown by Fig. 3, is considered in the design. Even though the controllability of the electromechanical mode with the ψ is higher than C, there is no supplementary stabilizer added in the DC voltage control loop since it required external storage energy connected to the capacitor, to provide required real power, which is not usually existing. The feedback signal for the STATCOM stabilizer and PSS is the speed deviation.

In this structure, the washout time constant T_w and the time constants $T_{2\&4}$ for both controllers (C & PSS) are usually prespecified. The controllers gains Kc & K_{PSS} , DC PI controllers parameters, and time constants $T_{1\&3}$ for both controller are remained to be determined by the optimization technique.

3.5 *Problem Formulation.*

To increase the system damping to the electromechanical model, the objective function J defined below is proposed.

$J = \min\{\zeta_i\}$ Where ζ_i is the electromechanical mode damping ratio of the *i*th loading condition.

This objective function will identify the minimum value of damping ratio among electromechanical modes of the loading condition considered in the design process. The design problem can be formulated as the following optimization problem format.

Minimize J

Subject to

$K_C^{min} \le K_C \le K_C^{max}$

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

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

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

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

$K_{PSS}^{min} \le K_{PSS} \le K_{PSSmax}$ &

$T_{PSS1}^{min} \le T_{PSS1} \le T_{PSS1}^{max}$

$T_{PSS3}^{min} \le T_{PSS3} \le T_{PSS3}^{max}$

The minimum and maximum value of the controller gains is set as 0.1 and 100 respectively. The maximum values of T_1 and T_3 are set to 1.0s.

3.6 *Application of PSO Algorithm*

Based on the linearized power system model in equation (9), Particle Swarm Optimization (PSO) [13] has been applied to the above optimization problem to search for optimal settings of the proposed stabilizer.

In this study, the STATCOM and PSS controllers' parameters are optimized over a wide range of operating conditions and system parameter uncertainties. Four loading conditions represent nominal, light, heavy, and leading power factor are considered. Each loading condition is considered without and with parameter uncertainties as given in Table 1. Hence, the total number of points considered for design process is 16.

Loading condition (P,Q) in pu values	Parameter uncertainties
Nominal (1.0,0.015)	No parameter uncertainty
Light (0.3,0.100)	30% increase of line reactance X
Heavy (1.1,0.100)	30% decrease of T_{do}'
Leading pf (0.7,-0.300)	25% decrease of machine inertia M

Table 1: Loading conditions and parameter uncertainties

The proposed approach has been implemented on a weakly connected power system. The detailed data of the power system used in this study is given in the appendix. The final settings of the optimized parameters for the proposed stabilizers are given in Table 2. Whereas Figure 5 shows the variations of the objective function of all controllers.

	Individual		*Coordinated*	
	C	*PSS*	*C*	*PSS*
Controller gain- K	*100*	*14.7626*	*100*	*100*
T1	*0.1*	*0.8355*	*0.7594*	*0.0303*
T2	*0.3*	*0.1*	*0.3*	*0.1*
T3	*1*	*0.1867*	*0.8527*	*0.2529*
T4	*0.3*	*0.1*	*0.3*	*0.1*
KDCP	*100*	*11.6042*	*7.5006*	
KDCI	*74*	*94.36*	*0.01*	

Table 2: The optimal settings of the controller parameters

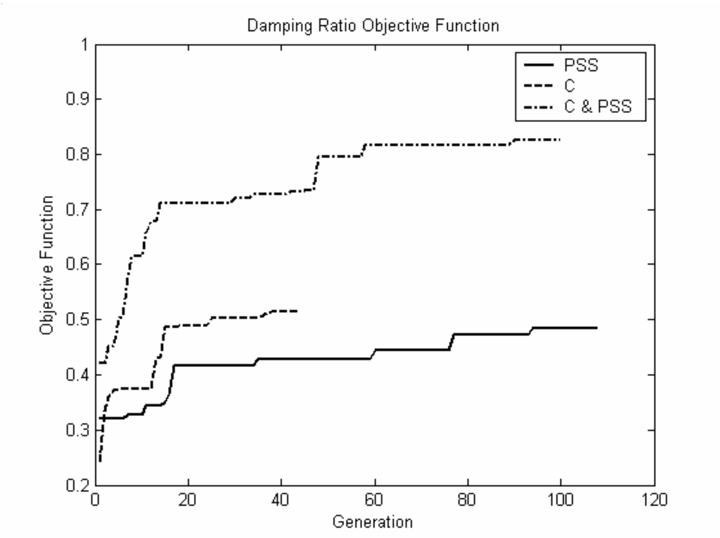

Figure 5: Convergence of the objective function for the three controllers' structures

4. SIMULATION RESULTS

To assess the effectiveness of the proposed stabilizers, three different loading conditions given in Table 3 were considered. At each loading condition the STATCOM ψ & C parameters have been recalculated so that STATCOM has no injections to the system.

Loading	*P(pu)*	*Q(pu)*
Nominal	1	0.015
Light (Leading *PF*)	0.7	-0.3
Heavy	1.1	0.4

Table 3 : Loading Condition

4.1 Eigenvalues Analysis

The system eigenvalues with the proposed stabilizers' structures for nominal, light and heavy loading conditions are given in Tables 4-6, respectively, where the first row represents the electromechanical mode eigenvalues and their damping ratios.

PSS-based controller	C-based controller	Coordinated [C & PSS]-based Controllers
-1.3939±3.4064i (0.3787)*	-1.7807±4.1709i (0.3926)*	-2.18±0.3558i (0.9869)*
-4.6198±23.2043i	-5.6621±5.6945i	-2.4096±2.8059i
-3.1499±12.4421i	-9.7383±74.8348i	-3.0017±1.8594i
-33.7913	-31.1193	-7.3597±6.9137i
-25.7516	-11.8722	-8.0924±18.0377i
-10.5662	-2.5485	-19.491±21.583i
-5.5446, -0.2021	-0.7464, -0.2010	-21.56, -0.2212, -0.0013, -0.2

* indicates the damping ratio of the electromechanical mode eigenvalue

Table 4: System eigenvalues of nominal loading condition

PSS-based controller	C-based controller	Coordinated [C & PSS]-based Controllers
-1.1856±4.9329i (0.2337)*	-0.5716±5.3103i (0.107)*	-2.2467±4.2434i (0.4679)*
-4.7757±19.9861i	-9.6973±66.6855i	-2.9996±0.3166i
-5.1595±7.9238i	-32.4474	-4.8401±6.2313i
-33.2020	-11.4559	-9.8591±14.0236i
-20.871	-7.2313	-16.5188±8.6456i
-11.3574	-4.8161, -2.9789	-27.2779, -0.2066
-5.8751, -0.2007	-0.7467, -0.2004	-0.2, -0.0013

* indicates the damping ratio of the electromechanical mode eigenvalue

Table 5: System eigenvalues of light loading condition

PSS-based controller	C-based controller	Coordinated [C & PSS]-based Controllers
-1.1873±3.4128i (0.3286)*	-1.9405±2.7727i (0.5734)*	-1.5317±1.9208i (0.6235)*
-3.6467±11.3826i	-5.8787±6.5827i	-8.3024±6.1164i
-4.1092±20.2565i	-9.7243±65.783i	-8.9218±15.6938i
-33.943	-29.9457	-19.033±26.6821i
-25.1739	-11.2856	-15.2178±1.8584i
-11.3994	-3.599	-19.3247, -3.7895, -1.9486
-5.5964, -0.2021	-0.7474, -0.203	-0.2248, -0.2, -0.0014

* indicates the damping ratio of the electromechanical mode eigenvalue

Table 6: System eigenvalues of heavy loading condition

It is clear from the eigenvalues analysis that the system stability is greatly enhanced with the proposed stabilizers. It can be also seen that the coordinated design outperforms the individual design at all points considered in the sense that the damping ration of the electromechanical modes at all points are greatly improved.

4.2 Non Linear Time Domain Simulation

The single machine infinite bus system shown in Fig. 1 is considered for nonlinear simulation studies. 6-cycle 3-φ fault on the infinite bus was created, at all loading conditions given in Table 3, to study the performance of the proposed controller.

Figures 6-8 show the rotor angle, the speed deviation response with above mentioned disturbance at nominal, light and heavy loading conditions respectively. Form the figure it can be seen that the coordinated design approach provides the best damping characteristic and enhance greatly the first swing stability at all loading conditions.

The stabilizing signal of PSS, U_{PSS}, response when designed individually and in coordinated manner at nominal and heavy loading conditions are compared and show in Fig. 9a & b, respectively. It is clear that the control effort is greatly reduced with the coordinated design approach.

5. CONCLUSION

In this study, the power system stability enhancement via PSS and STATCOM-based stabilizer when applied independently and also through coordinated application was discussed and investigated. A supplementary damping controller to the STATCOM AC voltage control loop was added to improve STATCOM power oscillation damping. The coordination between STATCOM damping stabilizer and internal PI voltage controllers is taken into consideration in the design stage. For the proposed stabilizer design problem, an eigenvalue-based objective function to increase the system damping ratio was developed. The tuning parameters of the proposed stabilizer were optimized using PSO. The proposed stabilizers have been applied and tested on power system under severe disturbance and different loading condition. The eigenvalues analysis and the nonlinear time domain simulation results show the effectiveness and the robustness of the proposed stabilizer and its ability to provide good damping of low frequency oscillation and improve greatly the system voltage profile.

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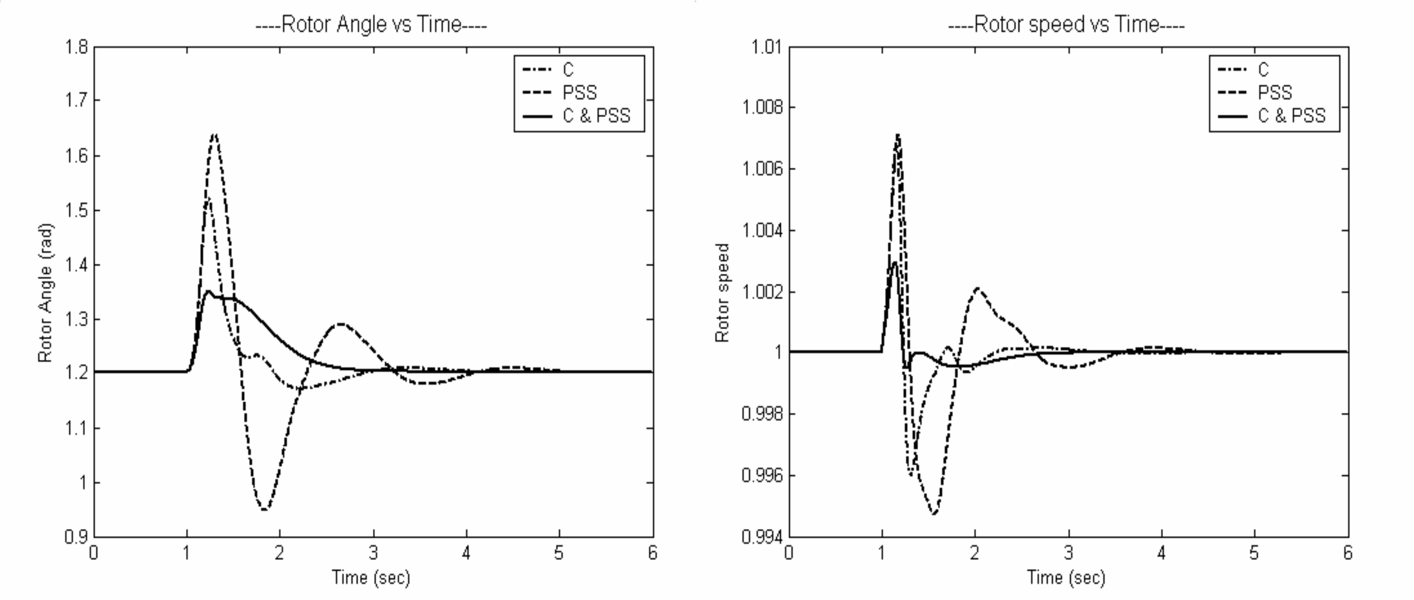


Figure 6: Machine rotor angle & speed response for a six cycles fault with nominal loading condition

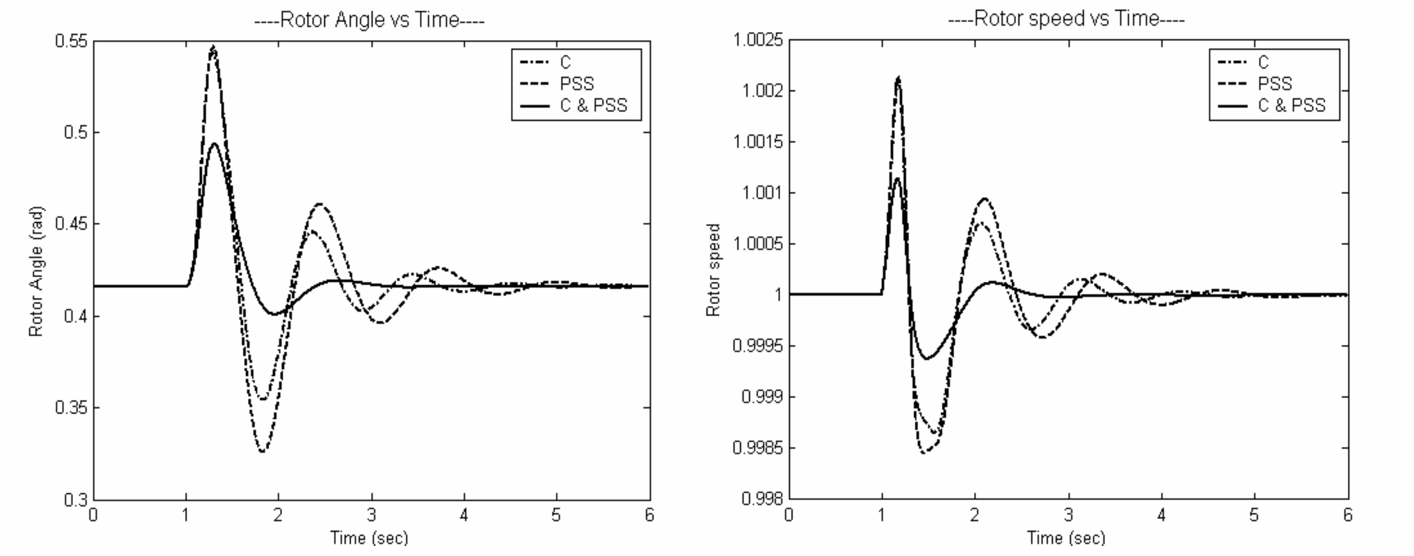


Figure 7: Machine rotor angle & speed response for a six cycles fault with light loading condition

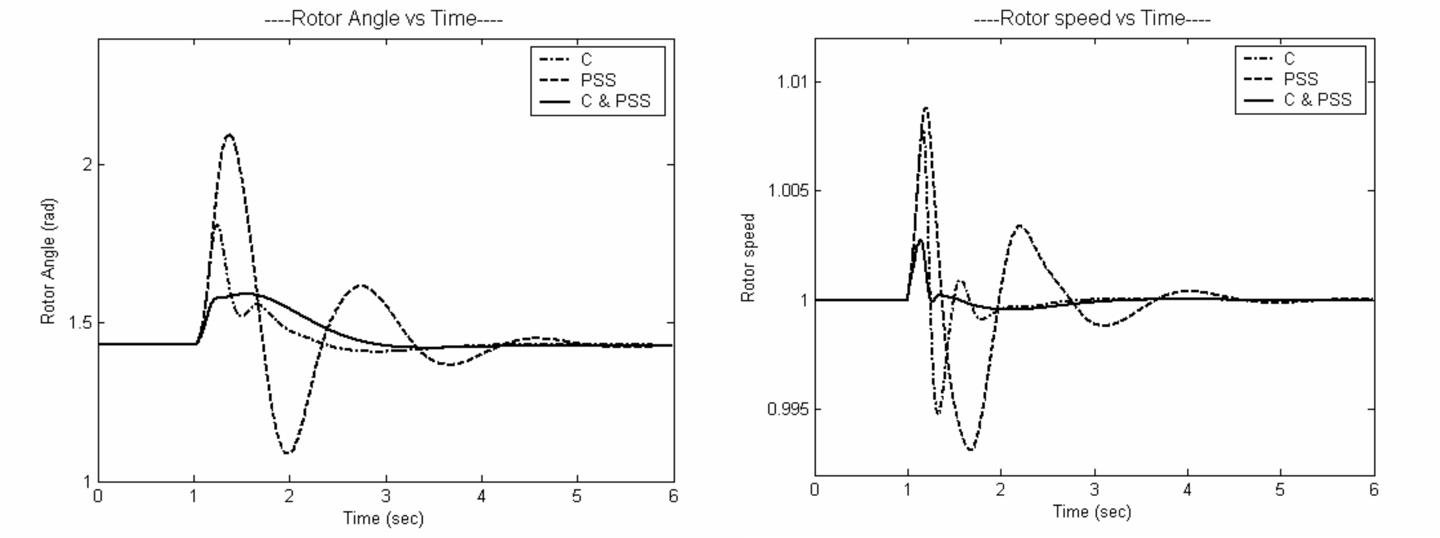
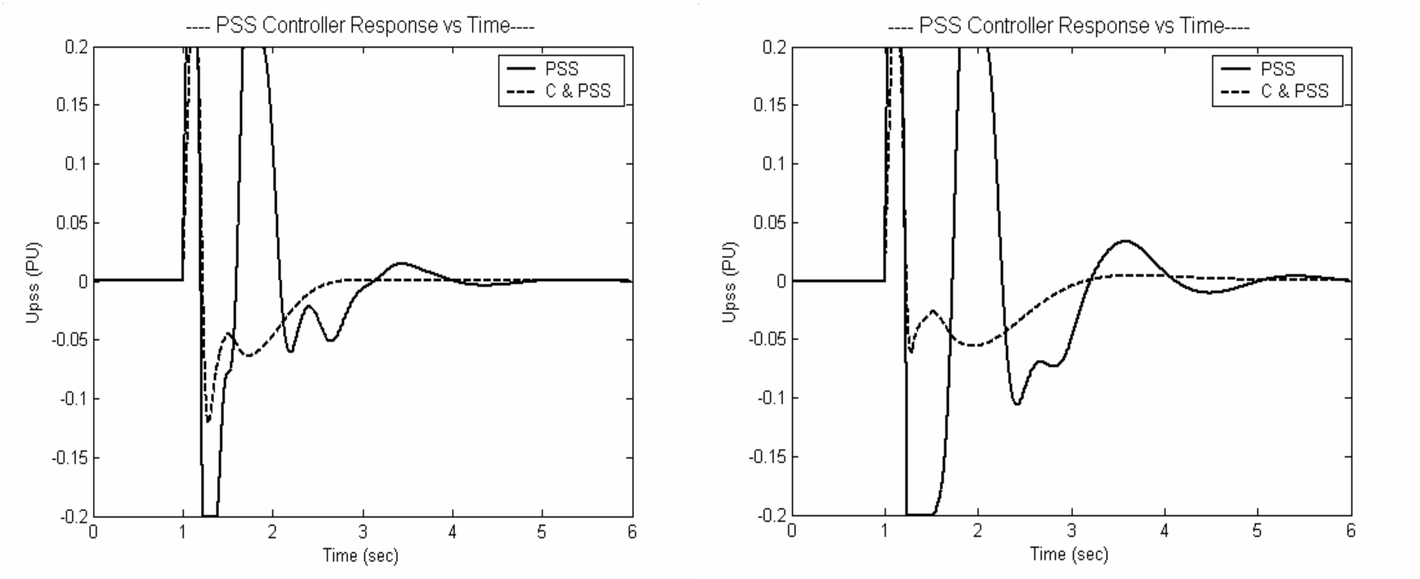


Figure 8: Machine rotor angle & speed response for a six cycles fault with heavy loading condition



(a)

(b)

Figure 9: PSS stabilizing signal response for a six cycles fault with (a) nominal loading; (b) heavy loading

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Appendix

Power system data in per unit value:
$M=9.26s$; $T_{do}=7.76$; $D=0$; $x_d = 0.973$; $x_d' = 0.19$;
$X_q = 0.55$; $X=0.997$; $Kc = 1.0$; $Tc=0.05$; $|E_{fd}|\leq 7.3$ pu ;
$Vdc=1, K_A=50$, $T_A=0.05$, $Tw=5$.

STATCOM ψ & C parameters have been recalculated, at each loading conditions, so that STATCOM has no injections to the power system.