Optimal Switched Feedback Controller Design for the Simultaneous Coordinated Design of UPFC and PSS in Power System

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Abstract—In this paper, an optimal switched feedback controller is designed which automatically finds a controller rather than having to make certain arbitrary choices as presented in conventional approch. This novel approach is presented for the simultaneous coordinated design of Unified power flow controller (UPFC) and Power System Stabilizer (PSS) in order to enhance the damping of oscillations in a Single Machine Infinite Bus (SMIB) power system. On the basis of the linearized Phillips-Herffron model, the coordinated design problem of PSS and UPFC is formulated as switching between two state feedback controller gains; one with respect to optimal controller and based on the location of closed loop eigenvalues from optimal control design another controller is designed using pole placement method. To ensure the betterness of simultaneous coordinated design of PSS & UPFC a preliminary control analysis is done by considering uncoordinated control of PSS & UPFC. The proposed feedback switching model presented here is tested on the modified SMIB linearised phillips heffron model of a power system using MATLAB/SIMULINK® platform.

Index Terms—PSS, UPFC, SMIB, FACTS, LQR, COC, SISO, MIMO.

I. INTRODUCTION

Recent years have witnessed an enormous growth of interest in dynamic systems that are characterised by a mixture of both continuous and discrete dynamics [2]. Such systems are commonly found in engineering practice and are referred to as hybrid or switching systems. The advantage of switching between different feedback structures is to combine the useful propoerties of each structure and to introduce new properties that are not present in any of the structures used.

In [3] the authors derived a necessary and sufficient condition for stability of arbitrarily switched second order LTI systems with marginally stable subsystem. Keith R Santarelli [4] made a comparison of a switching controller to two LTI controllers for a class of LTI Plants. It addressed the optimal switching problem for a class of switched systems with parameter uncertainty. In [5] by treating the order of switching, number of switchings and switching instants, all as decision variables, the authors construct a cost functional based on arbitrary switching. By using genetic algorithms(GA), the cost functional is solved to obtain the optimal the order of switching, number of switchings and switching instants. Tuhin Dasa and Ranjan Mukherjeeb [6] address the problem of optimal switching for switched linear systems in the framework of optimal control. The switching sequence, number of switchings, and switching instants were all treated as decision variables. By embedding the switched system in a larger family of systems, we were able to apply Pontryagins Minimum Principle and derive the condition for optimal switching.

In the past decades, the utilization of supplementary excitation control signals for improving the dynamic stability of power systems has received much attention. The k-constant model developed by Phillips and Heffron, is used to explain the small signal stability, high impedance transmission lines, line loading, and high gain, fast acting excitation systems. The power system stabilizer is a supplementary control system, which is often applied as part of excitation control system. The basic function of the PSS is to apply a signal to the excitation system, creating electrical torques to the rotor, in phase with speed variation, that damp out power oscillations.

Balwinder Singh Surjan and Ruchira Garg [7] have compared the effectiveness of conventional PSS and PID-PSS. In [8] a technique based on particle swarm optimization is developed for tuning the parameters of a fixed structure PSS. The algorithm offers designers the flexibility to achieve a compromise between con icting design objectives, the overshoot and control constraint. Ali M. Yousef and M K Ei-Sherbiny [9] have designed power system stabilizer (PSS) based on LQR Approach. The proposed PSS has robustness control property with power system parameters. In [10] Different techniques for designing of power system stabilizer is proposed for Modified Heffron-Phillips model, the parameters of the power system stabilizer have been tuned by the three ways, linear quadratic power system stabilizer, genetic algorithm power system stabilizer and proposed power system stabilizer. The effciency of the proposed design technique is much better than the linear quadratic power system stabilizer and genetic algorithm based power system stabilizer. The IPSO algorithm was introduced in [11]. This proposed IPSO was utilized to

find the optimal parameters of PSS for SMIB system by minimizing the fitness function. Using the proposed algorithm, the LFO can be reduced appropriately.

Hussain N and Al-Duwaish [12] have proposed an adaptive neural network based Sliding Mode Control (SMC) for a PSS of a single machine power system. The SMC is essentially a switching feedback control. Simulation results indicate that the controller performance is greatly improved by the use of adaptive SMC. In [13] the authors demonstare a methodology to make the power system controller design less conservative using switching controllers with constrained minimum switching interval. In [14] the authors proposed a self-tuning regulator (STR) with multi-identification models and a minimum variance controller that utilizes fuzzy logic switching. Vitthal Bandal and B. Bandyopadhyay [15] proposes, the design of PSS for SMIB power system based on fuzzy logic and output feedback sliding mode controller (SMC). It is found that designed controller provides good damping enhancement.

The Unified Power Flow Controller (UPFC) is a multi-functional flexible AC Transmission (FACTS) device, whose primary duty is power flow control. The secondary functions of the UPFC can be voltage control, transient stability improvement, oscillations damping. It combines features of both Static Synchronous Compensator (STATCOM) and Static Synchronous Series Compensator (SSSC).

The Unified Power Flow Controller (UPFC) is regarded as one of the most versatile devices in the FACTS device family [16-17] which has the ability to control the power flow in the transmission line, improve the transient stability, mitigate system oscillation and provide voltage support. It performs this through the control of the inphase voltage, quadrate voltage and shunts compensation due to its mains control strategy. The application of the UPFC to the modern power system can therefore lead to the more flexible, secure and economic operation [18]. When the UPFC is applied to the interconnected power systems, it can also provide significant damping effect on tie line power oscillation through its supplementary control.

In [19] authors have shown the control inputs δ_E and δ_B to provide robust performance when compared to the other damping controllers by applying a phase compensation control technique with respect to state space variable speed. In [20] authors have presented iterative particle swarm optimization (IPSO) based UPFC controller to achieve improved robust performance and to provide superior damping in comparison with the conventional particle swarm optimization (CPSO) for the control inputs δ_E and m_B . In [21] author has presented multi machine system, where some of the states having larger settling time with conventional LQR are well regulated with multistage LQR.

However, uncoordinated control of FACTS devices and PSS may cause destabilizing interactions. To improve overall system performance, many researches were made on the coordination between PSSs and FACTS damping controllers [22-23]. Some of these methods are based on the complex nonlinear simulation, while the others are based on the linearized power system model. In general, for the simplicity

of practical implementation of the controllers, decentralized output feedback control with feedback signals available at the location of the each controlled device is most favourable.

In the current paper, for the modified SMIB linearised Phillips-Heffron model, a preliminary control analysis with individual and coordinated (PSS & UPFC) is designed to ensure the robustness of simulataneous coordinated design compared to individual design. After doing preliminary analysis a switching concept is introduced for the simulataneous coordinated design of PSS & UPFC. The switching control algorithm from conventional approach [24] is suitably modified and implemented to switch between master & alternate feedback controllers. Thus the master controller is derived from optimal control theory of LQR and alternate controller is designed from the pole placement method eventhough its closed loop eigenvalues are not necessarily stable.

Paper is organized as follows, in Section 2, Dynamic model of PSS & UPFC is described. It is followed by preliminary control analysis, first with individual later with coordinated PSS & UPFC in Section 3. Section 4 describes the switching model for Philips-Heffron plant with simultaneous coordinated PSS & UPFC controllers along with the proposed switching rule. Results, Discussions and Conclusion follow in the next preceeding sections.

II. DYNAMIC MODEL OF PSS & UPFC

A single machine-infinite bus (SMIB) system is considered for the present investigations. A machine connected to a large system through a transmission line may be reduced to a SMIB system, by using Thevenins equivalent of the transmission network external to the machine. The linearized model of the studied power system consisted of synchronous machine connected to infinite bus bar through transmission line is represented in a block diagram as shown in Fig.1. [25,26]
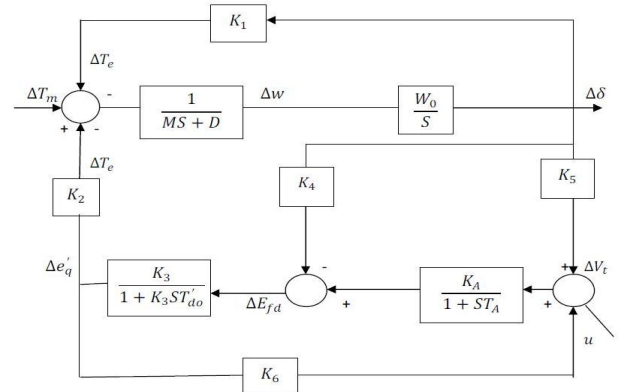

Fig. 1. Block Diagram of Power System

Its state space formulation can be expressed as follows [9,13]:

$$\dot{x}(t) = Ax(t) + Bu(t) \qquad (1)$$

where, the state variables are the rotor angle deviation ($\Delta\delta$), speed deviation ($\Delta\omega$), q-axis component deviation ($\Delta E'_q$) and

field voltage deviation (ΔE_{fd}). A and B represent the state and control input matrices given by

$$A = \begin{bmatrix} 0 & \omega_o & 0 & 0 \\ -\frac{k_1}{M} & -\frac{D}{M} & -\frac{k_2}{M} & 0 \\ -\frac{k_1}{T'_{do}} & 0 & -\frac{k_3}{T'_{do}} & \frac{1}{T'_{do}} \\ -\frac{k_A k_5}{T_A} & 0 & -\frac{k_A k_6}{T_A} & \frac{1}{-T_A} \end{bmatrix}$$

$$B = \begin{bmatrix} B_{pss} & B_{UPFC} \end{bmatrix}$$

Where, B_{PSS}= Control input matrix of PSS and B_{UPFC}= Control input matrix of UPFC and it consists of four input variables modulating index and phase angle of shunt inverter (m_E, δ_E) and modulating index and phase angle of series inverter (m_B, δ_B). For the current research the chosen input δ_E is considered.

$$B_{PSS} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{K_A}{T_A} \end{bmatrix} \quad B_{\delta_E(UPFC)} = \begin{bmatrix} 0 \\ -\frac{K_{p\delta e}}{M} \\ -\frac{K_{q\delta e}}{T'_{do}} \\ -\frac{K_A K_{v\delta e}}{T_A} \end{bmatrix}$$

All the relevant k-constants and variables along with their values used in the experiment are described in the appendix section at the end of paper.

III. Preliminary control analysis

In this section, a preliminary control analysis is done by controlling PSS & UPFC using LQR based controllers, in order to gain some knowledge on individual and coordinated controlling of PSS & UPFC. Analysis is done in two stages. In the first stage the conventional optimal control (COC) analysis is done by selecting PSS or UPFC control inputs individually resulting in two separate Single Input Single Output (SISO) systems,

$$\dot{x} = AX + \hat{B}u$$

where $\hat{B} = B_{PSS}$ or $\hat{B} = B_{UPFC}$.
The control law is given by

$$u = -Kx$$

where, $K = K_{PSS}$ or $K = K_{UPFC}$ are the controller gains for the inputs PSS and UPFC respectively. Both K_{PSS} and K_{UPFC} were designed by conventional LQR method and state variables were analysed. Refer Fig. 2 & 3.

In the second stage COC analysis is done by selecting both PSS and UPFC as the co-ordinated inputs resulting in a Multi Input Multi Output (MIMO) system with

$$B = \begin{bmatrix} B_{PSS} & B_{UPFC} \end{bmatrix}$$

Now controller gain K is $2X4$ matrix for this MIMO model obtained by LQR algorithm for MIMO system. The

experimental set up to test the preliminary analysis, the values of $A, B_{PSS}, B_{UPFC}, K_{PSS}$ & K_{UPFC} along with the coordinated design control $K_{(PSS\ \&\ UPFC)} = K_\beta$ are given below. Analysis results for all the variables are presented below in Fig. 2 to 3.

$$A = \begin{bmatrix} 0 & 377 & 0 & 0 \\ -.07076 & 0 & -.0214 & 0 \\ -.08322 & 0 & -.4873 & .1982 \\ 1513 & 0 & -3516 & -100 \end{bmatrix}$$

$$B_{PSS} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 10000 \end{bmatrix} \quad B_{UPFC} = \begin{bmatrix} 0 \\ -.1492 \\ 7.533 * 1.0e - 03 \\ -311 \end{bmatrix}$$

$$K_{PSS} = \begin{bmatrix} .8227 & -6.1592 & .1091 & .9901 \end{bmatrix}$$

$$K_{UPFC} = \begin{bmatrix} -2.9311 & -101.3626 & 5.9240 & -.6932 \end{bmatrix}$$

$$K_\beta = \begin{bmatrix} .1275 & -2.0043 & -.1212 & .9986 \\ -.6452 & -56.8949 & .2071 & -.0307 \end{bmatrix}$$
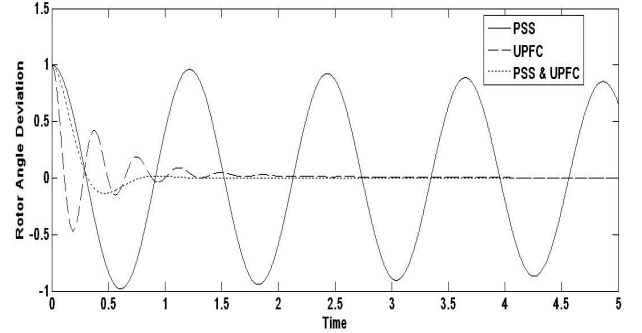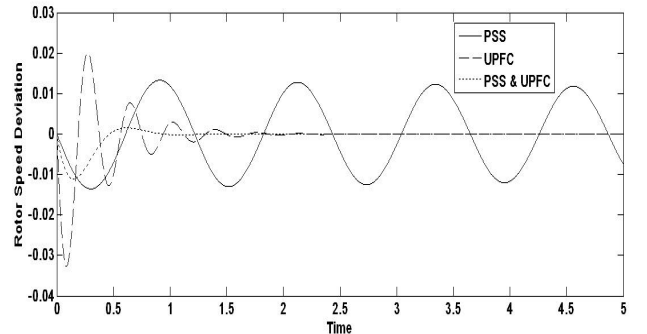

Fig. 2. rotor angle deviation response

Fig. 3. speed deviation response

TABLE I
COMPARISON OF PSS, UPFC AND COORDINATED DESIGN
OF PSS AND UPFC WITH RESPECT TO PEAK OVERSHOOTS

state	PSS	UPFC	Coordinated (PSS and UPFC)
Rotor Angle Deviation	1	-0.5	-0.15
Rotor Speed Deviation	-0.015	-0.03	-0.01

TABLE II
COMPARISON OF PSS, UPFC AND COORDINATED DESIGN
OF PSS AND UPFC WITH RESPECT TO SETTLING TIME

state	PSS	UPFC	Coordinated (PSS and UPFC)
Rotor Angle Deviation	30s	2.3s	1.2s
Rotor Speed Deviation	30s	2.1s	1s

In view of the above preliminary control analysis, investigation of Fig. 2, Fig. 3, Table 1 and Table 2 reveals that simultaneous coordinated design of PSS & UPFC provides better performance performance compared to the uncoordinated control of either PSS or UPFC with respect to peak overshoots and settling time.

IV. PROPOSED OPTIMAL SWITCHED FEEBACK CONTROLLER DESIGN

In this section, mathematical modeling of Philips-heffron system with coordinated PSS & UPFC device as a switched linear systems and the proposed switching algorithm will be explained.

A. Switched Linear Systems

Switching between different feedback structures automatically results in control systems that are no longer constrained by the limitations of linear design. Use of switching in control was proved to give better performance compared to the system without switching control.

A switched-linear system model (refer Fig. 4)for the current problem is as follows:

$$\dot{x}(t) = A_{\sigma(t)}x(t) \tag{2}$$

The switching signal $\sigma(t)$ indicates

$$\dot{x}(t) \quad = A_1 = \quad (A + BK_1)x(t) \tag{3}$$
$$= A_2 = \quad (A + BK_2)x(t)$$

Here the two controller gains K_1 and K_2 model the simultaneous coordinated design of PSS & UPFC gains. The two controller gains are derived from the optimal control theory of Linear Quadratic Regulator (LQR) and Pole Placement method respectively. For, the sake of completeness LQR and pole placement control method are explained briefly.
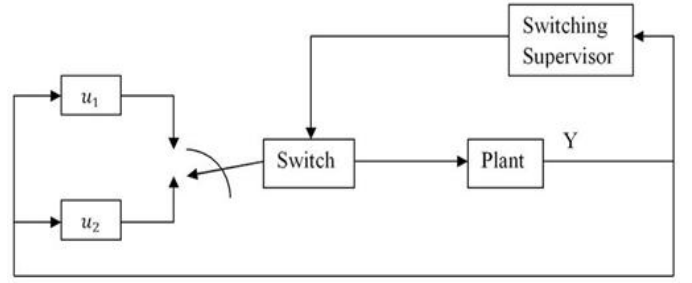

Fig. 4. General implementation of switched linear systems

B. Linear Quadratic Regulator Algorithm

A special case of optimal control problem which is of particular importance arises when the objective function is a quadratic function of x and u, and the dynamic equations are linear. The resulting feedback law in this case is known as the linear quadratic regulator (LQR). Consider a linear system characterized by Egn. (1) where (A, B) is stabilizable. Then the cost index that determines the matrix K of the LQR vector is [26]

$$J = \frac{1}{2} \int_0^\infty (x^T Q x + u^T R u) dt \tag{4}$$

Where Q and R are the positive-definite Hermitian or real symmetric matrix. From the above equations,

$$K = -R^{-1} B^T P \tag{5}$$

and hence the control law is,

$$u(t) = -Kx(t) = -R^{-1} B^T P x(t) \tag{6}$$

In which P must satisfy reduced Riccati equation:

$$PA + A^T P - PBR^{-1} + B^T P + Q = 0 \tag{7}$$

The LQR function allows you to choose two parameters, R and Q, which will balance the relative importance of the input and state in the cost function that you are trying to optimize. Essentially, the LQR method allows for the control of all outputs.

C. Pole Placement Method

Pole placement control design is based on placed poles of the closed loop system at any desired location by means of state feedback through an appropriate state feedback gain matrix.

The gain matrix K is designed in such a way that:

Step 1: Check whether the system is controllable

$$M = \begin{bmatrix} A & AB & A^2 B & - - - & A^{N-1}B \end{bmatrix}$$
$$|M| \neq 0$$

Step 2: Find $(SI - A) = s^n + a_1 s^{n-1} + - - + a_{n-1}s + a_n$

Step 3: Find the transformation matrix T

Step 4: Select the pole locations

$$(s + \alpha_1)(s + \alpha_2) + - + (s + \alpha_n) = s^n + \alpha_1 s^{n-1} + -\alpha_n$$

Step 5: Solve for K using,

$$K = \begin{bmatrix} \alpha_2 - a_2 & \alpha_1 - a_1 - - - \alpha_n - a_n \end{bmatrix} T^{-1}$$

D. Switching Algorithm Design

Design of a stabilizing switching control law is equivalent to finding switching boundary vectors F_1 & F_2. This can be achieved by carrying out the following steps[23]:

$$\begin{aligned} \dot{x}(t) &= (A + BK_1)x(t) & x' F_1' F_2 x > 0 \\ &= (A + BK_2)x(t) & x' F_1' F_2 x \leq 0 \end{aligned} \quad (8)$$

1) Design a secondary controller K_2 in such a way that it has $n-1$ closed loop real eigenvalues located at the left half of the s-plane.
2) Select a gain vector K_1 (primary controller) such that the closed loop eigenvalues of $A_1 = (A + BK_1)$ has $n-2$ common eigenvalues of $A_2 = (A + BK_2)$ and the remaining eigenvalues are not real.
3) To design F_1, multiply the left side eigenvalue polynomials of $(A + BK_1)$ and select the coefficients of expanded polynomial in ascending powers of s.
4) To design $F_2 = [F_1 + \mu\omega_2]$, ω_2 is calulated by multiplying the polynomial that is removed while designing the vector F_1(right side eigenvalue) with other $(n-2)$ left eigenvalues by selecting $\mu < 0$.

V. SIMULATION RESULTS

The experimental set-up to test the proposed algorithm consists of linearised Phillps-Heffron model of SMIB installed with simultaneous coordinated PSS & UPFC described by A and B matrices below. The controllers K_1 and K_2 are obtained by using LQR and pole placement technique respectively. The matrix C is vector with zeros along with 1 in any one position depending on the state variables. The proposed state feedback switching control vectors F_1 and F_2 are also given below. In the present study, the performance index J, is expressed as:

$$J = \int_0^{t_s} |M_p^2| dt \quad (9)$$

$$A = \begin{bmatrix} 0 & 377 & 0 & 0 \\ -.07076 & 0 & -.0214 & 0 \\ -.08322 & 0 & -.4873 & .1982 \\ 1513 & 0 & -3516 & -100 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & -.1492 \\ 0 & 7.533 * 1.0e - 03 \\ 10000 & -311 \end{bmatrix}$$

A. Master Controller Design

According to switching algorithm K_1, has been chosen so that the matrix A_1 has $n-2$ common eigenvalues of A_2, and other two eigenvalues are not real.

Using LQR control Algorithm,

$$[K, S, E] = lqr(A, B, Q, R, N) \quad (10)$$

The assumption in Eqn. (9) are matrix $N = 0$, matrix R and Q is as follows

$$R = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \qquad Q = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Solving Eqn. (9), the Riccati equation S is

$$S = \begin{bmatrix} .1688 & 4.2971 & -.0125 & 0 \\ 4.2971 & 381.68 & -1.3068 & -.0002 \\ -.0125 & -1.3068 & 1.1118 & 0 \\ 0 & -.0002 & 0 & .0001 \end{bmatrix}$$

Also, the optimal gain matrix K_1 is calculated as

$$K_1 = \begin{bmatrix} 0.1275 & -2.0043 & -.1212 & .9896 \\ -.6452 & -56.8949 & .2071 & -.0307 \end{bmatrix}$$

The eigenvalues are as follows

$$P = \begin{bmatrix} -10005 \\ -4 + 7i \\ -4 - 7i \\ -1 \end{bmatrix}$$

B. Alternate Controller Design

According to switching algorithm, the matrices A_1 and A_2 must have $n-2$ eigenvalues in common and it has real $n-1$ stable eigenvalues. For this research, we (arbitrarily) will move the eigenvalues located at $-4 + 7i$ and $-4 - 7i$ of the matrix A_1 to eigenvalues of $+1$ & -1 for the matrix A_2.

Using pole placement technique, place poles at

$$P = \begin{bmatrix} -10005 & -1 & -1 & 1 \end{bmatrix}$$

.

$$K = place(A, B, P)$$

$$K_2 = \begin{bmatrix} -4 & -2086 & -8 & -3 \\ -135 & -67075 & -251 & -97 \end{bmatrix}$$

C. Switching boundary vectors Design

The switching boundary vector F_1 is a normal vector to stable invariant subspace of the matrix $A + BK_2$:

$$(s + 10005)(s + 1)(s + 1)$$

Stacking the co-efficients of the resulting expanded polynomial into the vector F_1 in ascending powers of s:

$$F_1 = \begin{bmatrix} 10005 & 20011 & 10007 & 1 \end{bmatrix}$$

Recall, $F_2 = \omega_1' + \mu\omega_2'$ where, $\omega_1' = F_1$

ω_2 corresponds to the left eigenvector with the eigenvalue that is removed form $(A + BK_2)$ to form the characteristic polynomial of $(A + BK_1)$, which in this case is the left eigenvector corresponding to the eigenvalue -1. i.e., $(s + 10005)(s + 1)(s - 1)$.

$$\omega_2 = \begin{bmatrix} 10005 & 10005 & 1 \end{bmatrix}$$

According to the procedure, $\mu < 0$ to achieve a stable closed loop interconnection. If, we choose $\mu = -1$, the switching boundary vector F_2 is given by

$$F_2 = \begin{bmatrix} 20010 & 20012 & 2 & 0 \end{bmatrix}$$

TABLE III
COMPARISON OF SWITCHING AND WITHOUT SWITCHING CONTROL OF K_1 & K_2 WITH RESPECT TO PEAK OVERSHOOTS

state	K_1	Switching K_1 and K_2
Rotor Angle Deviation	-0.15	0
Rotor Speed Deviation	–0.01	-0.009

TABLE IV
COMPARISON OF SWITCHING AND WITHOUT SWITCHING CONTROL OF K_1 & K_2 WITH RESPECT TO SETTLING TIME

state	K_1	Switching K_1 and K_2
Rotor Angle Deviation	2.3s	0.4s
Rotor Speed Deviation	2.1s	0.3s

TABLE V
COMPARISON OF PERFORMANCE INDEX J WITH INDIVIDUAL CONTROLLERS

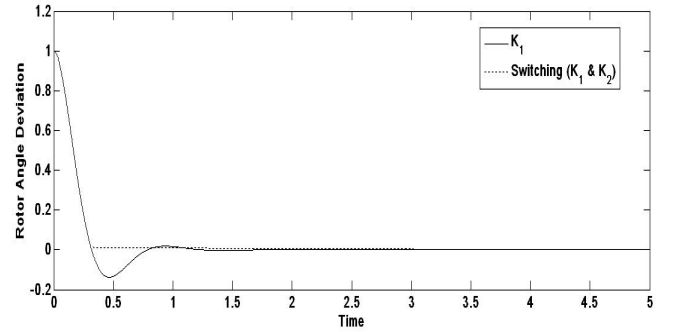| $J = \int_0^{t_s} \|M_p^2\|dt$	$UPFC$	$Coordinated$ PSS & $UPFC$	$Switching$ $Control$
$\Delta\delta$	0.5	0.012	0
$\delta\omega$	0.0018	0.00015	4*1.0e-05

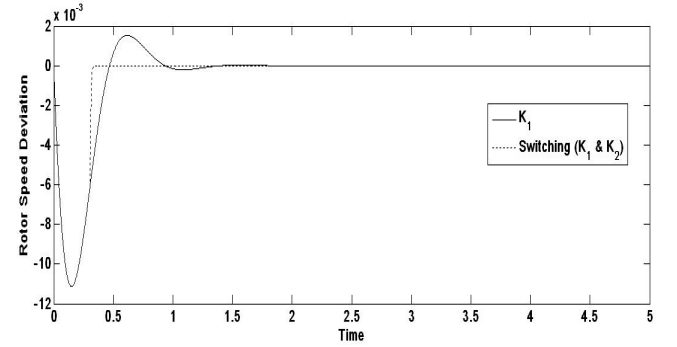Fig. 5. rotor angle deviation response

Fig. 6. speed deviation response

VI. DISCUSSIONS

The dynamic response curves for the state space variables, Rotor angle deviation($\Delta\delta$) and Speed deviation($\Delta\omega$), are plotted as shown in the Fig. 5 & Fig. 6, with the legend K_1 and Switching K_1 & and K_2 for the proposed optimal feedback switching control for the simultaneous coordinated design of PSS & UPFC. Switching Signal $\sigma(t)$ as a Function of time is also shown in Fig. 7.

From Fig. 5, Fig. 6, Table III and Table IV shows that the proposed optimal feedback switching control for the simultaneous coordinated design of PSS & UPFC between LQR and pole placement method provides better performance along with the stabilization in the Rotor angle and Rotor speed
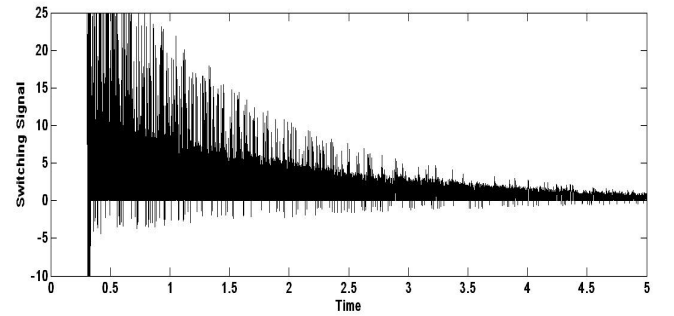

Fig. 7. Switching Signal

deviations compared to system response without switching control K_1 (LQR) and K_2 (Pole Placement) with respect to peak overshoot and settling time. To show the robustness of the proposed method performance index J is tabulated in Table V. It shows that optimality is achived in switching control between peak overshoot & settling time compared to individual control.

VII. CONCLUSION

In this paper, the simultaneous coordinated designing of the UPFC and the conventional power system stabilizer with switched feedback controllers is investigated. For the design problem, a preliminary control analysis with individual & co-ordinated (PSS & UPFC) is developed to ensure the robustness of simulatneous coordinated design compared to individual design. Then, switching concept is introduced for the simulatneous coordinated design of PSS & UPFC. The switching control algorithm from [23] is suitably modified and implemented to switch between master & alternate controllers in order to show the improved performance compared to indiviual master (LQR) controller as well as alternate controller. The effectiveness of the proposed switching control approach for improving transient stability performance of a simulatneous coordinated design of PSS & UPFC are demonstrated on the modified SMIB linearised phillips heffron model of a power system. Finally, to show the optimal control the performance index is tabulated.

APPENDIX

Synchronous Machine:
$H = 4.0$, $D = 0.0$, $T'_{do} = 5.044$.

Excitation System:
$k_A = 100$, $T_A = 0.01$

k constants for the nominal operating conitions:
$k_1 = 0.5661$, $k_2 = 0.1712$, $k_3 = 2.4583$

$k_4 = 0.4198$, $k_5 = -0.1513$, $k_6 = 0.3516$

$k_{pe} = 0.3795$, $k_{qe} = 1.1628$, $k_{ve} = -0.4591$

$k_{pb} = 0.1864$, $k_{qb} = 0.2855$, $k_{vb} = -0.1096$

$k_{p\delta e} = 1.1936$, $k_{q\delta e} = -0.0380$, $k_{v\delta e} = 0.0311$

$k_{p\delta b} = 0.0529$, $k_{q\delta b} = -0.0423$, $k_{v\delta b} = 0.0189$

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