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Design of Optimal controller for Enhanced Power System Stability using Multistage LQR with coordination operation of PSS and UPFC

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ABSTRACT

This paper presents, a multistage LQR is introduced and applied for simultaneous coordinated designing of the unified power flow controller (UPFC) and power system stabilizer (PSS) as a damping controller in the single machine power system. The results of these studies show that the proposed coordinated controllers have an outstanding capability in damping power system inter-area oscillations and enhance greatly the dynamic stability of the power system. The dynamic stability characteristics are investigated with PSS and UPFC acting individually and as a hybrid system. The hybrid controller shows a better performance compared to individual controllers. The proposed technique is implemented using MATLAB/SIMULINK platform.

Keywords: multistage LQR, unified power flow controller, Power System Stabilizer.

I. INTRODUCTION

With the ever-increasing complexities in power systems across the world, especially opening of electric power markets, it becomes more and more important to provide stable, secured, controlled and high quality electric power in today`s environment.

In the paper [1], the author has presented the results of comprehensive comparison and assessment of the damping function of multiple damping stabilizers. A multi-stage LQR concept introduced in another paper authored by R. K. Pandey [2],In this paper a settling time, minimum peak overshoot for a multi machine system has been realized.. . Shayeghi & H.A.Shayanfar [3]. Sasongko Pramono Hadi provides a detailed dynamics modeling of a multi machine power system equipped with GUPFC as the extension of UPFC configuration [4]. Mehdi Nikzad etal,provides Three robust methods considered and applied to design controllers are QFT, u-synthesis and H1 are applied on SMIB power system installed with UPFC and investigations are carried out on the stability parameter [5].

Sangu Ravindra has used an adaptive Artificial Neural Network (ANN) damping controller for UPFC. The performance of ANN controller has been compared with that of conventional lead-lag controller [6]. A.V.Sudhakara Reddy tried with an adaptive neuro-fuzzy controller for UPFC and compare the performance with lead-lag controller. The adaptive neuro-fuzzy controller shows good performance of reduce settling time and peak over shoot of low frequency oscillation [7]. The authors Mahdiyeh ESLAMI, Hussain SHAREEF have developed UPFC and PSS controllers using modified particle swarm optimization MPSO on multi machine system [8].The authors Mohammad Reza Esmaili etal have used UPFC and PSS coordinated controllers using a new hybrid particle swarm optimization based co-evolutionary cultural algorithm. In this optimization process, the best parameters of PSS and UPFC controller are obtained by using the nonlinear model of the system in order to increase the power system stability [9]. The authors S. Robak, M. Januszewski, D.D. Rasolomampionona have made a comprehensive study of PSS and UPFC from the point of damping of power swings. The work is carried out on a multi machine system.[10].

In this paper dynamic stability study is carried out on SMIB linearized Philips heffron model using Power System Stabilizer and Unified Power Controller based on Multistage LQR technique. The dynamic stability parameters are investigated with Unified Power Flow Controller and Power System Stabilizer acting individually and coordinating together. The coordinated controller (PSS+mB PSS+δB) shows a excellent performance compared to individual controllers

II. POWER SYSTEM INSTALLED WITH PSS

Here a single machine connected to infinite bus is considered for analysis, The linearized model of the studied power system consisted of synchronous machine connected to infinite bus bar through transmission line is represented in a scheme diagram as shown in Figure 1. [11]

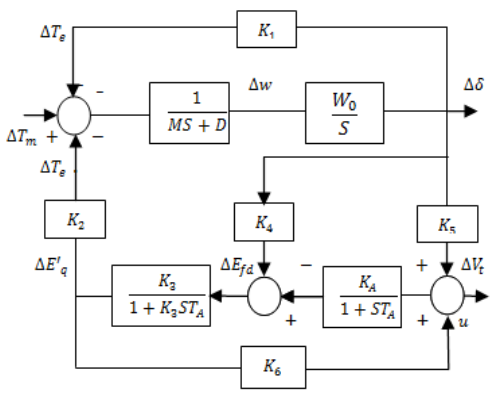

Figure 1. Block Diagram of Power System

The state space formulation for the above system can be expressed as follows [12] :

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

Where, the state variables are the rotor angle deviation (Δδ) speed deviation (Δw) , q-axis component deviation (Δ E'q) and field voltage deviation (ΔEfd) represent the state and control input matrices given by

$$A=\begin{bmatrix} 0 & w_0 & 0 & 0 \\ -\frac{k_1}{M} & -\frac{D}{M} & -\frac{k_2}{M} & 0 \\ -\frac{k_1}{T'_{d0}} & 0 & -\frac{k_3}{T'_{d0}} & \frac{1}{T'_{d0}} \\ -\frac{k_A k_5}{T_A} & 0 & -\frac{k_A k_6}{T_A} & \frac{1}{-T_A} \end{bmatrix}$$

$$B_{PSS}=\begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{K_A}{T_A} \end{bmatrix} \qquad B_{mB,\delta B(UPFC)}=\begin{bmatrix} 0 & 0 \\ -\frac{k_{pb}}{M} & -\frac{k_{p\delta b}}{M} \\ -\frac{k_{qb}}{T'_{d0}} & -\frac{k_{q\delta b}}{T'_{d0}} \\ -\frac{k_A k_{vb}}{T_A} & -\frac{k_A k_{\delta vb}}{T_A} \end{bmatrix}$$

with their values used in the experiment are described in the appendix section at the end of paper.

The values of matrix A and matrix B for this loading condition are taken from paper authored by L Yathisha [13].

The closed loop control system A_1 are given by

$$A_1 = A - BK \qquad (2)$$

Where, B_{PSS} = Control input matrix of Power System Stabilizer and B_{UPFC} = Control input matrix of Unified Power Flow Controller and it consists of four input variables modulating index and phase angle of shunt inverter (mE;δE) and modulating index and phase angle of series inverter(mB;δB). For the current research the chosen input is considered. All the relevant k-constants and variables along

$$A = \begin{bmatrix} 0 & 377 & 0 & 0 \\ -0.0168 & 0 & -0.1696 & 0 \\ -0.0393 & 0 & -0.484 & 0.1983 \\ 58.80 & 0 & -333.70 & -20 \end{bmatrix}$$

$$B_{PSS} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1000 \end{bmatrix} \quad B_{mB,\delta B(UPFC)} = \begin{bmatrix} 0 & 0 \\ -0.046 & 0.17 \\ 0.201 & 0.1501 \\ -561.2 & 0.60 \end{bmatrix}$$

III. OPTIMAL CONTROL THEORY

Optimal control theory, an extension of the calculus of variations, is a mathematical optimization method for deriving control policies. Optimal control deals with the problem of finding a control law for a given system such that a certain optimality criterion is achieved. A control problem includes a cost functional that is a function of state and control variables. An advantage of the quadratic optimal control method over the pole-placement method is that the former provides a systematic way of computing the state feedback control gain matrix. The optimized feedback controllers for the present research are derived from the Linear Quadratic Regulator (LQR). For, the sake of completeness the LQR control methods are explained briefly in the following sections.

A. Linear Quadratic Regulator

Consider with

$$\dot{x}(t) = Ax(t) + Bu(t) \qquad (3)$$

$$y(t) = Cx(t) \qquad (4)$$

The input u is expressed as r-Kx, where r is the reference input and K is the feedback gain, also called the control law. Now assume that the reference input r is zero and that the response of the system is excited by nonzero initial state $x(0)$, which in turn excited by external disturbances. The problem is then to find a feedback gain to force the response to zero as quickly as possible. This is called the regulator problem. If $r = 0$, then the input $u = -Kx$ and the closed loop system is given by

$$\dot{x}(t) = (A - BK)x(t) \qquad (5)$$

The most systematic and popular method is to find K to minimize the quadratic performance index

$$J = \int_0^\infty (x^T Qx + u^T Ru)dt \qquad (6)$$

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

$$K = -R^{-1}B^T P \qquad (7)$$

and hence the control law is,

$$u(t) = -Kx(t) = -R^{-1}B^T Px(t) \qquad (8)$$

in which P must satisfy reduced Riccati equation

$$PA + A^T P - PBR^{-1}B^T P + Q = 0 \qquad (9)$$

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.

B. Multistage LQR

LQR This technique for designing LQR is given by R K pandey in 2010. The design procedure in various stages is as follows:

(i) 1st **stage**: In this stage the LQR is designed using Bryson based LQR

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

$$[k1, s, e] = lqr(A, B, Q, R)$$

(ii) 2 nd **stage** : Choose Q_1 & R_1 matrices as

$$Q_1 = \begin{bmatrix} 10 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad R_1 = [1]$$

Select, $A_1 = A - (B * k_1)$

$$[k_2, s, e] = lqr(A_1, B, Q_1, R_1)$$

(iii) 3 rd **stage** : Choose Q_2 & R_2 matrices as

$$Q_2 = \begin{bmatrix} 100 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad R_2 = [1]$$

Select, $A_2 = A_1 - (B * k_2)$

$$[k_3, s, e] = lqr(A_2, B, Q_2, R_2)$$

(iv) 4 th **stage** : Choose Q_3 & R_3 matrices as

$$Q_3 = \begin{bmatrix} 1000 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad R_3 = [1]$$

Select, $A_3 = A_2 - (B * k_3)$

$$[k_4, s, e] = lqr(A_3, B, Q_3, R_3)$$

IV. SIMULATION RESULTS AND DISCUSSION

The simulation results is carried for all the four state variables rotor angle deviation *($\Delta\delta$)* rotor speed deviation *(Δw)* q-Axis component deviation *($\Delta E'_q$)* and field voltage deviation *(ΔE_{fd}).*

The feedback controller gains are given below:

$$k_{PSS} = 1.0e + 03 * [-0.0650 \; -5.165 \;\; 0.0710 \;\; 0.0002]$$

$$k_{mB} = 1.0e + 03 * [0.0484 \; 7.4234 - 0.1489 - 0.0009]$$

$$k_{\delta B} = [71.8865 \;\; 297.4276 \;\; 1.2723 \;\; -0.0309]$$

$$k_{PSS+mB} = \begin{bmatrix} -34.224 - 287.7463 & -0.2266 & 0.1775 \\ -63.394 - 530.1513 & -0.1846 & -0.0864 \end{bmatrix}$$

$$k_{PSS+\delta B} = \begin{bmatrix} -0.0364 & -0.1421 & 0.0503 & 0.2361 \\ 72.0769 & 299.5019 & 0.0014 & 0.0001 \end{bmatrix}$$

The simulation results of four state variables *($\Delta\delta$, Δw, $\Delta E'_q$& ΔE_{fd})* for nominal operating conditions PSS, mB, PSS+mB and PSS, δB, PSS+δB controller are plotted as given in Figures 2-7. Validation of the approach for this operating conditions is done by comparing peak overshoots & settling time as given in Tables 1to 4.

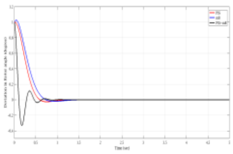

Figure 2 Deviation in rotor angle with Damping controller
(PSS, mB and PSS+mB)

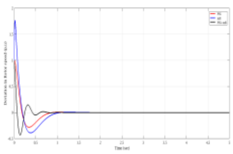

Figure 3 Deviation in rotor speed with Damping controller
(PSS, mB and PSS+mB)

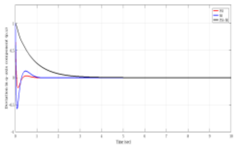

Figure 4 Deviation in q-axis component with Damping controller
(PSS, mB and PSS+mB)

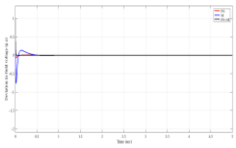

Figure 5. Deviation in field voltage with Damping controller
(PSS, mB and PSS+mB)

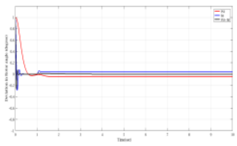

Figure 6. Deviation in rotor angle with Damping controller
(PSS, δB and PSS + δB)

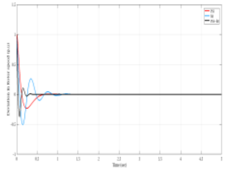

Figure 7. Deviation in rotor speed with Damping controller
(PSS, δB and PSS + δB)

Table 1. Comparision Of Peak Overshoot For Pss, Mb And Pss + Mb Control Inputs

State Variables	PSS	mB	PSS + mB
$\Delta\delta$	1.1	1.0	-0.35
Δw	1.75	-0.25	-0.35
$\Delta E'_q$	-0.20	-0.55	0
ΔE_{fd}	-0.05	-0.75	0

Table 2. Comparision Of Settling Time For Pss, Mb And Pss + Mb Control Inputs

State Variables	PSS	mB	PSS + mB
$\Delta\delta$	1.4sec	1.3sec	0.65sec
Δw	0.9sec	1.4sec	0.7sec
$\Delta E'_q$	1.0sec	1.0sec	4.5sec
ΔE_{fd}	0.15sec	0.8sec	0.01sec

Table 3. Comparision Of Peak Overshoot For Pss, Δb And Pss + Δb Control Inputs

State Variables	PSS	δB	PSS + δB
$\Delta\delta$	1.1	-0.3	-0.25
Δw	-0.25	-0.5	-0.35

Table 4. Comparision Of Settling Time For Pss, Δb And Pss + Δb Control Inputs

State Variables	PSS	δB	PSS + δB
$\Delta\delta$	1.7sec	1.1sec	0.25sec
Δw	0.8sec	1.3sec	0.35sec

Figures 2 to 5, show the plots of all the four state space variables *(Δδ, Δw, ΔE'q& ΔEfd)* with the legends PSS, mB and PSS+mB.

Figures 6 and 7, show the plots of all the four state space variables *(Δδ & Δw)* with the legends PSS, δB and PSS+δB. Tables I to II, show the comparison of peak overshoots and settling time for PSS, mB and PSS + mB control inputs

Tables III to IV, show the comparison of peak overshoots and settling time for PSS , δB and PSS + δB control inputs

Figure 2 to 5 and Tables I & II, reveal that the PSS + mB provides robust performance in peak overshoot and settling time for all the four state variables.

Figure 7 to 9 and Tables III & IV, PSS + δB provides better performance only for the state variable deviation rotor angle *(Δδ)* in peak overshoot and deviation in rotor angle, deviation in rotor speed (*Δδ, Δw)* effective in settling time.

V. CONCLUSION

This paper tries to provide a coordinated PSS and UPFC controller based on Multistage LQR technique. The main observations are summarized as below

- System stability (peak overshoot) is enhanced with proposed PSS+mB damping controller with.respect to Δδ, ΔE'qΔEfd for nominal loading condition.
- System stability (peak overshoot) is improved with proposed PSS+δB damping controller with respect to Δδ,and Δw nominal loading condition
- System stability (settling time) is enhanced with proposed PSS+mB damping controller with respect to Δδ, Δw and ΔEfd for nominal loading condition
- System stability (settling time) is improved with proposed PSS+δB damping controller with. respect to Δδ and Δw for nominal loading condition

APPENDIX

The test parameter data values are

Synchronous Machine

$H = 4.0,\ D = 0.0,\ T'_{do} = 5.044$

Excitation System

$k_A = 100, \quad T_A = 0.01$

k constants for the nominal operating conditions

$k_1 = 0.5661, k_2 = 0.1712, k_3 = 2.4583$

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

$k_{pe} = 0.3795, k_{qe} = 1.1618, k_{ve} = -0.4591$

$k_{pb} = 0.1864, k_{qb} = -0.1513, k_{vb} = 0.3516$

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

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

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