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ROBUST DAMPING CONTROL DESIGN FOR UPFC USING MIXED H_2/H_∞ TECHNIQUE

F. Shalchi [1,3] **H. Shayeghi** [2,3] **H.A. Shayanfar** [3]

1. Ardabil Power Electric Distribution Company, Ardabil, Iran, far.shalchi@yahoo.com
2. Technical Engineering Department, University of Mohaghegh Ardabili, Ardabil, Iran, hshayeghi@gmail.com
3. Center of Excellence for Power Systems Automation and Operation, Iran University of Science and Technology, Tehran, Iran, hashayanfar@gmail.com

Abstract- Power systems such as the other industrial plants contain different kinds of uncertainties which should be considered in controller design procedure. For this reason, the idea of robust mixed H_2/H_∞ control was used for designing of Unified Power Flow Controller (UPFC) Power Oscillation Damping (POD) controller. This newly developed design strategy combines the advantage of the H_2 and H_∞ control synthesizes and gives a powerful multi-objectives design addressed by the Linear Matrix Inequality (LMI) techniques. To achieve decentralization, using the Schauder fixed point theorem the synthesis and analysis of Multi-Input Multi-output (MIMO) control system is translated into set of equivalent Multi-Input Single-Output (MISO) control system. The proposed mixed H_2/H_∞ controller has a decentralized scheme and advantage of a decentralized controller design is reduction in the controller complexity and suitability for practical implementation. The effectiveness of the proposed control strategy was evaluated under operating conditions for damping low frequency oscillations in comparison with the classical controller to demonstrate its robust performance through nonlinear time simulation and some performance indices.

Keywords: UPFC, Mixed H_2/H_∞, Decentralized Controller, Power System Stability and Control.

I. INTRODUCTION

In the dynamical operation of power systems, it is usually important to aim for decentralization of control action to individual areas. This aim should coincide with the requirements for stability and load frequency scheduling within the overall system. In addition, the modern power system tends to be interconnected to obtain the most economic benefits. However, interconnection between remotely located power system give rises to occur low frequency oscillations on heavily loaded tie-lines especially after large or small disturbance in the range of 0.1-3.0 Hz. This causes the power systems to be operated near their stability limits. On the other hand, these oscillations constraints the capability of power transmission, threatens system security and damages the efficient operation of the power system. Thus, mitigation of low-frequency oscillations is necessary for secure operation of power systems. In recent years, the fast progress in the field of power electronics has opened new opportunities for the power industry via utilization of the controllable FACTS devices such as Unified Power Flow Controller (UPFC), which offer an alternative means to mitigate power system oscillations [1].

Because of the extremely fast control action associated with FACTS-device operations, they have been very promising candidates for mitigation power system oscillation in addition to improve power system steady-state performance [2, 3]. UPFC is regarded as one of the most versatile devices in the FACTS device family [4, 5], has the capabilities of control power flow in the transmission line, improving the transient stability, mitigation system oscillation and providing voltage support. The application of the UPFC to the modern power system can therefore lead to more flexible, secure and economic operation [6]. An industrial process, such as a power system, contains different kinds of uncertainties due to changes in system parameters and characteristics, loads variation and errors in the modeling. As a result, a fixed parameter controller based on the classical control theory such as lead-lag controller [7]-[9] is not certainly suitable for a UPFC control method. Thus, some authors have suggested fuzzy logic controllers [10] and neural networks methods [11] to deal with system parameters changes for enhance system damping performance.

However, the parameters adjustments of these controllers need some trial and error. On the other hands, several authors have been applied robust control methodologies to cope with system uncertainties for mitigation low frequency oscillation using UPFC. Although via these methods, the uncertainties are directly introduced to the synthesis. But, due to large model order of power systems the order of resulting controller will be very large in general, which is not feasible because of computational economical difficulties in implementing. In this study, using the Schauder fixed point theorem [12] the synthesis and analysis of the Multi-Input Multi-output (MIMO) control system under study is translated into a set of equivalent Multi-Input Single-Output (MISO) control system.

It is shown that each decentralized controller can be designed independently such that performance of the overall closed loop systems is guaranteed. In this paper, a new decentralized robust control strategy based on the mixed H_2/H_∞ control technique for UPFC damping controller design problem is proposed [13]. This newly developed design strategy combines advantage of the H_2 and H_∞ control synthesizes to achieve the desired level of robust performance against load disturbances, modelling uncertainties, system nonlinearities and gives a powerful multi-objectives design addressed by the Linear Matrix Inequality (LMI) techniques [14].

Using the generalized model, the UPFC problem is formulated as a decentralized multi-objective optimization control problem via a mixed H_2/H_∞ control technique and solved by the LMI approach to obtain the desired robust controllers [15, 16]. The proposed control strategy is compared with the classical PID and H_∞ controllers through nonlinear time simulation and some performance indices to illustrate its robust performance under different operation conditions for damping low frequency oscillation and load disturbances.

II. SYSTEM MODEL

Figure 1 shows a SMIB system equipped with a UPFC. The UPFC consists of an excitation transformer (ET), a boosting transformer (BT), two three-phase GTO based voltage source converters (VSCs), and a DC link capacitors. The four input control signals to the UPFC are m_E, m_B, δ_E, and δ_B, where, m_E is the excitation amplitude modulation ratio, m_B is the boosting amplitude modulation ratio, δ_E is the excitation phase angle and δ_B is the boosting phase angle [17, 18].

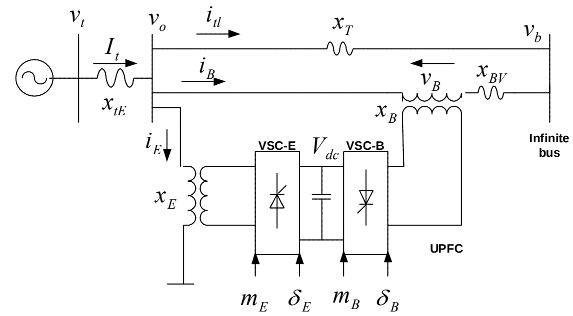

Figure 1. SMIB power system equipped with UPFC

A linear dynamic model is obtained by linearizing the nonlinear model around an operating condition. The linearized model of power system as shown in Figure 1 is described as follows:

$$\Delta\dot{\delta} = \omega_0 \Delta\omega \tag{1}$$

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

$$\Delta\dot{E}'_q = (-\Delta E_q + \Delta E_{fd})/T'_{do} \tag{3}$$

$$\Delta\dot{E}_{fd} = -\frac{1}{T_A}\Delta E_{fd} - \frac{K_A}{T_A}\Delta V \tag{4}$$

$$\begin{aligned}\Delta\dot{v}_{dc} &= K_7\Delta\delta + K_8\Delta E'_q - K_9\Delta v_{dc} + K_{ce}\Delta m_E + \\ &+ K_{c\delta e}\Delta\delta_E + K_{cb}\Delta m_B + K_{c\delta b}\Delta\delta_B\end{aligned} \tag{5}$$

where,

$$\begin{aligned}\Delta P_e &= K_1\Delta\delta + K_2\Delta E'_q + K_{pd}\Delta v_{dc} + K_{pe}\Delta m_E + \\ &+ K_{p\delta e}\Delta\delta_E + K_{pb}\Delta m_B + K_{p\delta b}\Delta\delta_B\end{aligned}$$

$$\begin{aligned}\Delta E'_q &= K_4\Delta\delta + K_3\Delta E'_q + K_{qd}\Delta v_{dc} + K_{qe}\Delta m_E + \\ &+ K_{q\delta e}\Delta\delta_E + K_{qb}\Delta m_B + K_{q\delta b}\Delta\delta_B\end{aligned}$$

$$\begin{aligned}\Delta V_t &= K_5\Delta\delta + K_6\Delta E'_q + K_{vd}\Delta v_{dc} + K_{ve}\Delta m_E + \\ &+ K_{v\delta e}\Delta\delta_E + K_{vb}\Delta m_B + K_{v\delta b}\Delta\delta_B\end{aligned}$$

K_1, K_2, K_9, K_{pu}, K_{qu} and K_{vu} are linearization constants. The block diagram of the linearized dynamic model of the SMIB power system with UPFC is shown in Figure 2.

The state-space model of power system is given by:

$$\dot{x} = Ax + Bu \tag{6}$$

where, the state vector x, control vector u, A and B are:

$$x = [\Delta\delta \quad \Delta\omega \quad \Delta E'_q \quad \Delta E_{fd} \quad \Delta v_{dc}]$$

$$u = [\Delta m_E \quad \Delta\delta_E \quad \Delta m_B \quad \Delta\delta_B]^T$$

$$A = \begin{bmatrix} 0 & w_0 & 0 & 0 & 0 \\ -\frac{K_1}{M} & 0 & -\frac{K_2}{M} & 0 & -\frac{K_{pd}}{M} \\ -\frac{K_4}{T'_{do}} & 0 & -\frac{K_3}{T'_{do}} & \frac{1}{T'_{do}} & -\frac{K_{qd}}{T'_{do}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vd}}{T_A} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ -\frac{K_{pe}}{M} & -\frac{K_{p\delta e}}{M} & -\frac{K_{pb}}{M} & -\frac{K_{p\delta b}}{M} \\ -\frac{K_{qe}}{T'_{do}} & -\frac{K_{q\delta e}}{T'_{do}} & -\frac{K_{qb}}{T'_{do}} & -\frac{K_{q\delta b}}{T'_{do}} \\ -\frac{K_A K_{vc}}{T_A} & -\frac{K_A K_{v\delta e}}{T_A} & -\frac{K_A K_{vb}}{T_A} & -\frac{K_A K_{v\delta b}}{T_A} \\ K_{ce} & K_{c\delta e} & K_{cb} & K_{c\delta b} \end{bmatrix}$$

III. DECENTRALIZED CONTROLLER SCHEME

A centralized controller design is often considered not feasible for large-scale systems such as power system; in turn decentralized control is adopted. The advantages of a decentralized controller design are reduction in the controller complexity and suitability for practical implementation. Here, the problem of decentralized UPFC controller based on Schauder fixed point theorem [12] is translated into an equivalent problem of decentralized control design for a Multi-Input, Multi-Output (MIMO) control system.

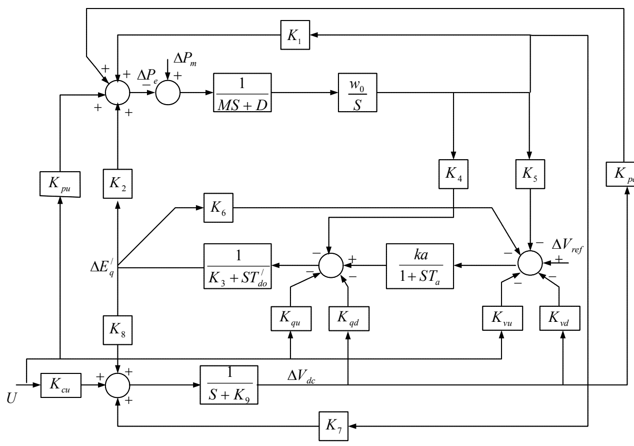

Figure 2. Modified Heffron-Phillips transfer function model

The basic MIMO compensation structure for an $m \times m$ MIMO system is shown in Figure 3. This consist of the uncertain plant P, the diagonal compensation system G, and prefilter F. These systems are defined as follows:

$$P(s) = [P_{ij}](s) = \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1m} \\ P_{21} & P_{22} & \cdots & P_{2m} \\ \vdots & \vdots & \cdots & \vdots \\ P_{m1} & P_{m2} & \cdots & P_{mm} \end{bmatrix} \quad (7)$$

$$G(s) = \mathrm{diag}\{g_i(s)\} = \begin{bmatrix} g_1 & 0 & \cdots & 0 \\ 0 & g_2 & \cdots & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & \cdots & g_m \end{bmatrix} \quad (8)$$

$$F(s) = [f_{ij}(s)] = \begin{bmatrix} f_{11} & f_{12} & \cdots & f_{1m} \\ f_{21} & f_{22} & \cdots & f_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ f_{m1} & f_{m2} & \cdots & f_{mm} \end{bmatrix} \quad (9)$$

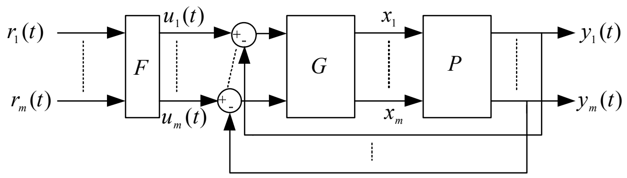

Figure 3. The MIMO control structure (m×m) system.

Here, it is developed a mapping that permits the analysis and synthesis of a MIMO control system by a set of equivalent MISO control system. This mapping results in m^2 equivalent systems, each with two inputs and one output. One input is designated as a desired input and the other as a disturbance input. The inverse of the plant matrix is given by:

$$P(s)^{-1} = \begin{bmatrix} P^*_{11} & P^*_{12} & \cdots & P^*_{1m} \\ P^*_{21} & P^*_{22} & \cdots & P^*_{2m} \\ \vdots & \vdots & \cdots & \vdots \\ P^*_{m1} & P^*_{m2} & \cdots & P^*_{mm} \end{bmatrix} \quad (10)$$

The m^2 effective plant transfer function is:

$$q_{ij} = \frac{1}{P^*_{ij}} = \frac{\det \cdot p}{adj \cdot p_{ij}} \quad (11)$$

There is a requirement that det(P) be minimum phase. The Q matrix is then described by:

$$Q = \begin{bmatrix} q_{11} & q_{12} & \cdots & q_{1m} \\ q_{21} & q_{22} & \cdots & q_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ q_{m1} & q_{m2} & \cdots & q_{mm} \end{bmatrix} = \begin{bmatrix} \frac{1}{P^*_{11}} & \frac{1}{P^*_{12}} & \cdots & \frac{1}{P^*_{1m}} \\ \frac{1}{P^*_{21}} & \frac{1}{P^*_{22}} & \cdots & \frac{1}{P^*_{2m}} \\ \vdots & \vdots & \cdots & \vdots \\ \frac{1}{P^*_{m1}} & \frac{1}{P^*_{m2}} & \cdots & \frac{1}{P^*_{mm}} \end{bmatrix} \quad (12)$$

where,

$$P = [P_{ij}],\ P^{-1} = [P^*_{ij}] = [\frac{1}{q_{ij}}],\ Q = [q_{ij}] = [\frac{1}{P^*_{ij}}]$$

The matrix P^{-1} is partitioned to the following form:

$$P^{-1} = [P^*_{ij}] = [\frac{1}{q_{ij}}] = \Lambda + B \quad (13)$$

where Λ is the diagonal part and B is the balance of P^1.

The system control ration relating r to y is $T = [I + PG]^{-1} PGF$. Pre-multiplying of system control ration by $[I + PG]$ yields:

$$[I + PG]T = PGF \quad (14)$$

when P is nonsingular, Pre-multiplying both sides of this equation by P^{-1} yields:

$$[P^{-1} + G]T = GF \quad (15)$$

Using Equation (13) and with G diagonal, Equation (14) can be rearranged as follows:

$$T = [\Lambda + G]^{-1}[GF - BT] \quad (16)$$

This is used to define the desired fixed point mapping where each of the m^2 matrix elements on the right side of Equation (24) can be interpreted as a MISO problem. Proof of the fact that design of each MISO system yields a satisfactory MIMO design is based on the Schauder fixed point theorem [14]. This theorem is described by defining a mapping $Y(T)$ by:

$$Y(T) = [\Lambda + G]^{-1}[GF - BT] \quad (17)$$

where, each member of T is from the accepted set $\Im$. If this mapping has a fixed point i.e. $T \in \Im$ such that $Y(T)=T$, then their T is a solution of Equation (16).

Figure 4 shows the four effective MISO loops resulting from a 2×2 system and the nine effective MISO loops resulting from a 3×3 system. Since Λ and G are both diagonal, the (1,1) element on the right side of Equation (17) for the 3×3 case, for a unit impulse input, yields the output:

$$y_{11} = \frac{q_{11}}{1 + g_1 q_{11}}[g_1 f_{11} - (\frac{t_{21}}{q_{12}} + \frac{t_{31}}{q_{12}})] \quad (18)$$

For each MISO system there is a disturbance input which is a function of all the other loop output. The object of the design is to have each loop track its desired input while minimizing the output due to the disturbance inputs.

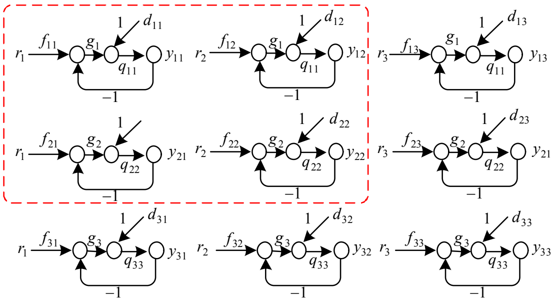

Figure 4. Effective MISO loops 2×2 (boxed-in loops) and 3×3 (all nine loops)

IV. MIXED H_2/ H_∞ CONTROLLER DESIGN FOR UPFC

The main goals of the UPFC controller design are: power system oscillation damping, DC voltage regulator and power flow controller. A damping controller is provided to improve the damping of power system oscillations. This controller may be considered as a lead-lag compensator. The four control parameters of the UPFC (m_B, m_E, δ_B and δ_B) can be modulated in order to produce the damping torque. In this study, m_B is modulated in order to damping controller design. The speed deviation $\Delta\omega$ is considered as the input to the damping controllers. The structure of UPFC based damping controller is shown in Figure 5. It consists of gain, signal washout and phase compensator blocks. The parameters of the damping controller using the phase compensation technique for the nominal operating condition as given in Appendix are obtained as follows:

$$Damping \;\; Controller = \frac{536.0145s(s+3.656)}{(s+0.1)(s+4.5)}$$

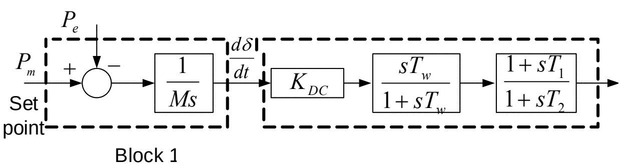

Figure 5. Transfer function block diagram of the UPFC based damping controller

We now proceed to design a decentralized power flow and DC voltage robust controller using the mixed H_2/H_∞ technique. MIMO system shown in Figure 6 decentralized into MISO system as shown in this. For each MISO system there is a disturbance input which is a function of all the other loop output. In fact, using the pervious mentioned procedure the UPFC power flow and DC voltage regulators controllers are designed independently based on mixed H_2/H_∞ technique with this decentralized method.

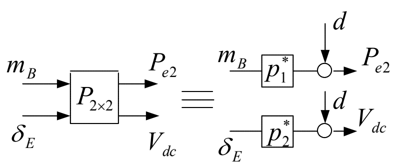

Figure 6. MIMO system translated into MISO system

To achieve our objectives and according to mixed H_2/H_∞ synthesis requirements, we propose the control strategy shown in Figure 7 for a power flow and DC voltage. This figure shows the main synthesis strategy for obtaining the desired decentralized controller. We can redraw Figure 7 as shown in Figure 8.

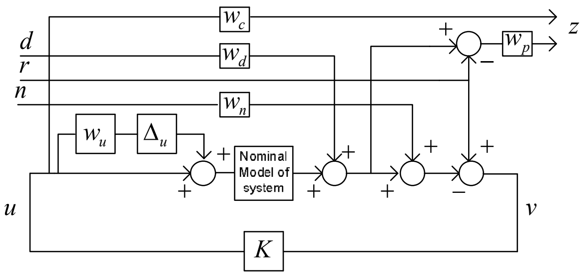

Figure 7. The proposed synthesis strategy for UPFC controller

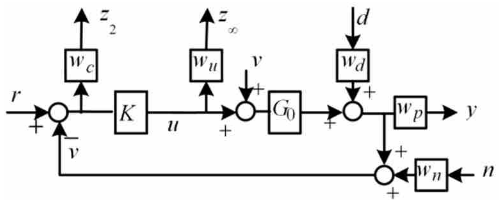

Figure 8. Synthesis framework for UPFC controller

It is shown that combination of H_2 and H_∞ (mixed H_2/H_∞) control techniques gives a powerful multi-objectives design problem. For this reason, the idea of mixed H_2/H_∞ control synthesis which gives a powerful multi-objectives design is used for design UPFC damping controller problem. We can redraw the Figure 6 as a mixed H_2/H_∞ general framework synthesis as shown in Figure 9, where $P(s)$ is the generalized plant that includes nominal system models and associated weighting functions. The state-space model of generalized plant can be obtained as:

$$\begin{aligned} \dot{x}_{GP} &= A_{GP}x_{GP} + B_1 w + B_2 u \\ z_\infty &= C_\infty x_{GP} + D_{\infty 1} w + D_{\infty 2} u \\ z_2 &= C_2 x_{GP} + D_{21} w + D_{22} u \\ y &= C_y x_{GP} + D_{y1} w \end{aligned} \qquad (19)$$

where, $w^T = [v \quad d \quad n \quad y_{ref}]$

Denoting by $T_\infty(s)$ and $T_2(s)$, the transfer functions from w to z_∞ and z_2, respectively, the mixed H_2/H_∞ synthesis problem can be expressed by the following optimization problem: design a controller $K(s)$ that minimize a trade off criterion of the form:

$$\alpha \left\| T_\infty(s) \right\|^2 + \beta \left\| T_2(s) \right\|^2 \qquad (\alpha, \beta \ge 0) \qquad (20)$$

This optimization problem is solved using the *hinfmix* function in the LMI control toolbox of Matlab [19], which gives an optimal controller to achieve the desire level of robust performance.

The designing steps of the proposed method can be summarized as follows:

i) Compute the state space model.

ii) Identify the uncertainty (W_u) and performance weighting functions (W_P and W_C).

iii) Problem formulation as a general mixed H_2/H_∞ control structure according to Figure 9.
iv) Identify the indexes α, β and solve optimization problem in (20) using the '*hinfmix*' function of LMI control toolbox to obtain the desired controller.
v) Reduce the order of resulted controller by using standard model reduction techniques.

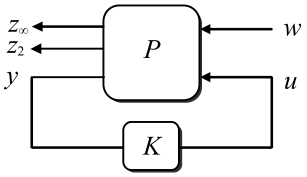

Figure 9. The mixed H_2/H_∞ synthesis structure

V. SIMULATION RESULT AND EVALUATION

For the nominal operation conditions (P = 1 pu, Q = 0.2 pu, V_t = 1.032 pu), we can consider plant shown in Figure 8. P is transfer function of system with damping controller.

A. Weighting Functions Selection

Uncertainty weights selection: For robust control design, an open loop system is represented by nominal plant model $P_{nom}(s)$ and the uncertainty set which covers the differences between $P_{nom}(s)$ and reality of the physical system. Representation of unstructured uncertainty involved using frequency-domain bounds on transfer functions. A power system can possess a large number of topological configuration and steady-state operation points. Variation of these operations points can be viewed as a source of unstructured uncertainty in the nominal linear plant model. The percentage model uncertainty is represented by the weight W_{uPe} and W_{uVdc} which corresponds to the frequency variation of the model uncertainty. These weighting functions are chosen to cover the maximum uncertainly as follows:

$$\omega_{up_e} = \frac{2s}{10.4s+1} \quad , \quad \omega_{uV_{dc}} = \frac{3s}{17.5s+1}$$

Performance weights selection: in order to guarantee robust performance and satisfy the control objectives of SMIB and UPFC problem, we need to add for each of the control P_{e2} and V_{dc}, a fictitious uncertainty block along with the corresponding performance weights W_C and W_P associated with the control effort and control error minimization, respectively. The selection of W_C and W_P entails a trade off among different performance requirements, particularly good regulation versus peak control action. More details on how these weights are chosen are given in [18]. Based on the above discussion, a suitable set of performance weighting functions for P_{e2} and V_{dc} is chosen as:

$$\omega_{P-Vdc} = \frac{425s+42500}{1.5s+1\mathrm{e}^{-5}} \quad , \quad \omega_{C\_VDC} = \frac{0.6s}{0.35s+1}$$

$$\omega_{P-pe} = \frac{60.04s+9000}{1.989s+1\mathrm{e}^{-6}} \quad , \quad \omega_{C\_P_e} = \frac{0.2s}{0.17s+1}$$

$$\omega_{d\_V_{dc}} = 1 \ , \ \omega_{n\_VDC} = 0.05 \ , \ \omega_{d\_P_e} = 0.1 \ , \ \omega_{n\_P_e} = 0.05$$

B. Mixed Controller Design

According to the synthesis methodology described in pervious section, a decentralized robust controller is designed using the '*hinfmix*' function in the LMI control toolbox. This function gives an optimal controller through the mentioned optimization problem (20) with α and *β* fixed at unity. The controllers are reduced to a 4rd order with no performance degradation using the standard Henkel norm approximation. The transfer functions of the reduced order controllers are given by:

$$K_{r-pe} = \frac{1.613e-7s^4+1.177s^3+5.996s^2+39.95s+4.009}{s^4+5.111s^3+36.11s^2+3.597s+0.0001529}$$

$$K_{r-dc} = \frac{0.06443s^4+0.5506s^3+0.5986s^2+0.3395s+0.01737}{s^4+3.36s^3+2.252s^2+0.1189s+9.716e-005}$$

C. Controller Evaluation

The effectiveness of the proposed mixed H_2/H_∞ based controller under different cases is evaluated by time domain simulation to illustrate its robust performance in comparison with the H_∞ based and Conventional UPFC (C-UPFC) controller. In conventional method, P-I type controller is considered for power-flow controller and DC-voltage regulator. Figures 10 and 11 show the transfer function of the P-I type power-flow controller and P-I type DC-voltage regulator, respectively. The optimal parameters of the power-flow controller (k_{pp} and k_{pi}) and DC-voltage regulator (k_{dp} and k_{di}) are obtianed using genetic algorithm [20] for operating condition 1 as listed in Appendix. Optimum values of the power-flow controller are obtained as k_{pp} = 0.5385 and k_{pi} = 1.8259, when the parameter of power-flow controller are set at their optimum values. The parameters of DC-voltage regulator are now optimized and obtained as k_{dp} = 0.398 and k_{di} = 0.5778. The damping controller is considered with the same structure as given in previous section and conventional controllers are designed by application of cited damping controller.

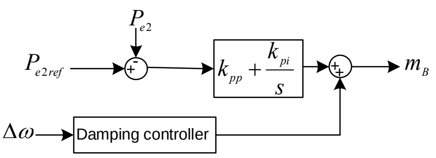

Figure 10. PI- type power flow controller with damping controller

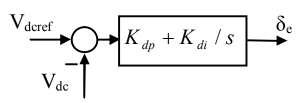

Figure 11. PI-type DC-voltage regulator

The performance of the different controllers with the damping controller m_B following a 10% step change in reference power on line 2 and reference mechanical power, are and shown in Figures 12 to 13 for power flow, DC voltage an frequency deviations. The loading condition and system parameters are given in Appendix. It can be seen that the proposed mixed H_2/H_∞ based UPFC controllers is very effective, achieve good robust performance and compared to other controllers have best ability to damp power system low frequency oscillations.

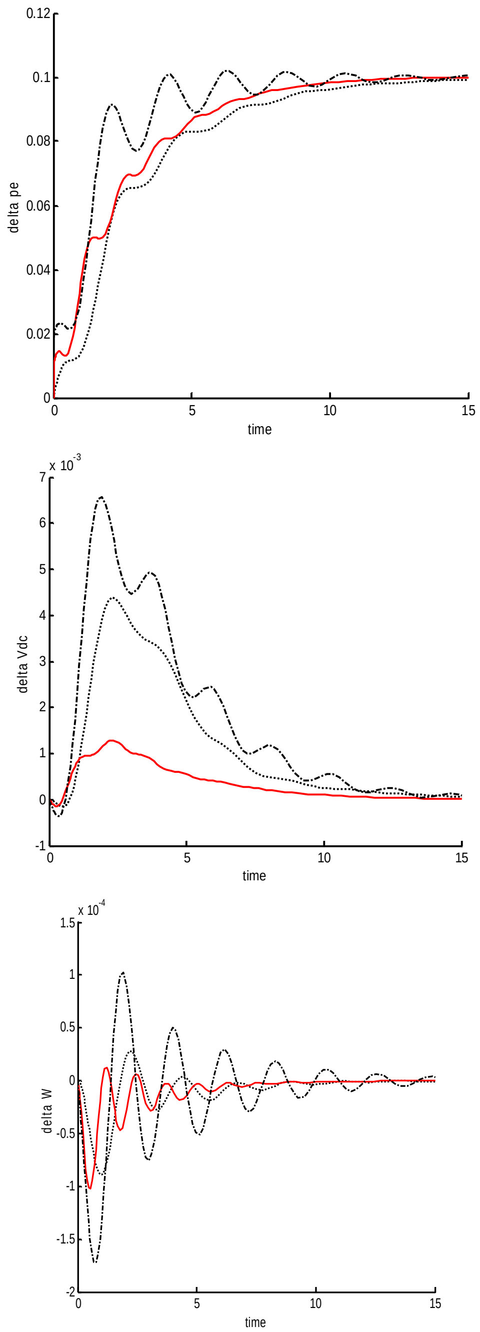

Figure 12. Power system response for operation point 2 (Heavy loading) under $\Delta P_{e2(ref)}$ =0.1 pu; Solid (mixed H$_2$/H$_\infty$), Dotted (H$_\infty$) and Dashed (Conventional)

To demonstrate performance robustness of the proposed control strategy, the Integral of the Time multiplied Absolute value of the Error (ITAE) and Figure of Demerit (FD) based on the system performance characteristics are being used as:

$$ITAE = \int_0^{20} (w_1 |\Delta P_{e2}| + w_2 |\Delta V_{dc}| + w_3 |\Delta \omega|) \cdot t dt \tag{27}$$

$$FD = (OS_w \times 10)^2 + (US_w \times 10)^2 + T_{sw}^2$$

where, $w_1 = 1$, $w_2 = 1000$ and $w_3 = 1000$, Overshoot (OS), Undershoot (US) and settling time of frequency deviation is considered for evaluation of the FD. The values of ITAE and FD are calculated for the different loading conditions as given in Appendix. Tables 1 and 2 show the damping performance of the robust and classical controllers.

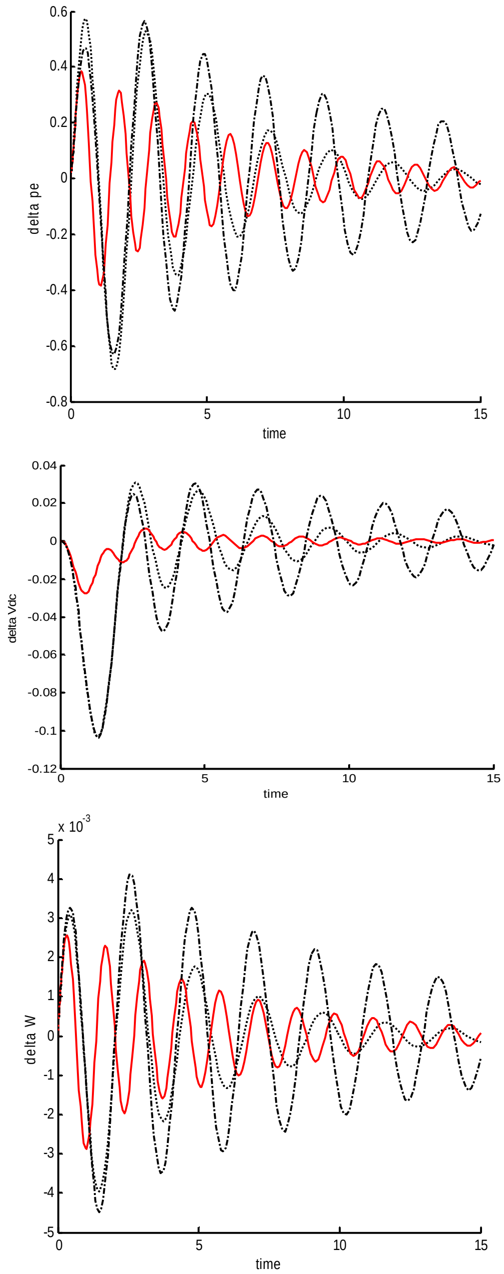

Figure 13. Power system response for operation point 3 (Very heavy loading) under ΔT_m = 0.1 pu; Solid (mixed H$_2$/H$_\infty$), Dotted (H$_\infty$) and Dashed (Conventional)

Table 1. ITAE value

Operating conditions	P_e = 0.1			T_m = 0.1		
	Mixed	H$_\infty$	PI	Mixed	H$_\infty$	PI
1	24.66	28.58	35.70	3.20	4.661	62.77
2	37.01	59.64	360.06	5.15	5.378	396.97
3	15.97	17.55	17.50	4.32	6.1943	39.84

Table 2. FD value

Operating conditions	P_e = 0.1			T_m = 0.1		
	Mixed	H$_\infty$	PI	Mixed	H$_\infty$	PI
1	20.48	48.953	50.61	8.19	40.1028	310.28
2	20.82	58.108	130.52	7.76	46.859	1007.2
3	20.61	47.316	49.09	8.91	37.382	279.78

Examination of Tables 1 and 2 reveal that in comparison with the H_∞ and PI controllers, the system performance is significantly improved by the mixed H_2/H_∞ based controller designed for UPFC in this paper against the loading conditions changes.

VI. CONCLUSIONS

In this paper, a decentralized robust controller for UPFC based on mixed H_2/H_∞ technique is proposed to damp low frequency oscillations. As the power system contains different kinds of uncertainties and disturbances because of increasing the complexity and change of power system structure. Thus, the UPFC damping controller design problem has been formulated as a decentralized multi-objective optimization control problem via a mixed H_2/H_∞ control approach and solved by LMI techniques to obtain optimal controller. Synthesis problem introduce appropriate uncertainties to consider of practical limits, has enough flexibility for setting the desired level of robust performance and leads to a set of simple controllers, which are ideally practical for the real world complex power systems. The simulation results show that the proposed control strategy achieve good performance for damping low frequency oscillations and improves the transient stability under different operating conditions and disturbances. The system performance characteristics in terms of 'ITAE' and 'FD' indices reveal that the proposed method is a promising control scheme for UPFC controller design and superior these of the H_∞ and conventional controllers.

APPENDIX

The nominal parameters and operating condition of the system are listed in Tables 3 and 4. The uncertainty area for active and reactive power is as: $0.7 \le P \le 1.15$ and $0.1 \le Q \le 0.3$.

Table 3. System parameters

Generator	$M = 8$ MJ/MVA	$T'_{do} = 5.044$ s	$X_d = 1$ pu
	$X_q = 0.6$ p.u	$X'_d = 0.3$ pu	$D = 0$
Excitation system		$K_a = 10$	$T_a = 0.05$ s
Transformers		$X_{tE} = 0.1$ pu	$X_E = 0.1$ pu
		$X_B = 0.1$ pu	
Transmission line		$X_{T1} = 1$ pu	$X_{T2} = 1.3$ pu
Operating condition		$P = 0.8$ pu	$Q = 0.15$ pu
		$V_t = 1.032$ pu	
DC link parameter		$V_{DC} = 2$ pu	$C_{DC} = 3$ pu
UPFC parameter		$m_B = 0.104$	$\delta_B = -55.87^\circ$
		$\delta_E = 26.9^\circ$	$m_E = 1.0233$

Table 4. Operating conditions

1. Nominal load	$P = 0.80$	$Q = 0.15$	$V_t = 1.032$
2	$P = 0.90$	$Q = 0.17$	$V_t = 1.032$
3	$P = 1.00$	$Q = 0.20$	$V_t = 1.032$

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BIOGRAPHIES

Farshid Shalchi received the B.S. and M.S. degrees in Electrical Engineering from Ardabil Branch, Islamic Azad University, Ardabil, Iran and Iran University of Science and Technology, Tehran, Iran in 2004 and 2010, respectively. His areas of interest in research are application of robust control to power system control.

Hossein Shayeghi received the B.Sc. and M.S.E. degrees in Electrical and Control Engineering in 1996 and 1998, respectively. He received his Ph.D. degree in Electrical Engineering from Iran University of Science and Technology, Tehran, Iran in 2006. Currently, he is an Associate Professor in Technical Engineering Department, University of Mohaghegh Ardabili, Ardabil, Iran. His research interests are in the application of robust Control, artificial intelligence and heuristic optimization methods to power system control design, operation and planning and power system restructuring. He has authored of five books in Electrical Engineering area, one in power systems analysis, one in Matlab, one in electric circuits, one in electric DC machines, and one in electric installations (all in Persian). Also, he is co-authored of a book chapter "A Review on Load Frequency Control Strategies" in the book "Complex Behaviour of the Distributed Generation System: Intelligent Management of the Renewable Energy Resources for assuring the DG System Power Quality and a Sustainable Development". He has been published more than 210 papers in international journals and conference proceedings. He is a member of Iranian Association of Electrical and Electronic Engineers (IAEEE) and IEEE.

Heidarali Shayanfar received the B.S. and M.S.E. degrees in Electrical Engineering in 1973 and 1979, respectively. He received his Ph.D. degree in Electrical Engineering from Michigan State University, USA, in 1981. Currently, he is a Full Professor in Electrical Engineering Department of Iran University of Science and Technology, Tehran, Iran. His research interests are in the application of artificial intelligence to power system control design, dynamic load modeling, power system observability studies, voltage collapse, and congestion management in a restructured power system, reliability improvement in distribution systems and reactive pricing in deregulated power systems. He has published more than 405 technical papers in the international journals and conferences proceeding. He is a member of Iranian Association of Electrical and Electronic Engineers and IEEE.