ROBUST DAMPING CONTROL DESIGN FOR UPFC USING MIXED $H_2/ H_\infty$ 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 $H_2/H_\infty$ 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 $H_\infty$ 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 $H_2/H_\infty$ 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 $H_2/H_\infty$, 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 $H_2/H_\infty$ control technique for UPFC damping controller design problem is proposed [13]. This newly developed design strategy combines advantage of the $H_2$ and $H_\infty$ 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 $H_2/H_\infty$ control technique and solved by the LMI approach to obtain the desired robust controllers [15, 16]. The proposed 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 $H_\infty$ 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 $m_E$, $m_B$, $\delta_E$ and $\delta_B$, where, $m_E$ is the excitation amplitude modulation ratio, $m_B$ is the boosting amplitude modulation ratio, $\delta_E$ is the excitation phase angle and $\delta_B$ is the boosting phase angle [17, 18].

\[ A = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ -K_{qu} & -K_{pd} & 0 & 0 & 0 \\ K_1 & 0 & K_2 & 0 & 0 \\ T_{do} & T_{do} & T_{do} & T_{do} & 0 \\ K_4 & K_5 & 0 & K_6 & 0 \\ T_{do} & T_{do} & T_{do} & T_{do} & 0 \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix} \]

\[ B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ -K_{pc} & -K_{pd} & 0 & 0 & 0 \\ K_1 & 0 & K_2 & 0 & 0 \\ T_{do} & T_{do} & T_{do} & T_{do} & 0 \\ K_4 & K_5 & 0 & K_6 & 0 \\ T_{do} & T_{do} & T_{do} & T_{do} & 0 \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix} \]

**III. DECENTRALIZED CONTROLLER SCHEME**

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:

\[ \Delta \delta = \omega_0 \Delta \omega \]  
\[ \Delta \omega = (-\Delta P_c - D \Delta \omega) / M \]  
\[ \Delta E_q' = (-\Delta E_q + \Delta E_{qd}) / T_{do}' \]

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:

\[ \Delta \delta = \omega_0 \Delta \omega \]  
\[ \Delta \omega = (-\Delta P_c - D \Delta \omega) / M \]  
\[ \Delta E_q' = (-\Delta E_q + \Delta E_{qd}) / T_{do}' \]
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:

$$P(s) = [P_y](s) = \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1m} \\ P_{21} & P_{22} & \cdots & P_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ P_{ml} & P_{m2} & \cdots & P_{mm} \end{bmatrix}$$  \hspace{1cm} (7)

$$G(s) = \text{diag}\{g_i(s)\} = \begin{bmatrix} g_1 & 0 & \cdots & 0 \\ 0 & g_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & g_m \end{bmatrix}$$  \hspace{1cm} (8)

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

The inverse of the plant matrix is given by:

$$P(s)^{-1} = \begin{bmatrix} P_{11}^{-1} & P_{12}^{-1} & \cdots & P_{1m}^{-1} \\ P_{21}^{-1} & P_{22}^{-1} & \cdots & P_{2m}^{-1} \\ \vdots & \vdots & \ddots & \vdots \\ P_{ml}^{-1} & P_{m2}^{-1} & \cdots & P_{mm}^{-1} \end{bmatrix}$$  \hspace{1cm} (10)

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:

$$q_{ij} = \frac{1}{P_{ij}^*} = \frac{\det\ p}{\text{adj}\cdot P_{ij}}$$  \hspace{1cm} (11)

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

$$Q = \begin{bmatrix} q_{11} & q_{12} & \cdots & q_{1m} \\ q_{21} & q_{22} & \cdots & q_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ q_{ml} & q_{m2} & \cdots & q_{mm} \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1m} \\ P_{21} & P_{22} & \cdots & P_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ P_{ml} & P_{m2} & \cdots & P_{mm} \end{bmatrix}$$  \hspace{1cm} (12)

where,

$$P = [P_y], \quad P^{-1} = [P_y^*] = \left[\frac{1}{q_{ij}}\right], \quad Q = [q_{ij}] = \left[\frac{1}{P_{ij}^*}\right]$$

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

$$P^{-1} = [P_y^*] = \left[\frac{1}{q_{ij}}\right] = \Lambda + B$$  \hspace{1cm} (13)

where $\Lambda$ is the diagonal part and $B$ is the balance of $P^*$. The system control ration relating $r$ to $y$ is $T = [I + PG]^{-1}PFG$. Pre-multiplying of system control ration by $[I + PG]$ yields:

$$[I + PG]T = PFG$$  \hspace{1cm} (14)

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

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

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

$$T = [\Lambda + G]^{-1}[GF - BT]$$  \hspace{1cm} (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:

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

where, each member of $T$ is from the accepted set $\mathcal{T}$. If this mapping has a fixed point i.e. $T \in \mathcal{T}$ 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 $\Lambda$ 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:

$$y_{11} = \frac{q_{11}}{1 + q_{11} g_{11}} \left[ g_{11} f_{11} - \left( \frac{t_{11}}{1 + q_{12} g_{12}} + \frac{t_{12}}{q_{12}} \right) \right]$$  \hspace{1cm} (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.
To achieve our objectives and according to mixed $H_2/H_\infty$ 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 8. Synthesis framework for UPFC controller](https://example.com/figure8.png)

It is shown that combination of $H_2$ and $H_\infty$ (mixed $H_2/H_\infty$) control techniques gives a powerful multi-objectives design problem. For this reason, the idea of mixed $H_2/H_\infty$ 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 $H_2/H_\infty$ 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:

$$
A_{GP}x_{GP} + B_1w + B_2u = \begin{bmatrix} w_1 & w_2 \end{bmatrix}w = \begin{bmatrix} v \end{bmatrix}v, \quad y = \begin{bmatrix} y_1 & y_2 \end{bmatrix}y,
$$

where, $w = \begin{bmatrix} v & d & n & \text{ref} \end{bmatrix}$.

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

$$
\alpha \|T_\varepsilon(s)\|^2 + \beta \|T_z(s)\|^2 \quad (\alpha, \beta > 0)
$$

This optimization problem is solved using the hinfnorm function in the LMI control toolbox of Matlab [19], which gives an optimal controller to achieve the desired 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 ($W_\varepsilon$) and performance weighting functions ($W_p$ and $W_c$).
iii) Problem formulation as a general mixed \( H_2/H_\infty \) control structure according to Figure 9.

iv) Identify the indexes \( \alpha, \beta \) 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.

\[
\begin{align*}
&\frac{\omega_{up}}{10.4s + 1}, \quad \frac{\omega_{up}V_{dc}}{1.989s + 1} \\
&\text{Performance weights selection: in order to guarantee robust performance and satisfy the control objectives of SMIB and UPFC problem, we need to add for each of the control } P_c \text{ and } V_{dc}, \text{ a fictitious uncertainty block along with the corresponding performance weights } W_C \text{ and } W_P \text{ associated with the control effort and control error minimization, respectively. The selection of } W_C \text{ and } W_P \text{ entails a trade off among different performance requirements, particularly good regulation versus peak control action. More details on how these weights are chosen are given in [18]. Based on the above discussion, a suitable set of performance weighting functions for } P_c \text{ and } V_{dc}, \text{ is chosen as:}
\end{align*}
\]

\[
\begin{align*}
&\omega_{P_{-Vdc}} = \frac{425s + 42500}{1.5s + 1e^{-5}}, \quad \omega_{C_{-Vdc}} = \frac{0.6s}{0.35s + 1} \\
&\omega_{P_{-pe}} = \frac{60.04s + 9000}{1.989s + 1e^{-6}}, \quad \omega_{C_{-pe}} = \frac{0.2s}{0.17s + 1} \\
&\omega_{d_{-e}} = 1, \quad \omega_{d_{-JDC}} = 0.05, \quad \omega_{e_{-pe}} = 0.1, \quad \omega_{e_{-pe}} = 0.05
\end{align*}
\]

**V. SIMULATION RESULT AND EVALUATION**

For the nominal operation conditions \((P = 1 \, \text{pu}, \quad Q = 0.2 \, \text{pu}, \quad V_r = 1.032 \, \text{pu})\), 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 \( W_{or} \) and \( W_{slidc} \) which corresponds to the frequency variation of the model uncertainty. These weighting functions are chosen to cover the maximum uncertainty as follows:

\[
\begin{align*}
\omega_{up} = \frac{2s}{10.4s + 1}, \quad \omega_{up}V_{dc} = \frac{3s}{17.5s + 1}
\end{align*}
\]

**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 \( P_c \) 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 \( P_c \) and \( V_{dc} \), is chosen as:

\[
\begin{align*}
&\omega_{P_{-Vdc}} = \frac{425s + 42500}{1.5s + 1e^{-5}}, \quad \omega_{C_{-Vdc}} = \frac{0.6s}{0.35s + 1} \\
&\omega_{P_{-pe}} = \frac{60.04s + 9000}{1.989s + 1e^{-6}}, \quad \omega_{C_{-pe}} = \frac{0.2s}{0.17s + 1} \\
&\omega_{d_{-e}} = 1, \quad \omega_{d_{-JDC}} = 0.05, \quad \omega_{e_{-pe}} = 0.1, \quad \omega_{e_{-pe}} = 0.05
\end{align*}
\]

**B. Mixed Controller Design**

According to the synthesis methodology described in a 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 \( \alpha \) and \( \beta \) 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:

\[
\begin{align*}
K_{r_{pe}} &= \frac{1.613s^4 - 7s^4 + 1.177s^4 + 5.996s^2 + 39.95s + 4.009}{s^4 + 5.111s^3 + 36.11s^2 + 3.597s + 0.0001529} \\
K_{r_{dc}} &= \frac{0.06443s^4 + 5.506s^3 + 0.5986s^2 + 0.3395s + 0.01737}{s^4 + 3.36s^3 + 2.252s^2 + 0.1189s + 9.716e^{-005}}
\end{align*}
\]

**C. Controller Evaluation**

The effectiveness of the proposed mixed \( H_2/H_\infty \) based controller under different cases is evaluated by time domain simulation to illustrate its robust performance in comparison with the \( H_\infty \) 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 \( (k_{pp} \text{ and } k_{dp}) \) and DC-voltage regulator \( (k_{dp} \text{ and } k_{d}) \) are obtained 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 \( k_{dp} = 1.8259 \), 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 \( k_{d} = 0.5778 \). 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 9. The mixed \( H_2/H_\infty \) synthesis structure](image)

![Figure 10. PI-type power flow controller with damping controller](image)

![Figure 11. PI-type DC-voltage regulator](image)
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:

\[
ITAE = \int_0^T \left( w_1 \Delta P_{eq} + w_2 |\Delta V_{dc}| + w_3 |\Delta \phi| \right) \cdot t \cdot dt
\]

\[
FD = (OS_u \times 10)^2 + (US_u \times 10)^2 + T_{sw}^2
\]

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.

<table>
<thead>
<tr>
<th>Operating conditions</th>
<th>( P_e = 0.1 )</th>
<th>( T_m = 0.1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mixed</td>
<td>H( _\infty )</td>
</tr>
<tr>
<td>1</td>
<td>24.66</td>
<td>28.58</td>
</tr>
<tr>
<td>2</td>
<td>37.01</td>
<td>59.64</td>
</tr>
<tr>
<td>3</td>
<td>15.97</td>
<td>17.55</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operating conditions</th>
<th>( P_e = 0.1 )</th>
<th>( T_m = 0.1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mixed</td>
<td>H( _\infty )</td>
</tr>
<tr>
<td>1</td>
<td>20.48</td>
<td>48.95</td>
</tr>
<tr>
<td>2</td>
<td>20.82</td>
<td>58.10</td>
</tr>
<tr>
<td>3</td>
<td>20.61</td>
<td>47.31</td>
</tr>
</tbody>
</table>
Examination of Tables 1 and 2 reveal that in comparison with the \(H_2\) and PI controllers, the system performance is significantly improved by the mixed \(H_2/H_\infty\) 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 \(H_2/H_\infty\) 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 \(H_2/H_\infty\) control approach and solved by LMI techniques to obtain optimal controller. Synthesis problem introduce appropriate uncertainties to consider by LMI techniques to obtain optimal controller. Synthesis of practical limits, has enough flexibility for setting the desired level of robust performance and leads to a set of desired level of robust performance and leads to a set of 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: \(0.7 \leq P \leq 1.15\) and \(0.1 \leq Q \leq 0.3\).

### Table 3. System parameters

<table>
<thead>
<tr>
<th>Generator</th>
<th>(M = 8) MJ/MVA</th>
<th>(X_q = 0.6) p.u.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_{dG})</td>
<td>5.044 s</td>
<td>(X_g = 1) pu</td>
</tr>
<tr>
<td>(X''_g)</td>
<td>0.3 pu</td>
<td>(D = 0)</td>
</tr>
<tr>
<td>Excitation system</td>
<td>(K_e = 10)</td>
<td>(T_e = 0.05) s</td>
</tr>
<tr>
<td>Transformers</td>
<td>(X''_L = 0.1) pu</td>
<td>(X_L = 0.1) pu</td>
</tr>
<tr>
<td>Transmission line</td>
<td>(X_{L1} = 1) pu</td>
<td>(X_{L2} = 1.3) pu</td>
</tr>
<tr>
<td>Operating condition</td>
<td>(P_{ref} = 0.8) pu</td>
<td>(Q_{ref} = 0.15) pu</td>
</tr>
<tr>
<td>DC link parameter</td>
<td>(V_{dc} = 2) pu</td>
<td>(C_{dc} = 3) pu</td>
</tr>
<tr>
<td>UPFC parameter</td>
<td>(m = 0.104)</td>
<td>(\delta = 55.87^\circ)</td>
</tr>
<tr>
<td></td>
<td>(\delta_g = 26.9^\circ)</td>
<td>(m_L = 1.0233)</td>
</tr>
</tbody>
</table>

### Table 4. Operating conditions

| \(P = 0.80\) | \(Q = 0.15\) | \(V_1 = 1.032\) |
| \(P = 0.90\) | \(Q = 0.17\) | \(V_1 = 1.032\) |
| \(P = 1.00\) | \(Q = 0.20\) | \(V_1 = 1.032\) |

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.