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Coordinated Design of Output Feedback PSS and UPFC Controllers for Enhancing Dynamic Stability of Power System

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Abstract

This paper presents a new method for Coordination of UPFC controllers. UPFC is one of the most important FACTS devices which have many applications include damping low-frequency oscillations, transient stability enhancement, active power and reactive power integrated control. Designing the appreciate controller for these devices has a major role in enhancing the stability and damping the oscillations. Using the Power System Stabilizer (PSS) is one of the most important methods for damping low-frequency oscillation which is economically efficient. In recent years, with the development of power electronics, the use of FACTS devices is one of the main strategies for damping low-frequency oscillations. Designing appropriate controllers for these devices has a major role in enhancing the stability and oscillation damping. In this study a new method based on output feedback is proposed for Designing UPFC controller. In this method input of the system expressed in terms of available outputs, so with the right choice of the output feedback gain of the target the system, it become stable. The output feedback gain are designed and compared for various UPFC and PSS controllers.

Keywords: Coordinated Design, Output Feedback, Power System Stabiliser, UPFC

1. Introduction

The rapid increase in load demand from consumers and the development of power grids, lead to expand network and connections between the regions, which leads to low frequency oscillations in power system. If these oscillations are not damped, may increase in terms of amplitude and cause the loss of stability of the system[1]. For several years, Power System Stabilizer (PSS) was the most common controller for damping oscillations. Power system stabilizer generates a supplementary control signal to damp the power system oscillations immediately after a disturbance[2–4]. Different methods have been proposed to design PSS. These methods include pole assignment[5], damping torque concepts[6], H_∞ method[7], nonlinear and variable structure[8,9], the different optimization and artificial intelligence techniques and fuzzy logic[4,10–12] and other approaches. Although PSS is the most important tool for damping oscillations, but in some Operating point it is not capable of damping oscillations, as well as is not capable to improve the voltage profile and power transmission control of the system. Furthermore, the PSS does not guarantee the system stability against sudden and severe disturbances such as three phase short circuit on the generator terminals[1].

Flexible AC Transmission Systems (FACTS) devices are the controllers based on the power electronics which due to advances in power electronics have rapidly expanded on recent years. FACTS devices have been identified as a reliable tool to control and improve the system stability[13–19].

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FACTS devices in addition to enhancing the damping of the power system oscillations, is able to control the power and the voltage of the system. Some of the FACTS devices include the Unified Power Flow Controller (UPFC), STATic synchronous COMpensator (STATCOM), Static Var Compensator (SVC), Inter-phase Power Flow Controller (IPFC), Static Synchronous Series Controller (SSSC), Thyristor Controlled Series Compensator (TCSC), Thyristor Controlled Phase Shifting Transformer (TCPST), and Super Conducting Magnetic Energy Storage (SMES)[3]. Nguyen and Gianto[15] use neural networks for coordination of PSSs and FACTS devices. They also use the optimisation-based control coordination of PSSs and FACTS devices[16]. Many techniques have been reported in the literature on the topic of coordinated design of PSS. Cai and Erlich[20] develop a simultaneous coordinated tuning of PSS and FACTS Damping Controllers in Large Power Systems. However, it has been recognized that a set of PSS parameters which works well under a certain operating condition may no longer yield satisfactory results when there is a drastic change in system operating conditions and configurations.

Among the FACTS devices, the UPFC has more features than other's[21]. UPFC is composed of a STATCOM and a SSSC which are connected by a DC link which is connected to a power system in series and shunt combination[22]. UPFC controls the parameters that influence on power flow, such as fault impedance, voltage magnitude and voltage angle, therefore, it can change the power flow in transmission line. UPFC can be applied to enhance transient stability, voltage control and damping system oscillation in addition to controlling the power flow of the transmission line. UPFC is able to simultaneously or selectively control of all parameters affecting the value of the power in transmission line (voltage, impedance and phase angle). Furthermore, it can be independently control the value of both active and reactive power in transmission line. Recently, many studies has been done in the field of modelling UPFC, dampers controller design for UPFC, use it in power flow and enhance transient stability[23–28]. A neural-network-Based Adaptive UPFC has been implemented for improving transient stability performance of power system in [24]. Ilango et al.[25] developed control algorithms for control of real and reactive power flows and power oscillation damping using UPFC. Intelligence technique has been applied in many researches[4,12,21,26].

In this paper, a novel method for the design of output feedback controller for UPFC is developed in order to enhance the damping of power systems low frequency oscillations. The system under study is a single machine connected to infinite bus equipped with a PSS and a UPFC controller. UPFC has four input controller signal which can be used to design the damping controller. First, the nonlinear and the linear model of the system is presented and then to demonstrate the efficiency of the proposed stabilizers, the results of this controller takes into account a wide range of operating conditions and system configurations and compared with a classic PSS controller.

2. Problem Statement

Figure 1 shows a SMIB system equipped with a UPFC. The power generated by Synchronous generator delivered to the infinite bus by a double-circuit transmission line

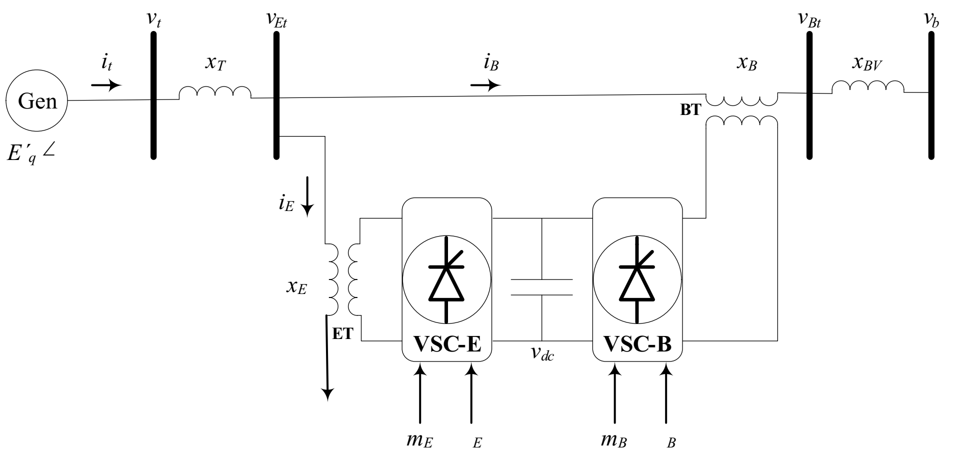

Figure 1. SMIB power system equipped with UPFC.

equipped with 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 DC link provides a path of active power exchange between the converters[11]. 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.

2.1 Power System Non-linear Model

The dynamic model of the UPFC is required in order to study the effect of the UPFC for enhancing the small signal stability of the power system. The system data is given in the Appendix. By applying Park's transformation the non-linear system model with UPFC obtained from neglecting resistance of ET and BT transformers, transmission lines and generators as well as neglecting transients of line and transformers. So, the UPFC can be modeled as [4,12].

$$\begin{bmatrix} v_{Etd} \\ v_{Etq} \end{bmatrix} = \begin{bmatrix} 0 & -x_E \\ x_E & 0 \end{bmatrix} \times \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \begin{bmatrix} \dfrac{m_E \cos\delta_E v_{dc}}{2} \\ \dfrac{m_E \sin\delta_E v_{dc}}{2} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} v_{Btd} \\ v_{Btq} \end{bmatrix} = \begin{bmatrix} 0 & -x_B \\ x_B & 0 \end{bmatrix} \times \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} + \begin{bmatrix} \dfrac{m_B \cos\delta_B v_{dc}}{2} \\ \dfrac{m_B \sin\delta_B v_{dc}}{2} \end{bmatrix} \quad (2)$$

$$\dot{v}_{dc} = \frac{3m_E}{4C_{dc}} \begin{bmatrix} \cos\delta_E & \sin\delta_E \end{bmatrix} \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \frac{3m_B}{4C_{dc}} \begin{bmatrix} \cos\delta_B & \sin\delta_B \end{bmatrix} \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} \quad (3)$$

where v_{Et}, i_E, v_{Bt}, and i_B are the excitation voltage, excitation current, boosting voltage, and boosting current, respectively; C_{dc} and v_{dc} are the DC link capacitance and voltage, respectively.

The non-linear model of the SMIB system of Figure 1 is

$$\dot{\delta} = \omega_b(\omega - 1) \quad (4)$$

$$\dot{\omega} = \frac{P_m - P_e - D(\omega - 1)}{M} \quad (5)$$

$$\dot{E}'_q = \frac{E_{fd} - E_q}{T'_{do}} \quad (6)$$

$$\dot{E}_{fd} = \frac{k_A(v_{ref} - v_t) - E_{fd}}{T_A} \quad (7)$$

where

$$P_e = v_{td} i_d + v_{tq} i_q, \; E_q = E'_q + (x_d - x'_d) i_{td}$$

$$v_t = v_{td} + j v_{tq}, \; v_{td} = x_q i_{tq} \; v_{tq} = E'_q - x'_d i_{td}$$

$$i_{td} = i_{tld} + i_{Ed} + i_{Bd} \; i_{tq} = i_{tlq} + i_{Eq} + i_{Bq}$$

where P_m and P_e are the input and output power, respectively; M and D the inertia constant and damping coefficient, respectively; x_b the synchronous speed; δ and ω the rotor angle and speed, respectively; E'_q, E_{fd} , and v the generator internal, field and terminal voltages, respectively; T'_{do} the open circuit field time constant; x_d , x'_d, and x_q the d-axis reactance, d-axis transient reactance, and q-axis reactance, respectively; k_A and T_A the exciter gain and time constant, respectively; v_{ref} the reference voltage; and U_{PSS} the PSS control signal.

Also, from Figure 1 we can have:

$$\bar{v}_t = jx_T(\bar{i}_B + \bar{i}_E) + \bar{v}_{Et} \quad (8)$$

$$\bar{v}_{Et} = \bar{v}_{Bt} + jx_{Bv}\bar{i}_B + \bar{v}_b \quad (9)$$

where i_t and v_b, are the armature current and infinite bus voltage, respectively; v_{Et}, v_{Bt}, and i_B the ET voltage, BT voltage, and BT current, respectively.

$$\begin{aligned} v_{td} + jv_{tq} &= x_q(i_{Eq} + i_{Bq}) + j(E'_q - x'_d(i_{Ed} + i_{Bd})) \\ &= jx_T(i_{Ed} + i_{Bd} + j(i_{Eq} + i_{Bq})) + v_{Etd} + jv_{Etq} \end{aligned} \quad (10)$$

$$i_{Ed} = \frac{x_{BB}}{x_{d\Sigma}} E'_q - \frac{m_E \sin\delta_E v_{dc} x_{Bd}}{2x_{d\Sigma}} + \frac{x_{dE}}{x_{d\Sigma}}(v_b \cos\delta - \frac{m_B \sin\delta_B v_{dc}}{2}) \quad (11)$$

$$i_{Ed} = \frac{x_{BB}}{x_{d\Sigma}} E'_q - \frac{m_E \sin\delta_E v_{dc} x_{Bd}}{2x_{d\Sigma}} + \frac{x_{dE}}{x_{d\Sigma}}(v_b \cos\delta - \frac{m_B \sin\delta_B v_{dc}}{2}) \quad (12)$$

$$i_{Eq} = \frac{m_E \cos\delta_E v_{dc} x_{Bd}}{2x_{q\Sigma}} - \frac{x_{qE}}{x_{q\Sigma}}(v_b \sin\delta - \frac{m_B \cos\delta_B v_{dc}}{2}) \quad (13)$$

$$i_{Bd} = \frac{x_E}{x_{d\Sigma}} E'_q + \frac{m_E \sin\delta_E v_{dc} x_{dE}}{2x_{d\Sigma}} - \frac{x_{dt}}{x_{d\Sigma}}(v_b \cos\delta + \frac{m_B \sin\delta_B v_{dc}}{2}) \quad (14)$$

where

$$x_{q\Sigma} = (x_q + x_T + x_E)(x_B + x_{Bv}) + x_E(x_q + x_T)$$

$$x_{Bq} = x_q + x_T + x_B + x_{Bv}$$

$$x_{qt} = x_q + x_T + x_E, x_{qE} = x_q + x_T$$

$$x_{d\sum} = (x_d' + x_T + x_E)(x_B + x_{Bv}) + x_E(x_d' + x_T)$$

$$x_{Bd} = x_d' + x_T + x_B + x_{Bv}, \; x_{Bd} = x_d' + x_T + x_E$$

$$x_{dE} = x_d' + x_T, x_{BB} = x_B + x_{Bv}$$

where x_E, x_B are the ET and BT reactances, respectively.

2.2 Power System Linearized Model

Considering the equations of the system and their linearization around a given operating point, the state-space of the power system with UPFC is expressed as follows. Where signals m_E, m_B, δ_E, and δ_B are UPFC control signals that are shown in Figure 1.

$$\Delta\dot{\delta} = \omega_b \Delta\omega \tag{15}$$

$$\Delta\dot{\omega} = \frac{-\Delta P_e - D\Delta\omega}{M} \tag{16}$$

$$\Delta\dot{E}_q' = \frac{\Delta E_{fd} - (x_d - x_d')\Delta i_{td} - \Delta E_q'}{T_{do}'} \tag{17}$$

$$\Delta\dot{E}_{fd} = \frac{k_A(\Delta v_{ref} - \Delta v_t) - \Delta E_{fd}}{T_A} \tag{18}$$

$$\Delta\dot{v}_{dc} = k_7\Delta\delta + k_8\Delta E_q' + k_9\Delta V_{dc} + k_{dme}\Delta m_E + k_{d\delta e}\Delta\delta_E + k_{dmb}\Delta m_B + k_{d\delta b}\Delta\delta_B \tag{19}$$

where

$$\Delta P_e = k_1\Delta\delta + k_2\Delta E_q' + k_{pdc}\Delta V_{dc} + k_{pme}\Delta m_E + k_{p\delta e}\Delta\delta_E + k_{pmb}\Delta m_B + k_{p\delta b}\Delta\delta_B \tag{20}$$

$$\Delta E_q' = k_4\Delta\delta + k_3\Delta E_q' + k_{edc}\Delta V_{dc} + k_{eme}\Delta m_E + k_{e\delta e}\Delta\delta_E + k_{emb}\Delta m_B + k_{e\delta b}\Delta\delta_B \tag{21}$$

$$\Delta v_t = k_5\Delta\delta + k_6\Delta E_q' + k_{vdc}\Delta V_{dc} + k_{vme}\Delta m_E + k_{v\delta e}\Delta\delta_E + k_{vmb}\Delta m_B + k_{v\delta b}\Delta\delta_B \tag{22}$$

where k_1, k_2, …, k_9, k_{du}, k_{pu}, k_{eu}, and k_{vu} are linearization constants.

In state-space representation, the power system can be modeled as:

$$\dot{X} = AX + BU \tag{23}$$

where the state vector X and control vector U are:

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E}_q' \\ \Delta\dot{E}_{fd} \\ \Delta\dot{v}_{dc} \end{bmatrix} = \begin{bmatrix} 0 & \omega_0 & 0 & 0 & 0 \\ -\frac{k_{p\delta}}{M} & 0 & -\frac{k_{peq}}{M} & 0 & -\frac{k_{pdc}}{M} \\ -\frac{k_{e\delta}}{T_{do}'} & 0 & -\frac{k_{eq}}{T_{do}'} & \frac{1}{T_{do}'} & -\frac{k_{edc}}{T_{do}'} \\ -\frac{k_A k_{v\delta}}{T_A} & 0 & -\frac{k_A k_{veq}}{T_A} & -\frac{1}{T_A} & -\frac{k_A k_{vdc}}{T_A} \\ k_{d\delta} & 0 & k_{deq} & 0 & k_{ddc} \end{bmatrix} \times \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E_q' \\ \Delta E_{fd} \\ \Delta v_{dc} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ -\frac{k_{pe}}{M} & -\frac{k_{p\delta e}}{M} & -\frac{k_{pmb}}{M} & -\frac{k_{p\delta b}}{M} \\ -\frac{k_{e\delta}}{T_{do}'} & -\frac{k_{e\delta e}}{T_{do}'} & -\frac{k_{emb}}{T_{do}'} & -\frac{k_{e\delta b}}{T_{do}'} \\ -\frac{k_A k_{ve}}{T_A} & -\frac{k_A k_{v\delta e}}{T_A} & -\frac{k_A k_{vmb}}{T_A} & -\frac{k_A k_{v\delta b}}{T_A} \\ k_{de} & k_{d\delta e} & k_{dmb} & k_{d\delta b} \end{bmatrix} \times \begin{bmatrix} \Delta m_E \\ \Delta\delta_E \\ \Delta m_B \\ \Delta\delta_B \end{bmatrix} \tag{24}$$

The block diagram of the linearized dynamic model of the SMIB power system with UPFC is shown in Figure 2.

3. Simulation Results

The potential of the output feedback UPFC controllers to enhance the dynamic stability is evaluated. To ensure the robustness of the proposed damping controller, the design process takes into account a wide range of operating conditions and system configurations. It should be noted that the four control parameter (m_E ،m_B ،δ_E and δ_B) in the UPFC, can be used as regulator to reduce the power system transient oscillations. In this paper, m_B and δ_E have been used for this purpose. And results

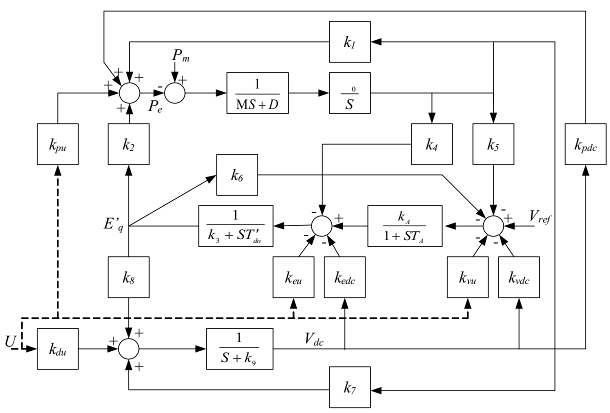

Figure 2. Modified Heffron–Phillips transfer function model.

are compared with the classical method of power system stabilizer. The desired controller must be capable of optimal performance in all operating conditions, especially in critical situations that require a reduction in oscillations. Therefore, several operating conditions have considered that are as follows:

- Nominal loading: P = 0.8 pu, Q = 2.14 pu and X_{BV} = 0.25 pu.
- Heavy loading: P = 1.2 pu, Q = 2.36 pu and X_{BV} = 0.25 pu.
- Light loading: P = 0.2 pu, Q = 1.98 pu and X_{BV} = 0.25 pu.

In this paper, the performance of the desired output feedback controller in the transient conditions has been investigated with a 10% initiate change within the input power generators. The power deviation, the generator terminal voltage deviation and generator speed deviation in the different operating conditions, based on the output feedback controller, with the input of m_B and δ_E and also power system stabilizer, are shown in Figures 3 to 11. This demonstrates that the overshoot, undershoot, settling time and speed deviations of the machine are greatly reduced by applying the proposed output feedback UPFC controller. Moreover, it can be concluded that the δ_E controller is the most robust controller.

4. Conclusion

UPFC is one of the FACTS device which is capable of controlling power and voltage simultaneously and can also improve network stability. Improve the transient stability

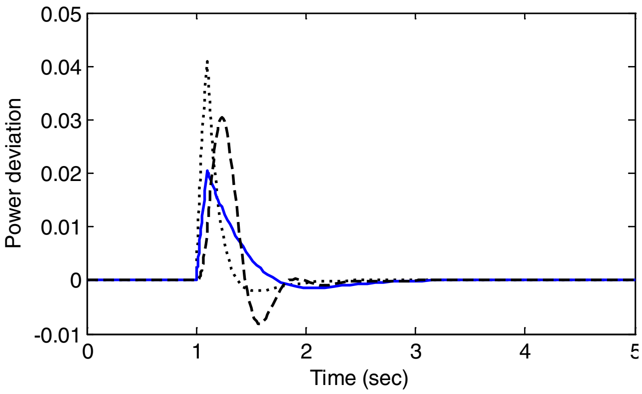

Figure 3. Dynamic responses for power deviation at nominal loading (*PSS*: dotted, m_B: dashed, and δ_E: solid).

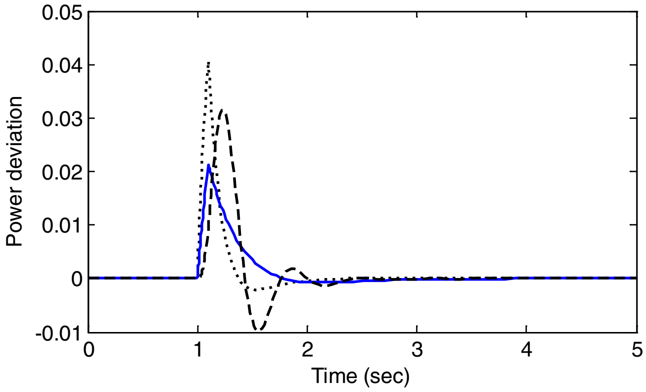

Figure 4. Dynamic responses for power deviation at heavy loading (*PSS*: dotted, m_B: dashed, and δ_E: solid).

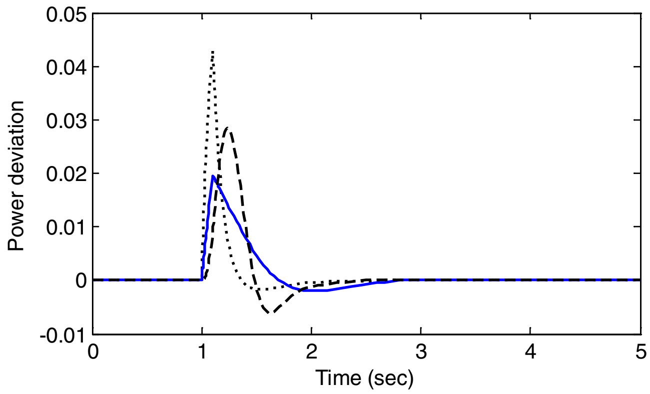

Figure 5. Dynamic responses for power deviation at light loading (*PSS*: dotted, m_B: dashed, and δ_E: solid).

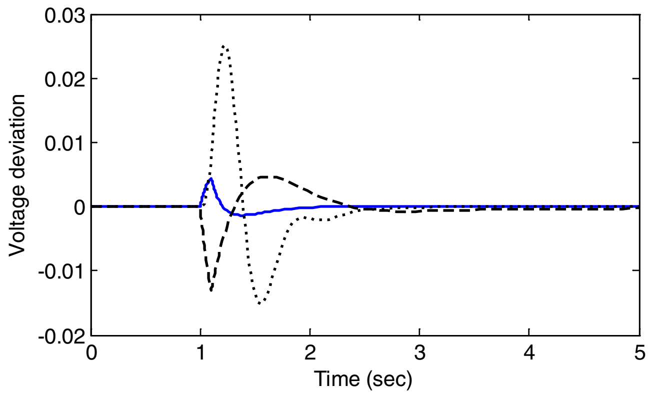

Figure 6. Dynamic responses for voltage deviation at nominal loading (*PSS*: dotted, m_B: dashed, and δ_E: solid).

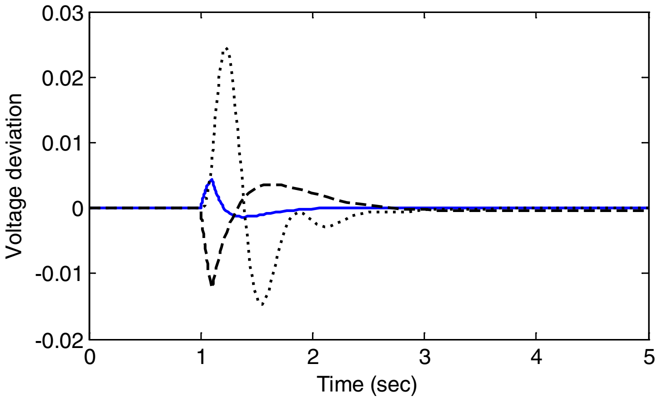

Figure 7. Dynamic responses for voltage deviation at heavy loading (*PSS*: dotted, m_B: dashed, and δ_E: solid).

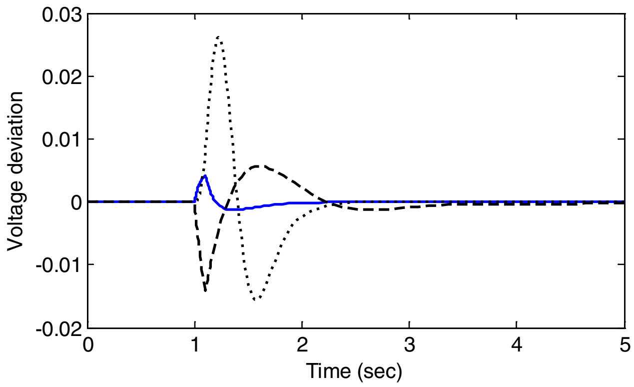

Figure 8. Dynamic responses for voltage deviation at light loading (*PSS*: dotted, m_B: dashed, and δ_E: solid).

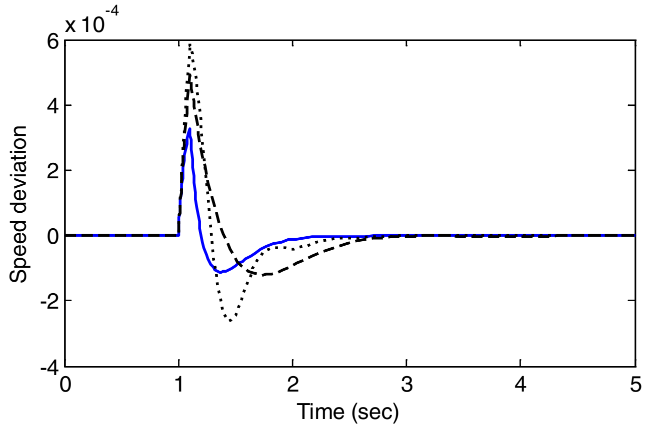

Figure 9. Dynamic responses for speed deviation at nominal loading (*PSS*: dotted, m_B: dashed, and δ_E: solid).

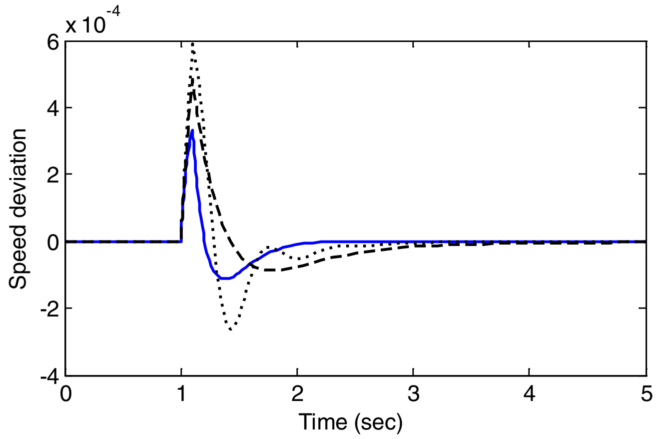

Figure 10. Dynamic responses for speed deviation at heavy loading (*PSS*: dotted, m_B: dashed, and δ_E: solid).

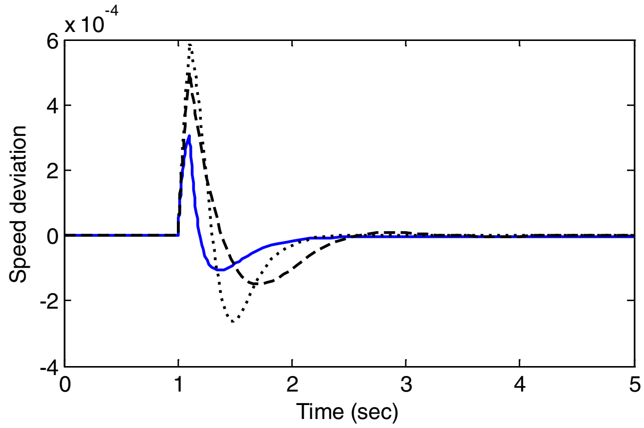

Figure 11. Dynamic responses for speed deviation at light loading (*PSS*: dotted, m_B: dashed, and δ_E: solid).

performance using the output feedback UPFC controller was studied in this paper. To ensure the robustness of the proposed damping controller, the design process was taken into account a wide range of operating conditions and system configurations. The simulation results of the proposed output feedback UPFC controllers at the different disturbances confirmed the high performance of this method compared with conventional PSS. Moreover, the system performance analysis under different operating conditions show that the δ_E based controller is superior to the m_B based controller. Therefore by using controllers based on δ_E can achieve more appropriate dynamic stability in the power system.

5. Appendix

The nominal parameters and operating condition of the system are listed in Table 1.

Table 1. The test system parameters of SMIB and UPFC

Generator	$M = 8$ MJ/MVA; $T'_{do} = 5.044$ s; $D = 0$; $w_b = 120\pi$ rad/s; $x_d = 1$; $x_q = 0.6$; $x'_d = 0.3$;
Excitation System	$k_A = 10$; $T_A = 0.05$ s;
Transformer	$x_T=0.1$; $x_B=0.1$;
Transmission Lines	$x_{BV} = 0.25$;
UPFC Parameters	$m_B = 0.08$; $\delta_B = -78.21°$; $m_E = 0.4$; $\delta_B = -85.35°$; $k_s = 1$; $T_s = 0.05$ s;
DC link Parameters	$v_{dc} = 1$; $C_{dc} = 1$;
Operating Condition	$v_t = 1.0$; $v_b = 1.0$; $P_e = 0.8$; $Q_e = 2.14$;

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