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# Tracking of Reference Signals by Advanced Unified Power Flow Controller

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***Abstract-*** Unified Power Flow Controller (UPFC) is the most real time multivariable device among the different FACTS controllers. Control of power flow in the transmission line is the most important property of UPFC. Due to importance of power flow control in transmission lines, the proper controller should be reliable against uncertainty and faults . For this purpose, an advanced controller is designed based on the Lyapunov theory . The main objective of this paper is to design an advanced controller which enables a power system to reach reference signals accurately and to be reliable in the presence of uncertainty of system parameters and faults. The performance of the proposed controller is simulated on a two bus test system and compared with a conventional PI controller. Simulations were carried out using MATLAB software to check the performance of UPFC.

***Index Terms*-** Multivariable device, Power flow control, Two bus system, UPFC

## I. Introduction

Generally the growth of power systems will rely more on increasing capability of existing transmission systems, rather than on building new transmission lines and power stations, for economical and environmental reasons. Due to deregulation of electricity markets, the existence for new controllers capable of increasing transmission capability, controlling power flows through predefined corridors and ensuring the security of energy transactions will certainly increase.

In order to expand or enhance the power transfer capability of existing transmission network the concepts of FACTS (Flexible AC transmission system) is developed by the Electric Power Research Institute (EPRI) in the late 1980s. The main objective of facts devices is to replace the existing slow acting mechanical controls required to react to the changing system conditions by rather fast acting electronic controls. FACTs means alternating current transmissions systems incorporating power electronic based and other static controllers to enhance controllability and increase power transfer capability [1].

The potential benefits with the utilization of flexible ac transmission system (FACTS) devices include reduction of operation and transmission investment costs, increasing system security and reliability, and increasing transfer capabilities in a deregulated environment. FACTS devices are able to change, in a fast and effective way, the network parameters to achieve a better system performance [2].

UPFC is a power electronic based device which can provide a proper control for impedance, phase angle and reactive power of a transmission line. Each converter of a UPFC can independently generate or absorb reactive power. This arrangement enables free flow of active power in either direction between the ac terminals of the two converters. In the case of the parallel branch of UPFC, the active power exchanged with the system, primarily depends on the phase shift of the converter output voltage with respect to the system voltage, and the reactive power is controlled by varying the amplitude of the converter output voltage. However series branch of UPFC controls active and reactive power flows in the transmission line by amplitude and phase angle of series injected voltage. Therefore active power controller can significantly affect the level of reactive power flow and vice versa.

In recent years a number of investigations have been carried out on various capabilities of UPFC such as power flow control, voltage control, transient stability enhancement, oscillation damping and control of active and reactive power flows in transmission lines [3].

The performance of the control scheme deteriorates in the presence of uncertainties in system parameters. In this paper, a new controller of UPFC based on Lyapunov theory for power flow control is designed which is able to reach reference signals accurately and is reliable in the presence of uncertainty of system parameters and faults [8]. The proposed controller is considered as effective controller which always consists of a set of error terms to provide stability condition in the presence of uncertainty and faults.

## II. UPFC model

The schematic diagram of a UPFC is shown in Figure 1. It consists of two back-to-back, self-commutated, voltage source converters connected through a common dc link.

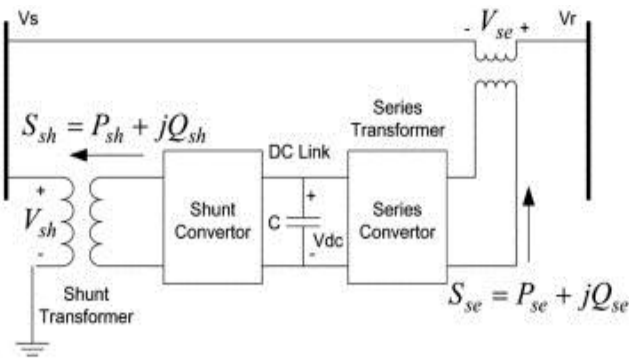


**Figure 1: Schematic diagram of the UPFC system.**

As it can be seen Figure 1 converter1 is coupled to the AC system through a shunt transformer (excitation transformer) and the converter 2 is coupled through a series transformer (boosting transformer). Note that, subscripts'*s*' and '*r*' are used to represent sending and receiving end buses respectively. By regulating the series injected voltage $v_{se}$, the complex power flow ($P_r + jQ_r$) through the transmission line can be controlled. The complex power injected by the converter 2, ($P_{se} + jQ_{se}$) depends on its output voltage and transmission line current. The injected active power $P_{se}$ of the series converter is taken from the dc link, which is in turn drawn from the AC system through the converter 1. On the other hand, both converters are capable of absorbing or supplying reactive power independently. The reactive power of the converter 1 can be used to regulate the voltage magnitude of the bus at which the shunt transformer is connected [4-7].

The single-phase representation of a three-phase UPFC system is shown in Figure 2. In this figure both converters are represented by voltage sources $v_{se}$ and $v_{sh}$, respectively. Also ($R = R_{se} + R_L$) and ($L = L_{se} + L_L$) represent the resistance and leakage inductance of series transformer and transmission line respectively, similarly $R_{sh}$ and $L_{sh}$ represent the resistance and leakage inductance of the shunt transformer respectively.

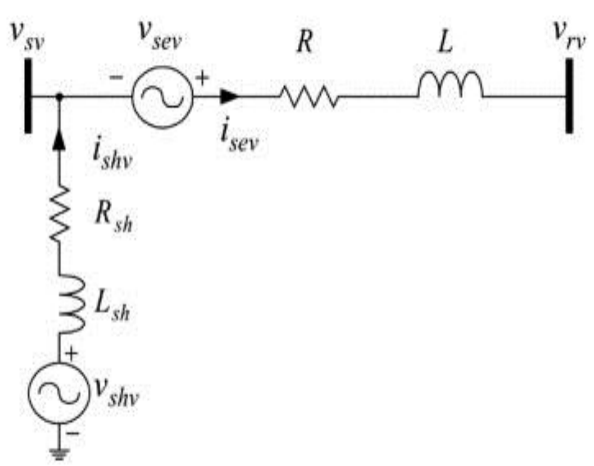


**Figure 2: Single phase representation of the UPFC system**.

The current through the series and shunt branches of the circuit of Figure 2 can be expressed by the following differential equations for one phase of the system. These equations can be written for other phases similarly.

$$\frac{di_{sea}}{dt}=\frac{1}{L}(-Ri_{sea}+v_{sea}+v_{sa}-v_{ra}) \tag{1}$$

$$\frac{di_{sha}}{dt}=\frac{1}{L}(-Ri_{sha}+v_{sha}-v_{sa}) \tag{2}$$

The three-phase system differential equations can be transformed into a "*d, q"* reference frame using Park's transformation as follows:

$$\begin{bmatrix}\dot{i}_{sed}\\ \dot{i}_{seq}\end{bmatrix}=\begin{bmatrix}\frac{-R}{L} & \omega_b\\ -\omega_b & \frac{-R}{L}\end{bmatrix}\cdot\begin{bmatrix}i_{sed}\\ i_{seq}\end{bmatrix}+\frac{1}{L}\begin{bmatrix}v_{sed}+v_{sd}-v_{rd}\\ v_{seq}-v_{rq}\end{bmatrix} \tag{3}$$

$$\begin{bmatrix}\dot{i}_{shd}\\ \dot{i}_{shq}\end{bmatrix}=\begin{bmatrix}\frac{-R_{sh}}{L_{sh}} & -\omega_b\\ -\omega_b & \frac{-R_{sh}}{L_{sh}}\end{bmatrix}\cdot\begin{bmatrix}i_{shd}\\ i_{shq}\end{bmatrix}+\frac{1}{L_{sh}}\begin{bmatrix}v_{shd}+v_{sd}\\ v_{shq}\end{bmatrix} \tag{4}$$

where $\omega_b = 2\pi f_b$, and $f_b$ is the fundamental frequency of the supply voltage. Since the Park's transformation used in finding (3) and (4) keeps the instantaneous power invariant and the *d*-axis lies on the space vector of the sending end voltage $v_s$, thus

$v_s = (v_{sd} + jv_{sq}) = (v_{sd} + j0)$.

Note that in the above equations, subscripts '*d*' and '*q*' are used to represent the direct and quadrature axes components, respectively ($x = x_d + jx_q$).

Since the dynamic equations of converter 1 are identical to that of converter 2 as described before, both converters should have identical control strategy. Therefore for the sake of brevity in this paper only the technique of designing the controller of converter 2 is described in detail in the form of state space.

$$\begin{aligned}\dot{\mathbf{x}}&=\mathbf{Ax}+\mathbf{Bu}+d\\ \mathbf{y}&=\mathbf{Cx}\end{aligned} \tag{5}$$

where $d$ is the uncertainty vector and **x**, **u** and **y** are respectively state, control and output variables vector of converter 2 which are defined as ,$\mathbf{X}=[i_{sed}\ \ i_{seq}]^T$, $\mathbf{u}=[\ v_{sed}\ \ v_{seq}]^T$ and $\mathbf{y}=[i_{sed}\ \ i_{seq}]^T$ .Comparing Eqs (3 )and (5), when $v_s$ and $v_r$ are kept constant, the system matrices **A**, **B**, and **C** can be written as:

$$\mathbf{A}=\begin{bmatrix}-R/L & \omega_b\\ -\omega_b & -R/L\end{bmatrix};\quad \mathbf{B}=\begin{bmatrix}1/L & 0\\ 0 & 1/L\end{bmatrix};\quad \mathbf{C}=\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix} \tag{6}$$

As mentioned previously, the common connection between the two converters is formed by a dc-voltage bus. When the losses in the converters are neglected, the active power balance equation at the dc link can be written as Eq. (8)

$$P_{dc}=P_{se}+P_{sh} \tag{7}$$

where $P_{sh}$ and $P_{se}$ are active power supplied by the converters 1 and 2, respectively which can be obtained as follows:

$$P_{se} = \frac{3}{2}(v_{sed}i_{sed} + v_{seq}i_{seq}) \quad (8)$$

$$P_{sh} = \frac{3}{2}(v_{shd}i_{shd} + v_{shq}i_{shq}) \quad (9)$$

Note that, since the power loss of the shunt transformer can be ignored, active power of converter 1 Eq.(9) can be written approximately as:

$$P_{sh} \approx \frac{3}{2}(v_{sd}i_{shd}) \quad (10)$$

Also the active power of the dc link is represented as equation(11)

$$P_{dc} = v_{dc}i_{dc} = -Cv_{dc}\frac{dv_{dc}}{dt} \quad (11)$$

Substituting Eq.(11) in (7) , Eq.(12) will be obtained.

$$\frac{dv_{dc}}{dt} = -\frac{1}{Cv_{dc}}(P_{se} + P_{sh}) \quad (12)$$

It is clear that the above equation is non linear, therefore for linearizing and simplifying, Eq.(14) is defined by substituting Eq.(13) into (12).

$$\frac{dv_{dc}^2}{dt} = 2v_{dc}\frac{dv_{dc}}{dt} \quad (13)$$

$$\frac{dv_{dc}^2}{dt} = -\frac{2}{C}(P_{se} + P_{sh}) \quad (14)$$

The following section is assigned to introduce the design of a controller based on the Lyapunovtheory. This analysis is based on a simplified mathematical model of the converter connected to a two bus system as shown in Figure 1.

## III. CONTROLLER DESIGN BASED ON LYAPUNOV THEORY

Figure 3 shows the schematic of a system state space. As it was mentioned, the main objective of this paper is to design an advanced controller which enables the power system to track reference signals accurately and to be reliable in the presence of uncertainty of system parameters and faults [8]. To reach this purpose a new controller is designed based on the Lyapunov theory in this paper. The controller based on the Lyapunov method is designed as slope changes of energy function which always remains negative ($\dot{V} < 0$). This energy function consists of a set of error terms which provides stability condition of error terms in the presence of uncertainty and disturbance. Therefore the tracking error and its derivative are defined as below:

$$e = X_d - X \quad (15)$$

$$\dot{\mathbf{e}} = \dot{\mathbf{x}}_d - \dot{\mathbf{x}} \quad (16)$$

where $\mathbf{x}$ is the vector of state variables and $\mathbf{x}_d = [\, i_{sed}^* \quad i_{seq}^* \,]^T$ is the vector of reference signals. In $\mathbf{x}_d$ equation, $i_{sed}^*$ and $i_{seq}^*$ can be obtained similarly by Eq.(8) and (9) knowing the active and reactive power references of transmission line $P_r^*$ and $Q_r^*$

$$i_{sed}^* = \frac{2}{3}\frac{(P_r^* v_{rd} + Q_r^* v_{rq})}{\Delta} \quad (17)$$

$$i_{seq}^* = \frac{2}{3}\frac{(P_r^* v_{rq} - Q_r^* v_{rd})}{\Delta} \quad (18)$$

where
$\Delta = v_{rd}^2 + v_{rq}^2$.

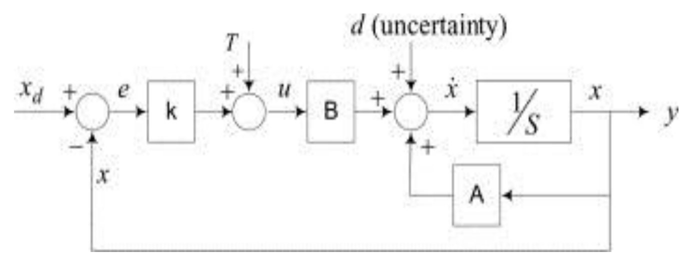


**Figure 3: Schematic of system state space.**

Substituting Eqs. (15) and (16) in (5), the derivative of tracking (dynamic error) can be obtained:

$$\dot{\mathbf{e}} = \mathbf{A}\mathbf{e} + \dot{\mathbf{x}}_d - \mathbf{A}\mathbf{x}_d - \mathbf{d} - \mathbf{B}\mathbf{u} \quad (19)$$

To fulfill stability condition of the system dynamic error, multiplication of control matrix and control variables vector is defined as:

$$\mathbf{B}\mathbf{u} = \mathbf{B}\mathbf{k}\mathbf{e} + \dot{\mathbf{x}}_d - \mathbf{A}\mathbf{x}_d - \mathbf{u}_s \quad (20)$$

$$\mathbf{u} = \mathbf{k}\mathbf{e} + \mathbf{B}^{-1}(\dot{\mathbf{x}}_d - \mathbf{A}\mathbf{x}_d - \mathbf{u}_s) = \mathbf{k}\mathbf{e} + \mathbf{T} \quad (21)$$

The control variables vector (21) is calculated by multiplication of $B^{-1}$ by Eq.(20). The amounts of variables of row matrix **k** at (20) are set such as the whole Eigen values of matrix **(A−Bk)** are laid on the left side of imaginary axis. Vector $u_s$ is also values of matrix **(A−Bk)** are laid on the left side of imaginary axis. Vector $u_s$ is also described as a robustness signal. The function of this vector is to accomplish stability condition based on Lyapunov theory. Therefore by substitution Eq. (20)

into (19), the new equation is obtained for dynamic error of the system.

$$\dot{\mathbf{e}} = \mathbf{A}_0\mathbf{e} - \mathbf{d} + \mathbf{u}_s \quad (22)$$

where in the above equation, $A_0 = A - Bk$

To accomplish stability condition, the robustness signal is defined as below:

$$\mathbf{u}_s = -I^* \frac{|\mathbf{e}^T\mathbf{P}|}{\mathbf{e}^T\mathbf{P}} \cdot d_m = -I^* \cdot d_m \cdot |\mathbf{e}^T\mathbf{P}| \cdot (\mathbf{e}^T\mathbf{P})^{-1} \quad (23)$$

where $I^*$ is a positive number $I^* \geq 1$.

It is necessary to be noted that ($e^TP$) is not a square matrix and therefore pseudo inverse matrix is used to calculate $\mathbf{u}_s$ vector .. The block diagram of the overall UPFCcontrol system is depicted in Figure 4. This block diagram is implemented for *d–q* axis.

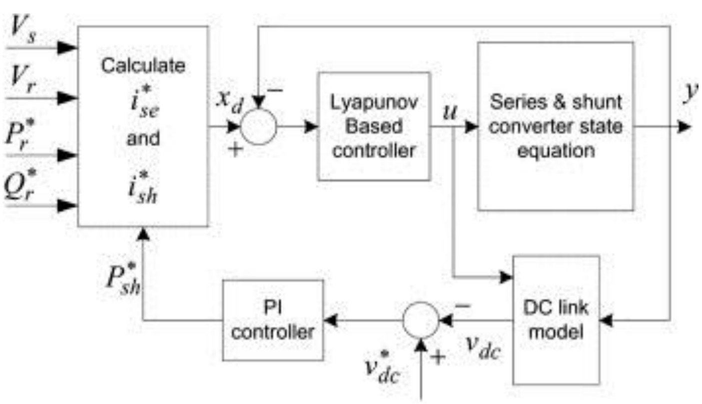


**Figure 4: Block diagram of the overall UPFC control system.**

## IV. SIMULATION RESULTS

In an ideal system, there is no uncertainty in system parameters. However, in a practical system, it is considered that the system parameters are corrupted by some uncertainties. It should be mentioned that such uncertainties are usually present in any physical system and will be often limited to achieve the desired performance. In this paper, the proposed controller is designed so as the uncertainty in the system is reduced. The uncertainty is entered to the system equations as a vector. The performance of the proposed controller, for various disturbances is evaluated through MATLAB/SIMULINK software in a two bus test system. The simulation results of proposed controller are compared with a conventional PI controller. The parameters of converters 1 and 2 of PI controllers are given in Table 1

**TABLE 1**

| parameters | Converter 1 | Converter 2 |
|---|---|---|
| $K_P$ | 0.27 | 0.3 |
| $K_I$ | 62 | 66 |

**TABLE 2**

| parameters | Value |
|---|---|
| *R( pu)* | 0.051 |
| *wL (pu)* | 0.25 |
| $R_{sh}$ *(pu)* | 0.015 |
| $wL_{sh}$ *(pu)* | 0.15 |
| *1/ wC (pu)* | 0.5 |

According to the parameters of the system and UPFC which are presented in the Table 2, the system matrices for these converters are as follow:

$$A_{se} = 100\pi \begin{bmatrix} -0.2 & 1 \\ -1 & -0.2 \end{bmatrix}, \quad B_{se} = 100\pi \begin{bmatrix} 4 & 0 \\ 0 & 4 \end{bmatrix}$$

$$A_{sh} = 100\pi \begin{bmatrix} -0.1 & 1 \\ 1 & -0.1 \end{bmatrix}, \quad B_{sh} = 100\pi \begin{bmatrix} 6.67 & 0 \\ 0 & 6.67 \end{bmatrix}$$

In the above matrices, fundamental frequency ($f_b$) is equal to 50 Hz. In this study, as it is shown in Figure 4 the sending and receiving end bus voltages are maintained constant and the dc link voltage, active and reactive powers of the transmission line are controlled.

The initial complex power flow ($P_r + jQ_r$) at the receiving end of the transmission line is found as (1.278−*j*0.5) p.u. In the first case study, the active power of the transmission line is changed from 1.278 to 2.278 p.u at $t = 2$ s for a system with 10% uncertainty. The simulation results of this study are depicted in Figure 5. It is shown that the speed of response of the proposed controller is much better than that of the conventional controller approach (PI controller).

In the second case study, both the active and reactive powers of the transmission line is changed from initial values to (2.278−*j*0.8) at $t = 2$ s. In this case, the uncertainty factor is considered to be equal to 16%. The simulation results of this scenario are displayed in Figure 6. As mentioned, the reactive power of the transmission line is changed too and the uncertainty factor is changed much more than previous case, but it is seen that the proposed controller has a good response to this changes.

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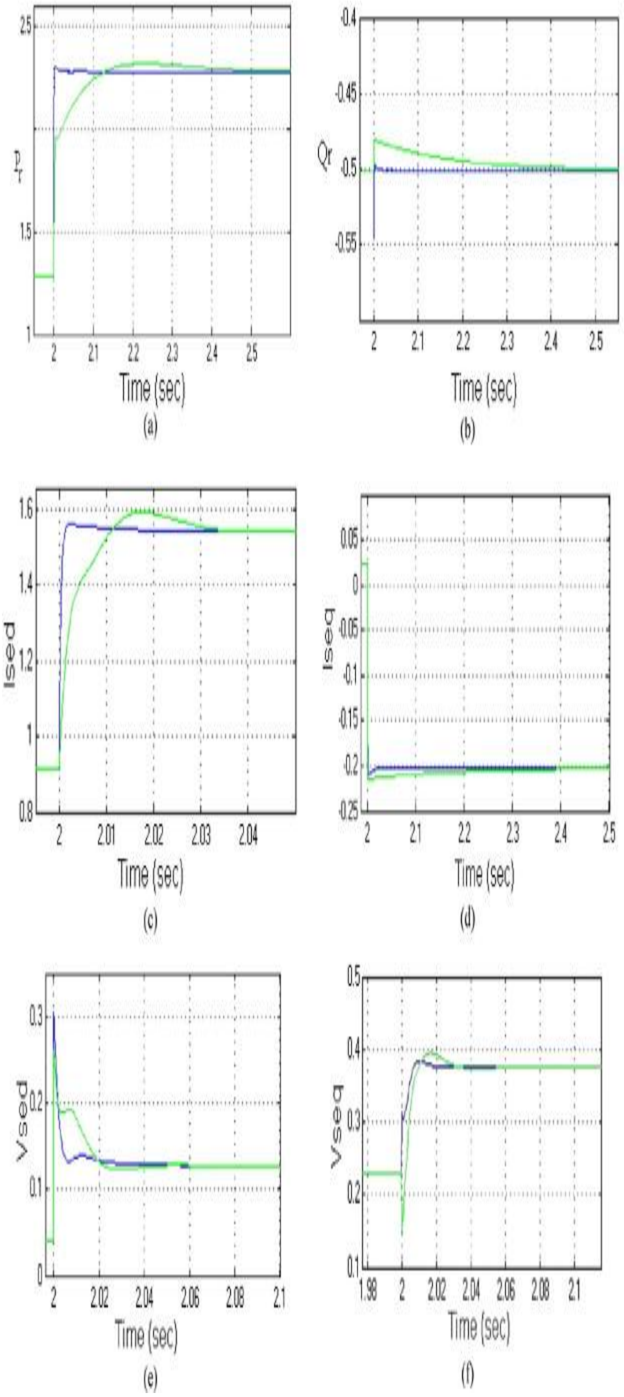


**Figure 5: Response of UPFC system with 10% uncertainty.**

Blue line, advanced controller; green line, PI controller.

(a) Real power of the transmission line;
(b) Kvar power of transmission line;
(c) D axis current reference of converter 2;
(d) **Q** axis current reference of converter 2;
(e) D axis voltage reference of converter 2;
(f) Q axis voltage reference of converter 2.

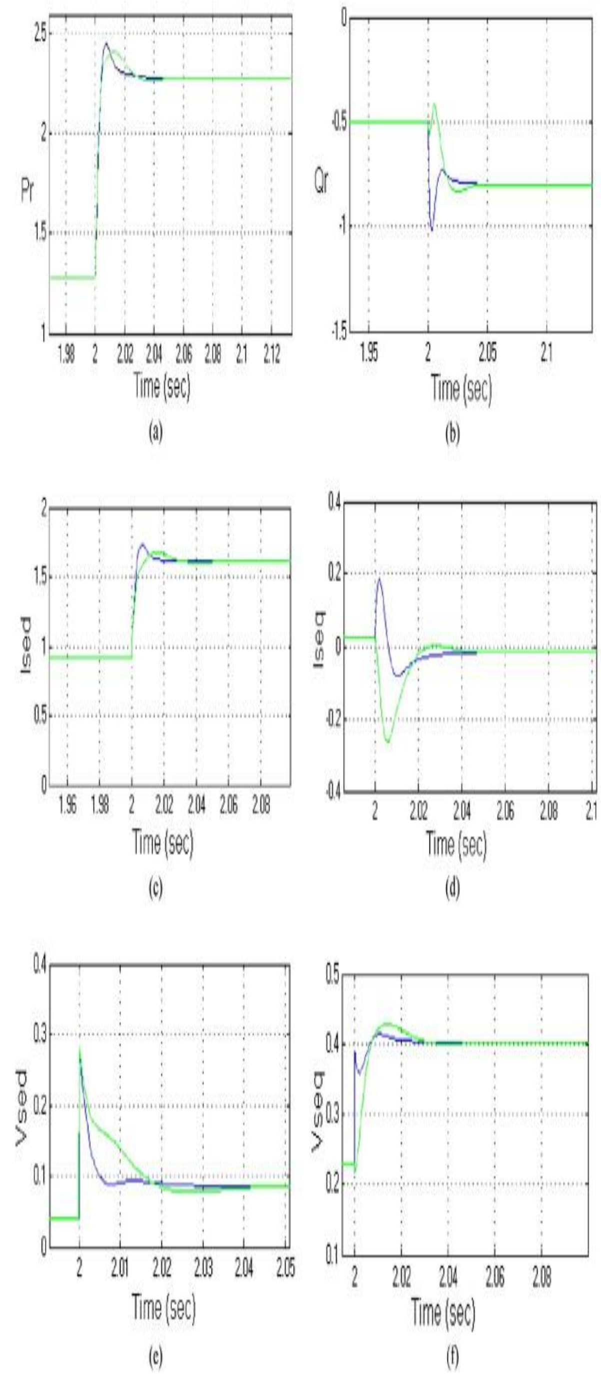


**Figure 6: Response of UPFC system with 16% uncertainty.**

Blue line, advanced controller; green line, PI controller.

(a) Real power of the transmission line;
(b) Kvar power of transmission line;
(c) D axis current reference of converter 2;
(d) Q axis current reference of converter 2;
(e) D axis voltage reference of converter 2;
(f) Q axis voltage reference of converter 2.

## V. CONCLUSION

This paper presented an advanced design of controller which enables a power system to reach reference signals accurately and to be reliable in the presence of uncertainty of system parameters and faults. The new controller which is designed based on the Lyapunov theory is successful in reaching the reference signals. The main advantage of the proposed approach with respect to PI controller is the stability of the closed loop system under uncertainties. The proposed approach also has simple structure and quick performance in comparison with intelligence methods such as fuzzy theory and neural network. The simulation results of the proposed controller are compared with a conventional PI controller and its performance is evaluated in a two bus test system. In this study, the sending and receiving end bus voltages were maintained constant and the dc link voltage, active and reactive powers of the transmission line were controlled. The obtained results from above case studies describe the power, accuracy, fast speed and relatively low overshoot response of the proposed controller.

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