

A robust adaptive fuzzy control of a unified power flow controller

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Abstract

This paper investigates the control of a unified power flow controller (UPFC) to improve the stability of a power system, hence providing security under increased power flow conditions. The proposed control methods include a direct proportional and integral (PI) controller and an adaptive fuzzy logic controller (AFLC). The performances of these controllers were evaluated under different operating conditions of the power system and the results demonstrated that PI and AFLC are very effective in improving the transient power system stability and very robust against variable transmission line parameters.

Key Words: FACTS, UPFC, PI controller, adaptive control, fuzzy logic

1. Introduction

Flexible AC transmission systems (FACTS) are high-power electronics-based devices capable of altering voltage, phase angle, and/or impedance at particular points in power systems [1]. Their fast response offers high-power system stability enhancement, therefore preventing possible voltage collapse. Examples of FACTS include unified power flow controllers (UPFC).

The UPFC is capable of directing real and reactive power flows through a designated route and regulating the system voltage by providing fast reactive power compensation. Consequently, the transmittable power capability of the transmission facilities can be utilized more efficiently.

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The UPFC consists of 2 forced-commutated voltage source converters (VSC) connected through a common DC link. One converter is shunt-connected and the other is connected in series with the transmission line, as illustrated in Figure 1. The name “unified power flow controller” comes from the fact that it is possible for the device to control both transmitted active and reactive power as well as the AC bus voltage at the point where the shunt converter is connected (i.e., point A). The UPFC can provide different functions when the inserted series voltages v_s have different magnitudes and phase angles. It will function as a pure voltage regulator if the inserted series voltage is in phase with the AC bus voltage. It will function as a pure series line compensator if the inserted series voltage is perpendicular to the line current. It is also possible for the UPFC to function as a phase angle regulator. Each UPFC converter can independently generate or absorb reactive power. This arrangement enables the free flow of active power in either direction between the AC terminals of the 2 converters [2]. In the case of the parallel branch of the 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, the series branch of the UPFC controls active and reactive power flows in the transmission line by the amplitude and phase angle of the series injected voltage. Therefore, the active power controller can significantly affect the level of reactive power flow and vice versa.

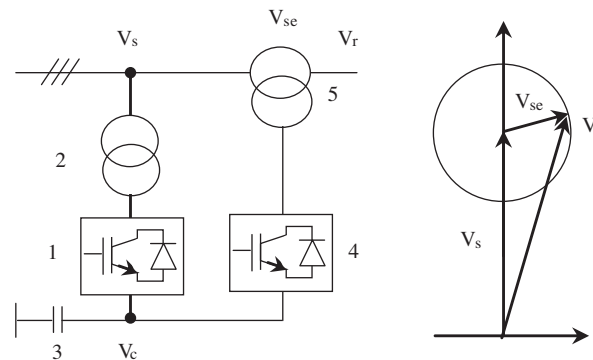


Figure 1. Basic diagram circuit of a UPFC.

To improve the performance of the UPFC, the interaction between the active and reactive power flow control system must be reduced [3]. In recent years, a number of investigations have been carried out to demonstrate the capabilities of UPFC as an effective power flow control [3-8], providing voltage control [9,10], transient stability enhancement [11,13], and oscillation damping [14-18]. It has been reported in the literature that a strong dynamic interaction exists between the active and reactive power flows through a transmission line when they are controlled by series injected voltage v_{se} of the UPFC. Furthermore, the UPFC is highly nonlinear because it consists of converters, power transformers, filters, and surge arrestors. Uncertainties in the power system make it difficult to model the transmission system accurately [21].

Control schemes based on fuzzy logic, neural networks, and adaptive techniques are useful for modeling and/or controlling systems characterized by uncertainties and nonlinearities. Fuzzy logic control application to power systems has been an active research area for the last 2 decades [22,23]. In this paper, a new adaptive fuzzy logic-based controller (AFLC) is designed and applied to the control of the UPFC. The proposed controller ensures accurate tracking of the reference signals and is robust against parameter uncertainty and disturbances acting on the power system. The proposed controller can be considered as a better solution of energy function,

which always consists of a set of error terms, to provide stability conditions in the presence of uncertainty and disturbance.

The performance of the proposed AFLC was evaluated and compared with a conventional proportional and integral (PI) controller. A simulation study is presented to demonstrate the effectiveness and accuracy of the proposed controller. The rest of the paper is organized as follows: Section 2 presents the model of the UPFC. Section 3 develops the AFLC algorithm. In Section 4, a simulation study to evaluate the performance of the AFLC is presented. Conclusions regarding this contribution are summarized in Section 5.

2. Modeling of the UPFC

The schematic diagram of the UPFC is shown in Figure 1. It consists of 2 back-to-back, self-commutated VSCs connected through a common DC link [8]. The first converter (1) is coupled to the AC system through a shunt transformer (2; excitation transformer), and the second converter (4) is coupled through a series transformer (5; boosting transformer). The injected active power of the series converter is taken from the DC link (3), which is in turn drawn from the AC system through the first converter.

The equivalent circuit of a UPFC system is shown in Figure 2, where the series and shunt inverters are represented by the 2 voltage sources v_{se} and v_{sh} , respectively.

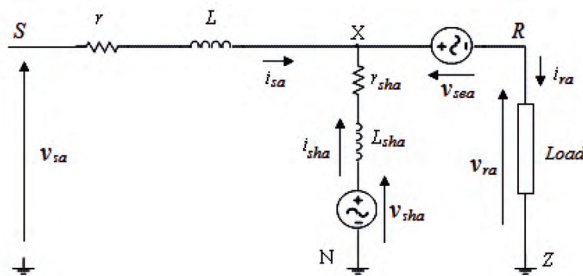


Figure 2. Per phase equivalent circuit of UPFC system.

The single-phase representation of a 3-phase UPFC system is shown in Figure 2. Both converters are represented by voltage sources v_{se} and v_{sh} , respectively, while $(r = r_{se} + r_L)$ and $(L = L_{se} + L_L)$ represent the resistance and leakage inductance of the series transformer and transmission line, respectively. Similarly, r_{sh} and L_{sh} represent the resistance and leakage inductance of the shunt transformer, respectively [8].

The nonlinearities caused by the switching of the semiconductor devices, transformer saturation, and controller time delays were neglected in the equivalent circuit and it was assumed that the transmission system was symmetrical [12,20].

2.1. Model of the series branch of the UPFC

The currents through the series branch of the circuit of Figure 2 can be expressed by the following differential equations for 3 phases of the system [8].

$$\begin{cases} L \frac{di_{sa}}{dt} = -ri_{sa} + v_{sa} - v_{sea} - v_{ra} \\ L \frac{di_{sb}}{dt} = -ri_{sb} + v_{sb} - v_{seb} - v_{rb} \\ L \frac{di_{sc}}{dt} = -ri_{sc} + v_{sc} - v_{sec} - v_{rc} \end{cases} \quad (1)$$

2.2. Model of the shunt branch of the UPFC

Proceeding in a similar way, the differential equations for the shunt branch currents are obtained as follows.

$$\begin{cases} L_{sh} \frac{di_{sha}}{dt} = -r_{sh}i_{sha} + v_{sha} - v_{sea} - v_{ra} \\ L_{sh} \frac{di_{shb}}{dt} = -r_{sh}i_{shb} + v_{shb} - v_{seb} - v_{rb} \\ L_{sh} \frac{di_{shc}}{dt} = -r_{sh}i_{shc} + v_{shc} - v_{sec} - v_{rc} \end{cases} \quad (2)$$

The 3-phase system differential equations can be transformed into a “d, q” reference frame using Park’s transformation, as follows [1,2].

$$\frac{d}{dt} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} -\frac{r}{L} & \omega \\ -\omega & -\frac{r}{L} \end{bmatrix} \cdot \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \frac{1}{L} \begin{bmatrix} v_{sd} - v_{sed} - v_{rd} \\ v_{sq} - v_{seq} - v_{rq} \end{bmatrix} \quad (3)$$

$$\frac{d}{dt} \begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} = \begin{bmatrix} -\frac{r_{sh}}{L_{sh}} & -\omega \\ -\omega & -\frac{r_{sh}}{L_{sh}} \end{bmatrix} \cdot \begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} + \frac{1}{L_{sh}} \begin{bmatrix} v_{shd} - v_{sed} - v_{rd} \\ v_{shq} - v_{seq} - v_{rq} \end{bmatrix} \quad (4)$$

The relations between the different currents can be expressed as follows.

$$i_{rd} = i_{sd} + i_{shd} \quad (5)$$

$$i_{rq} = i_{sq} + i_{shq} \quad (6)$$

2.3. Model of the DC capacitor voltage

The performance of the UPFC depends on the stability of the DC link voltage between the series and shunt converters. In the case of ideal converters, the shunt converter must be capable of handling the amount of real power that is exchanged between the series converter and the line. Thus, the UPFC as a whole exchanges zero real power with the transmission line. However, during dynamic conditions, the input power to the shunt converter should be equal to the sum of series injected power and the rate of change of stored energy in the capacitor on an instantaneous basis [20]. Thus, by writing the power balance, the following dynamic equation is obtained:

$$\frac{dV_C}{dt} = \frac{3}{2.C.V_C} (v_{sed}i_{rd} + v_{seq}i_{rq} - v_{shd}i_{shd} - v_{shq}i_{shq}). \quad (7)$$

The active and reactive powers of the source are as follows.

$$P_s = \frac{3}{2} (v_{sd}.i_{sq} + v_{sq}.i_{sd}) \quad (8)$$

$$Q_s = \frac{3}{2} (v_{sq}.i_{sd} - v_{sd}.i_{sq}) \quad (9)$$

The active and reactive powers of the receiver are as follows.

$$P_r = \frac{3}{2} (v_{rd}.i_{rq} + v_{rq}.i_{rd}) \quad (10)$$

$$Q_r = \frac{3}{2} (v_{rq}.i_{rd} - v_{rd}.i_{rq}) \quad (11)$$

3. Design of controllers

3.1. PI Control

The configuration of the overall system with PI control is shown in Figure 3. The proportional (K_p) and integral (K_i) gains are obtained via a pole placement method.

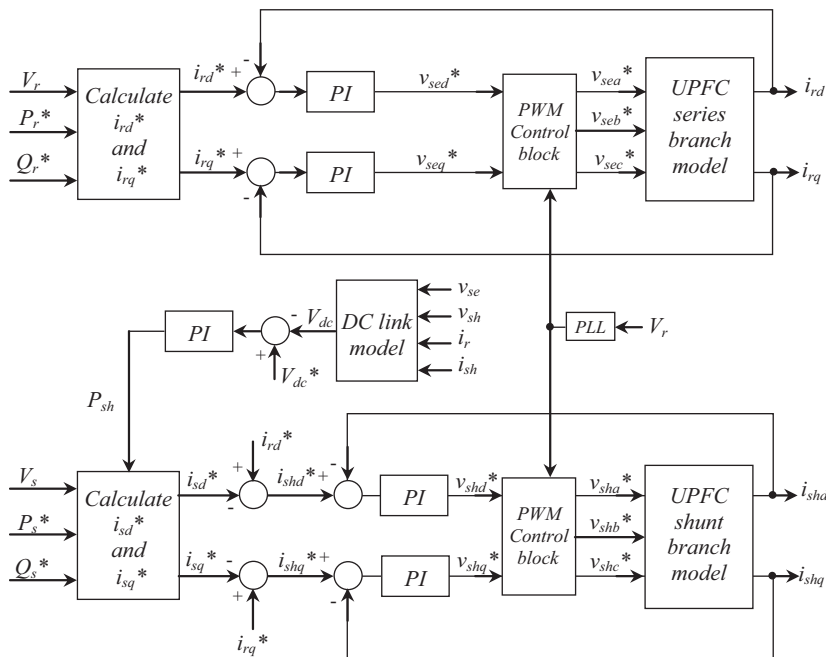


Figure 3. Control design with PI controller.

3.2. AFLC design methodology

The structure of the proposed AFLC applied to the UPFC is very similar to those used for the establishment of the adaptive controllers. The principal difference between the controller that we present here and an adaptive controller basically lies in the mechanism leading to the instantaneous choice of the control parameters. Instead of being drawn from a given matrix, the parameters will be provided by a fuzzy system established on a set of rules derived from the knowledge and intuitive perception of a skilled and generic operator [4,15].

The main goal of the proposed structure is to reduce the control scheme complexity and, at the same time, to keep a high level of the dynamic performances and statics of the process, whose modeling is difficult or whose parameters are inaccessible. In this case, the fuzzy controller is designed to adapt PI parameters K_p and K_i , in order to reduce at least some inherent characteristics (overshoot, response time, etc.) of the error between the reference and system response.

The fuzzy logic controller (FLC) used will generate its control signal based on the proportional and integral actions of the PI controller. Figure 4 illustrates the structure of the developed control.

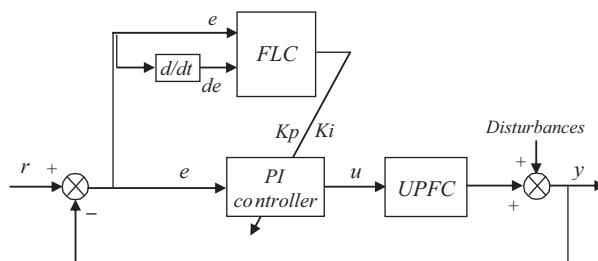


Figure 4. Structure of the AFLC.

The controller inputs are the error (e) and the error derivative (de). The fuzzy controller outputs are K_p and K_i , representing the weights of the proportional and integral actions of the PI controller.

Three fuzzy sets were defined for the input variables: negative (N), zero (Z), and positive (P) (Figures 5a and 5b), and for the output variables, five fuzzy sets were defined: negative big (NB), negative medium (NM), zero (ZE), positive medium (PM), and positive big (PB) (Figure 5b). For fuzzification, the min-max method was used, and the defuzzification process was based on the maximum method.

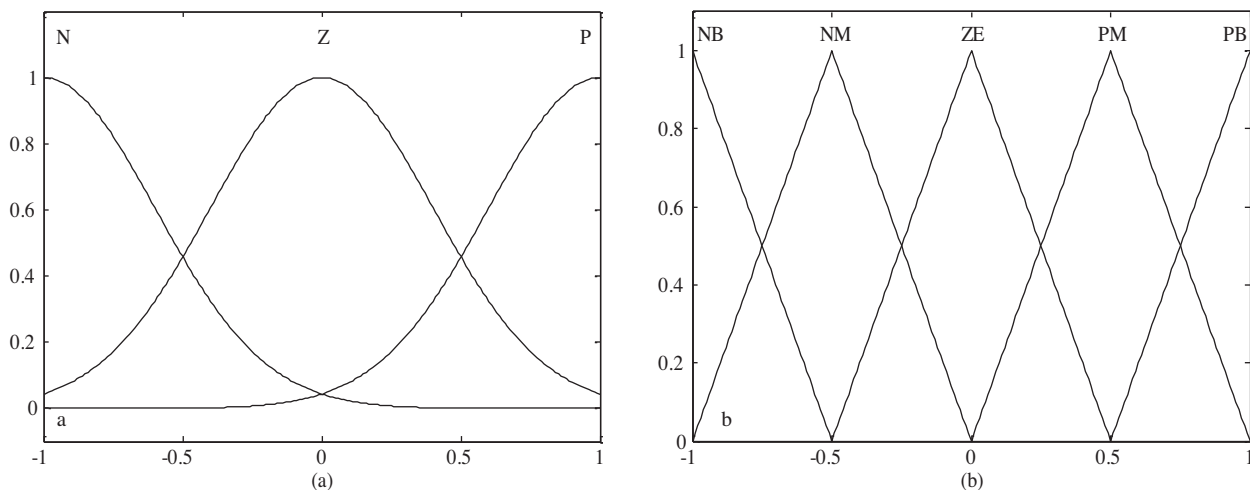


Figure 5. The membership functions for the input and output variables: a) membership functions of the error and its first derivative, b) membership functions of the outputs.

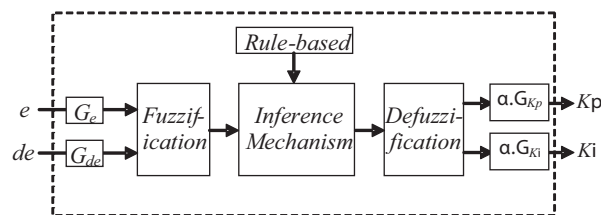
The prolonged drifting experiment for the analysis of the reaction of the generic process under the action carried out by a proportional-integral-derivative (PID) regulator was employed for the definition of the rules for varying the parameters [6-10].

The purpose of the FLC is to find the fuzzy input and produce the appropriate fuzzy output. Despite the skill of the process operator, he is sometimes unable to translate his experience for the correct definition of input and output factor membership, which is strictly necessary to achieve proper control system expertise. For these reasons, the availability of controllers based on a limited number of rules could be of great interest in dealing with the implementation of the system in almost unlimited quantities, as the rules may be properly settled and deal consistently with the phenomena involved in the process control [8-11]. Therefore, the rules that support the FLC, derived from criteria based on what is already acknowledged, are expressed in this study in Table 1.

Table 1. The fuzzy rules.

e	de	K_i	K_p
N	$-$	ZE	PB
Z	N	NM	PB
Z	Z	ZE	PM
Z	P	PM	NB
P	$-$	ZE	PB

The quantities e and de are normalized by using scaling factors (SFs) G_e and G_{de} , respectively, as shown in Figure 6. The obtained normalized quantities are crisp in nature and therefore need to be first converted to their corresponding fuzzy variables. After fuzzification, the fuzzified inputs are given to the fuzzy inference mechanism, which, depending on the given fuzzy rule base, gives the normalized control output. This output is converted to actual control outputs K_p and K_i by using the scaling factors G_{kp} and G_{pi} , respectively.


Figure 6. The block diagram of the FLC.

The SFs are the main parameters used for tuning any FLC because variation of the SFs changes the normalized universe of discourse of input and output variables and their corresponding membership functions. Generally, selection of suitable values for G_e , G_{de} , G_{kp} , and G_{ki} are made based on knowledge about the process to be controlled and sometimes through trial and error to achieve the best possible control performance. This is so because, unlike conventional nonfuzzy controllers, there is no well-defined method for selecting appropriate values of SFs for the FLC. However, if required, it is possible to tune these parameters to achieve a given control objective using some optimization techniques [22]. Therefore, the appropriate values for the SFs in this work are given in Table 2. G_{kp} and G_{ki} were multiplied by weighting factor α to give more importance to the weight of the PI controller parameters K_p and K_i in order to accelerate the dynamic of the system response.

4. Simulation results

This simulation study was performed with MATLAB/Simulink®. The performance of the proposed controller was evaluated under various operating conditions, including model parameter uncertainties and disturbances acting on the power system. The simulation results of the proposed controller were compared with a conventional PI controller. The PI controller's parameters for the shunt and series converters and DC link are listed in Table 3.

The parameters of all PI controllers were obtained via a placement pole design method.

In the first case study, the active power of the transmission line, whose parameters are given in Table 4, was changed from 1000 to 1500 W at $t = 0.4$ s, and it was changed again from 1500 to the initial value at $t = 0.6$ s. The simulation results of this study are depicted in Figure 7. It was shown that the speed of response of the proposed controller is much better than that of the conventional PI controller approach.

Table 2. Scaling factors.

Parameters	G_e	G_{de}	G_{kp}	G_{ki}
Values	0.1	0.01	1	1

Table 3. Parameters of the PI controllers.

	Shunt converter	Series converter	DC link
K_p	84.1034	88.1034	300
K_i	3.1077e+003	3.1077e+003	30,000

Table 4. Parameters of the transmission line with UPFC.

Parameters	$r (\Omega)$	$\omega L (\Omega)$	$r_s (\Omega)$	$\omega L_s (\Omega)$	$1/\omega c (\Omega)$
Values	0.8	31.4159	0.4	18.8496	1.5708

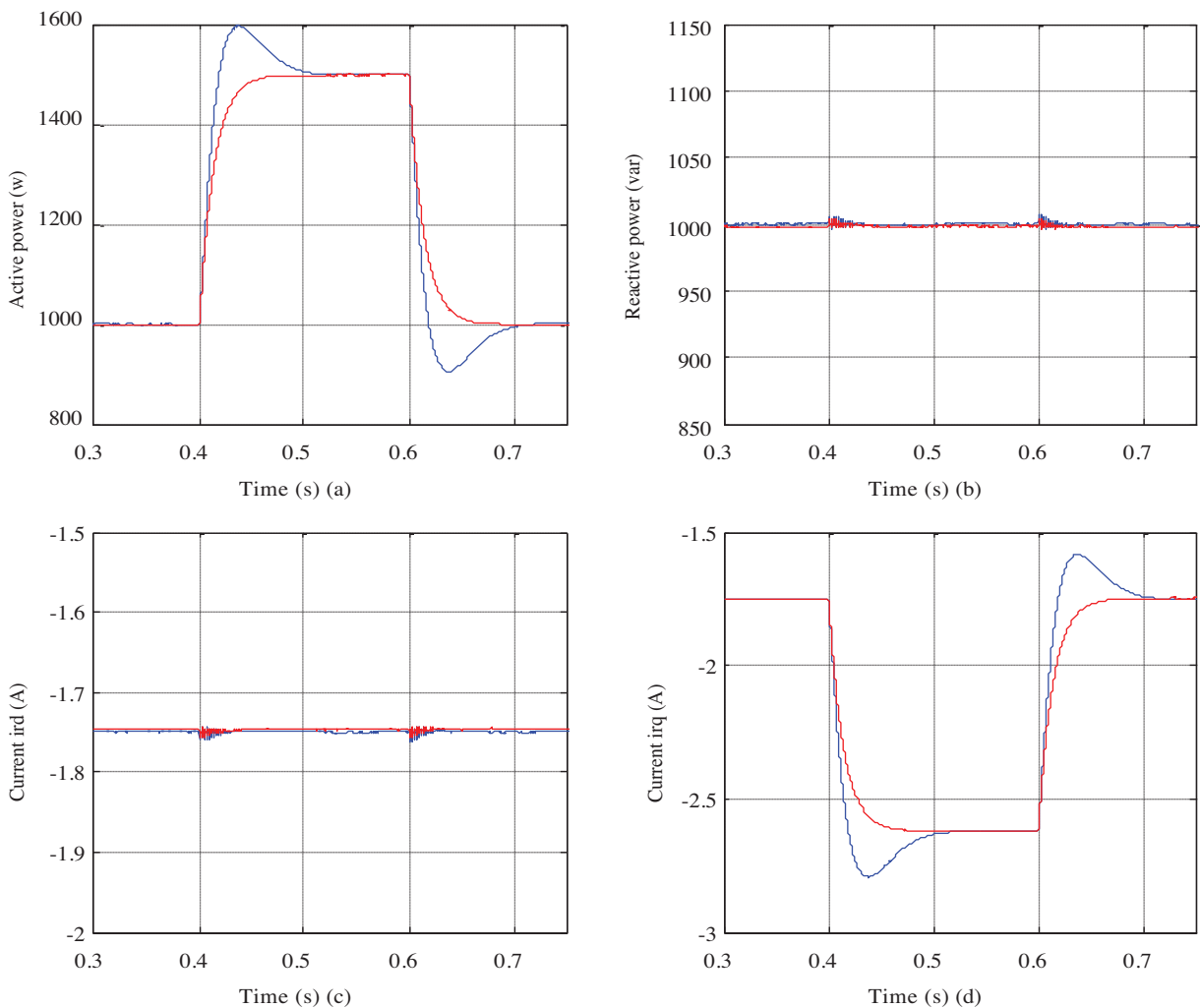


Figure 7. Response of the UPFC system in the receiving end. Red line: proposed controller, blue line: PI controller, a) active power, b) reactive power, c) direct-axis current of converter, d) quadrature-axis current of converter.

In the second case study, the reactive power of the transmission line was changed from the initial value (1000 var) to 500 var at $t = 0.4$ s, and then from this value to the initial value at $t = 0.6$ s. The simulation results of this scenario are displayed in Figure 8.

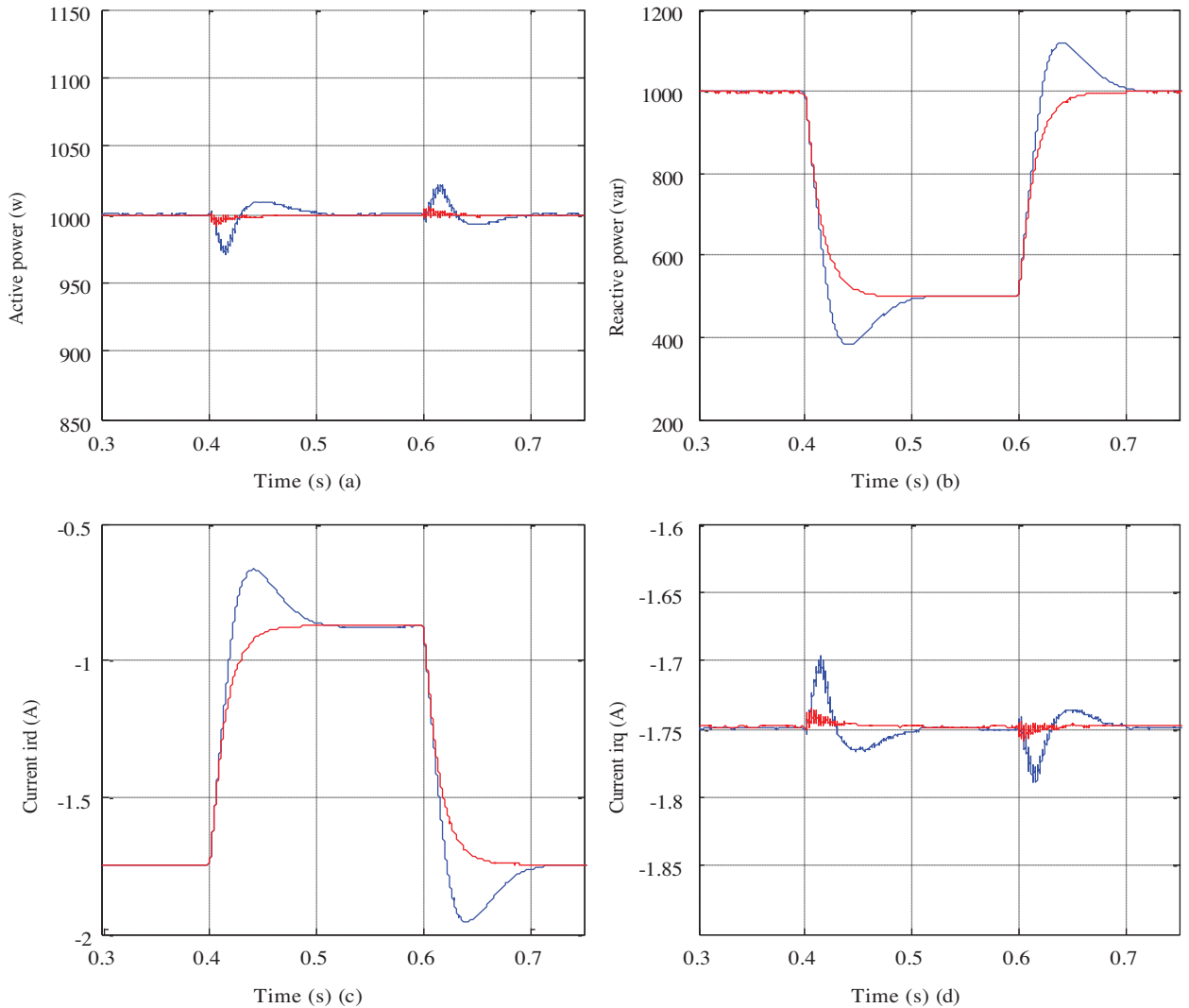


Figure 8. Response of the UPFC system in the receiving end. Red line: proposed controller, blue line: PI controller, a) active power, b) reactive power, c) direct-axis current of converter, d) quadrature-axis current of converter.

As mentioned earlier, due to the interaction, the active power of the transmission line is also affected. However, it can be seen that the proposed controller gave better transient response characteristics than the conventional controller.

To illustrate the effect of a disturbance on the active and reactive powers of the transmission line, the active and reactive powers were stepped at $t = 0.4$ s from their initial values of 1000 W, 1000 var to 1500 W, 500 var, respectively, and back to their original values at $t = 0.6$ s. These results are shown in Figure 9.

Figure 9 shows the response of the proposed controller for the worst case that is likely to occur in practice. The proposed controller demonstrated good robustness against these uncertainty and disturbance conditions.

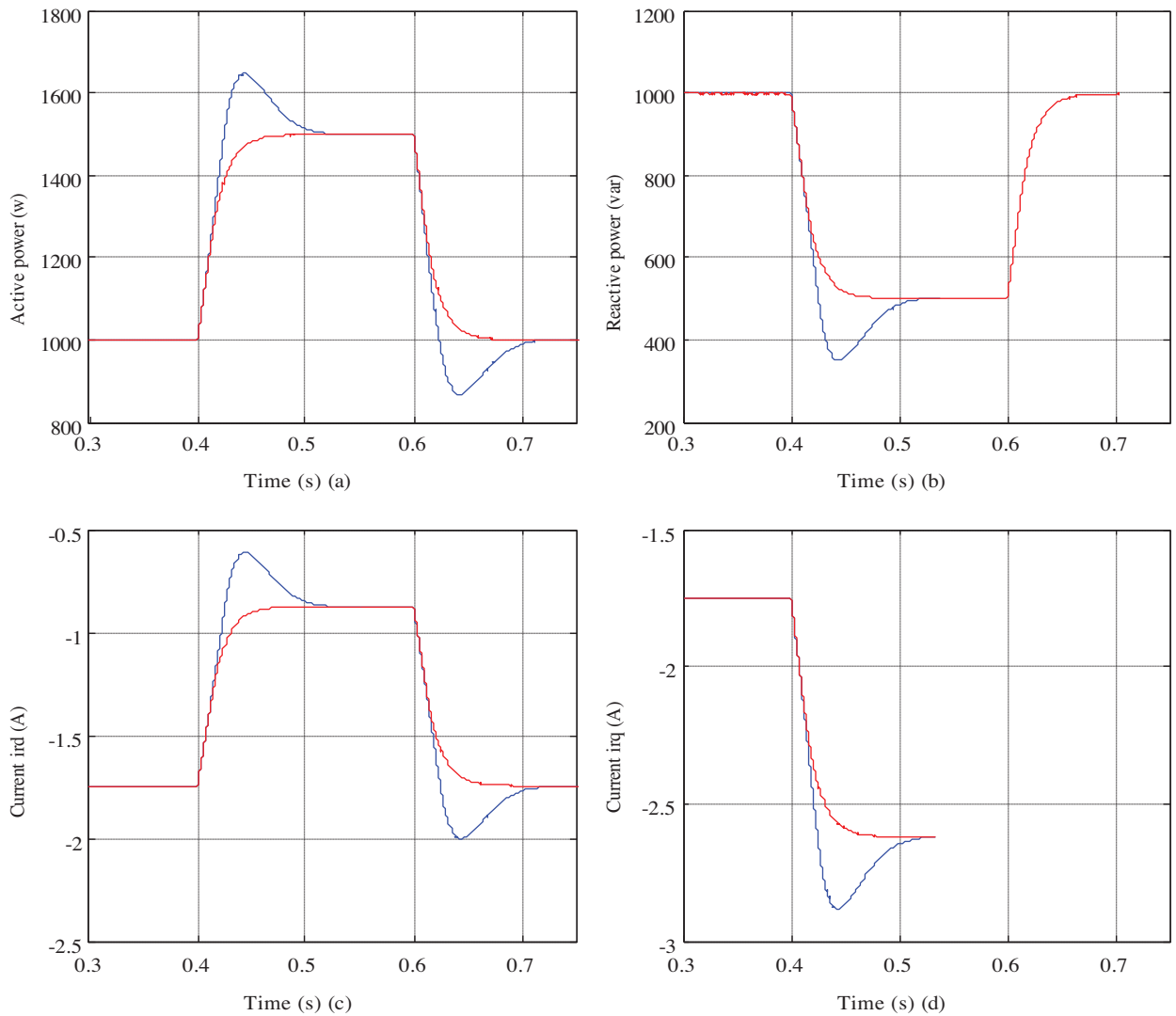


Figure 9. Response of the UPFC system in the receiving end. Red line: proposed controller, blue line: PI controller, a) active power, b) reactive power, c) direct-axis current of converter, d) quadrature-axis current of converter.

Figure 10 shows the DC link voltage waveform related to the previous case studies.

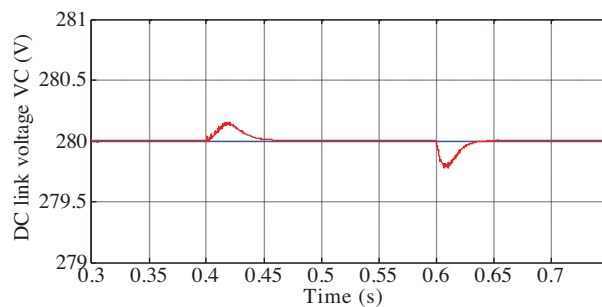


Figure 10. DC link voltage waveform. Blue line: reference DC voltage, red line: real DC voltage.

Figure 11 shows the influence of weighting factor α on the system behavior. For example, as the evolution of active power is chosen, it is clear that much weight value allows the system to reach its steady state as soon as possible. In other words, using a large weight value can also improve the response time of the system. It is noteworthy that all previous simulations were performed with a weighting factor of $\alpha = 2$.

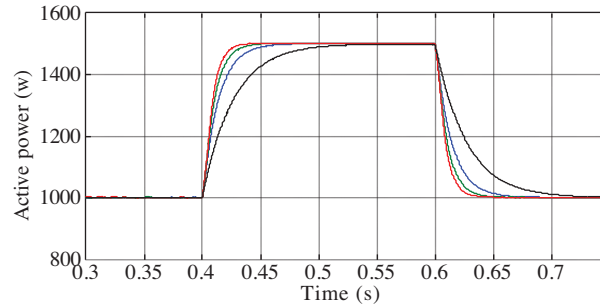


Figure 11. The active power response with different values of α . Black line: $\alpha = 1$, blue line: $\alpha = 2$, green line: $\alpha = 3$, red line: $\alpha = 4$.

5. Conclusion

The main goal of this study was to design a controller that enables a power system to track reference signals precisely and to be robust in the presence of uncertainty of system parameters and disturbances. To reach this goal, a new controller was designed based on fuzzy logic theory. The main advantage of the proposed approach with respect to PI controllers is the stability of the closed-loop system under uncertainties. The proposed approach also has a simple structure and quick performance.

The simulation results of the proposed controller were compared with a conventional PI controller and its performance was evaluated. In this study, the sending and receiving end bus voltages were maintained constant, and the DC link voltage and active and reactive powers of the transmission line were controlled. The obtained results from the above case studies describe the power, accuracy, fast speed, and any overshoot response of the proposed controller.

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