Journal of Energy and Power Engineering 5 (2011) 252-259

Fuzzy Logic Based Power Flow Control Analysis of Advanced Unified Power Flow Controller

S.K. Srivastava[1] and S.N. Singh[2]

1. Department of Electrical Engineering, MMM Engineering College, Gorakhpur-273010, India

2. Department of Electrical Engineering, Indian Institute of Technology Kanpur-208016, India

Received: July 12, 2010 / Accepted: October 30, 2010 / Published: March 31, 2011.

Abstract: Due to rapidly development of high power semiconductor devices with fast control features have made possible to control the power flow more efficiently and effectively. The Flexible AC Transmission Systems (FACTS) in this category introduces several innovative operating control devices. One of the recent devices is Advanced Unified Power Flow Controller (AUPFC) or multi-converter UPFC, which can control bus voltage and real and reactive power flows of more than one line or even a sub-network. This paper presents performance analysis of AUPFC based on d-q axis model theory. Based on the analysis, a new fuzzy logic rules based control algorithm has been developed in this paper which improves the system performance. The control rules are structured depending upon the relationship between series inserted voltages in multi-line and the desired changes of real and reactive power flows in the control network. The impacts of different controllers along with parameters of series connected transformers and transmission lines have been investigated through developed control block models in SIMULINK. The effectiveness of the proposed scheme is demonstrated by a case study.

Key words: FACTS, AUPFC, multi-converter, UPFC, fuzzy-PI controller, SIMULINK, FLC.

1. Introduction

With the development of latest installations of Flexible AC Transmission Systems (FACTS) devices, several innovative control concepts have been introduced that have made feasible and more flexible power flow control in electric power system without generation rescheduling [1-3]. In addition to these, FACTS controllers can also facilitate the reduced power flows in heavily loaded lines resulting in increase loadability, low system loss, improved stability of system and reduced cost of production. Besides of these, other applications of FACTS controllers are in multi functional power flow management as reported by authors [4]. There are several possibilities of operating configurations by combining two or more converter blocks with greater flexibility. Among them, the Interline Power Flow Controller (IPFC) and the Advanced Unified Power Flow Controller (AUPFC) are two novel operating configurations, which are significantly extension to power flow control of multi-lines or sub-networks.

The advanced version of Unified Power Flow Controller is one of the latest generation FACTS device that can control bus voltage and power flows of more than one line or even sub-network [4, 5]. With combining three or more switching converters working together extends the concepts of voltage and power flow control beyond that is achievable with the known two converters based Unified Power Flow Controller.

For simplification of control analysis and to improve the dynamic performance of UPFC, various control strategies including d-q axis control have been reported by authors. Some have described the dynamic modeling of UPFC with conventional PI & PID based

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Corresponding author: S.K. Srivastava, associate professor, research fields: power system restructuring, FACTS, power system optimization and control, ANN & Fuzzy-Neural applications in power system. E-mail: sudhirksri05@gmail.com.

control techniques [6, 7]. Whereas in papers [8-10], fuzzy-rules based controllers of UPFC have been suggested to regulate the power system parameters and improve the dynamic performances.

In fuzzy logic, the controller is represented as a set of rules. These rules are obtained from human experts based knowledge and observations. Fuzzy rules based logic controller have a number of distinguished advantages over the conventional PI [9, 11], as it is not so sensitive to the variation of system structure, parameters, and operation points. The control law developed by fuzzy can be easily implemented in a large scale nonlinear system.

In this paper application of these control techniques is extended for the control of AUPFC. An attempt has made here to develop fuzzy rules based PI controller to replace the conventional one as proposed in Ref. [12]. A comprehensive model of proposed advanced controller based on d-q axis decoupled structure in SIMULINK block sets, has been developed, and followed by fuzzy logic controller. The simulation results based on performances, with a case study on developed fuzzy controller have been presented here and compared those results with the conventional PI controller.

2. Dynamic Representation of AUPFC

The generalized or advanced unified power flow controller consists of three converters, one connected in shunt and the other two in series with the transmission lines which is shown in Fig. 1. This controller is capable of providing voltage control at a bus as well as independent real and reactive power flow on two transmission lines therefore controlling a total of five power system quantities. The dynamic model of proposed controller is derived in the d-q (synchronously rotating at the system angular frequency, ω) frame of reference [6, 7, 13], and followed by fuzzy PI rules based control strategy incorporated in shunt and series converters for active and reactive power flow control.

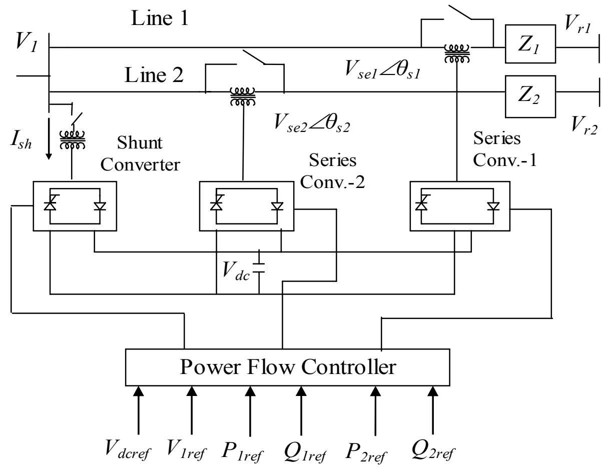

Fig. 1 Basic representation of AUPFC.

The equivalent single line diagram of AUPFC is shown in Fig. 2. The series and shunt converters are represented by controllable voltage sources V_{se1}, V_{se2} and V_{sh} respectively. R_s and L_s are source resistance and inductance respectively. R_{r1}, L_{r1} and R_{r2}, L_{r2} are resistances and inductances of transmission line-1 and transmission line-2 respectively. R_{sh} and L_{sh} represent the resistance and leakage inductance of the shunt transformer, respectively. R_{se} and L_{se} represent the resistance and leakage inductance of the series transformers, respectively. Performing standard d-q transformation [4, 5, 7] of the current through the shunt transformer and series transformers derives the dynamic model of controller.

2.1 Analysis of Shunt Converter

From Fig. 2 a mathematical model of the transmission system including the shunt part of controller can be derived and is given by following equations.

$$\frac{di_{shd}}{dt} = -i_{shd}\frac{R_{sh}}{X_{sh}}\omega_{Base} + \omega_{Base} i_{shq} + \frac{\omega_{Base}}{X_{sh}}(V_{1d} - V_{shd}) \tag{1}$$

$$\frac{di_{shq}}{dt} = -i_{shq}\frac{R_{sh}}{X_{sh}}\omega_{Base} - \omega_{Base} i_{shd} + \frac{\omega_{Base}}{X_{sh}}(V_{1q} - V_{shq}) \tag{2}$$

where the quantities with subscript d and q are d-axis and q-axis quantities, respectively. Time t is in seconds

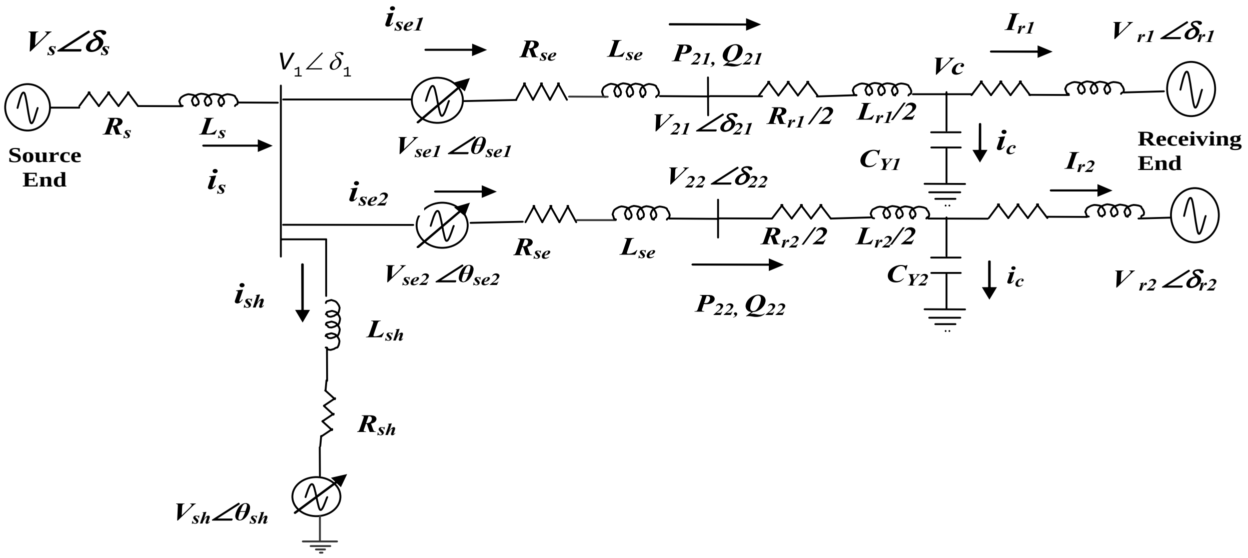

Fig. 2 Circuit representation of two-transmission system.

and ω_{Base} is base frequency in rad/sec. All other quantities are in per unit system.

2.2 Analysis of Series Converter-1

As shown in Fig. 2 a mathematical model of the transmission system including the series converter 1 can be derived and is given by Eqs. (3) and (4).

$$\frac{di_{se1d}}{dt} = -i_{se1d}\frac{R_{se}}{X_{se}}\omega_{Base} + \omega_{Base}\, i_{se1q} + \frac{\omega_{Base}}{X_{se}}(V_{1d} + V_{se1d} - V_{21d}) \qquad (3)$$

$$\frac{di_{se1q}}{dt} = -i_{se1q}\frac{R_{se}}{X_{se}}\omega_{Base} - \omega_{Base}\, i_{se1d} + \frac{\omega_{Base}}{X_{se}}(V_{1q} + V_{se1q} - V_{21q}) \qquad (4)$$

2.3 Analysis of Series Converter-2

Similarly a mathematical model of the transmission system including the series converter 2 can be derived and is given by Eqs. (5) and (6).

$$\frac{di_{se2d}}{dt} = -i_{se2d}\frac{R_{se}}{X_{se}}\omega_{Base} + \omega_{Base}\, i_{se2q} + \frac{\omega_{Base}}{X_{se}}(V_{1d} + V_{se2d} - V_{22d}) \qquad (5)$$

$$\frac{di_{se2q}}{dt} = -i_{se2q}\frac{R_{se}}{X_{se}}\omega_{Base} - \omega_{Base}\, i_{se2d} + \frac{\omega_{Base}}{X_{se}}(V_{1q} + V_{se2q} - V_{22q}) \qquad (6)$$

2.4 Analysis of DC Link Voltage Controller

Net power input (real power in shunt branch minus real power flows into series branches) to controller should instantaneously meet the charging of capacitor and losses in the total system. The mathematical equations can be derived and written as follows:

$$P_{sh} - P_{se1} - P_{se2} = V_{dc}\left[C\frac{dV_{dc}}{d\theta} + g_c V_{dc}\right] \qquad (7)$$

or,

$$V_{dc}\left[C\frac{dV_{dc}}{d\theta} + g_c V_{dc}\right] = V_{shd}\, i_{shd} + V_{shq}\, i_{shq} - V_{se1d}\, i_{se1d} - V_{se1q}\, i_{se1q} - V_{se2d}\, i_{se2d} - V_{se2q}\, i_{se2q} \qquad (8)$$

Where $\theta = \omega_{Base}\, t$, therefore Eq. (8) can be written as:

$$\frac{dV_{dc}}{dt} = -\frac{g_c\omega_{Base}}{b_c}V_{dc} + \frac{\omega_{Base}}{b_c V_{dc}}\Big[V_{shd}\, i_{shd} + V_{shq}\, i_{shq} - V_{se1d}\, i_{se1d} - V_{se1q}\, i_{se1q} - V_{se2d}\, i_{se2d} - V_{se2q}\, i_{se2q}\Big] \qquad (9)$$

The dynamic behavior of the DC-capacitor voltage can be realized by Eq. (9), where b_c is susceptance and g_c is the conductance of the DC link capacitor, respectively. DC voltage level is controlled by the shunt converter, which adjusts the amount of real power flow from the AC system into the common DC link.

3. Fuzzy PI Based Control Structure

The advantages of fuzzy system are well reported in the literature [14]. A Fuzzy rule based controller for

GUPFC is designed to imitate the traditional PI control action at every control interval using the known values of error (e) and rate of error (Δe), as shown in Fig. 3. For this, a set of rules is needed to determine for control action for the various combination of error and rate of error [8-10, 14, 15]. Basically, a fuzzy controller is used to adjust the error of the input signal of original PI controller. The fuzzy proportional (P) improves overshoot and rises time response whereas the conventional integral (I) reduces the steady state error. The rules evaluate the difference between the measured value and the set value i.e error signal. Compatible with the cascade structure of a conventional PI controller is considered. It consists of two inputs (error and rate of change of error) and an output (incremental control). Combining the proportional integral terms derives its control signal, given as:

$$u(t) = K_p e(t) + K_I \int e(t)dt \qquad (10)$$

where K_p, K_I are the controller parameters. Its discritized and incremental control effort at k^{th} instant is expressed as:

$$\begin{aligned}\Delta u(k) &= u(k) - u(k-1)\\ &= K_p[e(k) - e(k-1)] + K_I Te(k) \qquad (11)\end{aligned}$$

In hybrid (Fuzzy+PI) controller [8, 9], uses an incremental fuzzy logic controller in place of proportional term while integral term keep unchanged. Therefore Eq. (11) can be referred as:

$$\Delta u(k) = K_p{}^* \Delta u_f(k) + K_I Te(k) \qquad (12)$$

where $\Delta u_f(k)$ is the output of the incremental FLC, $K_p{}^*$ is proportional coefficient and T is the sampling time period.

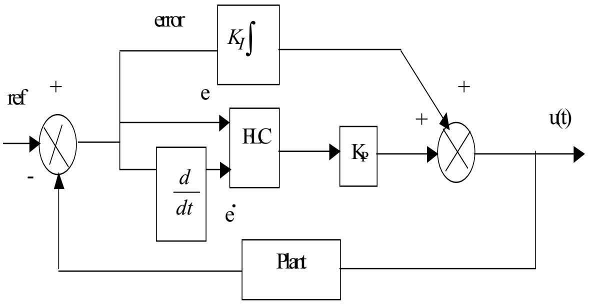

Fig. 3 Fuzzy-PI Controller.

4. Rule Base Control Algorithm of Fuzzy Logic Controller

The standard incremental fuzzy logic controller as used has two inputs $e(k)$, $e^\bullet(k)$ and an output $u(k)$. The membership functions of inputs and output are defined and shown in Fig. 4. In proposed controller, seven membership functions (NB, NM, NS, ZZ, PS, PM, PB) are assigned with linguistic variables to fuzzify physical quantities [8, 11, 16]. The fuzzified inputs are inferred to a fuzzy rule base, which is used to characterize the relationship between fuzzy inputs and fuzzy outputs. In this case, the fuzzy rule base of the incremental fuzzy logic controller is fixed, as shown in Table 1.

The following rules are being imposed for controller.

Rule 1: **IF** $e(k)$ =NB ‘**AND**’ $e^\bullet(k)$=PB ‘**THEN**’ $\Delta u_f(k)$ = ZZ

Rule 2: **IF** $e(k)$=NM ‘**AND**’ $e^\bullet(k)$=PB ‘**THEN**’ $\Delta u_f(k)$ = PS

Rule 3: **IF** $e(k)$=NS ‘**AND**’ $e^\bullet(k)$=PB ‘**THEN**’ $\Delta u_f(k)$ = PM

Rule 4: **IF** $e(k)$=ZZ ‘**AND**’ $e^\bullet(k)$=NS ‘**THEN**’ $\Delta u_f(k)$=NS

Rule 5: **IF** $e(k)$=PS ‘**AND**’ $e^\bullet(k)$=PB ‘**THEN**’

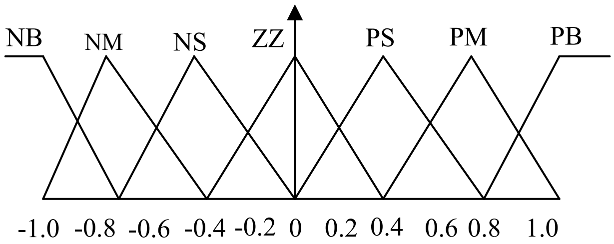

Fig. 4 Membership functions of error and change of error.

Table 1 Rules for fuzzy controller.

Δe/e	NB	NM	NS	ZZ	PS	PM	PB
PB	ZZ	PS	PM	PB	PB	PB	PB
PM	NS	ZZ	PS	PM	PB	PB	PB
PS	NM	NS	ZZ	PS	PM	PB	PB
ZZ	NB	NM	NS	ZZ	PS	PM	PB
NS	NB	NB	NM	NS	ZZ	PS	PM
NM	NB	NB	NB	NM	NS	ZZ	PS
NB	NB	NB	NB	NB	PM	NS	ZZ

$\Delta u_f(k)$ =PB

Rule 6: **IF** $e(k)$ =PM '**AND**' $e^{\bullet}(k)$=PB '**THEN**' $\Delta u_f(k)$ =PB

Rule 7: **IF** $e(k)$ =PB '**AND**' $e^{\bullet}(k)$=NB '**THEN**' $\Delta u_f(k)$ =ZZ

Therefore, according to defined inputs, membership functions and fuzzy rule base, we get 49 rule combinations, which is shown in Table 1.

The response of each fuzzy rule is weighted corresponding to degree of membership of its input conditions. In the rule base as shown, only Zadeh's logical **'AND'** is used.

5. Defuzzification

In Defuzzification step, it is required to transform the fuzzy control action into crisp output value of the FLC. For the incremental FLC, the commonly used "Center of Mass" (COM) formula is employed to defuzzify the control part [14], as given by Eq. (13). In order to analyze the Fuzzy PI controller, it has derived the formulation of the incremental fuzzy logic controller that possesses the different combination regions according to defined inputs and fuzzy rule base.

$$\Delta u_f(k) = \frac{\sum \left\{ \begin{matrix} membershipvalue\ of\ input \times output\ corresponding \\ to\ the\ membershipvalue\ of\ input \end{matrix} \right\}}{\sum (membershipvalue\ of\ input)} \quad (13)$$

For the fuzzy PI controller, the value ranges of two inputs (error and change of error) are decomposing into 49 adjacent input combination regions. The above defined control rules, along with the selected membership functions are used to generate the appropriate fuzzy control action for each region.

6. Simulink Based Modeling of AUPFC

Models for transmission line, shunt control, series control and DC voltage control are developed separately and then grouped together to get the complete model of AUPFC [12]. The block diagram representation of SIMULINK based model of controller is shown in Fig. 5.

7. Simulation Results

The performances of the developed block models in SIMULINK are evaluated with Fuzzy-PI controllers by simulation in MATLAB 7.01. Two 220 kV, 100 MVA lines are considered for simulation study. First one is 150 km long and the other is 100 km long. The active and reactive powers flow at the GUPFC terminal in transmission line i.e. $P_{21,} Q_{21,} P_{22}$ and Q_{21} (as shown in Fig. 2) are controlled to desired real and reactive power flows ($P_{1ref,} Q_{1ref,} P_{2ref}$ *and* Q_{2ref}) in the two lines. At the initial state, the receiving end voltage, active and reactive powers are specified for the power system. The reference currents i_{sed}^{ref} and i_{seq}^{ref} are computed from equations as reported in Ref. [12], for the both lines. The reference voltages, V_1^{ref} and V_{dc}^{ref}, are equal to their respective steady state values. The specifications of the system taken for testing the simulation study are given in Appendix. The proposed control strategy has been tested under step changes in active and reactive power flows. The simulation is started with no power flow ($V_s = 1\angle 0$, $V_{r1} = 1\angle 0$, $V_{r2} = 1\angle 0$) and initial parameters setting of controller are zero. After achieving the steady state, the reference settings in active and reactive power flow corresponding to Line1 and Line2 are changed at 0.03 sec. It can see from Figs. 5-9, the active power changes from 0.65 to 0.75 pu in Line1 and from 0.62 to 0.68 pu in Line2. Similarly, the reactive power changes from 0.4 to 0.44 pu in Line1 and 0.35 to 0.38 in Line2. Also, the case study is performed by fuzzy controller and gets similar observations of the step changes in active and reactive power flow.

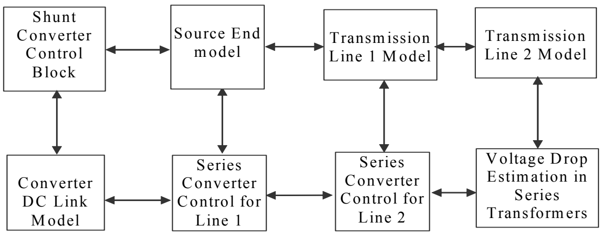

Fig. 5 Block diagram representation of UPFC model.

Therefore, the comparative performance of AUPFC in terms of real and reactive power flows corresponding to the lines, DC link voltage, shunt voltage magnitude and series injected voltage magnitudes are shown in Figs. 6-13.

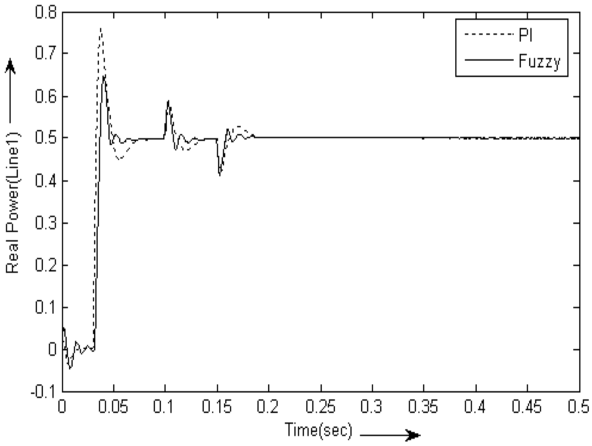

Fig. 6 **Real power flow (Line1).**

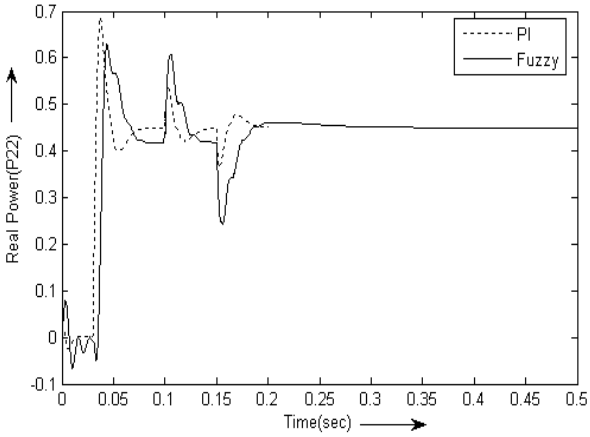

Fig. 7 **Real power flow (Line2).**

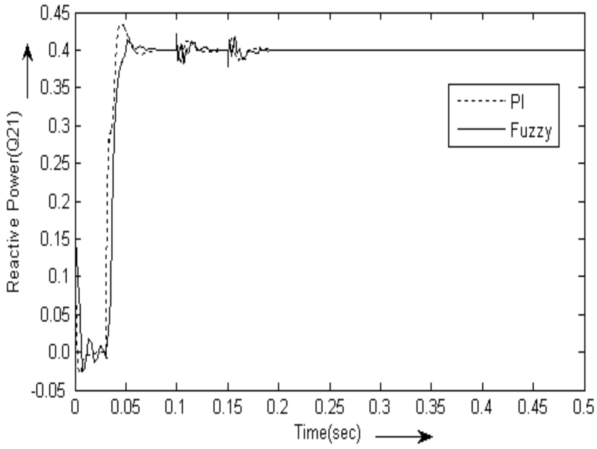

Fig. 8 **Reactive power flow (Line1).**

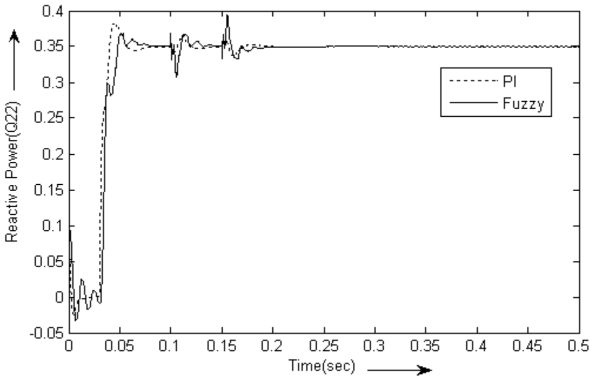

Fig. 9 **Reactive power flow (Line2).**

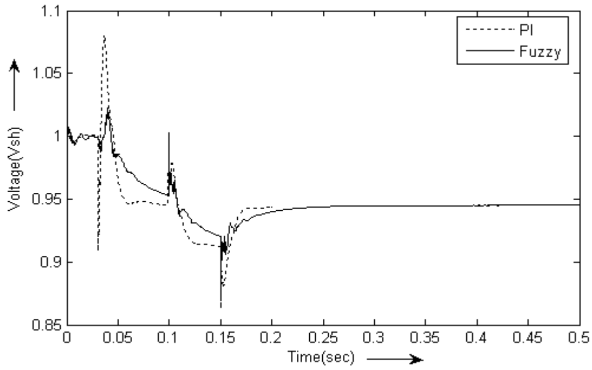

Fig. 10 **Shunt voltage magnitude.**

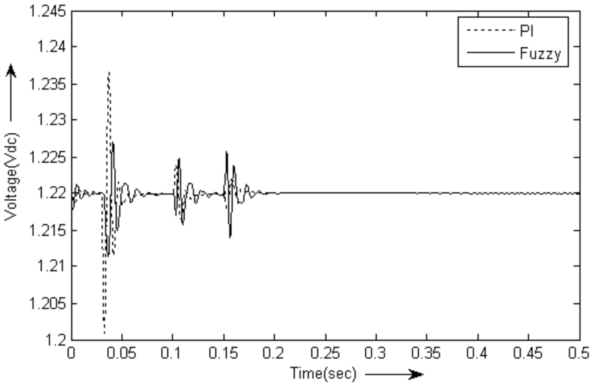

Fig. 11 **DC link capacitor voltage.**

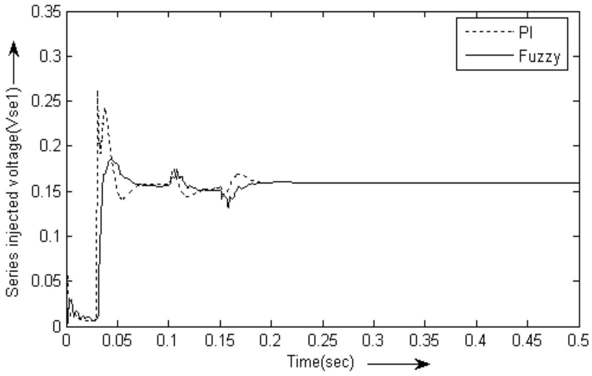

Fig. 12 **Series injected voltage (Line1).**

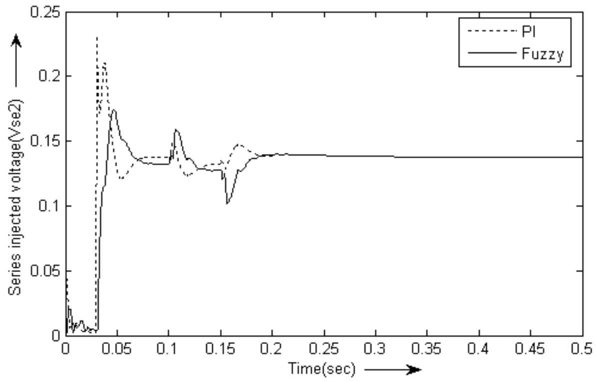

Fig. 13 Series injected voltage (Line2).

8. Conclusions

This paper presented a comprehensive model of an advanced UPFC with separate control structure for the series and shunt converters in a coordinated control way. The SIMULINK block model for complete controller is developed using d-q control theory, which includes series controllers, shunt controller, DC bus voltage controller and transmission lines. The effect of series transformer impedance, transmission line charging and source impedance is considered. The dynamic model of proposed controller is derived in the synchronously rotating d-q frame of reference and followed by Fuzzy-PI control strategy for real and reactive power control. The proposed Fuzzy controller rules are structured depending upon the relationship between series inserted voltages and the desired changes in real/reactive power flow in the power system.

The simulation results are given for step changes in active and reactive power flows corresponding two transmission lines. From the above simulation results, the combination of Fuzzy + PI controller has shown better regulating properties over the simple PI controller. The proposed Fuzzy PI controller tracks the active and reactive power reference setting more effectively with limited overshoots compared to conventional PI controller.

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Appendix 1: System Data

The test system taken for simulation study of proposed controller is shown in Fig. 2, which is a single-line circuit diagram of GUPFC installed in a power system. Two 220 kV, 100 MVA lines are considered for simulation study. First one is 150 km long and the other is 100 km long. Specifications of the system taken for testing the simulation study are:

$\omega_{Base} = 2\pi f_0$, $f_0 = 50$Hz, $R_s = 0.01$ pu, $X_s = 0.15$ pu, $R_{r1} = 0.0248$ pu, $X_{r1} = 0.1265$ pu, $R_{r2} = 0.0166$ pu, $X_{r2} = 0.0843$ pu, $C_{y1} = 0.1008$ pu, $C_{y2} = 0.0672$ pu, $R_{sh} = 0.04$ pu, $X_{sh} = 0.1$ pu, $g_c = 0.0067$ pu, $b_c = 1.5708$ pu, $R_{se} = 0.01$ pu, $X_{se} = 0.025$ pu.

Appendix 2: Controller Data

The parameters of the PI controllers are determined by a thorough and repeated study of the system response under various operating condition. The PI gains, which give the best responses under the tested conditions, are listed below:

(a). PI Controller

$$k_{psh1} = 1.5,\ k_{ish1} = 750,\ k_{psh2} = 2.0,\ k_{ish2} = 2000$$

$$k_{psed} = 0.5,\ k_{ised} = 60,\ k_{pseq} = 0.75,\ k_{iseq} = 250$$

(b). Fuzzy-PI Controller

(i). Shunt converter control

$k_{psh1} = 0,\ k_{ish1} = 750,$ gains $K_1 = 0.5$, $K_2 = 0.01$

$k_{psh2} = 0,\ k_{ish2} = 2000$, gains $K_3 = 0.6$, $K_4 = 0.0005$

(ii). Series Converter 1

$k_{psed} = 0,\ k_{ised} = 60$, gains $K_1 = 1.8$, $K_2 = 0.06$

$k_{pseq} = 0,\ k_{iseq} = 250$ gains $K_3 = 0.7$, $K_4 = 0.002$

(iii). Series Converter 2

$k_{psed} = 0,\ k_{ised} = 60$, gains $K_1 = 0.1$, $K_2 = 0.002$

$k_{pseq} = 0,\ k_{iseq} = 250$ gains $K_3 = 0.6$, $K_4 = 0.001$