Application of Fuzzy Logic Control for Performance Analysis of Transmission System Using Unified Power Flow Controller

Suhail A. Almani[1,*], Jagdesh Kumar[1], Asad A. Chandio[1], Sarfraz Ahmed[2]

[1]Department of Electrical Engineering, QUEST, Nawabshah, Pakistan.
[2]Department of Electronic Engineering, QUCEST, Larkana, Pakistan.
[*]Corresponding author: suhailalmani@quest.edu.pk

Abstract

The load demand in power systems is increasing exponentially, making it difficult for the existing power system networks to meet targets due to scarcity of resources. To address this issue, this paper proposes a unified power flow controller application to meet the increased load demand in the existing power system networks. The proposed technique uses a Fuzzy Logic Controller (FLC) as an intelligent tool to overcome the limitations of the existing UPFC controller under varying operating conditions. The UPFC shunt and series controllers based on FLC are developed as a stand-alone module in PSCAD software. The proposed FLC based UPFC is tested using IEEE-14 bus system with various test cases and compared with the exiting Proportional-Integral (PI) controller based UPFC to demonstrate its effectiveness. Our results show that the proposed FLC successfully improves the performance of UPFC by enhancing the active power flow. In addition, it further reduces the reactive power and improves the voltage profile.

Keywords—Fuzzy logic controller, flexible alternating current transmission, PI controller, unified power flow controller.

1 Introduction

In interconnected networks, utilities can draw power from generator reserves of different areas to build up the reliability of the power system. However, large interconnected networks may encounter instability conditions such as voltage or frequency instability and line overloading which may lead to a large number of blackouts in different areas [1]. One way to overcome these problems is the installation of new transmission lines in order to enhance the reliability of the interconnected power system [2]. However, the problems of finite energy sources, climate restraint, capital and time needed to construct new transmission systems have compelled the researchers to look for other options to boost the power system ability within the existing transmission systems. Among these options, Flexible Alternating Current Transmission System (FACTS) devices have gained popularity as a mean to increase the performance of already existing transmission networks [3].

UPFC has the capacity of offering support together or selectivity for regulation phase angle, voltage series compensation, voltage regulation, and control of power flow individually transferred over the line [4] [5]. When reactive power flow changes in transmission system, it affects the UPFC bus voltage and other parameters. This is one of the dedicated challenges of UPFC for power control [6]. The UPFC comprises of a STATCOM associated consecutive over DC interface capacitor and static synchronous series compensator (SSSC) as shown in Figure 1. The SSSC is a manageable voltage source, while the STATCOM acts as a controllable current source [7] [8]. A three-phase transformer is used to connect STATCOM with AC system network which predominantly creates the real power for the

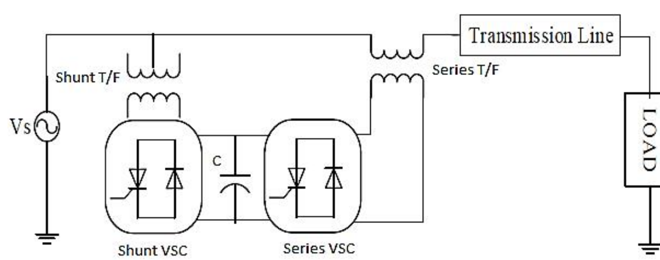

Fig. 1: Circuit Diagram of UPFC

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consumption of SSSC. Furthermore, the STATCOM helps the transmission network in order to compensate the reactive power. The SSSC recovers voltage drops in the power line by infusing AC voltage of controllable phase and magnitude, thus enhancing reactive and active power transmission. Reactive power can be swapped by both the converters autonomously at the terminals [9] [10].

Existing conventional UPFC controllers employ Proportional-Integral (PI) controllers which may not be suitable due to the transient nature of power system. It is because PI controllers encounter problem in their parameters tuning. Incorrect tuning of PI parameters may cause failure during frequency oscillation, overloading and transient conditions [11] [12]. Some solutions have been proposed to improve the tuning of PI controllers such as particle swarm optimization (PSO) technique [13]. It has been observed that with the use of PSO technique, the response of PI controller is improved. However, it also increases the complexity of the system. To address this issue, this paper considers the application of the fuzzy logic control as a suitable option.

2 Methodology

In this section, modelling of UPFC with its main parts such as series and shunt converters in PSCAD/EMTDC software is presented. It is further followed by the modelling of control strategies for both series and shunt controllers of UPFC based on PI controller. Furthermore, the development of FLC based UPFC in PSCAD/EMTDC software is also discussed. Finally, the UPFC shunt and series controller parameters in IEEE-14 bus system are presented for both FLC and PI controllers.

2.1 Modeling of UPFC in PSCAD/EMTDC

The proposed UPFC model and test system are designed in PSCAD/EMTDC software version 4.2.1. The UPFC model designed in PSCAD/EMTDC is shown in Figure 2. Two generators are installed at both ends of the transmission line. Series and shunt transformers are used to link UPFC with the power network. UPFC comprises of two VSC's which are connected by means of DC link capacitor. STATCOM is a shunt VSC and SSSC is series VSC. Each converter is built as a three-phase, six-pulse controlled bridge. Switching devices for both converters can be made from IGBTs with anti-parallel diodes.

2.1.1 Modeling of Shunt Converter

Shunt converter is a three-phase six-pulse VSC, built using six IGBT switches coupled in a bridge configuration as shown in Figure 2. The IGBT is considered as a self-commutating component that enables the bi-directional operation of the UPFC. Thus, UPFC can provide the real power exchange between both converters as well as to generate or absorb the reactive power at the AC sides of both converters independently. Among different power switches, IGBT is chosen to build the UPFC converters due to its ability to deal with higher power rating and speed switching compared to other power switches [14]- [16].

The available IGBT block in PSCAD software is modelled without anti-parallel diode. Therefore, the anti-parallel diode should be added in parallel with IGBT model in PSCAD software to enable the bi-directional operation of the UPFC. A snubber circuit is connected in parallel with each IGBT to overcome the transient voltage across IGBT during the switching operation. A snubber circuit consists of a series resistor (500 ohm) and capacitor (0.1 pF) connected in parallel across IGBT [16]. Low-pass LC filter is connected in each phase of the shunt converter in order to block the harmonics developed due to switching operation. A three-phase shunt transformer is used to connect the shunt converter with the transmission line in order to provide segregation and altering current or voltage levels. It avoids a DC link capacitor being shorted because of switching operation of different devices.

2.1.2 Modeling of Series Converter

The modeling of a series converter is similar to the shunt converter design as shown in Figure 2. The series converter consists of a full-bridge, three-phase, six-pulse converter. IGBT switches with anti-parallel diodes and snubber circuits are chosen to build the series converter. The rating of the IGBTs is chosen as the same as that of the shunt converter IGBTs.

In order to eliminate the current harmonics produced due to the switching operation, low-pass filters are used in each phase. The series converter is linked with transmission line via three single phase series transformers while the turn's ratio is 1/1.

The design process of the UPFC includes the selection of the shunt and series transformer ratings, filter circuits and DC link capacitor rating. To find out losses in the whole system before installation of the UPFC, it is necessary to know the parameters of the power network for the initial test. The parameters of the DC link capacitor, low-pass filter, shunt and series transformers for IEEE-14 test system are mentioned in Table 1 [17].

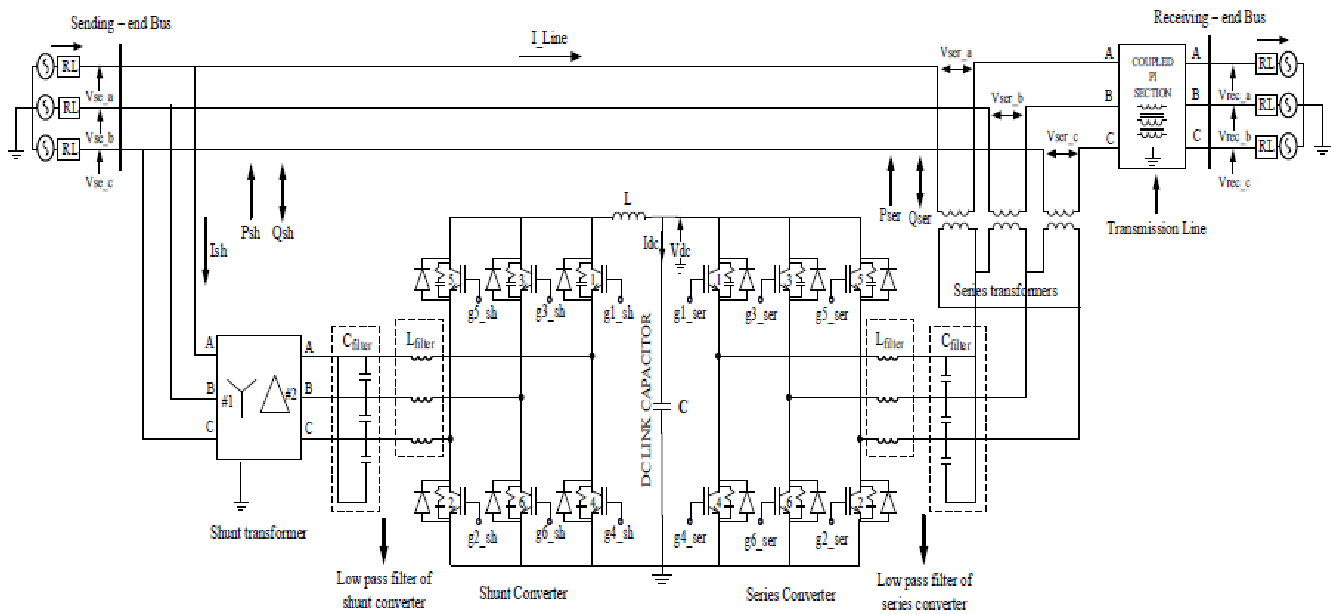

Fig. 2: UPFC model designed in PSCAD/EMTDC software

TABLE 1: Shunt and series converter parameter

UPFC Location Across LINE 9-14	
Shunt transformer	Three Phase Y/Δ coupling transformer Transformer Capacity: 100MVA Line Voltage (RMS): 138 kV/33 kV Leakage Reactance: 0.1 pu Air Core Reactance: 0.2 pu
Low Pass Filter of Shunt Converter	Capacitance: $95\mu F$ Inductance : 0.05 H
Series transformer	Three Phase isolation transformer Transformer Capacity: 25MVA Line Voltage (RMS): 14.33 kV/14.33 kV Leakage Reactance: 0.1 pu Air Core Reactance: 0.2 pu
Low Pass filter of Series Converter	Capacitance: $165\mu F$ Inductance : 0.04 H
DC Link Capacitance	$1600\mu F$

2.2 Modeling of Series and Shunt Controllers

The following sections explain the modeling of series and shunt controllers.

2.2.1 UPFC Shunt and Series Converter Control Strategies Based on PI Controller

Figure 3 shows the flow chart for power flow control by PI based UPFC. The operation of the shunt and series controller depends on the UPFC mode of operation. The shunt converter mode of the operation is chosen as an automatic voltage control. Whereas, the series converter mode of the operation is chosen as a power flow control. In this section, the design of both controllers of UPFC based on PI and fuzzy controller is presented. Both the controllers are implemented using PSCAD/EMTDC software.

Figure 4 shows the PI controller based mechanism for DC link. Whereas, Figure 5 shows the SPWM procedure for UPFC shunt converter [18]. The switching signals can be acquired from SPWM techniques. The magnitude shunt inserted voltage ($Vmag\_sh$) can be used as the magnitude of reference sine wave. The carrier signal having 4.5 kHz frequency is compared with the reference signal in SPWM technique in order to generate firing signals ($g1\_sh, g4\_sh, g3\_sh, g6\_sh, g5\_sh$ and $g2\_sh$) for IGBT switches of shunt converter [19].

The control procedure of series controller of UPFC developed in PSCAD/EMTDC environment is shown in Figure 6. Following equations are used to compute

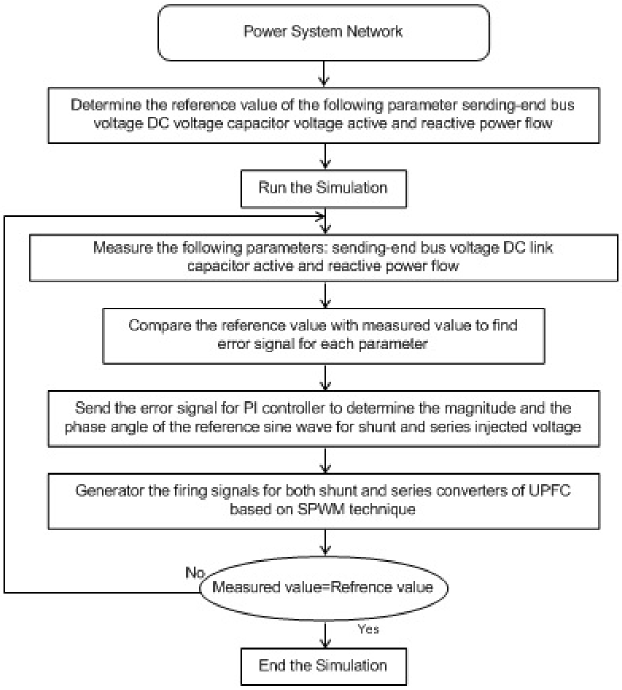

Fig. 3: Flowchart of PI controller based UPFC

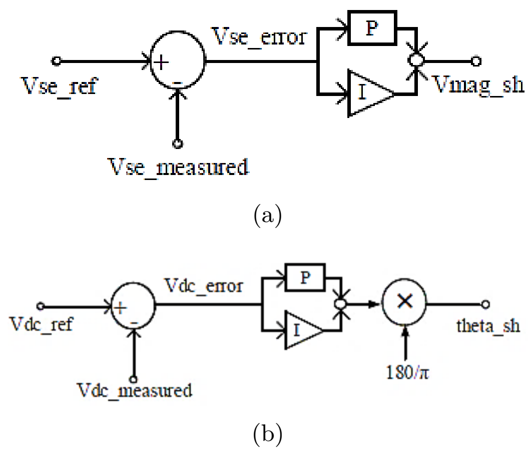

Fig. 4: PI controller mechanism for DC link and sending voltage

the series magnitude and phase angle [17]:

$$V_{mag\_ser} = \sqrt{V_d^2 - V_q^2} \quad (1)$$

$$theta\_{ser} = tan^{-1}\frac{V_q}{V_d} \quad (2)$$

Similar to the shunt in series controller, the process of switching signal generation is also conducted using SPWM technique. The mechanism for providing the switching signals for SPWM technique for series converter, IGBT switch is shown in Figure 7. The output signals of the SPWM are provided as switching firing

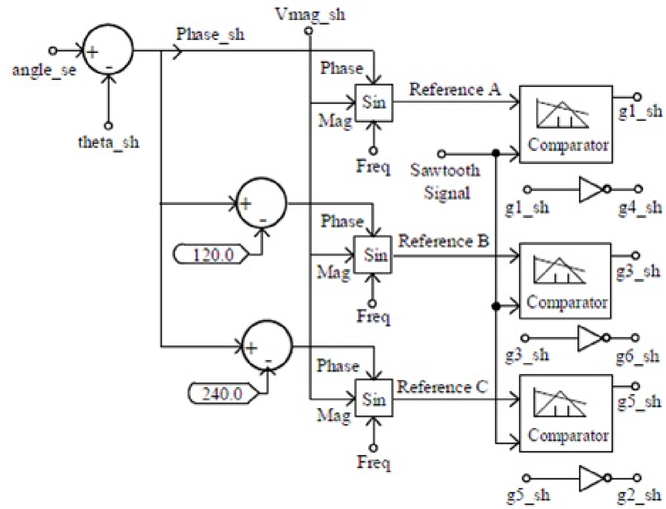

Fig. 5: Mechanism of SPWM technique for shunt converter

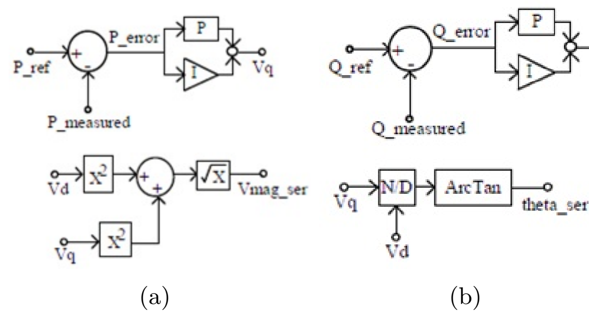

Fig. 6: PI controller for P and Q power flow

signals $g1\_ser$, $g4\_ser$, $g3\_ser$, $g6\_ser$, $g5\_ser$ and $g2\_ser$ for the series converter IGBT switches.

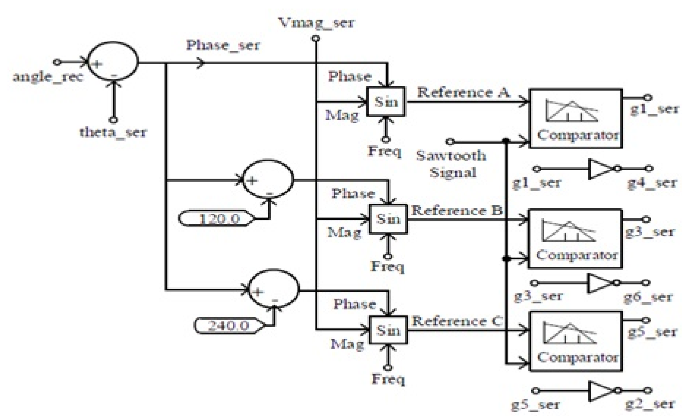

Fig. 7: Mechanism of SPWM technique for series converter

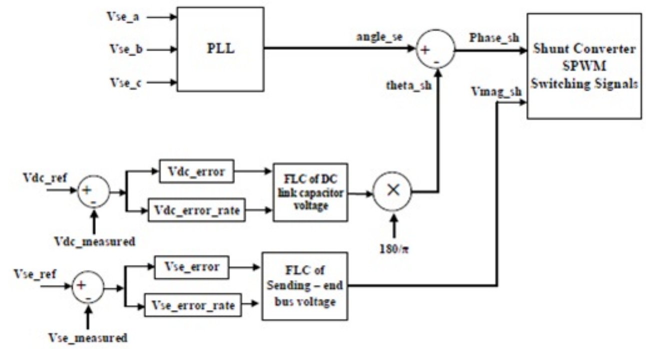

Fig. 8: Mechanism of SPWM technique for series converter

2.2.2 UPFC Shunt and Series Converter Control Strategies Based on Fuzzy Logic Controller

The control method for PI based shunt and series UPFC converters has been discussed in the preceding section. However, PI controller does not guarantee the fast response with minimum output of the UPFC due to some limitations. The main limitation of PI controller is its difficulty in tuning its parameters (K_p, K_i) in transient systems and sub-optimal performance in the nonlinear systems. To address this issue, we proposes a FLC based UPFC. FLC is able of tackling complicated control problems whose system behaviour has large uncertainties and is not well understood. FLC is more robust and has many advantages over traditional PI controller because it doesn't require any exact mathematical model of the system and can give quick reaction with least control signals during rapid changing conditions of the power system [20]. Furthermore, FLC possesses robustness to control the power system parameters under varying operating conditions. The shunt converter control mechanism based on the fuzzy logic designed in PSCAD/EMTDC is displayed in Figure 8 and 9. The difference of $V_{se\_measured}$ and reference value V_{se_ref} is used to produce the error signal of sending-end voltage. Magnitude of inserted shunt voltage V_{mag_sh} can be taken from another FLC with input error signal V_{se_error} and error rate $V_{se\_error\_rate}$. The rest of the procedure to produce the SPWM switching signals is similar to the control strategy for shunt converter based on PI controller which is explained in section 2.2.1.

PSCAD/EMTDC software is used to build fuzzy logic control design of series converter given in Figure 10-11. In order to control the active power flow, $P\_measured$ is measured and compared to the reference active power flow P_ref. The error signals P_error and P_error_rate can pass through FLC

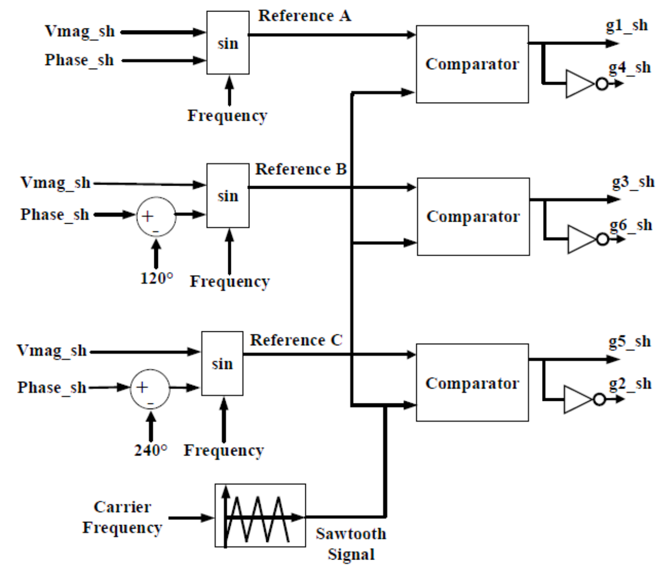

Fig. 9: Mechanism of SPWM technique for series converter

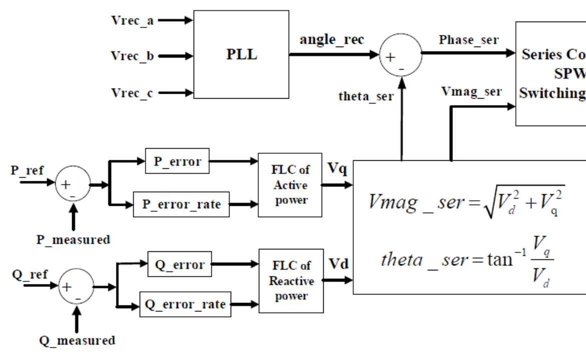

Fig. 10: FLC of the P and Q power flow

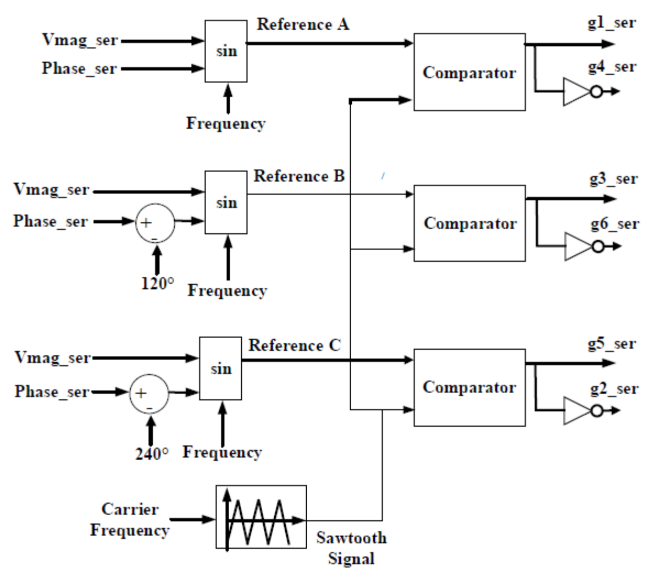

Fig. 11: SPWM technique to generate firing signals for series converter of UPFC

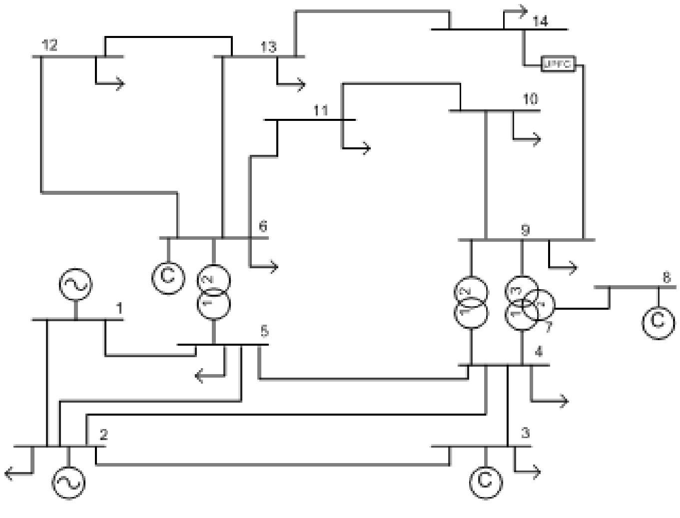

Fig. 12: IEEE-14 Bus System

block to create series injected voltage quadrature component V_q.

2.3 Modeling of Test System and Proposed Fuzzy Controller

IEEE-14 bus is used as a test system designed in PSCAD software for the simulation before and after the installation of UPFC. Out of 14 buses, Bus 2 and 1 are generator buses (PV buses) of the test system and buses 8, 6, 3 are connected with synchronous condensers to furnish reactive power support to network. The remaining 11 buses are load buses.

This study employs 138 kV and 100 MVA as the base values. In order to know the optimal region of UPFC in IEEE-14 bus network, Voltage Collapse Point Indicators (VCPI) and line stability factor (LQP) stability indices are used in the same way as discussed in [21]. The value of LQP or VCP indices are monitored to remain below 1.0 in the transmission network by adding all PQ loads at all buses by specific percentages. The line whose index value exceeds 1.0 is considered as unstable and also the location for UPFC placement. The same procedure is implemented for IEEE-14 bus network and it is found that the index value for line 9-14 reaches 1.0 [22]. Thus, the optimal location of the proposed UPFC is line 9-14 in IEEE-14 bus network, as shown in Figure 12. The Takagi-Sugeno fuzzy inference system module is designed in MATLAB whereas IEEE-14 bus test system are modelled in PSCAD. FLC based UPFC is installed across lines 9-14 whose membership functions are shown in Figure 13. Figure 13(a) shows the membership functions for input error of reactive power (Q), active power (P), V_{dc} and V_{se}. The membership functions of ($error\_rate$) are illustrated in Figure 13(b) in which the output

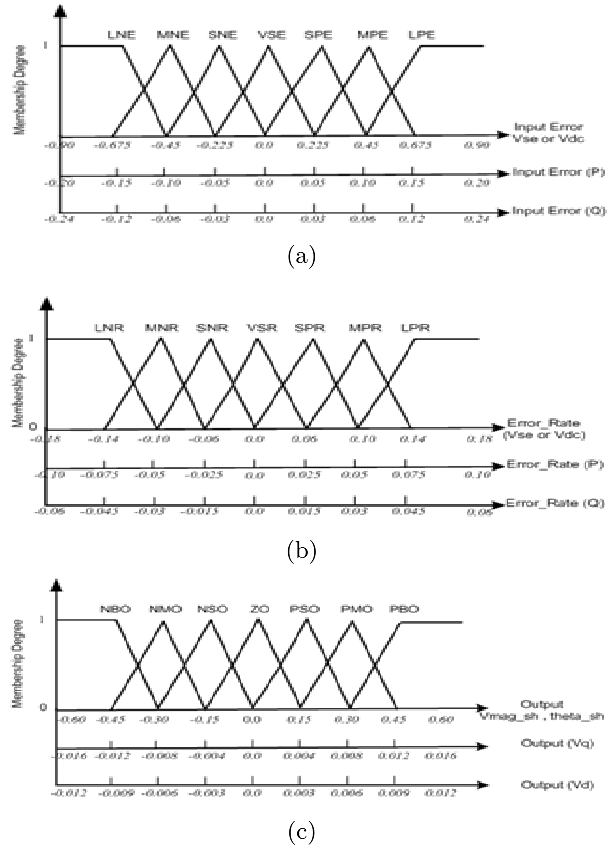

Fig. 13: Membership Functions of normalized Vse, Vdc, P and Q in IEEE-14 bus system

references of direct and quadrature part of the series injected voltage (V_d, V_q) the shunt injected voltage ($Vmag\_sh, theta\_sh$) are shown in Figure 13(c).

3 Simulation Results

The IEEE-14 bus system is simulated without UPFC to compute the reference values required in the design of UPFC controller. The obtained power system values, such as active/reactive power flow and bus voltage, are used to analyze the effectiveness of the proposed UPFC by comparing the power system values before and after the UPFC installation. The simulation results consist of performance analysis of the proposed FLC based UPFC connected at buses 9-14 and compared with the conventional PI UPFC to show its effectiveness.

3.1 Analysis of FLC based UPFC connected at bus 9-14

The reactive power, active power and voltage profile improvement at different buses under steady sate condition are tested by using FLC based UPFC. The base values for line 9-14 are selected as follows: active power

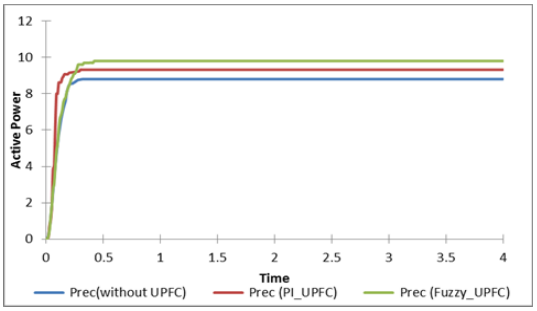

Fig. 14: Active power flow across line 9-14

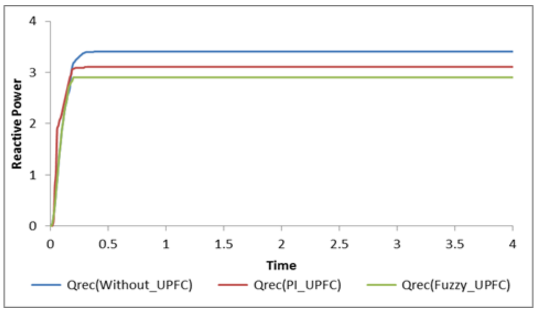

Fig. 15: Flow of reactive power Across Line 9-14

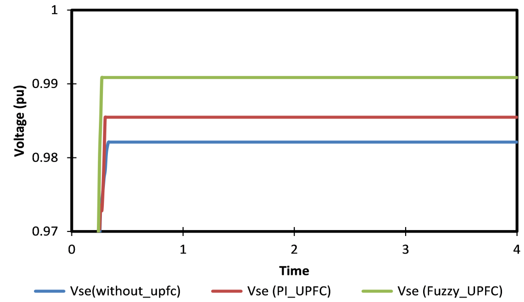

Fig. 16: Voltage at Sending Bus

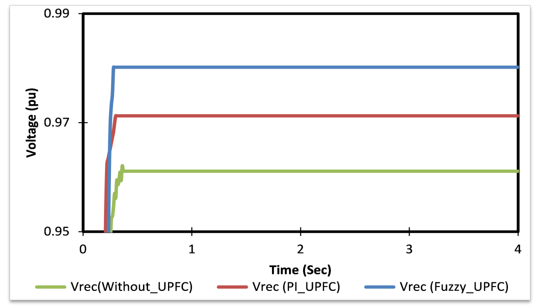

Fig. 17: Voltage at Receiving Bus

= 10MW, reactive power = 2.80 MVAR, and sending end voltage = 1.0 pu. The proposed UPFC, conventional UPFC and the UPFC without response for active power are shown in Figure 14. It can be noticed from Figure 14 that the measured active power flows through the bus 9-14 without UPFC, with PI UPFC, and with fuzzy UPFC are 8.8081 MW, 9.3254MW and 9.8048 MW, respectively. Thus, fuzzy UPFC enhances the active power compared to PI UPFC. Furthermore, it is observed that PI UPFC enhances the power flow by 5.87%. Whereas, the fuzzy UPFC enhances the power flow by 11.31%. Thus, the proposed FLC UPFC has better performance compared to PI based UPFC in terms of controlling the active power at the receiving bus. Similarly, reactive power flow response of all these controllers is shown in Figure 15. It can be noticed from Figure 15 that measured reactive power flow through 9-14 bus without UPFC, with fuzzy UPFC and PI UPFC are 3.4058 MVar, 3.1081 MVar and 2.9032 MVar, respectively. Thus, it is clear that fuzzy UPFC significantly reduces the reactive power compared to PI based UPFC. Furthermore, it is observed that PI UPFC reduces reactive power by 8.74% and fuzzy based UPFC reduces power up to 14.76%. In terms of controlling reactive power at the receiving bus, fuzzy based UPFC shows better performance than PI based UPFC. The voltage profile at sending end bus and receiving end bus are shown in Figure 16-17. It can be visibly understood from Figure 16-17 that fuzzy based UPFC has slightly better voltage profile compared to PI based UPFC for sending end and receiving end bus.

4 Discussion

The response of different power network factors such as active power, reactive power and voltage for IEEE-14 bus test system are investigated with PI based UPFC, FLC UPFC, and without UPFC to evaluate their performance for improving the overall operation of system. Figure 18 shows the percentage-wise improvement in active power by PI controller and fuzzy based UPFC controller. Whereas, Figure 19 shows the percentage-wise improvement in reactive power by PI controller and fuzzy based UPFC controller. It

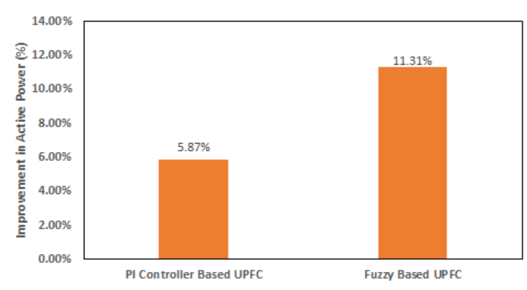

Fig. 18: Percentage-wise improvements in active power by UPFC controllers

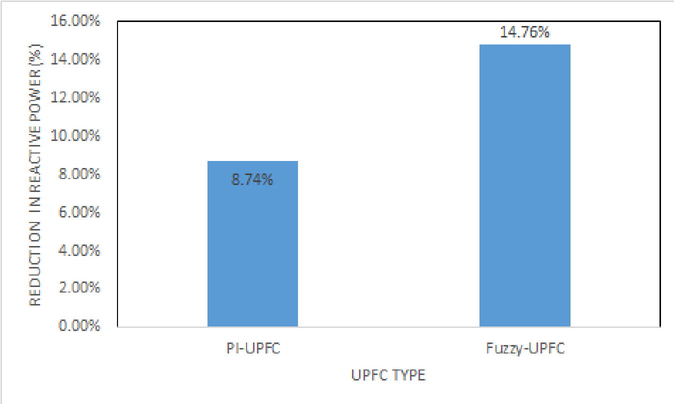

Fig. 19: Percentage-wise reduction in reactive power by UPFC controllers

can be observed from Figure 18 that percentage-wise improvement in active power by PI controller based UPFC is 5.87%. Whereas, using fuzzy based UPFC, it is improved by 11.31% at the receiving bus of the system. Similarly, it can be noticed from Figure 19 that reactive power reduced by PI UPFC is 8.74%. Whereas, the proposed UPFC reduces the reactive power by 14.759%. The voltage at the receiving bus is also improved by both controllers. Furthermore, similar effects can be observed on sending bus (i.e., Bus 9) with the improvement in active power flow, voltage profiles of all buses in the system and reduction in reactive power. Therefore, the proposed FLC UPFC demonstrates its potential by improving the power flow capacity of the system.

5 Conclusion

The electric power system operates at their peak capacity due to exponential increase in the load demand. To address this issue, we propose and design a FLC based UPFC to overcome the existing problems of UPFC controllers under varying operating conditions. The FLC based UPFC shunt and series controllers have been developed as a stand-alone module and applied on IEEE-14 bus. In order to demonstrate the effectiveness of FLC UPFC, its response is matched with PI based UPFC and without UPFC. The simulation results affirmed that FLC based UPFC has improved active power flow at receiving bus up to 11.31% in contrast to 5.87% improvement by PI controller based UPFC. In addition, the power loss without UPFC, with PI based UPFC, and fuzzy based UPFC are found to be 1.20 MW, 0.68 MW and 0.20 MW, respectively. Furthermore, the proposed fuzzy based UPFC has reduced the reactive power by 14.76%, compared to PI based UPFC which has reduced it by 8.74%.

Hence, it can be concluded that using FLC based UPFC, the active power flow can be enhanced, while the power losses can be reduced, resulting in better voltage profile of the existing transmission system. Thus, by using UPFC devices, the capacity of the existing power systems can be enhanced to meet the increased load demands.

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