Abstract—A unified power quality controller (UPQC) using a fuzzy controller (FC) has been proposed. The FC replaces the conventional PI controller in this paper. The results obtained through the FC are good in terms of dynamic response because of the fact that the FC is based on linguistic variable set theory and does not require a mathematical model of the system. Moreover, the tedious method of tuning the PI controller is not required in case of FC. Simulations are carried out using MATLAB/Simulink to validate the theoretical findings.

Index Terms—Fuzzy controller, harmonics, PI controller, reactive power, unified power quality controller.

I. INTRODUCTION

There has been a continuous rise of nonlinear loads over the years due to intensive use of power electronic control in industry as well as by domestic consumers of electrical energy. The utility supplying these nonlinear loads has to supply large vars. Moreover, the harmonics generated by the nonlinear loads pollute the utility. The basic requirements for compensation process involve precise and continuous var control with fast dynamic response and on-line elimination of load harmonics. To satisfy these criterion, the traditional methods of var compensation using switched capacitor and thyristor controlled inductor [1-3] coupled with passive filters are increasingly replaced by active power filters (APFs) [4-8]. The APFs are of two types; the shunt APF and the series APF. The shunt APFs are used to compensate current related problems, such as reactive power compensation, current harmonic filtering, load unbalance compensation, etc. The series APFs are used to compensate voltage related problems, such as voltage harmonics, voltage sag, voltage swell, voltage flicker, etc.

The unified power quality conditioner (UPQC) aims at integrating both shunt and series APFs through a common DC link capacitor. The UPQC is similar in construction to a unified power flow controller (UPFC) [9]. The UPFC is employed in power transmission system, where as the UPQC is employed in a power distribution system. The primary objective of UPFC is to control the flow of power at fundamental frequency. On the other hand the UPQC controls distortion due to harmonics and unbalance in voltage in addition to control of flow of power at the fundamental frequency.

The schematic block diagram of UPQC is shown in Fig. 1. It consists of two voltage source inverters (VSIs) connected back-to-back, sharing a common DC link in between. One of the VSIs act as a shunt APF, where as the other as a series APF. The performance of UPQC mainly depends upon how quickly and accurately compensation signals are derived. Control schemes of UPQC based on PI controller has been widely reported [10-13]. The PI control based techniques are simple and reasonably effective. However, the tuning of the PI controller is a tedious job. Further, the control of UPFC based on the conventional PI control is prone to severe dynamic interaction between active and reactive power flows [10]. In this work, the conventional PI controller has been replaced by a fuzzy controller (FC). The FC has been used in APFs in place of conventional PI controller for improving the dynamic performance [14, 15]. The FC is basically nonlinear and adaptive in nature. The results obtained through FC are superior in the cases where the effects of parameter variation of controller are also taken into consideration. The FC is based on linguistic variable set theory and does not require a mathematical model. Generally, the input variables are error and rate of change of error. If the error is coarse, the FC provides coarse tuning to the output variable, and if the error is fine, it provides fine tuning to the output variable.

In the normal operation of UPQC, the control circuitry of shunt APF calculates the compensating current for the current harmonics and the reactive power compensation. In the conventional methods, the DC link capacitor voltage is sensed and is compared with a reference value. The error signal thus derived is processed in a controller. A suitable sinusoidal reference signal in-phase with the supply voltage is multiplied with the output of the PI controller to generate the reference current. Hysteresis band is normally (most often but not always) is imposed on top and bottom of this reference current. The width of the hysteresis band is so adjusted such that the supply current total harmonic distortion (THD) remains within the international standards. The function of the series APF in UPQC is to compensate the voltage. The control circuitry of the series APF calculates the reference voltage to be injected by the series APF by comparing the terminal voltage with a reference value of voltage.

R. Mahanty is with the Department of Electrical Engineering, Institute of Technology, Banaras Hindu University, Banaras Hindu University, Varanasi 221005, India (corresponding author phone: +91-542-2575388; e-mail: mahantyr@yahoo.co.in).

Chirag Patel is with the Department of Electrical Engineering, Dr. S & S. Gandhhy College of Engineering & Technology, Surat 395001, India (e-mail: chirag6903@gmail.com).

Department of Electrical Engineering, Univ. College of Engg., Osmania University, Hyderabad, A.P, INDIA.
II. CONTROL STRATEGY OF UPQC

The control scheme of three-phase UPQC is shown in Fig. 2. It consists of shunt APF and series APF. Both the shunt and series APFs are current controlled. The shunt APF is indirect current controlled [16].

A. Principle of Control of Shunt APF

The sensed DC link voltage \( v_{dc} \) is compared with a reference voltage \( v_{dc}^* \). The error signal obtained is processed in FC. The output of the FC, \( I_{sp}^* \) is considered as the amplitude of three-phase reference supply currents. The three-phase unit current vectors \( (u_{sa}, u_{sb} \) and \( u_{sc} \) are derived in phase with the three-phase supply voltages \( (V_{sa}, V_{sb} \) and \( V_{sc} \)). The unit current vectors form the phase of three-phase reference supply currents. Multiplication of magnitude \( I_{sp}^* \) with \( u_{sa}, u_{sb} \) and \( u_{sc} \) results in three-phase reference supply currents \( (i_{sa}^*, i_{sb}^* \) and \( i_{sc}^* \)). Subtraction of load currents \( (i_a, i_b \) and \( i_c \)) from the reference supply currents \( (i_{sa}^*, i_{sb}^* \) and \( i_{sc}^* \)) results in three-phase reference currents \( (i_{sa}, i_{sb} \) and \( i_{sc} \)) for the shunt APF. These reference currents are compared with the actual shunt compensating currents \( (i_{sha}, i_{shb} \) and \( i_{shc} \)) and the error signal is converted into PWM gating signals. Depending on the PWM signals, the shunt APF supplies harmonic currents and reactive power demand of the load.

The amplitude of the supply voltage is computed from the three-phase sensed values of voltages as

\[
v_{sm} = \sqrt{\frac{2}{3} (V_{sa}^2 + V_{sb}^2 + V_{sc}^2)}
\]

The three-phase unit current vectors are computed as

\[
u_{sa} = \frac{v_{sa}}{v_{sm}}, \quad u_{sb} = \frac{v_{sb}}{v_{sm}} \quad \text{and} \quad u_{sc} = \frac{v_{sc}}{v_{sm}}.
\]

Multiplication of three-phase unit current vectors \( (u_{sa}, u_{sb} \) and \( u_{sc} \)) with the amplitude of the supply current \( (i_{sp}) \) results in three-phase reference supply currents as

\[
i_{sa}^* = i_{sp}u_{sa}, \quad i_{sb}^* = i_{sp}u_{sb} \quad \text{and} \quad i_{sc}^* = i_{sp}u_{sc}.
\]

To obtain reference currents, three-phase load currents are subtracted from three-phase supply currents as

\[
i_{sha} = i_{sa} - i_a, \quad i_{shb} = i_{sb} - i_b \quad \text{and} \quad i_{shc} = i_{sc} - i_c.
\]

B. Principle of Control of Series APF

In the series APF, the three load voltages \( (v_a, v_b \) and \( v_c \)) are subtracted from three supply voltages \( (V_{sa}, V_{sb} \) and \( V_{sc} \)) resulting into three-phase reference voltages \( (v_{sa}^*, v_{sb}^* \) and \( v_{sc}^* \)) to be injected in series with the load. By taking a suitable transformation, the three reference currents \( (i_{sea}^*, i_{seb}^* \) and \( i_{sec}^* \)) of the series APF are obtained from the three-phase reference voltages \( (v_{sa}^*, v_{sb}^* \) and \( v_{sc}^* \)). The reference currents \( (i_{sea}^*, i_{seb}^* \) and \( i_{sec}^* \)) are fed to a current controller along with their sensed counterparts \( (i_{sea}, i_{seb} \) and \( i_{sec} \)). The supply voltage and load voltage are sensed and there from the desired injected voltage is computed as

\[
v_{inj} = v_s - v_l.
\]

The three-phase reference values of injected voltage are expressed as

\[
v_{ia}^* = \sqrt{2} V_{inj} \sin(\alpha + \delta_{inj}),
\]

\[
v_{ib}^* = \sqrt{2} V_{inj} \sin\left(\alpha + \frac{2\pi}{3} + \delta_{inj}\right)
\]

\[
v_{ic}^* = \sqrt{2} V_{inj} \sin\left(\alpha - \frac{2\pi}{3} + \delta_{inj}\right)
\]

where \( \delta_{inj} \) is the phase of the injected voltage.

The three-phase reference currents of the series APF are computed as follows

\[
i_{sea} = \frac{v_{ia}^*}{Z_{se}}, \quad i_{seb} = \frac{v_{ib}^*}{Z_{se}} \quad \text{and} \quad i_{sec} = \frac{v_{ic}^*}{Z_{se}}.
\]

The impedance \( Z_{se} \) includes the impedance of the transformer inserted.

The currents \( (i_{sea}^*, i_{seb}^* \) and \( i_{sec}^* \)) are the ideal currents to be maintained through the secondary winding of the transformer in order to inject voltages \( (v_{ia}, v_{ib} \) and \( v_{ic} \)), thereby accomplishing the desired task of compensation of voltage sag. The currents \( (i_{sea}^*, i_{seb}^* \) and \( i_{sec}^* \)) are compared with the series compensating currents \( (i_{sha}, i_{shb} \) and \( i_{shc} \)) in the PWM current controller for obtaining signals for the switches.
III. FUZZY CONTROLLER

In FC, basic control action is determined by a set of linguistic rules. These rules are determined by the system. Since the numerical variables are converted into linguistic variables, mathematical modelling of the system is not required in FC.

To convert the numerical variables into linguistic variables, the fuzzy levels chosen are: NB (negative small), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium) and PB (positive big) [14]. The FC is characterized as: (i) seven fuzzy sets for each input and output, (ii) triangular membership functions for simplicity, (iii) fuzzification using continuous universe of discourse, (iv) implication using Mamdani’s ‘min’ operator and (v) defuzzification using the ‘height’ method.

In UPQC, the active power, reactive power, terminal voltage of the line and capacitor voltage are required to be maintained. In order to control these parameters, they are sensed and compared with the reference values. To achieve this, the membership functions of FC are: error, change in error and output as shown in Figs. 3(a), (b) and (c). In the present work, for fuzzification, nonuniform fuzzifier has been used. If the exact values of error and change in error are small, they are divided conversely and if the values are large, they are divided coarsely. The set of FC rules are derived from (8).

\[ u = -[\alpha E + (1 - \alpha)C] \]  

where \( \alpha \) is called the self-adjustable factor which can regulate whole region of operation, \( E \) is the error of the system, \( C \) is the varying ratio error and \( u \) is the control variable. A large value of error \( E \) indicates that given system is not in the balanced state. If the system is unbalanced, the controller should enlarge its control variables to balance the system as early as possible. One the other hand, small value of the error \( E \) indicates that the system is near to balanced state. Overshoot plays an important role in the system stability. Less overshoot is required for system stability and in restraining oscillations. In such conditions, \( C \) in (8) plays an important role, while the role of \( E \) is diminished. The optimization is done by \( \alpha \). During the process, it is assumed that neither the UPQC absorbs active power nor it supplies active power during normal conditions. So the active power flowing through the UPQC is assumed to be constant. The control surface of the proposed FC is shown in Fig. 4. It indicates two inputs, one output and a surface showing input-output mapping. The set of FC rules is made using Fig. 4 is given in Table I.
TABLE I
SET OF FC RULES

<table>
<thead>
<tr>
<th>Change in error</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL</td>
<td>PL</td>
</tr>
<tr>
<td>PM</td>
<td>PM</td>
</tr>
<tr>
<td>PS</td>
<td>PS</td>
</tr>
<tr>
<td>Z</td>
<td>Z</td>
</tr>
<tr>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>NM</td>
<td>NM</td>
</tr>
<tr>
<td>NL</td>
<td>NL</td>
</tr>
</tbody>
</table>

IV. SIMULATION STUDIES

In order to test the performance of the UPQC using the proposed FC, it has been simulated for a 400 V, 50 Hz three-phase AC supply using MATLAB/Simulink. A three-phase diode rectifier feeding an RL load is considered as nonlinear load. The maximum load power demand is considered as 13 kW + j10 kVAR. The values of source resistance Rs = 0.1 Ω and source inductance Ls = 0.1 mH. DC link capacitor value is 2200 µF. To test the operation of UPQC under the voltage sag and swell conditions, 20% sag and 30% swell in line voltage has been created.

The UPQC has been simulated using the proposed FC. The source current waveform before and after connecting the UPQC is shown in Fig. 5. It may be noticed that the source current is distorted before connecting the UPQC and it becomes sinusoidal after connecting the UPQC at 0.1s. The harmonic spectrum of the source current before connecting the UPQC is shown in Fig. 6. The THD of the source current before connecting the UPQC is 24.54%. Harmonic spectrum of the source current after connecting the UPQC is shown in Fig. 7. The THD of the source current after connecting the UPQC is 2.61%. The variation of the system power factor (PF) can be observed from Fig. 8. It may be noticed that the PF improves from 0.88 to 0.98 after switching on the UPQC. The DC link capacitor voltage is shown in Fig. 9. The DC link capacitor voltage is held constant at its reference value by the FC.

To investigate the performance of the proposed UPQC using FC, under voltage sag and voltage swell conditions, 20% sag and 30% swell has been created in the all the phases of the supply voltage. The simulation results of these cases are shown in Figs. 10 and 11. Fig. 10 (a) shows the supply voltage with 20% voltage sag in all the phases from 0.06s to 0.13s. Fig. 10 (b) shows the compensated voltage injected by the series APF. Figs. 11 (a) and (b) show the load voltage, supply voltage and compensation voltage of the UPQC using FC under 30% voltage swell condition.
Fig. 7. UPQC using FC: harmonic spectrum of the source current after connecting the UPQC.

Fig. 8. UPQC using FC: variation of the system PF.

Fig. 9. UPQC using FC: DC link capacitor voltage.

Fig. 10. UPQC using FC (20% voltage sag condition): (a) supply voltage and (b) compensation voltage.
V. CONCLUSION

UPQC using FC has been investigated for compensating reactive power and harmonics. It is clear from the simulation results that the UPQC using FC is simple, and is based on sensing the line currents only. The THD of the source current using the proposed FC is well below 5%, the harmonic limit imposed by IEEE-519 standard.

REFERENCES