Fuzzy Logic Based Three-Phase Four-Wire and Four-Leg Shunt Active Power Filter for Harmonics, Reactive and Neutral Current Compensation

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Abstract— **Active filters are widely employed in distribution system to suppress the harmonics and to compensate reactive power and neutral current. This paper proposes a fuzzy logic based three phase four wire four-leg shunt active power filter to suppress harmonic currents, compensate reactive power and neutral line current and balance the load currents. Modified instantaneous p-q theory is applied for calculating the compensating current. Fuzzy-logic based adaptive hysteresis band technique is applied for the current control to derive the switching signals for the voltage source inverter. The fuzzy-adaptive hysteresis band current controller (HBCC) adjusts the hysteresis bandwidth according to modulation frequency, supply voltage, dc capacitor voltage and the slope of the reference compensator current wave. Computer simulations are carried out on a sample power system to demonstrate the suitability of the proposed techniques.**

1. INTRODUCTION

Harmonic distortion is one of the main power quality disturbances frequently encountered by the utilities. The harmonic disturbances in the power supply are caused by the non-linear characteristics of the loads. The harmonic currents flow through the power system impedance, causing voltage distortion. The distorted voltage waveform causes harmonic current to be drawn by other loads connected at the point of common coupling (PCC). The presence of harmonics leads to transformer heating, electromagnetic interference and solid state device malfunction. Hence, it is necessary to reduce the dominant harmonics below 5% as specified in IEEE 519-1992 harmonic standard [1].

Conventionally, passive L-C filters [2] were used to eliminate line harmonics. However, the passive filters have the demerits of fixed compensation, bulkiness and occurrence of resonance with other elements. The recent advances in power semiconductor devices have resulted in the development of Active Power Filters (APF) [3-5] for harmonic suppression. Various topologies of active filters have been proposed for harmonic mitigation. The shunt APF based on Voltage Source Inverter (VSI) structure is an attractive solution to harmonic current problems. The shunt active filter is a Pulse Width Modulated (PWM) voltage source inverter that is connected in parallel with the load. Active filter injects harmonic current into the AC system with the same amplitude but opposite phase than that of the load. The principal components of the APF are the Voltage Source Inverter (VSI), DC energy storage device, coupling transformer and the associated control circuits. The performance of an active filter depends mainly on the technique used to compute the reference current and the control method used to inject the compensation current into the line.

There are two major approaches that have been proposed in the literature for harmonic detection [2], namely, frequency domain and time domain methods [3]. The frequency domain methods require large memory, computation power and the results provided during the transient condition may be imprecise. On the other hand, the time domain methods require less calculation and are widely followed for computing the reference current. The two mostly used time domain methods are synchronous reference (d-q-0) theory [4] and instantaneous real-reactive power (p-q) theory [5][6]. P-q theory has good transient response time and steady state accuracy [7]. But it is not suitable under non-ideal voltage source conditions. Modified Instantaneous p-q theory [8][9] is followed in this work for harmonic detection.

There are several current control strategies proposed in the literature [10-14], namely, PI control, Average Current Mode Control (ACMC), Sliding Mode Control (SMC) and hysteresis control. Among the various current control techniques, hysteresis control is the most popular one for active power filter applications. Hysteresis current control [15] is a method of controlling a voltage source inverter so that the output current is generated which follows a reference current waveform. The current control with a fixed hysteresis band has the disadvantage that the switching frequency varies within a band, because peak-to-peak current ripple is required to be controlled at all points of the fundamental frequency wave. Kale et al [16] have proposed an adaptive band controller for APF application. The adaptive hysteresis band current controller (HBCC) changes the hysteresis bandwidth as a function of reference compensator current variation to optimize switching frequency and Total Harmonic Distortion (THD) of the supply current. This paper proposes a fuzzy-adaptive hysteresis band control, where the hysteresis bandwidth is calculated with the help of a fuzzy logic controller (FLC).

2. PROPOSED SHUNT ACTIVE FILTER

The active power filter topology presented in this paper is shown in fig.1.The power system is configured with four wires. The AC source is connected to a set of non-linear loads. Voltages V_a, V_b, V_c and current I_a, I_b, I_c indicate the phase voltages and currents at the load side respectively. I_n is the neutral current of the load side. The Active Power Filter consists of three principal parts, a three phase four leg full bridge voltage source inverter, a DC side capacitor and the coupling inductance L_f. The capacitor is used to store energy and the inductance is used to smoothen the ripple present in the harmonic current injected by the active power filter.The shunt active filter generates the compensating currents I_{fa}, I_{fb}, I_{fc} to compensate the load currents I_a, I_b, I_c so as to make the current drawn from the source (I_{sa}, I_{sb}, I_{sc}) as sinusoidal and balanced. The performance of the active filter mainly depends on the technique used to compute the reference current and the control system used to inject the desired compensation current into the line. In this paper, the modified p-q theory is used to determine the current references (I_{ca}*, I_{cb}*, I_{cc}*). In fig.1, the blocks indicated inside the dotted line corresponds to the reference current calculation. A PI controller is developed to control V_{dc}.

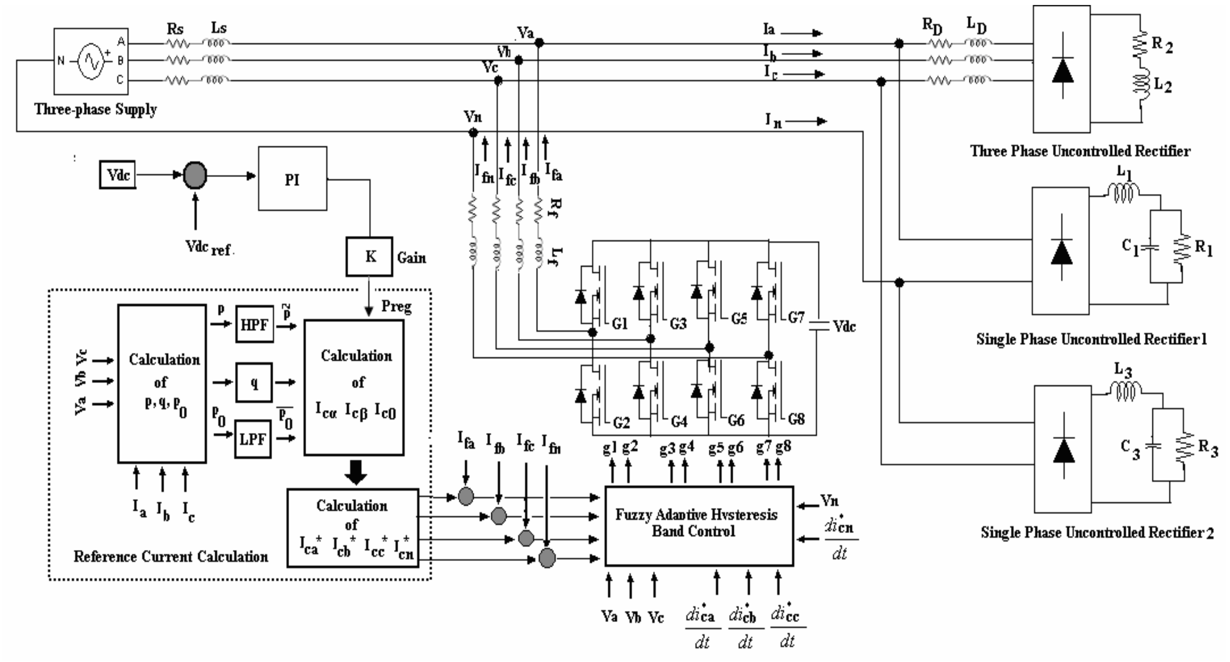


Fig.1. Active Power Filter with the proposed control technique

A fuzzy adaptive HBCC is used for generating the required switching signals for the inverter. The source reference current $\frac{di^*_{fa}}{dt}$ and the supply voltage $v_s(t)$ are given as input and the hysteresis bandwidth is the output of the fuzzy controller.

Another important task in the development of active filter is the maintenance of constant DC voltage across the capacitor connected to the inverter. This is necessary because there is energy loss due to conduction and switching power losses associated with the diodes and IGBTs of the inverter in APF, which tend to reduce the value of voltage across the DC capacitor. In this paper, PI controller [14] is used to control the DC bus voltage.

An active filter is simulated using Matlab/ Simulink using the proposed control strategy and connected in a sample power system to demonstrate the effectiveness of the proposed approach in suppressing the harmonics.

3. CONTROL STRATEGY

Active filters produce sinusoidal supply current by measuring the harmonic currents and then injecting back into the power system with a $180°$ phase shift. A controlled current inverter is required to generate this compensating current. Hysteresis current control is a method of controlling a voltage source inverter so that an output current is generated which follows a reference current waveform. This method controls the switches in an inverter asynchronously to ramp the current through an inductor up and down so that it tracks a reference current signal. Conventional hysteresis current control operates by comparing a current error between the reference and the current being injected by the inverter against fixed hysteresis bands. When the error exceeds the upper hysteresis band, the inverter output is switched low, and when the error falls below the lower hysteresis band, the inverter output switches high. This process is illustrated in fig.2.

This basic hysteresis technique is affected by the drawbacks of irregular switching frequency and of a heavy interference among the phases in the case of a three phase system with insulted neutral. A further improvement of the hysteresis control is proposed in this paper, based on fuzzy-logic [17][18] which offers all the advantages of the hysteresis technique with constant switching frequency resulting in the minimization of the ripple. Fig.1 shows the block diagram of Active filter based on fuzzy adaptive hysteresis technique. The principle of operation of the proposed technique is explained by considering the equivalent circuit of a single phase voltage source inverter (VSI) as shown in fig.3 where L_f and R_f are the smoothing inductance and resistance of the filter and υ is the supply voltage.

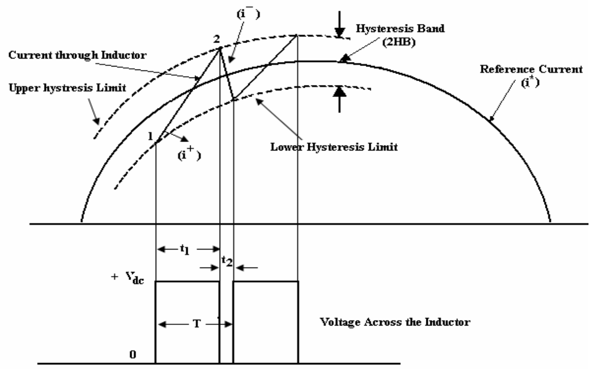


Fig.2. Hysteresis band current control

The instantaneous inverter output voltage (u_o) has a rectangular waveform of amplitude V_{dc} with a period T as shown in fig.1. The load current i satisfies the equation

$$u_0 = R_f i + L_f \frac{di}{dt} + V_s \tag{1}$$

If i^* is the reference current, the instantaneous current error can be defined as

$$\delta = i - i^* \tag{2}$$

and the reference voltage as

$$u_o^* = R_f i + L_f \frac{di^*}{dt} + V_s \tag{3}$$

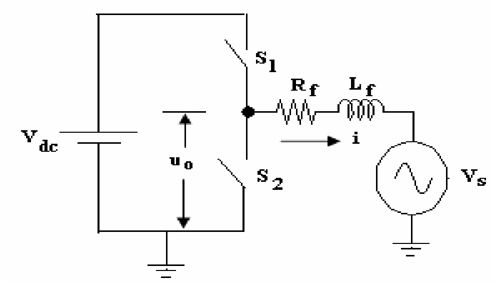


Fig.3. Single phase voltage- source inverter

By considering negligible resistance, eqn (3) becomes

$$u_o^* = L_f \frac{di^*}{dt} + V_s \tag{4}$$

In fig.2,the current i tends to cross the lower hysteresis band at point1 hence the switch S_1 is closed. The linearly rising current (i^+) then touches the upper band at point 2, where the switch S_2 is closed. The following equations can be written in the respective switching intervals t_1 and t_2 from fig.1.

$$\frac{di^+}{dt} = \frac{1}{L_f}(V_{dc} - V_s) \tag{5}$$

$$\frac{di^-}{dt} = -\frac{1}{L_f}(V_{dc} + V_s) \tag{6}$$

From the geometry of fig.1,

$$\frac{di^+}{dt}t_1 - \frac{di^*}{dt}t_1 = 2HB \tag{7}$$

$$\frac{di^-}{dt}t_2 - \frac{di^*}{dt}t_2 = -2HB \tag{8}$$

$$t_1 + t_2 = T_c = \frac{1}{f_s} \tag{9}$$

where f_s is the switching frequency.

Adding (7) and (8) and substituting (9), it can be written as

$$t_1 \frac{di^+}{dt} + t_2 \frac{di^-}{dt} - \frac{1}{f_s}\frac{di^*}{dt} = 0 \tag{10}$$

Subtracting (8) from (7), it gives

$$4HB = t_1 \frac{di^+}{dt} - t_2 \frac{di^-}{dt} - (t_1 - t_2)\frac{di^*}{dt} \tag{11}$$

Substituting (6) in (11), gives

$$2HB = (t_1 + t_2)\frac{di^+}{dt} - (t_1 - t_2)\frac{di^*}{dt} \tag{12}$$

Substituting (6) in (10), simplifying

$$t_1 - t_2 = \frac{di^* / dt}{f_s (di^+ / dt)} \tag{13}$$

Substituting (13) in (12)

$$HB = \left\{ \frac{0.125V_{dc}}{f_s L_f} \left[1 - \frac{4L_f^{\,2}}{V_{dc}^{\,2}} \left(\frac{V_s}{L_f} + \frac{di^*}{dt} \right)^2 \right] \right\} \tag{14}$$

Eqn.14 shows the hysteresis bandwidth as a function of modulation frequency, supply voltage, dc capacitor voltage and slope of the reference current wave. Hysteresis band can be modulated as a function of V_s and $\frac{di^*}{dt}$. Hence, these variables are taken as input to the fuzzy controller, and the hysteresis band width (HB) is the output. Five linguistic variables namely, NL (Negative Large), NM (Negative Medium), EZ (Zero), PM (Positive Medium) and PL (Positive Large) are assigned to the input and five linguistic variables, namely PVL (Positive Very Low), PL (Positive Low), PB (Positive Big) and PVB (Positive Very Big) are assigned to output variables. The membership functions of the input and output variables are shown in Fig.4. The fuzzy rule base with 25 rules is given in table I.

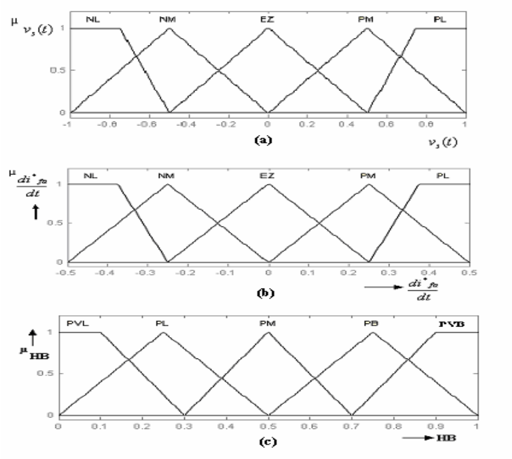


Fig.4. Membership functions for the input variables (a) $v_s(t)$, (b) $\frac{di^*_{fa}}{dt}$ and (c)output variable HB

TABLE I

Fuzzy Rule Base for Current Controller

$\frac{di^*_{fa}}{dt}$ \ $v_s(t)$	NL	NM	EZ	PM	PL
NL	PB	PM	PM	PM	PB
NM	PB	PM	PL	PM	PB
EZ	PVB	PM	PVL	PM	PVL
PM	PB	PM	PL	PM	PB
PL	PB	PM	PM	PM	PB

In this approach, the switching frequency is kept constant and the current error is appreciably reduced ensuring better stability and insensitivity to parameter variation.

These parameters are given as input to the fuzzy controller. The hysteresis band width calculated by fuzzy controller is applied to the variable hysteresis band current controller. The pulses produced from the controller are sent to the IGBT inverter.

4. SIMULATION RESULTS

This section presents the details of the simulation carried out to demonstrate the effectiveness of the proposed control strategy for the active filter for harmonic current filtering, reactive power compensation, load current balancing and neutral current elimination. Fig.5 shows the test system used to carry out the analysis. The test system consists of a three phase supply connected to a set of non-linear loads namely, a three-phase uncontrolled rectifier with RL load and two single-phase uncontrolled rectifiers with RLC load. The active filter is connected to the test system through an inductor L. The values of the circuit elements used in the simulation are given in Table II. MATLAB/SIMULINK is used to simulate the test system and the proposed shunt active filter. The simulation was conducted under two different conditions, namely, ideal voltage source, unbalanced voltage source and unbalanced-distorted voltage source conditions. The comprehensive simulation results are presented below.

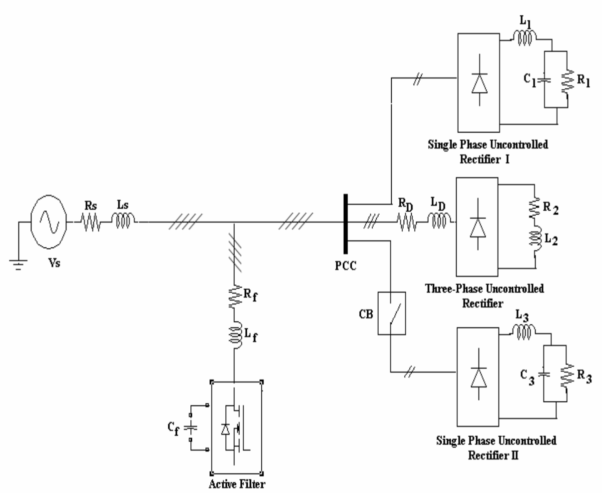


Fig.5 Test System

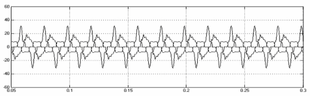
TABLE II System Parameters

Supply phase to phase voltage, frequency	415 V (rms), 50 Hz
Supply line Parameters	Rs=1 Ω,Ls=1mH
Load Parameters	R_1=50Ω, L_1=1mH, C_1 = 47µF R_2= 70 Ω, L_2 = 37mH R_3,= 60Ω ,L_3 =1mH ,C_3 =470 µF R_D= 0.1 Ω, L_D= 3mH
Filter coupling Inductance	$L_{f=}$3 mH, R_f =0.5 Ω
Inverter DC bus capacitor	1mF
DC Voltage Control: **Reference Voltage**	 700V
Sampling Time	2e^{-6} sec

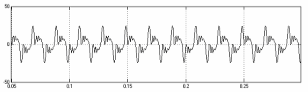
Case A: Ideal Voltage Source

First the system is simulated with ideal voltage source and without any filter. The three phase source current waveform in this case is shown in Fig 6(a). Fig

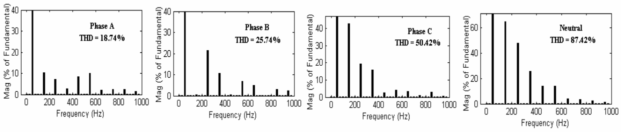
6(b) shows neutral current waveform. The Total Harmonic Distortion (THD) of the distorted three-phase line currents (I_a, I_b & I_c) are 18.74%, 25.74% and 50.42% respectively. The THD level of neutral current is 87.29%.The harmonic spectrum of phase and neutral currents are shown in fig 6(c). Next, the active filter is simulated using the proposed control strategy and connected in parallel with the load. Fig.7 shows the waveforms obtained in this case. The harmonic spectrum of the source current is shown in fig.7(c). The THD of current in phase A, B and C has reduced to 2.72%, 3.66% and 3.64% respectively. As shown in Fig.7(b) and (d) after the installation of the filter, the three phase source current is balanced and sinusoidal and it is in phase with the supply voltage. As shown in fig.8 (a), the neutral current has been completely eliminated. The instantaneous real and reactive power supplied from the source in phase A is shown in fig. 8 (b). From the figure it is found, that the source delivers constant real power and zero reactive power to the load which indicates that the source side power factor is maintained at unity.



a) Distorted Three Phase Source Current

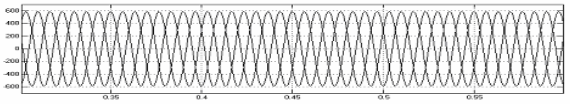


b) Neutral Current

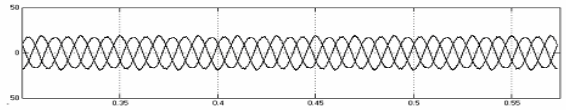


c) Harmonic Spectrum of Phase and Neutral Current

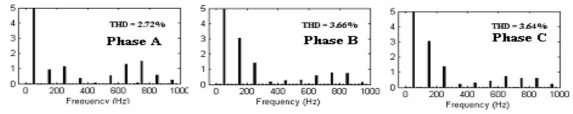
Fig 6. Distorted Phase and Neutral current and harmonic spectrum



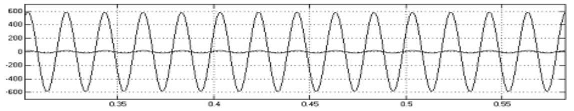
a) Source Voltage



b) Source Current



c) Harmonic Spectrum of Source Current

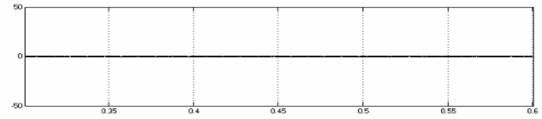


d) Source Voltage and Current (Phase A)

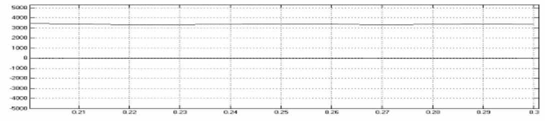
Fig.7 Harmonic current filtering under ideal voltage source conditions with Fuzzy-Adaptive HBCC Technique

Case B: Unbalanced Voltage Source

In this case, the source voltage is made unbalanced from 0.4 sec to 0.5 sec as shown in fig.9 (a). The unbalance is due to the voltage deviation in phase A. The unbalanced load current is shown in fig 9 (b). In the absence of the active filter, the THD level of the three phase currents and neutral current between the time period 0.4 sec to 0.5 sec are 20.91%, 25.74%, 50.92% and 92.06% respectively. The source current waveform and its harmonic spectrum after installing the active filter with modified p-q theory and the proposed control strategy are given in fig.10.

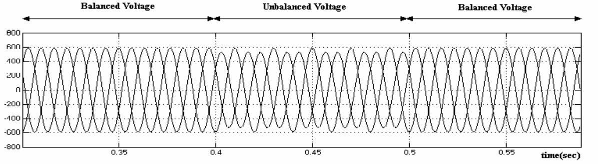


a) Neutral Current

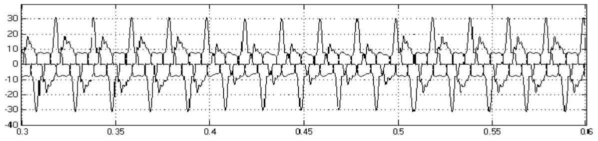


b) Instantaneous Real and Reactive Power

Fig.8 Reactive and Neutral Current Compensation under ideal voltage source conditions with Fuzzy-Adaptive HBCC Technique

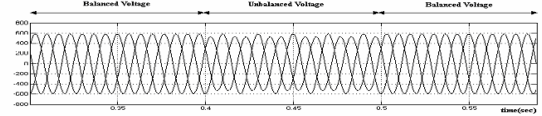


a) Unbalanced Source Voltage

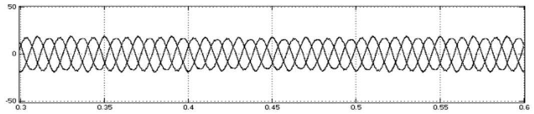


b) Unbalance Load Current

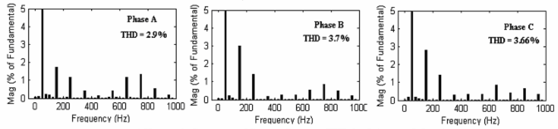
Fig.9 Unbalanced Voltage Source and Load Current



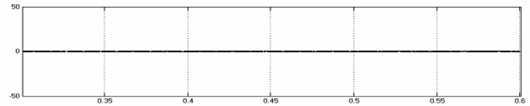
a) Unbalanced Source Voltage



b) Source Current



c) Harmonic Spectrum of Source Current (THD for 0.4 sec to 0.5 sec)



d) Neutral Current

Fig.10 Harmonic current filtering under unbalanced voltage source conditions with Fuzzy-Adaptive HBCC Technique

TABLE III

Detailed Summary of source current and their THD under unbalanced voltage source

Three Phase	Total Harmonic Distortion (THD) (%)					
	Without Filter		General p-q theory		Modified p-q theory	
	Balanced Voltage (t>0.5 sec)	Unbalanced Voltage (0.4 sec<t>0.5	Balanced Voltage (t>0.5 sec)	Unbalanced Voltage (0.4 sec<t>0.5	Balanced Voltage (t>0.5 sec)	Unbalanced Voltage (0.4 sec<t>0.5
Phase A	18.74	20.91	3.07	13.65	2.72	2.9
Phase B	25.74	25.74	4.5	11.49	3.66	3.7
Phase C	50.42	50.92	3.8	15.86	3.64	3.66

In this case, the THD level has reduced to 2.9%, 3.7% and 3.66% in phase A, B and C respectively. For comparison, the filter was simulated with general p-q theory for reference current calculation. Since the compensation current references have negative-sequence component, the three phase compensated source current is not sinusoidal with general p-q theory. Also in this case, the THD value of source current after compensation exceeds the IEEE standard limit as shown in table III. This shows that the general p-q theory is not suitable for compensation under unbalanced voltage source conditions.

5. CONCLUSION

This paper has presented a fuzzy logic based approach for developing the active filter for three-phase four-wire distribution system. Modified p-q theory was employed for effectively computing the reference current under non-ideal voltage source conditions. The active filter was simulated using MATLAB/Simulink and the performance was analyzed in a sample power system with a source and set of non-linear loads. The simulation results show that the proposed technique is effective in current harmonic filtering, reactive power compensation, neutral current elimination under unbalanced load and non-ideal voltage source conditions. Further the proposed technique has quick response time and it keeps the switching frequency nearly constant with good quality of filtering.

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