

# Artificial Intelligent Controller based Three-Phase Shunt Active Filter for Harmonic Reduction and Reactive Power Compensation

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**Abstract**— Active filters have been considered as a potential candidate to reduce the harmonics. In this paper, a fuzzy logic-controlled shunt active power filter capable of reducing the total harmonic distortion is developed. The optimal controllers for the control of DC voltage response of condenser and the inverter current of shunt active filter are designed by an artificial intelligence technique. The instantaneous p-q theory is used for calculating the compensating current. Fuzzy-adaptive hysteresis band technique is adopted for the current control to derive the switching signals for the voltage source inverter. The fuzzy-adaptive hysteresis band current controller changes the hysteresis bandwidth according to the supply voltage and the slope of the reference compensator current wave. A fuzzy logic-based controller is developed to control the voltage of the DC capacitor. Simulation results obtained are presented and compared with the conventional controller. Simulation results show the effectiveness of the proposed technique for harmonic reduction.

**Index Terms**— Active power filter (APF), harmonics, hysteresis band, fuzzy logic control.

## I. 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 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- 4] 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) 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 (VSI) that is connected in parallel with the load. It has the capability to inject harmonic current into the AC system with the same amplitude but opposite phase than that of the load

[1,2]. The principal components of the APF are the VSI, a DC energy storage device that in this case is capacitor, a 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 desired compensation current into the line.

There are two major approaches that have emerged for the harmonic detection [2], namely, time domain and the frequency domain methods. The frequency domain methods include, Discrete Fourier Transform (DFT), Fast Fourier Transform (FFT), and Recursive Discrete Fourier Transform (RDFT) based methods. The frequency domain methods require large memory, computation power and the results provided during the transient condition may be imprecise [4]. On the other hand, the time domain methods require less calculations and are widely followed for computing the reference current. The two mostly used time domain methods are synchronous reference (d-q-0) theory and instantaneous real-reactive power (p-q) theory. Instantaneous p-q theory is followed in this work.

There are several current control strategies proposed in the literature [4-8], 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 [9] 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 [10] have proposed an adaptive band controller for APF. The adaptive hysteresis band controller changes the hysteresis bandwidth as a function of reference compensator current variation to optimize switching frequency and THD of supply current. This paper proposes a fuzzy-adaptive hysteresis band control, where the hysteresis bandwidth can be easily calculated with the help of a fuzzy logic controller (FLC).

Another important task in the active filter design 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

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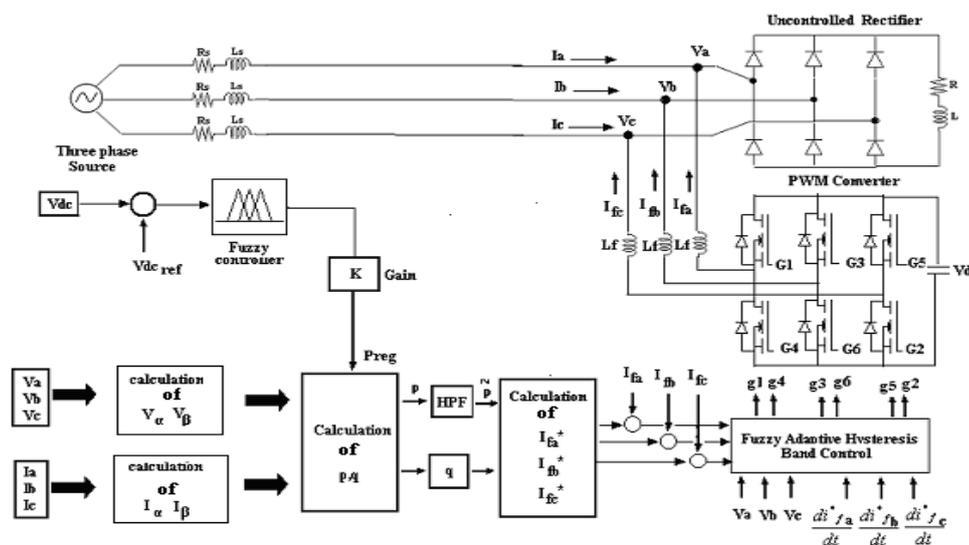


Fig. 1 Active Power Filter with the proposed control technique

capacitor. Generally, PI controller [8] is used to control the DC bus voltage. The PI controller based approach requires precise linear mathematical model which is difficult to obtain. Also, it fails to perform satisfactorily under parameter variations, non-linearity, and load disturbances [12]. This paper proposes a fuzzy logic controller for D.C voltage control.

Computer simulations are carried out on a sample power system to demonstrate the effectiveness of the proposed approach in suppressing the harmonics.

## II. CONTROL STRATEGY FOR SHUNT ACTIVE FILTER

The performance of the active filter mainly depends on the methodology adopted to generate the reference current and the control strategy adopted to generate the gate pulses.

The block diagram representation of the proposed control strategy for the shunt active filter is shown in Fig.1. The control strategy is implemented in three stages. In the first stage, the essential voltage and current signals are measured to gather accurate system information. In the second stage, compensating currents are derived based on instantaneous p-q theory. In the third stage, the gating signals for the solid-state devices are generated using hysteresis-based current control method. The instantaneous p-q theory [8] is based on “ $\alpha$ - $\beta$ ” transformation of voltage and current signals to derive compensating signals. The instantaneous active and reactive power can be computed in terms of transformed voltage and current signals. From instantaneous active and reactive powers, harmonic active and reactive powers are extracted using low-pass and high-pass filters. From harmonic active and reactive powers, using reverse “ $\alpha$ - $\beta$ ” transformation, compensating commands in terms of currents are derived. The detail of p-q theory is given in Appendix A.

Hysteresis current controller derives the switching signals of the inverter power switches in a manner that reduces the current error. The switches are controlled asynchronously to ramp the current through the inductor up and down so that it follows the reference. The current ramping up and down between two limits is illustrated in Fig.2. When the current through the inductor exceeds the upper hysteresis limit a negative voltage is applied by the inverter to the inductor. This causes the current in the inductor to decrease. Once the

current reaches the lower hysteresis limit a positive voltage is applied by the inverter to the inductor and this causes the current to increase and the cycle repeats.

The current controllers of the three phases are designed to operate independently. Each current controller determines the switching signals to the inverter. The switching logic for phase A is formulated as below

If  $i_{fa} < (i_{fa}^* - HB)$  upper switch (G1) is OFF and lower switch (G4) is ON

If  $i_{fa} > (i_{fa}^* + HB)$  upper switch (G1) is ON and lower switch (G4) is OFF

In the same fashion, the switching of phase B and C devices are derived.

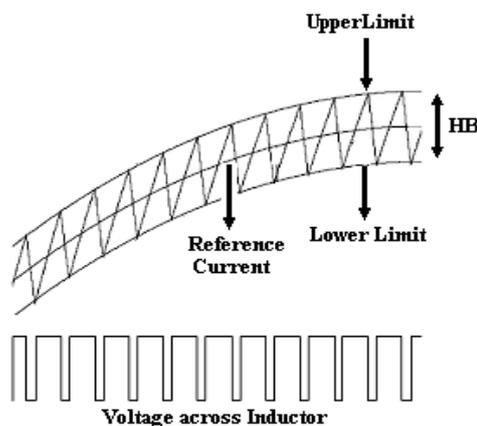


Fig. 2 Hysteresis Current Control Operation Waveform

This method has the drawbacks of variable switching frequency, heavy interference between the phases in case of three phase active filter with isolated neutral and irregularity of the modulation pulse position [10]. These drawbacks provide high current ripples, acoustic noise and difficulty in designing input filter. To overcome these undesirable drawbacks, this paper presents a adaptive hysteresis band control in which the band width can be determined by the fuzzy logic controller. The adaptive hysteresis band (HB) can be modulated at different points of the fundamental

frequency of the cycle to control the PWM switching pattern of the inverter. The implementation of this method is discussed in the next section.

The DC side of the inverter is connected to a capacitor. The DC capacitor provides a constant DC voltage and the real power necessary to cover the losses of the system. In the steady state, the real power supplied by the source should be equal to the real power demand of the load plus a small power to compensate the losses in the active filter. Thus, the DC capacitor voltage can be maintained at a reference value. However, when the load condition changes the real power balance between the mains and the load will be disturbed. The real power difference is to be compensated by the DC capacitor. This changes the DC capacitor voltage away from the reference voltage. A fuzzy logic controller is applied to maintain the constant voltage across the capacitor by minimizing the error between the capacitor voltage and the reference voltage.

### III. DESIGN OF FUZZY LOGIC CONTROLLER

#### A. Fuzzy Logic-based DC Voltage Control

To design the FLC, variables which can represent the dynamic performance of the plant to be controlled should be chosen as the inputs to the controller. It is common to use the output error (e) and the rate of error (e') as controller inputs. In the case of the fuzzy logic based DC voltage control, the capacitor voltage deviation and its derivative are considered as the inputs of the FLC and the real power (Preg) requirement for voltage regulation is taken as the output of the FLC. The input and output variables are converted into linguistic variables. In this case, seven fuzzy subsets, NL(Negative Large), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PL (Positive large) have been chosen. Membership functions used for the input and output variables used here are shown in Fig.3. As both inputs have seven subsets, a fuzzy rule base formulated for the present application is given in table I.

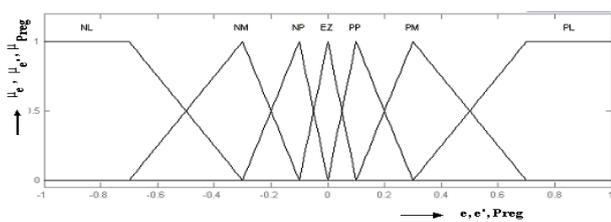


Fig. 3. Membership function for the input and output variable

TABLE I  
FUZZY CONTROL RULE

e de	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	ZE
NM	NL	NL	NL	NM	NS	ZE	PS
NS	NL	NL	NM	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PM	PL	PL
PM	NS	ZE	PS	PM	PL	PL	PL
PL	NL	NM	NS	ZE	PS	PM	PL

#### B. Fuzzy Adaptive Hysteresis Current Control

The switching signals for the voltage source inverter are going to be generated by the adaptive hysteresis band current controller. The band width of the hysteresis current controller is given by [10],

$$HB_j = \frac{V_{dc}}{6f_m L_f} \left( 1 - \frac{9L_f^2}{V_{dc}} \left( \frac{v_s(t)}{L_f} + \frac{di_{fa}^*}{dt} \right) \right), j=1,2,3 \quad (4)$$

where  $f_m$  is the modulation frequency,  $i_{fa}^*$  is the source reference current,  $\frac{di_{fa}^*}{dt}$  represents its slope,  $L_f$  is the decoupling inductance of the active power filter,  $V_{dc}$  is the DC bus voltage and  $v_s(t)$  is the supply voltage. From eqn 2, it is noted that the hysteresis band width is the function of  $\frac{di_{fa}^*}{dt}$  and  $v_s(t)$ . Hence these variables are selected as input variables to the fuzzy controller, and the hysteresis band width (HB) is the output. Five linguistic variables are assigned to the input and output variables in this case. The membership functions of the input and output variables are shown in Fig.4. The fuzzy rule table with 25 rules is given in Table II.

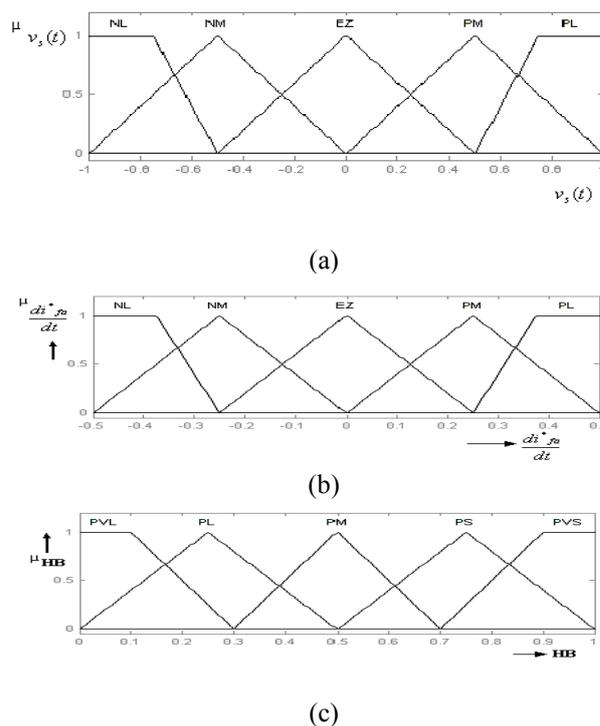


Fig. 4. Membership function for the input variables (a)  $v_s(t)$ , (b)  $\frac{di_{fa}^*}{dt}$  and (c) output variable HB

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

TABLE II  
FUZZY INFERENCE RULE

$v_s(t)$	$\frac{di_{fa}^*}{dt}$	NL	NM	EZ	PM	PL
		PS	PM	PM	PM	PS
NL		PS	PM	PM	PM	PS
NM		PS	PM	PL	PM	PS
EZ		PVS	PM	PVL	PM	PVL
PM		PS	PM	PL	PM	PS
PL		PS	PM	PM	PM	PS

IV. 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 to reduce the harmonics. Fig.5 shows the test system used to carry out the analysis. The test system consists of a three phase voltage source, and an uncontrolled rectifier with RL 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 Appendix B. MATLAB/SIMULINK is used to simulate the test system and the proposed shunt active filter.

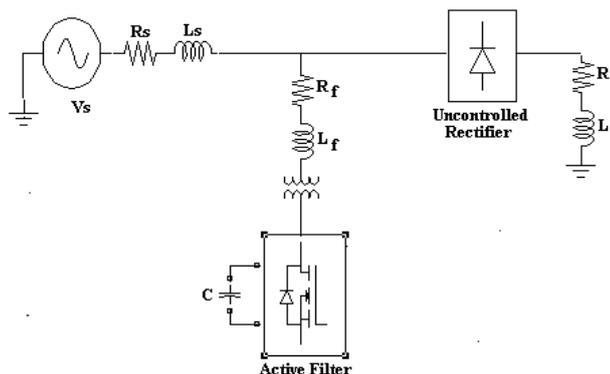
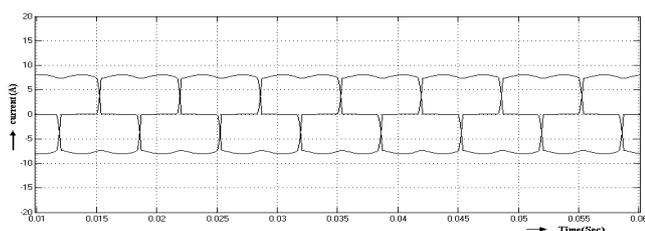
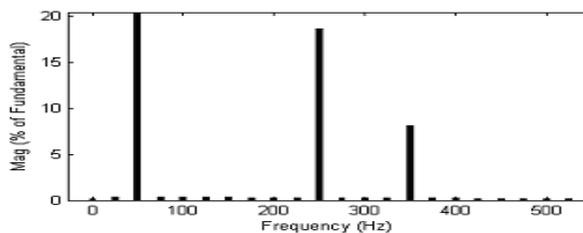


Fig. 5. Test System

The three phase load current waveform in the absence of the filter is shown in Fig. 6 (a). Fig 6 (b) shows the harmonic spectrum of the distorted waveform. The Total harmonic Distortion (THD) of the distorted line current is 26.34%. From the harmonic spectrum, it is evident that, the supply current is distorted due to the dominance of fifth and seventh harmonic spectral components.



a) Distorted three phase line current



b) Harmonic Spectrum of the line current

Fig. 6 Distorted line current and harmonic spectrum caused by three phase uncontrolled rectifier

Next, an active filter with fixed hysteresis band current control (HB=0.5A) and PI voltage control is connected in parallel with the load. Figures 7(a) shows the source voltage, source current, and filter current in this case. The THD in this case has decreased from 26.32 to 4.1%.

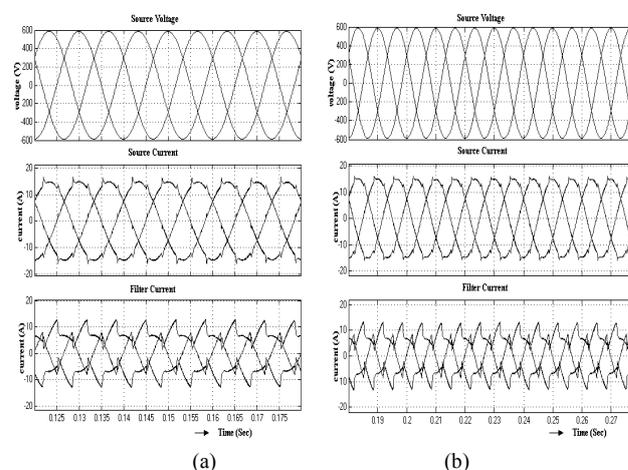


Fig. 7 Harmonic Compensation with fixed hysteresis band control with DC bus voltage control using (a) PI control (b) Fuzzy control

The performance of the system with fixed hysteresis band control and fuzzy logic-based DC bus voltage control was analyzed and the resultant waveforms are shown in Fig 7 (b). It shows that the source harmonic current has reduced and the THD has decreased from 26.32 to 3.6%. The performance of PI and fuzzy controller in maintaining DC bus voltage is shown in fig.8. It is observed that the DC bus voltage is exactly maintained at the reference value by the fuzzy logic controller, whereas some deviations are present with the PI controller.

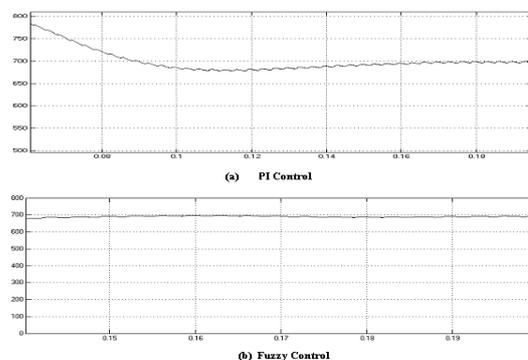


Fig.8. DC bus voltage maintenance-Performance comparison of PI and Fuzzy control

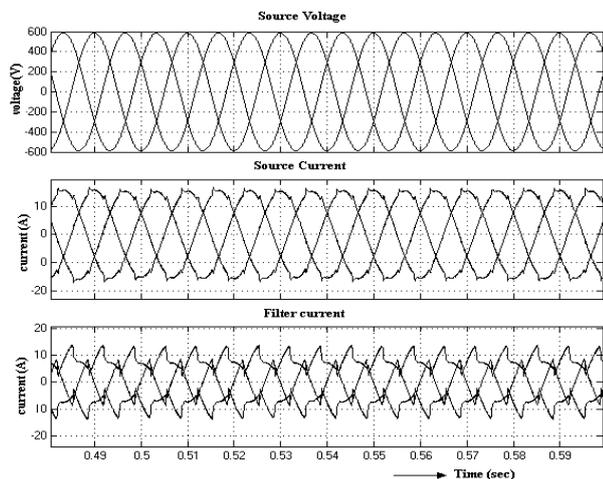


Fig. 9. Harmonic compensation with adaptive hysteresis current control

To further reduce the harmonics, the active filter was simulated with fuzzy adaptive hysteresis band current control and fuzzy logic-based DC voltage control. Fig.12 shows the performance characteristics of the active power filter with the fuzzy-adaptive control scheme. The performance of the active filter with the proposed control algorithm is found to be excellent, and the source current is practically sinusoidal and it is in phase with the supply voltage as shown in fig.10. The THD has decreased from 26.34 before filtering to 2.8% with fuzzy band after filtering. In this case, the modulation frequency is maintained constant at 10Khz.

Fig 11 shows the real and reactive power delivered by the source to the load. From the figure it is clear that the source supplies zero reactive power to the load. For Comparison, the system was simulated with the same parameters with adaptive hysteresis control and the modulation frequency was held constant at 11 KHz. The performance of the active power filter in this case is shown in fig.9. In this case the source current THD has decreased from 26.32 to 3.2 %.

TABLE III  
HARMONIC CONTENTS OF THE SUPPLY CURRENT

VoltageControl Technique	Current Control Technique	THD (%)	Individual harmonic Content (% of Fundamental)									
			3	5	7	9	11	13	15	17	19	
Without Filter			26.34	0	23	12	0	9	7	0	5	4
PI	FixedHysteresis	4.1	0.5	1.5	1.52	0.12	1.61	1.45	0.26	1.33	0.9	
Fuzzy	FixedHysteresis	3.6	0.1	1.5	1.4	0.15	1.7	1.4	0.15	1.4	1	
Fuzzy	AdaptiveHysteresis	3.2	0.09	1.2	1.3	0.04	1.4	1.3	0.008	1.2	1	
Fuzzy	Fuzzy-adaptive Hysteresis	2.8	0.1	1.1	1.1	0.04	1.3	1.15	0.002	1.0	0.9	

TABLE IV  
HARMONIC CONTENTS OF THE SUPPLY VOLTAGE

VoltageControl Technique	Current Control Technique	THD (%)	Individual harmonic Content (% of Fundamental)								
			3	5	7	9	11	13	15	17	19
PI	FixedHysteresis	3.4	0.0015	0.13	0.17	0.007	0.25	0.25	0.008	0.35	0.3
Fuzzy	FixedHysteresis	3.14	0.0015	0.15	0.14	0.006	0.3	0.25	0.001	0.37	0.25
Fuzzy	AdaptiveHysteresis	3.0	0.006	0.12	0.15	0.018	0.26	0.25	0.024	0.35	0.28
Fuzzy	Fuzzy-adaptive Hysteresis	2.8	0.01	0.1	0.13	0.02	0.31	0.23	0.02	0.3	0.31

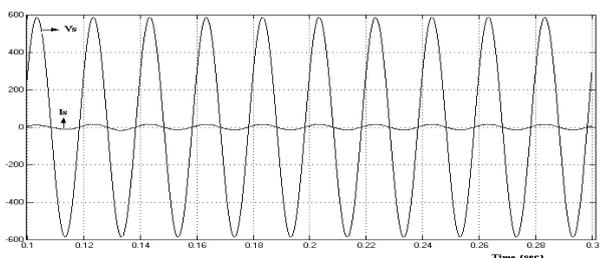


Fig. 10. Source voltage and Current

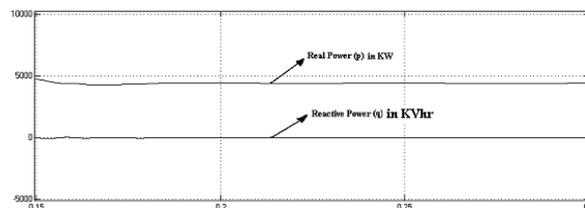


Fig. 11. Real and Reactive power supplied by source to Load.

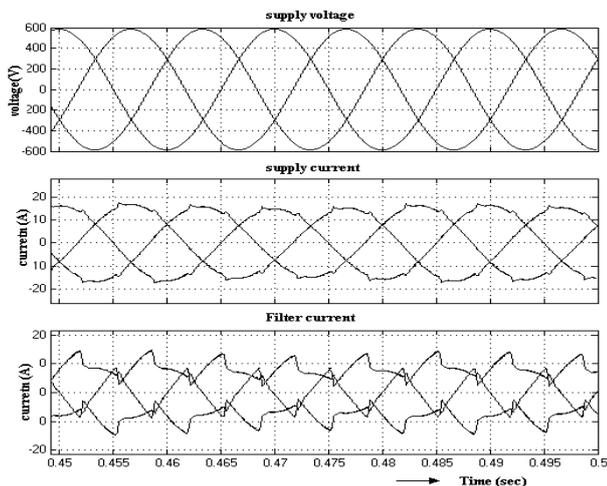


Fig. 12. Harmonic compensation with Fuzzy-adaptive hysteresis current control

TABLE V  
HARMONIC CONTENTS OF THE FILTER CURRENT

Voltage Control Technique	Current Control Technique	Filter Current THD (%)	Average Switching Frequency (KHz)
PI	Fixed Hysteresis	31.47	16.4
Fuzzy	Fixed Hysteresis	27.77	12
Fuzzy	Adaptive Hysteresis	25	11
Fuzzy	Fuzzy-adaptive Hysteresis	23	10

Table III and IV shows the percentage THD of individual harmonics of supply current and voltage for various control techniques respectively. The results in table IV show that the magnitude of the switching noise is low for the fuzzy-adaptive hysteresis technique compared to other technique. The average switching frequency is found for different techniques and the result is summarized in table V which shows that the switching frequency is minimum for the proposed technique compared with other techniques. Table V shows the percentage of filter switching noise and the average switching frequency.

## V. CONCLUSION

This paper has presented a fuzzy- adaptive hysteresis based current control technique for active filter. The active filter was simulated using MATLAB/Simulink and the performance was analyzed in a sample power system with a source and a non-linear load. The fuzzy-adaptive hysteresis control has quick response time and it keeps the switching frequency nearly constant with good quality of filtering. The simulation results show the efficiency of the fuzzy logic controller in maintaining the DC voltage set point .

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