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Comparison between Two Types of Current Control Techniques Applied to Shunt Active Power Filters and Development of a Novel Fuzzy Logic Controller to Improve SAPF Performance

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Abstract*— In this paper two types of current control techniques, namely, direct and indirect current control techniques are employed to a three phase shunt active power filter for the compensation of the harmonics in the current caused by the non-linear loads. The difference between these two types of current control technique is in the number of current sensors used. In direct current control technique both load and filter currents are sensed whereas indirect current control technique is based up on sensing source side current only. For both the schemes a simple PI-controller is used to obtain reference current templates. Also, a novel fuzzy logic based controller is developed to replace the conventional PI-controller. The advantages of fuzzy controllers over conventional controllers are that they do not require an accurate mathematical model, they can work with imprecise inputs, can handle non-linearity and they are more robust. Various simulations are presented for direct and indirect current control techniques along with PI-controller and Fuzzy Logic Controller under both steady state and transient conditions.

***Keywords*— shunt active power filter, harmonics, direct current control technique, indirect current control technique, fuzzy logic controller, dc-link voltage**

	List of Symbols
$i_{sa}^*, i_{sb}^*, i_{sc}^*$	Three phase reference source currents
$i_s(t), i_l(t), i_f(t)$	Instantaneous value of source, load and filter current
$v_s(t), V_m(t)$	Instantaneous and peak value of source voltage
R_s, L_s	Source resistance and inductance
R_f, L_f	Filter resistance and inductance
i_{sp}, i_{sl}	Peak value of reference current and loss current
V_{dc}, V_{dcref}	Actual and reference value of DC capacitor voltage
$p_l(t)$	Instantaneous load power
$p_f(t), p_r(t), p_h(t)$	Instantaneous fundamental(real), reactive and harmonic power
$\cos\phi_1$	Displacement factor

I. INTRODUCTION

Power electronics based non-linear loads are increasing in a never before rapid rate both in industry and domestic application. Power electronics based converters are increasingly used in industrial applications such as adjustable speed drives, furnaces etc. HVDC transmission systems and renewable electric power generation systems also use power electronics based instruments. Use of power electronics based home appliance like TV set, personal computers are also growing rapidly. These loads are known as generators of current harmonics and tend to distort the supply current. They are also responsible for low system efficiency, poor power factor, disturbance to other consumers and interference in nearby communication networks. Conventionally shunt passive filters consisting of LC filter have been used for suppression of harmonics. But, passive filters have many disadvantages such as resonance with source impedance, larger size and weight. The concept of using active power filters in order to compensate harmonic currents and reactive power of the locally connected non-linear loads has been so far investigated and shown to be viable solution for power quality improvement [1,2]. APFs, may be classified into pure active filters and hybrid active filters [4,5]. Hybrid APFs are primarily used for harmonic mitigation. Fast switching, low power loss power electronic devices and fast digital signal processing devices available at an affordable cost, it is feasible to embed a variety of functions into a pure APF to make it a power quality conditioner [9]. APF eliminates system harmonics by injecting a current to the system that is equal to the load harmonic current. Since the load harmonics to be compensated may be very complex and changing rapidly and randomly. APF has to respond quickly and work with very high control accuracy in current tracking [3]. Two types of current control techniques, namely, direct and indirect current control have been discussed in [6,7]. The difference between these two types of current control technique is in the number of current sensors used. In direct current control technique both load and filter currents are sensed whereas indirect current control technique is based up on sensing source side current only. For both the schemes a simple PI-controller is used to obtain reference current templates. However, the design of PI controller requires precise linear mathematical model of the system which is difficult to obtain and may not give satisfactory performance under parameter variations. On the other hand, the intelligent control that is based on artificial intelligence can emulate the human thinking process. In the knowledge of expert that expressed in rules, fuzzy logic presents a slightly superior dynamic performance when compared with a more conventional scheme [10]. The advantages of fuzzy logic controller over conventional controllers are that they do not require an accurate mathematical model, they can work with imprecise inputs, can handle non-linearity and they are more robust than conventional nonlinear controllers [8]. A novel Mamdani type fuzzy logic based controller has been proposed in this paper.

II. GENERATION OF REFERENCE SOURCE CURRENT

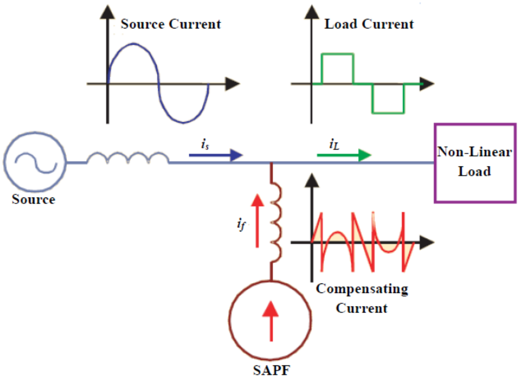


Fig.1

The active filter is controlled to draw/supply a compensating current i_f, from/to the utility, so that it cancels current harmonics on the AC side and supplies the reactive power required by the load, and makes the source current in phase with the source voltage.

In fig.1 the instantaneous currents can be written as

$$i_s(t) = i_L(t) - i_f(t) \tag{1}$$

Source voltage is given by

$$v_s(t) = V_m \sin \omega t \tag{2}$$

Because of the non-linear load, the load current will not be purely sinusoidal, hence it will have a fundamental component and harmonic components. So load current can be represented as

$$i_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \phi_n) = I_1 \sin(\omega t + \phi_1) + \sum_{n+2}^{\infty} I_n \sin(n\omega t + \phi_n) \tag{3}$$

The instantaneous load power can be given as

$$p_L(t) = v_s(t) * i_L(t)$$

$$= V_m I_1 \sin^2 \omega t * \cos\phi_1 + V_m I_1 \sin\omega t * \cos\omega t * \sin\phi_1 + V_m \sin\omega t * \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n) \tag{4}$$

$$= p_f(t) + p_r(t) + p_h(t) \tag{5}$$

From equation (4), the fundamental power drawn by the load is

$$p_f(t) = V_m I_1 \sin^2 \omega t * \cos\phi_1 = v_s(t) * i_s(t) \tag{6}$$

From equation (6), the source current supplied by the source after compensation is

$$i_s(t) = \frac{p_f(t)}{v_s(t)} = I_1 \cos\phi_1 \sin\omega t = I_{sm} \sin\omega t$$

Where $I_{sm} = I_1 \cos\phi_1$

There would be some switching losses in the voltage sourced inverter. The utility must supply a small extra amount for this additional loss and for the capacitor leakage in addition to the real power of the load. Therefore the total peak current supplied by the source is

$$I_{sp} = I_{sm} + I_{sl} \tag{7}$$

If the active filter provides the total reactive and harmonic power, then i_s(t) will be in phase with the utility voltage and purely sinusoidal. At this time, the active filter must provide the following compensating current.

$$i_f(t) = i_L(t) - i_s(t)$$

Hence, for accurate and instantaneous compensation of reactive and harmonic power it is necessary to estimate the fundamental component of the load current as the reference current. Fundamental component of load current will be easily determined if we are able to determine peak value of these reference currents. This peak value multiplied by unit vectors in phase with source voltages will give the corresponding reference source currents.

The DC side capacitor of the SAPF serves two main purposes: it maintains a DC voltage with small ripple in steady state, and it serves as an energy storage element to supply a real power difference between load and source during the transient period. In the steady state, the real power supplied by the source should be equal to the real power demand of the source 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. This real power difference is compensated by the DC capacitor. This changes the DC capacitor voltage away from the reference voltage. In order to keep satisfactory operation of the active filter, the peak value of the reference current must be adjusted to proportionally change the real power drawn from the source. This real power charged/discharged by the capacitor compensates the real power consumed by the load. If the DC capacitor voltage is recovered and attains the reference voltage, the real power supplied by the source is supposed to be equal to that consumed by the load again. Thus, in this fashion the peak value of the reference source current can be obtained by regulating the average voltage of the DC capacitor [8].

III. TWO TYPES OF CURRENT CONTROL TECHNIQUES

In [11] and [12], the authors have proposed two comparatively simple schemes based on sensing load current and line current respectively. Two more simplified approaches were given in [13] known as direct current control and in [7] known as indirect current control. These two important current control techniques are given below

A. Direct Current Control Technique:

In this method the reference source peak current I^{*}_{max} is computed using closed loop control of dc-link capacitor voltage. The reference instantaneous source currents i^{*}_{sa}, i^{*}_{sb} and i^{*}_{sc} are computed using this peak value and unit vectors of respective phase voltages. Now the command currents of active filter i^{*}_{fa}, i^{*}_{fb}, i^{*}_{fc} are computed by taking difference between source reference currents (i^{*}_{sa}, i^{*}_{sb}, i^{*}_{sc}) and sensed load currents (i^{*}_{La}, i^{*}_{Lb}, i^{*}_{Lc}). The hysteresis rule based carrierless PWM current controller is employed over the reference filter currents (i^{*}_{fa}, i^{*}_{fb}, i^{*}_{fc}) and sensed filter currents (i_{fa}, i_{fb}, i_{fc}) to obtain the gating signals to the devices of the active filter.

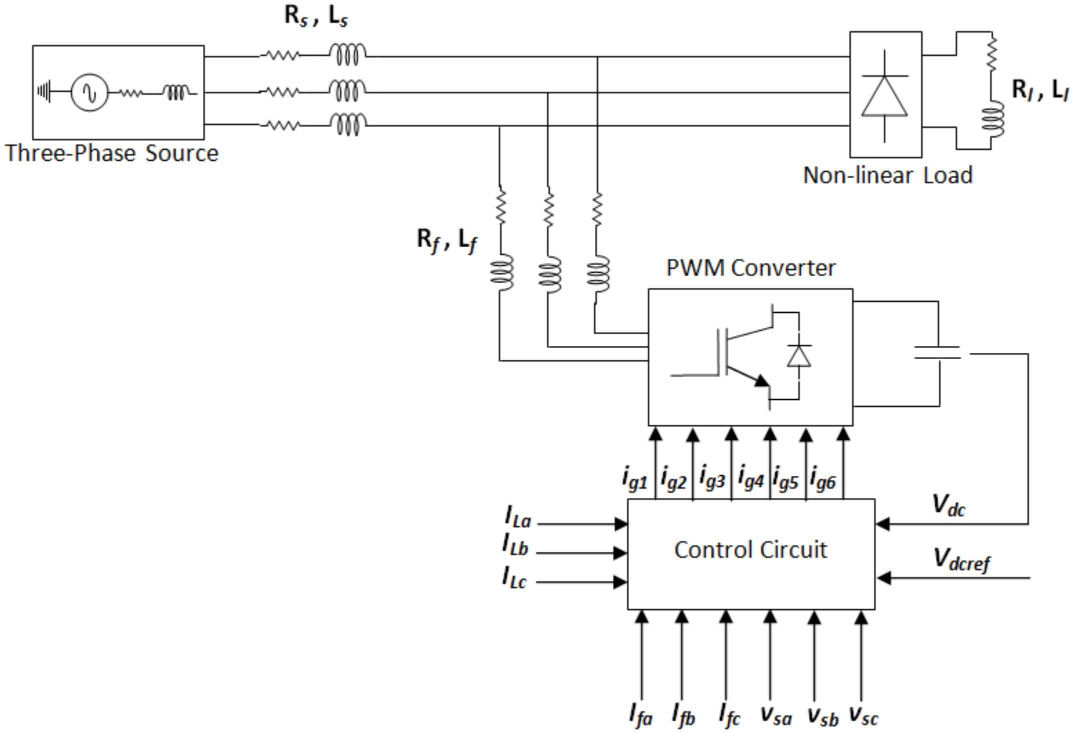


Fig.2 Direct Current Control Technique

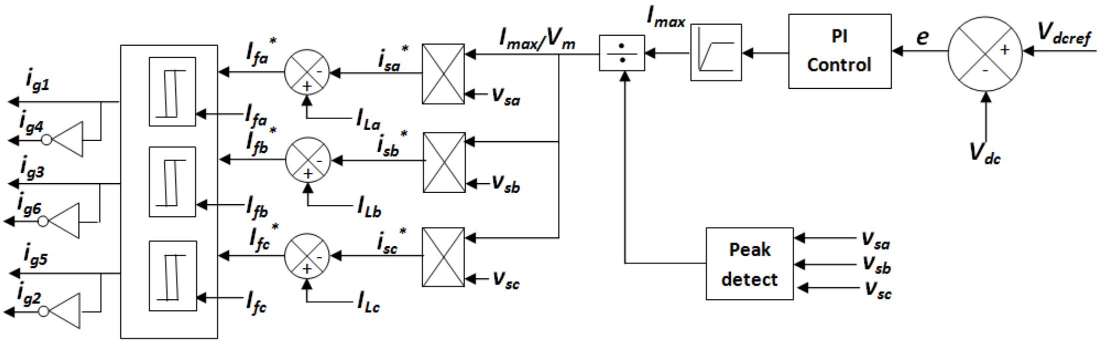


Fig.3 Direct Current Control Technique implementation using PI controller

B. Indirect Current Control Technique:

In this method the active power filter is implemented with a four quadrant, current controlled PWM rectifier, in which the nonlinear load is connected between it and their current sensors. On doing that, the rectifier begins to behave as a shunt active power filter, but without losing its characteristics as a four quadrant rectifier. The current controlled rectifier does not detect the presence of the non-linear load. It simply tries to keep the mains current sinusoidal. In this way there is no need to sense, neither the non-linear load current nor the filter current [7]. Simply source reference currents (i^*_{sa}, i^*_{sb}, i^*_{sc}) are calculated and the hysteresis rule based carrierless PWM current controller is employed over reference source currents (i^*_{sa}, i^*_{sb}, i^*_{sc}) and sensed source currents (i_{sa}, i_{sb}, i_{sc}) to obtain the gating signals to the device.

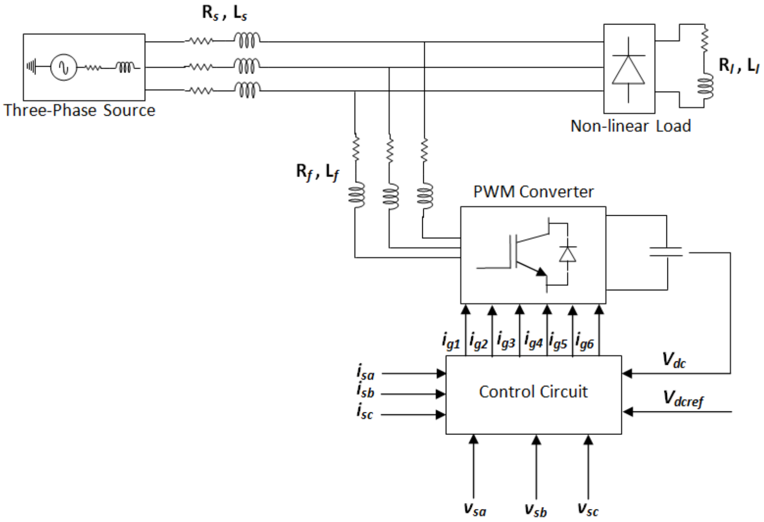


Fig.4 Indirect Current Control Technique

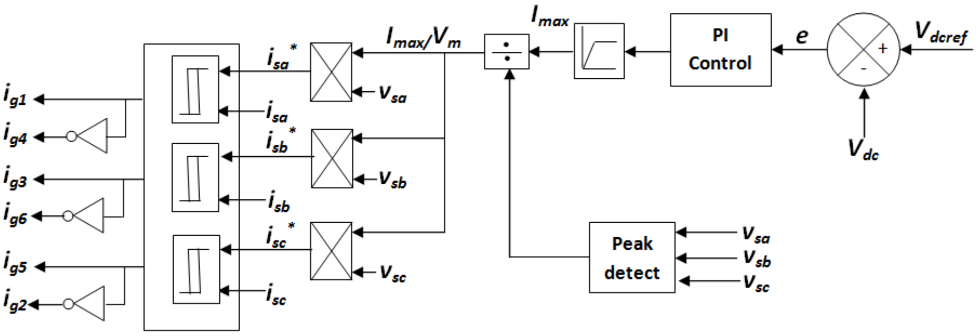
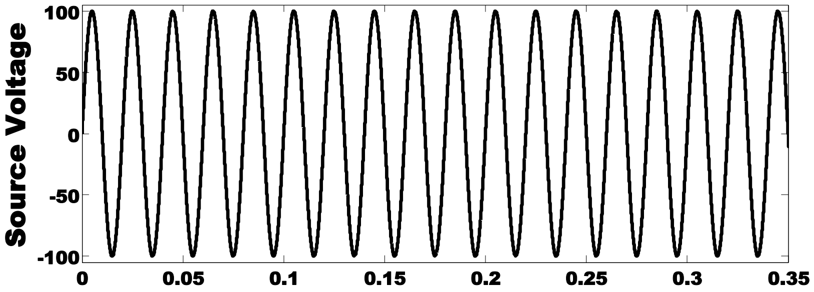


Fig.4 Indirect Current Control Technique implementation using PI controller

IV. SIMULATION RESULTS FOR TWO TYPES OF CURRENT CONTROL TECHNIQUES

The parameters selected for simulation are: V_s=100V(peak), R_s=0.1Ω, L_s=0.15mH, R_f=0.1Ω, L_f=0.66mH, V_{dcref}=220V, R_l=6.7Ω & 10Ω, L_l=20mH, C_{dc}=2000μF. A three phase diode rectifier with R-L load is taken as non-linear load. To analyze system performance under dynamic conditions, at time t=0.4s the resistance is increased from 6.7Ω to 10Ω. And again at time t=0.7s it is decreased to 6.7Ω. Simulation results for both steady state and dynamic conditions are given in Fig.5-7



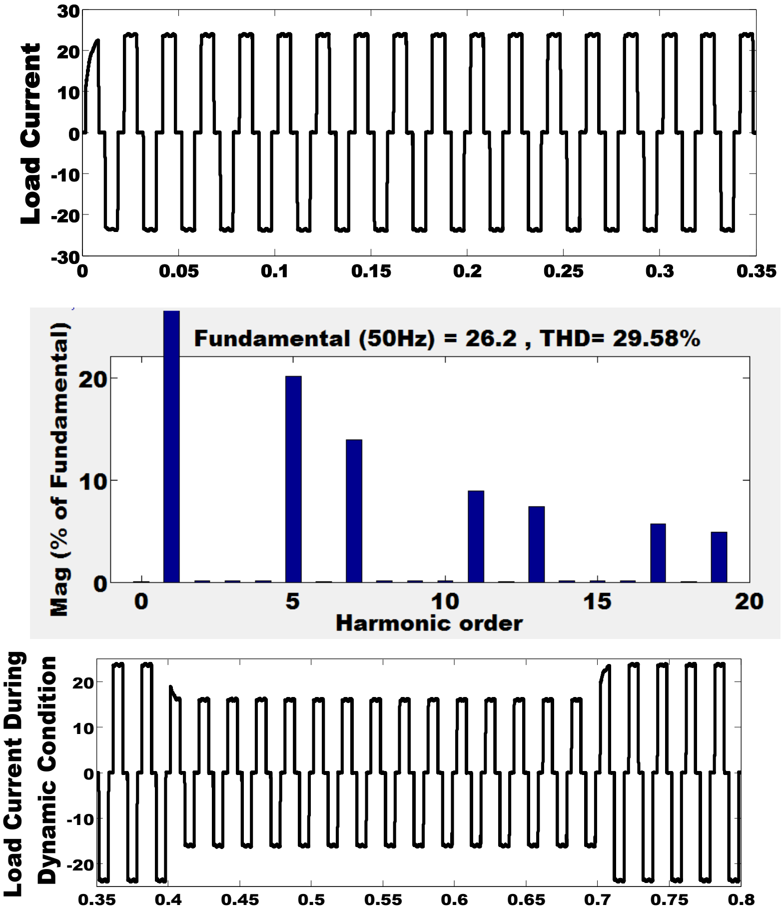
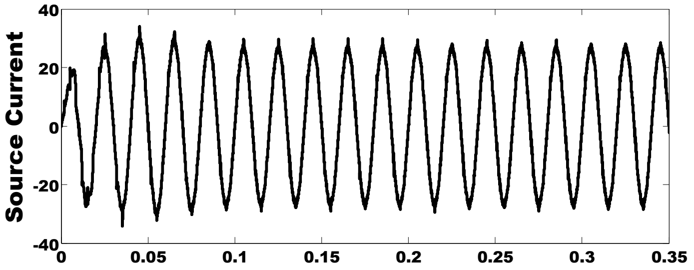
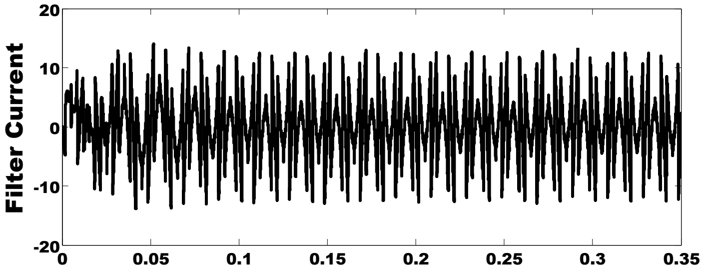


Fig.5 System without power filter





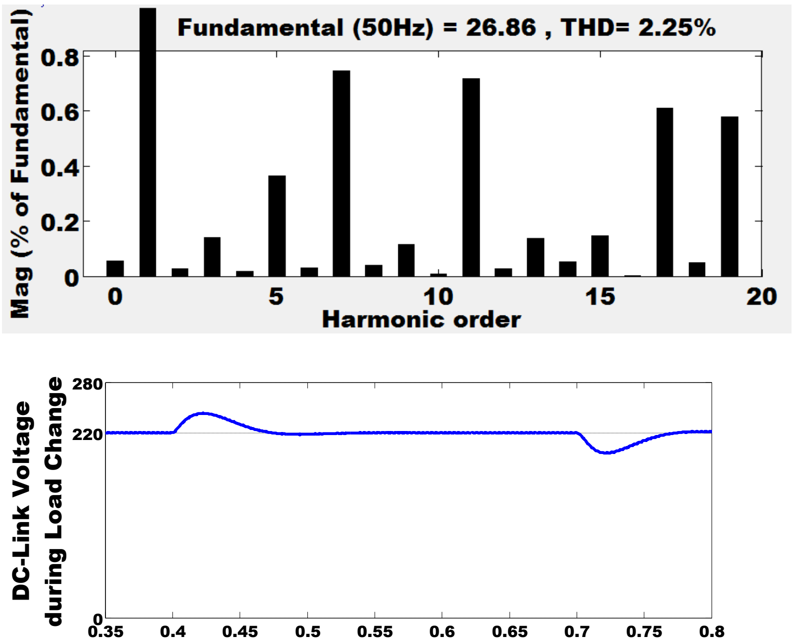
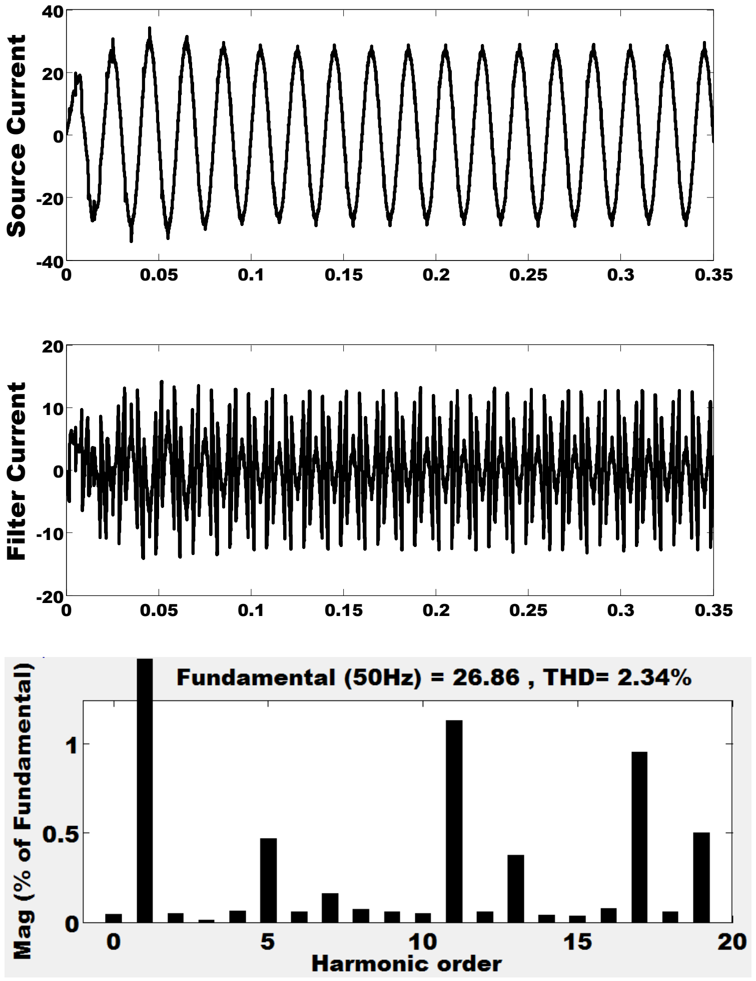


Fig.6 System with Direct current Control based SAPF



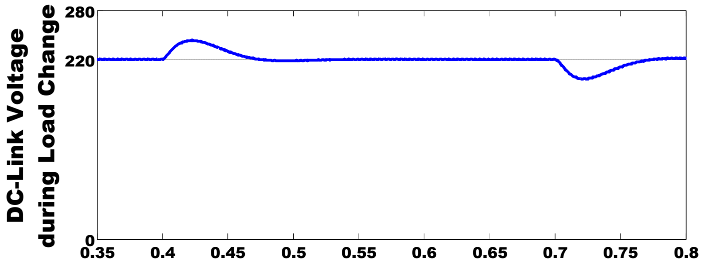


Fig.7 System with indirect current Control based SAPF

From above simulation results we can conclude that, Total Harmonic Distortion (THD) in source current after compensation for both direct and indirect current control techniques are nearly same. Also during load change the settling time for dc-link capacitor voltage is also nearly same. For direct current control technique it is 0.155 sec and for indirect current control technique it is 0.15 sec. This parameter is important in the context that the real power balance between source and load is realized when dc-link capacitor voltage settles down to its reference value.

V. DESIGN OF A FUZZY LOGIC BASED CONTROLLER

The design of a fuzzy logic controller (FLC) is mainly based on intuitive feeling for and experience of, the process. The error $e(k)=V_{dcref}-V_{dc}(k)$ and change in error $ce(k)=e(k)-e(k-1)$ are used as inputs to the Mamdani type Fuzzy Logic Controller. The output is change in peak value of reference source current. The controller scheme structure is given in Fig.8. We have used normalized input and output membership functions as shown in Fig.9. That is why gains G_1, G_2, G_3 are used. Their value depends upon actual values of error and change in error. Also indirect current control technique is used here, as we have seen from the previous discussion that it requires less hardware while performance being equal to direct current control technique.

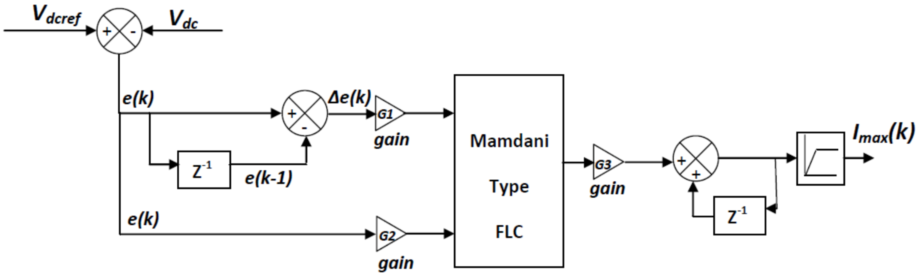


Fig.8 Fuzzy Logic Control Scheme

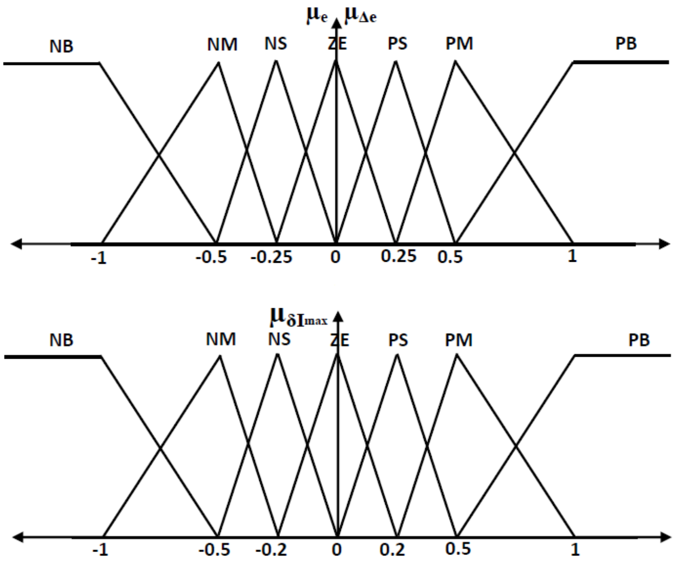


Fig.9 Normalized input and output Membership Functions

Determination of the membership functions depends on the designer's experience and expert knowledge. It is not trivial to choose a particular shape that is better than others. A fuzzy set can take many shapes, triangular, trapezoidal, sigmoid, bell shape etc. We have taken triangular membership functions for its advantages of simplicity and easier implementation. The performance of the fuzzy controller is determined by the set of linguistic rules based on knowledge. To construct a rule base, the inputs and output are partitioned into seven primary fuzzy sets labeled as {NB, NM, NS, ZE, PS, PM, PB}.

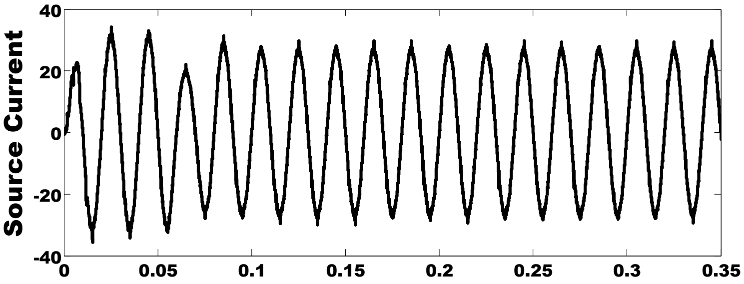
The rule is expressed in the form **IF** (antecedent) **THEN** (consequence). The FLC rule-base constitutes of the form **IF** e is A_1 **AND** Δe is B_1 **THEN** I_{max} is C_1. And Control rule table is given in Table.1. The elements of the rule table are obtained from an understanding of filter behavior. The basic principle is that in transient state, large errors need coarse control, which requires coarse input/output variables; in steady state, small errors need fine control, which requires fine input/output variables. The elements are modified according to the simulation performance.

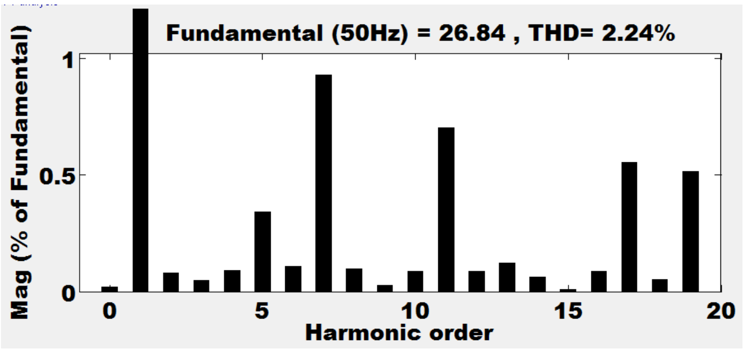
Various inference mechanisms have been developed to defuzzify the fuzzy rule. We have applied max-min inference method to obtain an implied fuzzy set of tuning rules. The imprecise fuzzy control action generated from inference engine must be transformed into a precise control application in real applications. The centre-of-mass method was used to defuzzify the implied fuzzy control variables.

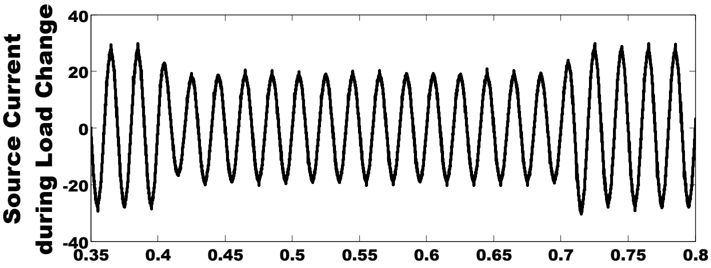
e Δe	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Table.1 Control Rule Table

VI. SIMULATION RESULTS FOR FUZZY LOGIC CONTROLLER







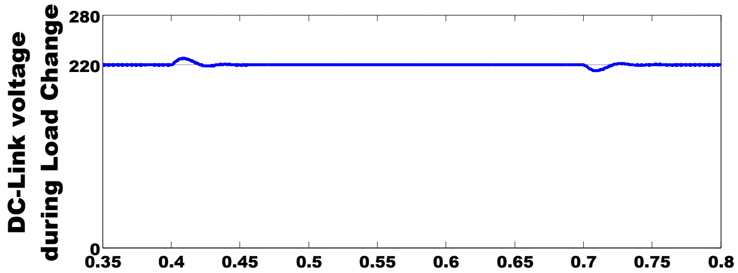


Fig.10 System with FLC based SAPF

VII. COMPARISON

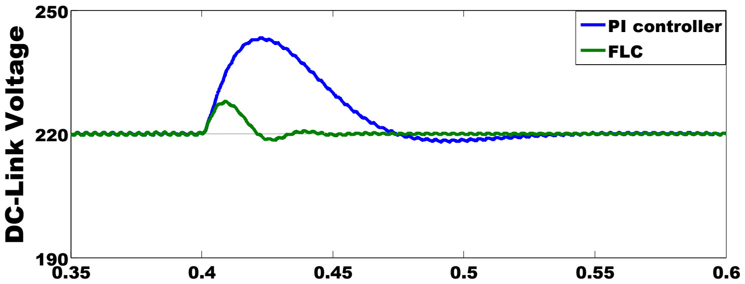


Fig.11 DC-Link voltage settling time comparison

We have seen from the above simulation result that Fuzzy Logic controlled SAPF performance is far better than PI-controlled filters. We are able to reduce THD to 2.24%. Also dc-link capacitor voltage settling time during load change can be reduced to 0.06 sec. A comparative study on above three simulations on the basis of harmonic reduction and dc link voltage settling time is given in table.2.

Parameters	Direct Current Control Technique (PI-Controller based)	Indirect Current Control Technique	
		PI- Controller	Fuzzy Logic Controller
THD	2.25%	2.34%	2.24%
Settling Time of DC-Link Voltage during Load Change	0.155 sec	0.15 sec	0.06 sec
DC-Link Voltage Rise/Drop during Load Change	23 Volt	23 Volt	7.5 Volt
No of Current Sensors Required	6	3	

Table.2

VIII. CONCLUSIONS

In this paper, two types of current control techniques have been implemented for the control of Shunt Active Power Filter using MATLAB SIMULINK tool. We have observed that there is no major difference in performance of the SAPF. However, hardware requirement is less in case of indirect current control technique. A novel fuzzy logic controller has also been proposed to obtain reference current templates. Settling time of dc link voltage during load change is important because it implies real power balance. In some cases, dc link voltage rise might play an important role in choosing switching devices for active filter. Simulation results show satisfactory performance of the fuzzy logic controller in terms of harmonic compensation, reduction in dc link voltage settling time, the Total Harmonic Distortion is far less than IEEE standard requirement i.e. 5% and dc link voltage settling time is also 0.06 sec. only, which makes it immensely useful for rapid load changing industrial environment.

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