Fuzzy Logic Controlled Adaptive Active Power Filter for Harmonics Minimization and Reactive Power Compensation under Fast Load Variation

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Abstract: - This paper describes the application of a new fuzzy based control strategy to a three-phase shunt active power filter for harmonics minimization and reactive power compensation required by a variable non-linear load. To improve dynamic behaviour of shunt active power filter and make it robust under wide range of load variations, the value of load current is considered as an input of fuzzy controller. The proposed scheme is extensively tested for wide range of variable load current under stochastic conditions and results are found to be quite satisfactory to improve dynamic behaviour of shunt active power filter and mitigate harmonics from the utility current.

Key-Words: - Shunt active power filter, Adaptive control, Harmonics compensation, Fuzzy logic controller, Power quality, Power factor correction

1 Introduction

Non-linear loads connected to AC electric mains generate undesired harmonics in the current dynamics which are usually responsible of additional power losses and the risk of equipment damage or malfunctioning [1]-[3]. Traditionally, current harmonics have been compensated with passive filters which, as all passive devices, have several intrinsic limitations rendering their use ineffective in realistic situations characterized by different and not a priori fixable operative modes. In the last decades, the fast development of power electronics components and control processors has led to a growing interest in the so-called active power filters (APF) [4]. These devices are potentially able to properly work and to guarantee performances in a wide range of operating conditions overtaking in this way intrinsic limitations of passive devices. A particular kind of APF are the shunt active filters (SAF) whose purpose is to inject into the mains a proper current/power in order to compensate partially or totally for the harmonic current generated by nonlinear load [5], [6]. The SAF considered in this paper is based on three-phase three-wire AC/DC boost converter topology and it is connected in parallel with distorting loads as it is shown in Fig. 1. This kind of devices is suitable for three-phase, three-wire harmonic compensation, i.e. it is suitable for AC three-phase line grid and neglect current in the neutral. Different approaches dealing with this kind of SAF have been presented in literature [4]. In this respect, the main distinguishing marks are *the filter current control algorithm methods* adopted to determine the filter current objective. The high performances of hysteresis current controllers are exploited in [7], [8]. However PI controller was used for the generation of a reference current template. The PI controller requires precise linear mathematical models, which are difficult to obtain and fails to perform satisfactory under parameter variations, nonlinearity, load disturbance, etc.

Recently, fuzzy logic controllers (FLCs) have generated a good deal of interest in certain applications [9]-[11]. The advantages of FLCs over conventional controllers are that they do not need an accurate mathematical model, they can work with imprecise inputs, can handle non-linearity, and they are more robust than conventional nonlinear controllers. Jain, Agrawal and Gupta used fuzzy logic controller to overcome some difficulties with PI controllers [12]. In Bhende, Mishra and Jain Takagi-Sugeno (TS)-type fuzzy logic controller is applied to a three-phase shunt active power filter in order to reduce number of fuzzy sets, fuzzy rules and coefficients which decreases the controller complexity and computational time [13].

However using fuzzy logic controller for reference current estimation improves dynamic behaviour of shunt active power filter, it is still vulnerable to fast and stochastic load variations which usually happen in realistic condition. The settling of DC capacitor voltage to its reference value is quite important in the context that at this condition, the real power balance between the source and load is realized. Therefore, apart from the reduction in total harmonic distortion (THD), there is also a need to bring back the DC voltage as early as possible to its reference value.

This paper presents a new fuzzy based control strategy for a three-phase shunt active power filter with the objective to: 1) reduce the settling time of DC capacitor voltage excursion and 2) reduce THD. To make an adaptive control the value of load current is considered as controller input. An extended TS fuzzy logic based control scheme is developed and compared with a conventional PI controller via computer simulation.

2 Shunt Active Power Filter

2.1 Basic compensation principals

Fig. 1 shows the basic compensation principle of the shunt APF. A current controlled voltage source inverter with necessary passive components is used as an APF.

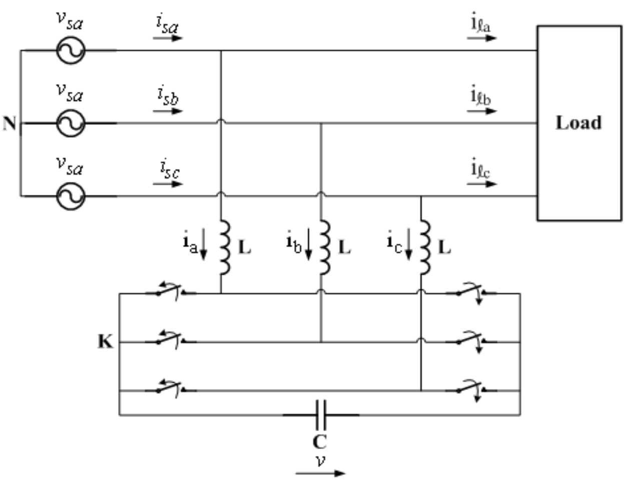

Fig. 1 Shunt active filter scheme

It is controlled to draw/supply a compensated current from/to the utility, such that it eliminates reactive and harmonic currents of the non-linear load. Thus, the resulting total current drawn from the ac mains is sinusoidal. Ideally, the APF needs to generate just enough reactive and harmonic current to compensate the non-linear loads in the line [14]-[16].

2.2 Generation of reference source currents

Fig. 2 shows the basic compensation principle of a shunt active power filter. It is controlled to draw/supply a compensating current i_c from/to the utility, so that it cancels current harmonics on the ac side and makes the source current in phase with the source voltage.

From Fig. 2, the instantaneous currents can be written as:

$$i_s(t) = i_l(t) - i_c(t). \tag{1}$$

Source voltage is given by

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

if the nonlinear load is applied, then the load current will have a fundamental component and harmonic components, which can be expressed as

$$\begin{aligned} i_l(t) &= \sum_{2}^{\infty} I_n \sin(n\omega t + \phi_n) = \\ & I_1 \sin(\omega t + \phi_1) + \sum_{2}^{\infty} I_n \sin(n\omega t + \phi_n). \end{aligned} \tag{3}$$

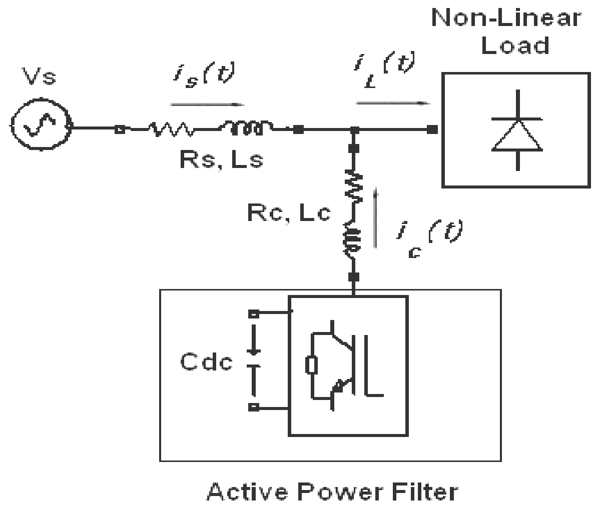

Fig. 2 Basic compensation principle of APF

The instantaneous load power can be given as

$$p_l(t) = v_s(t) * i_l(t) =$$
$$V_m I_1 \sin^2 \omega t * \cos\phi_1 + V_m I_1 \sin\omega t * \cos\omega t * \sin\phi_1$$
$$+ V_m \sin\omega t * \sum_{n=2}^{n=\infty} I_n \sin(n\omega t + \phi_n) = \quad (4)$$
$$p_f(t) + p_r(t) + p_h(t).$$

from (4), the real power drawn by the load is

$$p_f(t) = V_m I_1 \sin^2 \omega t * \cos\phi_1 = v_s(t) * i_s(t). \quad (5)$$

from (5), the 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 are also some switching losses in the PWM converter, hence the utility must supply a small overhead for the capacitor leakage and converter switching losses in addition to the real power of the load. Therefore, the total peak current supplied by the source (I_{sp}) is

$$I_{sp} = I_{sm} + I_{sl} \quad (6)$$

where I_{sl} is the peak value of loss current. If the active filter provides the total reactive and harmonic power, then $I_s(t)$ will be purely sinusoidal and in phase with the utility voltage. At this time, the active filter must provide the following compensation current

$$i_c(t) = i_l(t) - i_s(t) \quad (7)$$

hence, for accurate and instantaneous compensation of reactive and harmonic power, it is necessary to estimate the fundamental of load current ($i_s(t)$). The peak value of the reference current I_{sp} can be estimated by controlling the DC-side capacitor voltage. In ideal compensation, irrespective of the load current nature, the mains current must be sinusoidal and in phase with the source voltage,

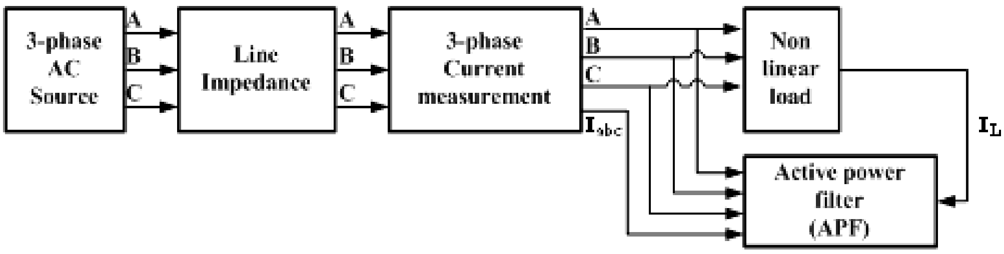

Fig. 3 Compensation system

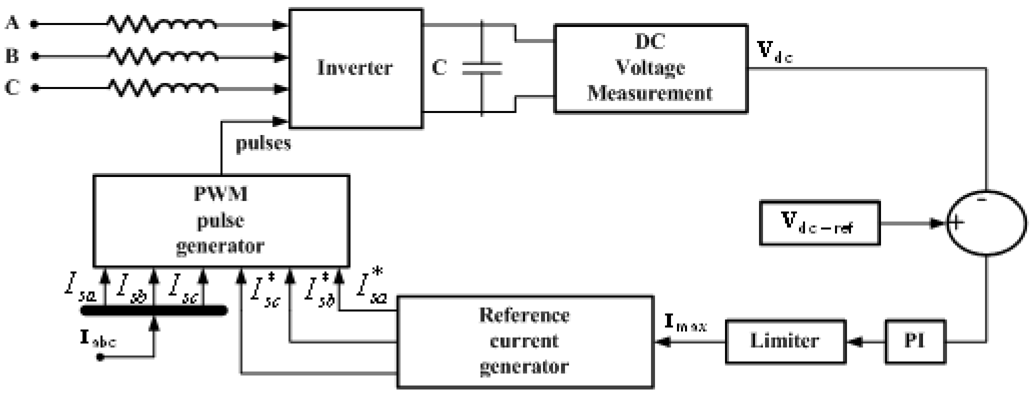

Fig. 4 Compensation system

so the desired source currents can be given as

$$I_{sa}^{*} = I_{sp}\ sin\,\omega\,t$$
$$I_{sb}^{*} = I_{sp}\ sin(\,\omega t - 120\,) \quad (8)$$
$$I_{sc}^{*} = I_{sp}\ sin(\,\omega\,t + 120\,)$$

where I_{sp} is the amplitude of the desired source current, while the phase angle can be obtained from waveform and phase of the source currents are known, and only the magnitudes of the source current must to be determined. In conventional current controlled voltage source PWM converter based shunt APFs the peak value of the reference current has been estimated by regulating the DC-side capacitor voltage of the PWM converter. The DC capacitor voltage is compared with a reference value and the error is processed in a PI controller. The output of the PI controller has been considered as the amplitude of the desired source current, and the reference currents are estimated by multiplying this value with the unit vectors in phase with the source voltages. Figs 3 and 4 show the conventional active power filter compensation system and the schematic diagram of the control scheme, respectively.

3 Proposed Fuzzy Control Scheme

Figs 5 and 6 show the proposed active power filter compensation system and the schematic diagram of the proposed fuzzy control scheme, respectively. Accurate estimation of load reference template decreases the excursion time of DC capacitor voltage, while it minimizes the total harmonic distortion in line current. As the reference value of load is not fixed and varies with change in load current, however, the nature of variation is nonlinear, and it is difficult to relate it by mathematical expressions. Also in practice, the nature of input power to load is not pure sinusoidal rather stochastic in nature. Hence, estimation of variable reference value through PI controller may not be able to fully compensate the effect of harmonics especially in a short time. Fuzzy logic is an alternative approach to handle this type of problem, which has become more popular during past four decades due to its advantages of robustness against parameter variation, popularity, customization, etc. When system is too complex or too poorly understood to be described in precise mathematical terms, fuzzy modelling provides the ability to linguistically specify approximate relationships between the input and desired output. The relationships are represented by a set of fuzzy If-then rules in which the antecedent is an approximate representation of the state of the system and the consequent provides a range of potential responses. In this paper a new fuzzy logic based control scheme proposed to estimate the reference value according to load current. In order to implement the control algorithm of a shunt active power filter in a closed loop, the DC capacitor voltage (V_{dc}) is sensed and compared with the reference value (V_{dcref}). In case of a fuzzy logic control scheme, the error ($e = V_{dcref} - V_{dc}$), integration of error signal ($\int e$) and load current value (I_L) are used as inputs for fuzzy processing. The output of the fuzzy controller, after a limit, is considered as the magnitude of peak reference current $I_{\max}$. The switching signal for the PWM converter are obtained from comparing the actual source currents ($i_{sa,} i_{sb}, i_{sc}$) with the reference current templates ($I_{sa}^{*}, I_{sb}^{*}, I_{sc}^{*}$) in a hysteresis current controller. The output pulses are applied to the switching devices of the PWM converter.

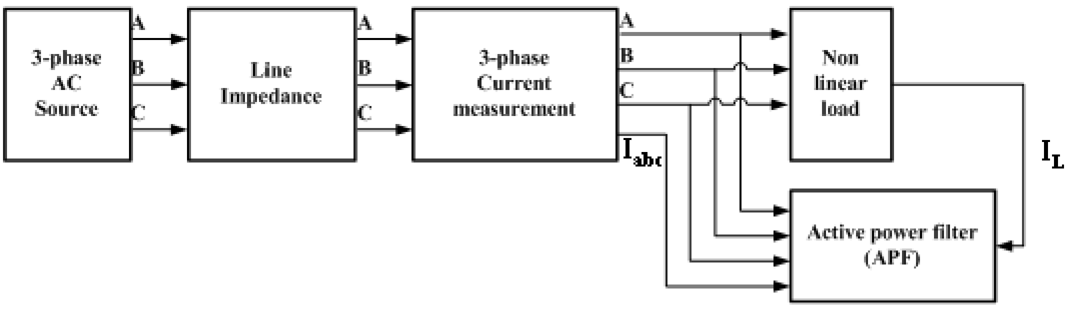

Fig. 5 Connection of Proposed active power filter

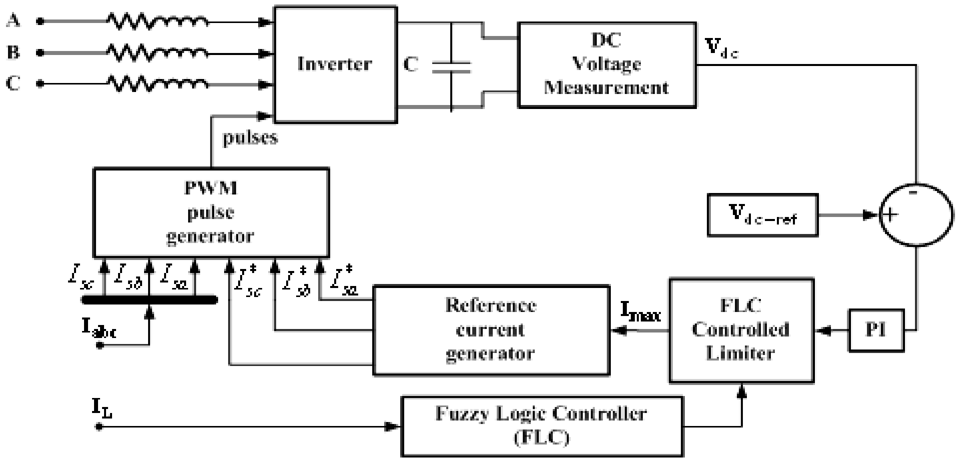

Fig. 6 Proposed active power filter topology with fuzzy logic controller

The range of operating current and particular band of operating current is one of the important design factors of fuzzy controller. The proposed FLC compensates the harmonic current for any load current variation between 1 and 70 A.

3.1 Membership function for input and outputs variable

Computational efficiency, memory requirements and computational time are the few important aspects of evolutionary computational methods. In TS fuzzy controller the linguistic rule consequent is made variable by means of its parameters. As the rule consequent is variable, the Ts fuzzy control scheme can produce an infinite number of gain variation characteristics. In essence, the TS fuzzy controller is capable of offering more and better solutions to a wide variety of nonlinear control problems. Also the number and type of membership function (MF) decides the computational efficiency of a FLC. The shape of fuzzy set affects how well a fuzzy system of If-then rules approximate a function. Triangles have been the most popular If-part set shape for approximating non-linear function [17]. For this work, a TS type fuzzy controller with three inputs is designed. Three fuzzy sets with triangle and custom defined MFs are used to fuzzify the input variables. In order to trade-off between accuracy and complexity, through rigorous simulation studies it has been found that two MFs are sufficient for fuzzification of error and its integration, however four MFs are required for load current to produce desired results in required band. Reducing the number of MFs will produce improper results at some band, while increasing the number of MFs will produce a delay due to more computational steps required.

Input fuzzy sets used to fuzzify error and its integration are *P* (positive) and *N* (negative). The membership function used for the positive set is

$$\mu_P(x_i)=\begin{cases} 0, & x_i \langle -L \\ \dfrac{x_i+L}{2L}, & -L \le x_i \le L \\ 1, & x_i \rangle L \end{cases} \tag{9}$$

where $x_i(k)$ denotes the input to the fuzzy controller at the *K* sampling instant given by

$$x_1(k)=e(k)=I_{Lref}-I_L$$

and

$$x_2(k)=\sum e(k). \tag{10}$$

for the negative set

$$\mu_N(x_i)=\begin{cases} 1, & x_i \langle -L \\ \dfrac{-x_i+L}{2L}, & -L \le x_i \le L \\ 0, & x_i \rangle L \end{cases} \tag{11}$$

The membership functions for x_1 and x_2 are shown in Figs. 7 and 8, respectively. The value of L_1 and L_2 are chosen on the basis of the maximum value of error and its integration.

For load current, four triangle MFs are defined by $M = (a,b,c)$, where a,b,c are starting, middle point with unity membership grade, and end points, respectively. Fig. 9 shows membership functions for load current ($I(k)$). Also linguistic names of each fuzzy set with their definition are given in table 1.

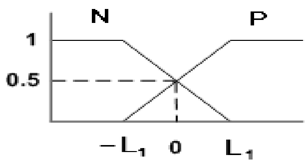

Fig. 7 Membership functions for

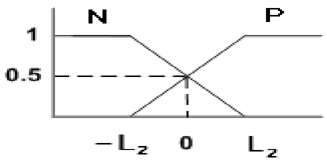

Fig. 8 Membership function for

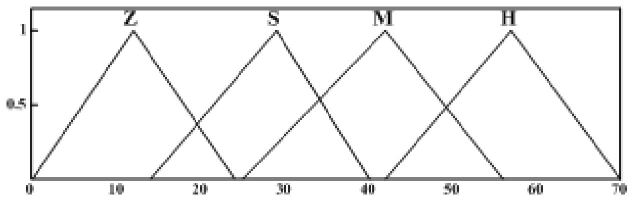

Fig. 9 Membership functions for $I(k)$

Table 1 Description of membership function considered for input variable

Linguistic name	Left end point	Modal value	Right end point
Zero	0	12	24
Small	14	28	40
Medium	25	42	56
High	42	57	70

In case of sugeno type FLC [18], no membership functions are used for representing output variable, rather these are mapped as mathematical expression of consequent part of rule base. In present case, the function of fuzzy logic is to map a nonlinear input-output function. Thus, the number of rules is directly related with number of MF for input and output. Hence, in the present case sixteen rules are made. The weighted factor of sugeno FLC is an important factor for producing accurate output. Since, the antecedent part of rules are chosen as linear combination of input, the weighted factors are also linear and of zero order.

3.2 Design of rule base

In general, the rule-base of sugeno type fuzzy controller is given by

(R_i): IF error value is $x_1(k)$ AND its integration is $x_2(k)$ AND load current is $I(k)$, THEN $u_i(k) = a_i.x_1(k) + b_i.x_2(k) + c_i I(k)$, for i =1… 16.

In the above rules, u_1, …, u_{16} represent the consequent of the TS fuzzy controller. Using Zadeh's rule for AND operation and the general defuzzifier, the output of TS fuzzy controller is

$$u(k) = \frac{\sum_{i=1}^{16} (\mu_j)^{\gamma} u_i(k)}{\sum_{i=1}^{16} (\mu_i)^{\gamma}}. \qquad (12)$$

However, for $\gamma = 1$, we get the centroid defuzzifier.

4 Modeling of the Compensation System

4.1 PWM converter

The PWM converter has been modelled as having a three phase AC voltage applied through a filter impedance (R_c, L_c) on its input, and a DC bus capacitor on its output [19]. The three phase voltages v_{ca}, v_{cb} and v_{cc} reflected on the input side can be expressed in terms of the DC bus capacitor voltage V_{dc} and switching functions stating the on /off status of the devices of each leg T_A, T_B and T_c as

$$\begin{aligned} v_{ca} &= \frac{V_{dc}}{3}(2T_A - T_B - T_C) \\ v_{cb} &= \frac{V_{dc}}{3}(-T_A + 2T_B - T_C) \\ v_{cc} &= \frac{V_{dc}}{3}(-T_A - T_B + 2T_C) \end{aligned} \qquad (13)$$

The three phase currents i_{ca}, i_{cb}, i_{cc} flowing through the filter impedance (R_c, L_c) are obtained by solving the following differential equations:

$$pi_{ca} = \left(\frac{1}{L_c}\right)\left(R_c i_{ca} + (v_{sa} - v_{ca})\right)$$
$$pi_{cb} = \left(\frac{1}{L_c}\right)\left(R_c i_{cb} + (v_{sb} - v_{cb})\right) \tag{14}$$
$$pi_{cc} = \left(\frac{1}{L_c}\right)\left(R_c i_{cc} + (v_{sc} - v_{cc})\right)$$

The DC side capacitor current can be obtained in terms of phase currents i_{ca}, i_{cb}, i_{cc} and the switching status (1 for on and 0 for off) of the devices T_A, T_B and T_c.

$$i_{dc} = i_{ca}T_A + i_{cb}T_B + i_{cc}T_c$$

From this, the model equation of the DC side capacitor voltage can be written as

$$pV_{dc} = \left(\frac{1}{C_{dc}}\right)\left(i_{ca}T_A + i_{cb}T_B + i_{cc}T_C\right) \tag{15}$$

4.2 Hysteresis controller

The hysteresis current controller decides the switching signals for the devices of the PWM converter. The switchings are obtained as: if $i_{si} \rangle (i_{si}^* + hb)$, the upper switch of the *i*th leg is on and lower switch is off, and if $i_{si} \langle (i_{si}^* + hb)$, the upper switch of the *i*th leg is off and the lower switch is on, where *hb* is the hysteresis band around the reference current and *i=a, b, c* stands for the three legs of the PWM converter. In this way three currents are regulated within the hysteresis band of their respective values.

5 Simulation Results

The system parameters selected for the simulation studies are given in table 2. The three-phase source voltages are assumed to be balanced and sinusoidal. Values of K_p and K_i have been calculated and optimized, using integral time square error (ITSE) performance index, and are respectively 0.75 and 9.15. The performance of the PI controller and proposed fuzzy based control strategy is analyzed by considering a variable load with highly non-linear characteristics. Fig 10 shows the random loading and unloading of non-linear loads, in terms of load current on DC side of non-linear load. The load is varied in random steps to test the effectiveness of the proposed APF. The initial load given in table 1 is 30Ω. Load current is increased at 0.2, 0.35, 0.5 and 0.65, and decreased at 0.8, 0.95, 1.1 and 1.25 s in equal step sizes. Also random variations are made at 1.4, 1.55, 1.7, 1.85, 2 and 2.15 s. Figs. 11 and 12 show load current between 1.5 and 1.8 s when APF is not connected and APF with FLC is connected respectively. The APF starts working at .05 s. Every individual load is connected for 0.15 s and figs. 13 and 14 show the dc capacitor voltage when PI controller is implemented and fuzzy logic controller is implemented respectively. These very clearly illustrate the capability of FLC to improve dynamic behaviour of shunt APF. On the other hand THD percentage in the load current is up to 26% which is equal to source current when the compensator is not connected. FFT analysis is done for “every cycle” (0.02 s) of the entire time and results of FFT analysis are depicted in figs. 15 and 16.

As it is evident from these results, THD has reduced to a very small value (well below the required norms) with the aid of APF with FLC as compared to the case without APF which is up to 26% and APF with PI controller. Also, the response of the APF to the change in load is very fast.

Table 2 System parameters

System parameters	Values
Source voltage (V_s)	100 *V* (peak)
System frequency (f)	50 *Hz*
Source impedance (R_s ; L_s)	$0.1\Omega;\ 0.15mH$
Filter impedance (R_c ; L_c)	$0.1\Omega;\ 0.66mH$
Load impedance (R_L ; L_L)	$14\Omega;\ 20mH$
Reference DC link voltage (V_{dcref})	220 V

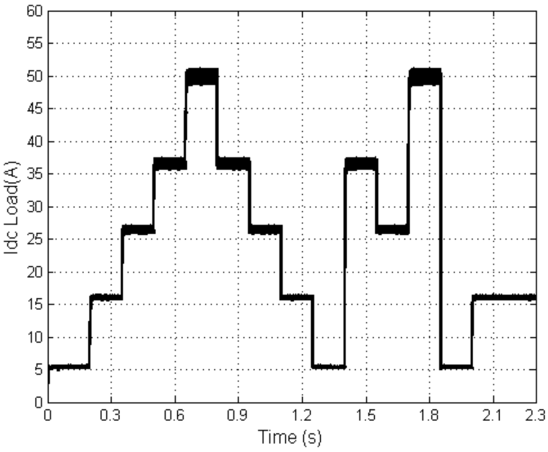

Fig. 10 DC side load current

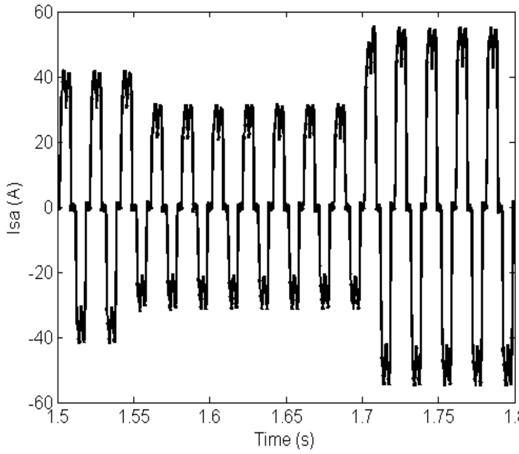

Fig. 11 Source current between 1.5 and 1.8 second when compensator is not connected

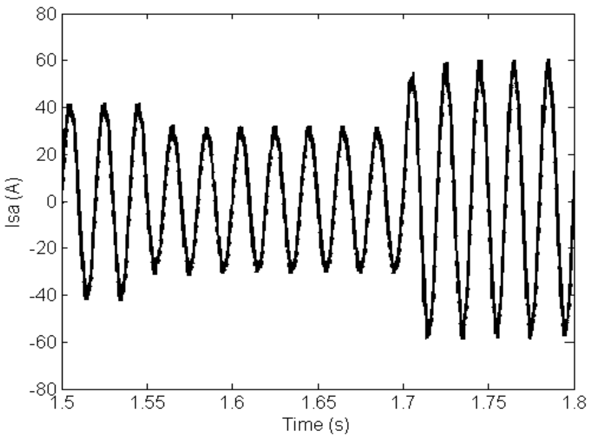

Fig. 12 Source current between 1.5 and 1.8 second when compensator is connected

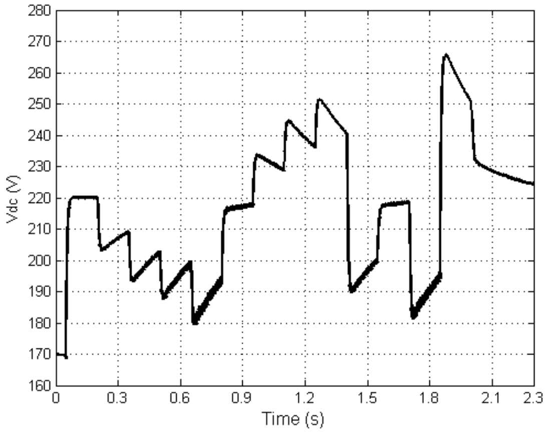

Fig. 13 DC capacitor voltage when PI controller is applied to APF control system

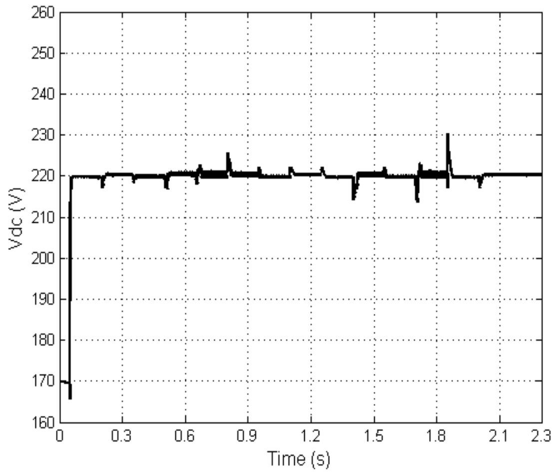

Fig. 14 DC capacitor voltage when load feedback is used to tune PI controller coefficients through fuzzy logic controller

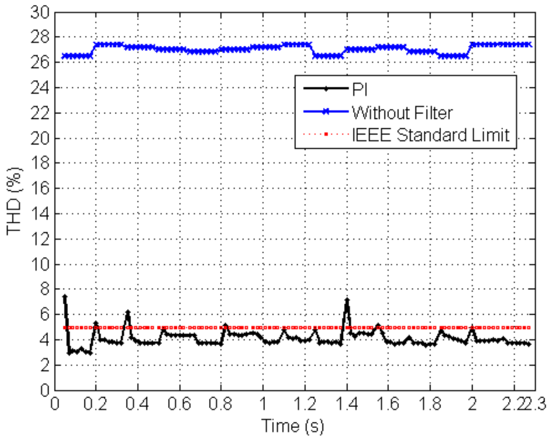

Fig. 15 THD percentage of source current when PI is connected

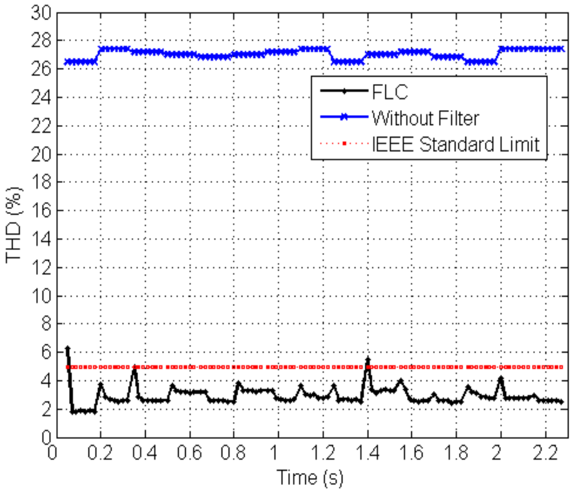

Fig. 16 THD percentage of source current when fuzzy logic controller is connected

Apart from harmonic mitigation and robustness, proposed APF with FLC is also providing the reactive power compensation very effectively as given in table 3. The worst utility power factor when proposed APF with FLC load feedback is connected is 0.999767 which is quite satisfactory.

Table 3 Reactive power compensation by proposed fuzzy based APF

Time (s)	**Active power (W)**	**Reactive power (VAR)**	**Total power factor**
0.15	1000	4.2	0.999991
0.3	2750	8.1	0.999996
0.45	4500	11.54	0.999997
0.6	6000	15.43	0.999997
0.75	8200	28.01	0.999994
0.85	6000	15	0.999997
1	4500	10.95	0.999997
1.15	2750	8	0.999996
1.3	1000	4.1	0.999991
1.45	6000	15.5	0.999997
1.6	4500	10.95	0.999997
1.75	8200	29	0.999994
1.9	1000	3.8	0.999991
2.05	2750	8.3	0.999996

It is important to mention here that at 1.4, 1.7 and 1.85 s, the load is changing dramatically at the rate of 700, 100 and 1000% respectively. Proposed APF is capable to compensate all these loads simultaneously and maintain THD percentage under standard limits.

6 Conclusion

A new fuzzy logic based adaptive active power filter for power quality improvement under fast load variations is presented in this paper. Using load value as an input of fuzzy logic controller improves dynamic behaviour of active power filter and makes it robust under fast load variation.

The proposed control technique is found extremely satisfactory to mitigate harmonics and reactive power components from utility current especially under variable load condition. Proposed APF topology is tested for non-linear varying load in different steps, and Simulation results show that system has a fast dynamic response for such a randomly varying load, while it limits THD percentage of source current under limits of IEEE-519 standard.

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