Fuzzy Logic Controlled Active Power Line Conditioners for Power quality Improvements

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***Abstract*—This paper describes a novel fuzzy logic controller for a three-phase shunt active power filter for the power-quality improvement such as reactive power and harmonic current compensation generated due to nonlinear loads. The approach of fuzzy logic control is linguistic description, so it does not require a mathematical model of the system. The application of the Mamdani-type fuzzy logic controller to a three-phase shunt active power filter is investigated. The controller is capable of controlling dc capacitor voltage and generating reference source currents. Hysteresis current controller is used for current control in PWM inverter. Extensive simulation studies under both transient and steady states are conducted. The simulation results reveal that the active filter performs perfectly in conjunction with fuzzy logic controller.**

***Index Terms*- Active Power Line Conditioners (APLC), Current Harmonics, Power quality, Fuzzy Logic Controller (FLC).**

1. INTRODUCTION

The ac power supply feeds different kind of linear and non-linear loads. The non-linear loads produce harmonics [1] [2]. The reactive power and harmonics cause poor power factor and distort the supply voltage at the common coupling point. This distortion is mainly induced from the line impedance or the distribution transformer leakage inductance. Passive L-C filters is used to compensate the lagging power factor of the non-linear load, but there are drawbacks such as resonance, large size, weight, etc., the alternative solution, is an active power filter (APF) that provides an effective solution for harmonics elimination and reactive power compensation absorbed by the non-linear load [3]. Many authors have proposed many possible alternatives; most of them are meant for three phase systems and some solutions are for single-phase system [4].

The controller is the most important part of the active power filter and currently lot of research is being conducted in this area. Conventional PI controllers have been used to control the harmonic current and dc capacitor voltage of the shunt APF [5, 6]. However, the conventional PI controller requires precise linear mathematical model of the system, which is difficult to obtain under parameter variations, nonlinearity, and load disturbances. Another drawback of the system is that the proportional and integral gains are chosen heuristically.

Recently, fuzzy logic controllers (FLC) are used in power electronic system and drive applications [4]. The advantages of FLC's over the conventional controllers are: (i) It does not need accurate mathematical model; (ii) It can work with imprecise inputs ;(iii) It can handle nonlinearity; (iv) It is more robust than conventional nonlinear controllers.

This paper explores the potential and feasibility of fuzzy logic control schemes that are suitable for harmonic current mitigation and inverter dc voltage control to improve the performances of the shunt APF. The performance of fuzzy controller is evaluated through computer simulations under steady state and transient conditions. The results show that, the proposed active filter with fuzzy logic controller is capable of providing sinusoidal source current(s) with low harmonic distortion and the current is in phase with the corresponding line voltage. The operation of APF is demonstrated in details. The method of extracting reference current(s) and dc capacitor voltage is also presented. The concept is validated through extensive simulation.

2. DESIGN OF SHUNT ACTIVE POWER FILTER

The active power filter comprises of six power transistors (IGBT), six power diodes, a dc capacitor $\left(C_{DC}\right)$, three filter inductor $\left(L_C\right)$ and reference value of DC side capacitor voltage $\left(V_{DC,ref}\right)$. The filter capacitors and reactors have the function of suppressing the harmonic currents caused by the switching operation of the power transistors. Reduction of current harmonics is achieved by injecting equal but opposite current harmonic components at the point of common coupling (PCC), there by canceling the original distortion and improving the power quality on the connected power system. The block diagram of APF consists of current reference generator, gating signal generator and a dc voltage control unit (Fig 1). The output voltage of the inverter is controlled with respect to the voltage at the point of common coupling. The design of these components is based on following assumptions; the ac source voltage is sinusoidal, the ac side line current distortion is to be limited to about 5%, fixed capability of reactive power compensation of the active filter, the PWM converter is operating in the linear modulation mode $\left(0 \le m_a \le 1\right)$.The design of the DC side capacitor is based on the principle of instantaneous power flow. The selection of C_{DC} can be governed by reducing the voltage ripple. For a 5 kVA compensation capacity, 120 V $\left(V_{RMS}\right)$, 50 Hz system, the following parameters are simulation study: L_C =1.66 mH, $V_{DC,ref}$ = 220 V, C_{DC} = 2100 µF.

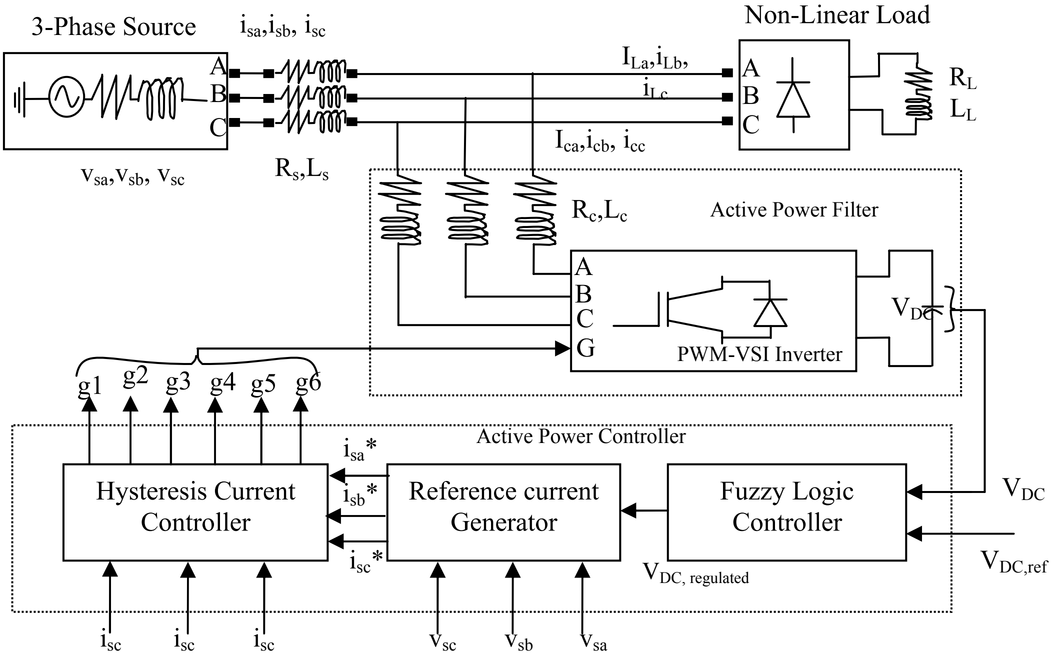


Fig 1 Proposed Fuzzy logic controlled based Shunt Active power line conditioners

The instantaneous current can be written as

$$i_s(t) = i_L(t) - i_c(t) \qquad (1)$$

Source voltage is given by

$$v_s(t) = V_m \sin \omega t \qquad (2)$$

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

$$i_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \Phi_n)$$

$$= I_1 \sin(\omega t + \Phi_1) + \left(\sum_{n=2}^{\infty} I_n \sin(n\omega t + \Phi_n) \right) \qquad (3)$$

The instantaneous load power can be given as

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

$$= V_m \sin^2 \omega t * \cos\phi_1 + V_m I_1 \sin \omega t * \cos \omega t * \sin \phi_1$$

$$+ V_m \sin \omega t * \left(\sum_{n=2}^{\infty} I_n \sin(n\omega t + \Phi_n) \right)$$

$$= p_f(t) + p_r(t) + p_h(t) \qquad (4)$$

From the equation the real (fundamental) power drawn by the load is

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

From this equation the source current supplied by the source, after compensation is

$$i_s(t) = \frac{p_f(t)}{v_s(t)} = I_1 \cos\phi_1 \sin \omega t = I_{sm} \sin \omega t \quad (6)$$

where,

$$I_{sm} = I_1 \cos\phi_1 \qquad (7)$$

The total peak current supplied by the source is

$$I_{sp} = I_{sm} + I_{sl} \qquad (8)$$

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 compensation current:

$$i_c(t) = i_L(t) - i_s(t) \qquad (9)$$

The desired source currents, after compensation, can be given

$$i_{sa}* = I_{sp} \sin \omega t \qquad (10)$$

$$i_{sb}* = I_{sp} \sin(\omega t - 120^0) \qquad (11)$$

$$i_{sc}* = I_{sp} \sin(\omega t + 120^0) \qquad (12)$$

Where $I_{sp} = I_{sm} + I_{sl}$ is the amplitude of the desired source current, while the phase angle can be obtained from the source voltages [3]. This peak value of the reference current has been estimated by regulating the DC side capacitor voltage of the PWM converter.

3 FUZZY LOGIC CONTROL SCHEME

Fuzzy logic control is derived from fuzzy set theory introduced by Zadeh in 1965. In fuzzy set theory, the transition between membership and nonmembership can be gradual. Therefore, boundaries of fuzzy sets can be vague and ambiguous, making it useful for approximate systems. FLC's are an attractive choice when precise mathematical formulations are not possible. Fig. 1 shows the active power filter compensation system and the fuzzy control scheme. 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 then compared with the reference value $V_{DC,ref}$.

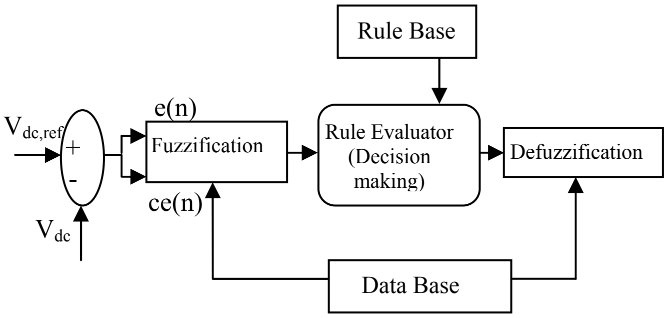


Fig 2 Fuzzy logic controller

In case of a fuzzy logic control scheme, the error $\left(e = V_{DC,ref} - V_{DC}\right)$ and integration of error signal $\left(\int e\right)$ are used as inputs for fuzzy processing (see Fig. 2). The output of the fuzzy controller after a limit is considered as the magnitude of peak reference current $I_{\max}$. The switching signals for the PWM inverter are obtained by comparing the actual source currents $\left(i_{sa}, i_{sb}, i_{sc}\right)$ with the reference current templates $\left(i_{sa}{*}, i_{sb}{*}, i_{sc}{*}\right)$ in the hysteresis current controller [7-9]. The output pulses are then given to the switching devices of the PWM converter.

Hysteresis Band Current Control:

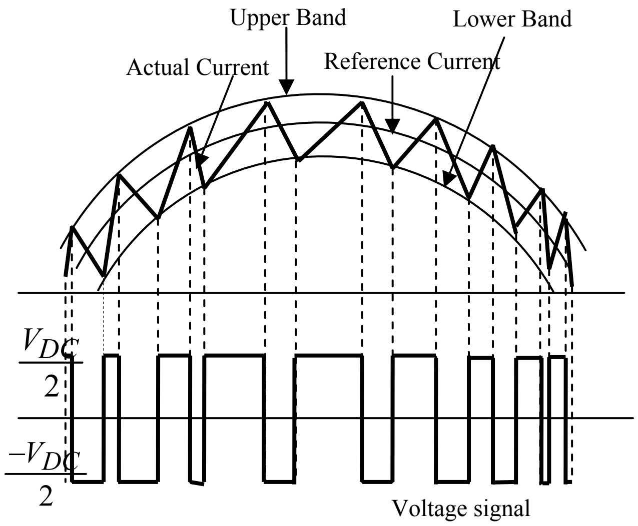


Fig 3) Diagram of hysteresis current control

Hysteresis current control is the easiest control method to implement (Brod and Novotny 1985). One disadvantage is that there is no limit to the switching frequency, but additional circuitry can be used to limit the maximum switching frequency (Malesani *et al*1996). A hysteresis current controller is implemented with a closed loop control system and is shown in diagrammatic form in Figure 4. An error signal, $e(t)$, is used to control the switches in an inverter. This error is the difference between the desired current $i_{ref}(t)$ and the current being injected by the inverter $i_{actual}(t)$. If the error current exceeds the upper limit of the hysteresis band, the upper switch of the inverter arm is turned off and the lower switch is turned on. As a result, the current starts to decay. If the error current crosses the lower limit of the hysteresis band, the lower switch of the inverter arm is turned off and the upper switch is turned on. As a result, the current gets back into the hysteresis band. The minimum and maximum values of the error signal are $e_{\min}$ and $e_{\max}$ respectively. The range of the error signal $e_{\max} - e_{\min}$ directly controls the amount of ripple in the output current from the inverter.

Fuzzification:

Fuzzy logic uses linguistic variables instead of numerical variables. In a control system, error between reference and output can be labeled as zero (ZE), positive small (PS), negative small (NS), positive medium (PM), negative medium (NM), positive big (PB), negative big (NB). The process of converting a numerical variable (real number) convert to a linguistic variable (fuzzy number) is called fuzzification.

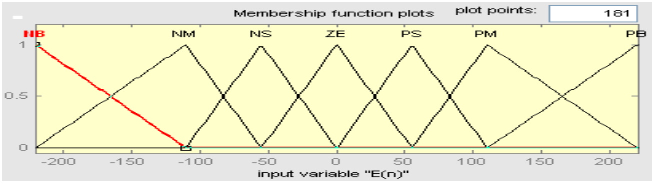


Fig 3 Error input e(n)

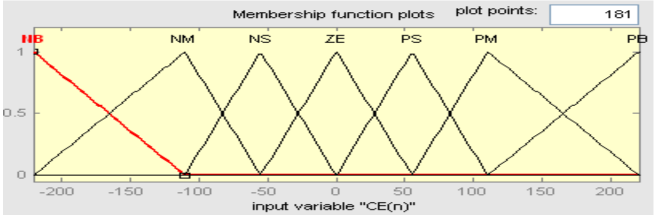


Fig 4 Change in error input ce(n)

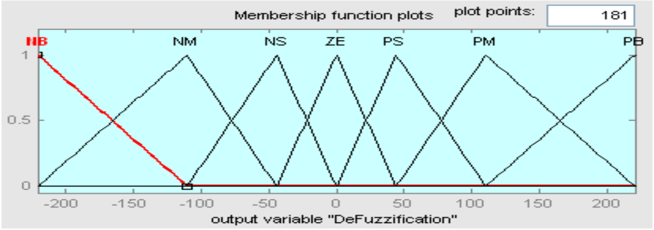


Fig 5 Change of reference output

Rule Elevator:

In conventional controllers, we have control gains or control laws which are combination of numerical values. In FLC, the equivalent term is rules and they are linguistic in nature. A typical rule can be written as follows;

$$R_k : If\ e\ is\ A_i\ and\ ce\ is\ B_i\ then\ output\ is\ C_i$$

Where A_i, B_i, C_i are the labels of linguistic variables of error (e) ,change of error (ce) and output respectively. Here e, ce and output represents degree of membership.

Let X be a collection of objects denoted generically by $\{x\}$, which could be discrete or continuous, X is called the universe. If an element in the universe, say x, is a member of fuzzy set A then mapping is given as

$$\mu(x) \in [0,1]$$

$$A = [x, \mu(x) \mid x \in X)]$$

The basic fuzzy set operations needed for evaluation of fuzzy rules are $AND(\cap)$, $OR(\cup)$ and $NOT(-)$

AND -Intersection: $\mu_{A \cap B} = \min[\mu_A(X), \mu_B(x)]$

OR -Union: $\mu_{A \cup B} = \max[\mu_A(X), \mu_B(x)]$

NOT -Complement: $\mu_A = 1 - \mu_A(x)$

Defuzzification:

The rules of FLC generate required output in a linguistic variable (Fuzzy Number), according to real world requirements, linguistic variables have to be transformed to crisp output (Real number). The choices available for defuzzification are numerous. So far the choice of strategy is a compromise between accuracy and computational intensity. Finally, crisp output is obtained by using

$$\text{Output} = \sum A_i * x_i / \sum A_i$$

Database:

The Database stores the definition of the membership function required by fuzzifier and defuzzifier. Storage format is a compromise between available memory and MIPS of the digital controller chip.

Rule Base:

The Rule base stores the linguistic control rules required by rule evaluator (decision making logic). The rules used in this paper are shown in table 1.

ce(n) e(n)	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	MN	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 Rule base table

4 SIMULATION RESULT AND ANALYSIS

The simulation results of the proposed shunt active power filter controlled by fuzzy logic is presented. We used SIMULINK toolbox in the MATLAB software in order to model and test the system under steady state and transient conditions. The table 2 represents steady state system parameters of active power line conditioners with Non linear load.

System Parameters	Values
Source voltage(V_S)	120Vrms
System frequency(f)	50Hz
Source impedance(R_S,L_S)	0.1Ω; 0.5mH
Filter impedance(R_C,L_C)	1Ω; 1.66 mH
Load impedance(R_L,L_L)	Steady state:7Ω; 200mH Transient : 3.5Ω; 100mH
DC link capacitance (C_{DC})	2100μF
Reference Voltage (V_{DC})	220V
Power Devices	IGBT/Diode

Table 2 steady state system parameters

Case 1: Steady state condition:

Fuzzy logic controlled APF system comprises of a three-phase source, a nonlinear load (six pulse diode Rectifier Bridge feeding an RL load) and a PWM voltage source inverter with a dc capacitor input. The simulation time T=0 to T=0.4 with load of diode rectifier with R L load parameter values of 7 ohms and 200 mH respectively. The source current after compensation is presented in fig. 6 (a) that indicates the current becomes sinusoidal. The load current is shown in (b). These current waveforms are for a particular phase (phase a). Other phases are not shown as they are only phase shifted by 120^0 and we have considered only a balanced load. The actual reference currents for phase (a) are shown in fig. 6(c). This wave is obtained from our proposed fuzzy controller. The APF supplies the compensating current that is shown in Fig. 6(d). The current after compensation is as shown in (a) which would have taken a shape as shown in (b) without APF. It is clearly visible that this waveform is sinusoidal with some high frequency ripples. We have additionally achieved power factor correction as shown in Fig. 6(e), phase (a) voltage and current are in phase. The time domain response of the fuzzy controller is shown in Fig. 6(f) that clearly indicates the controller output settles after a few cycles.

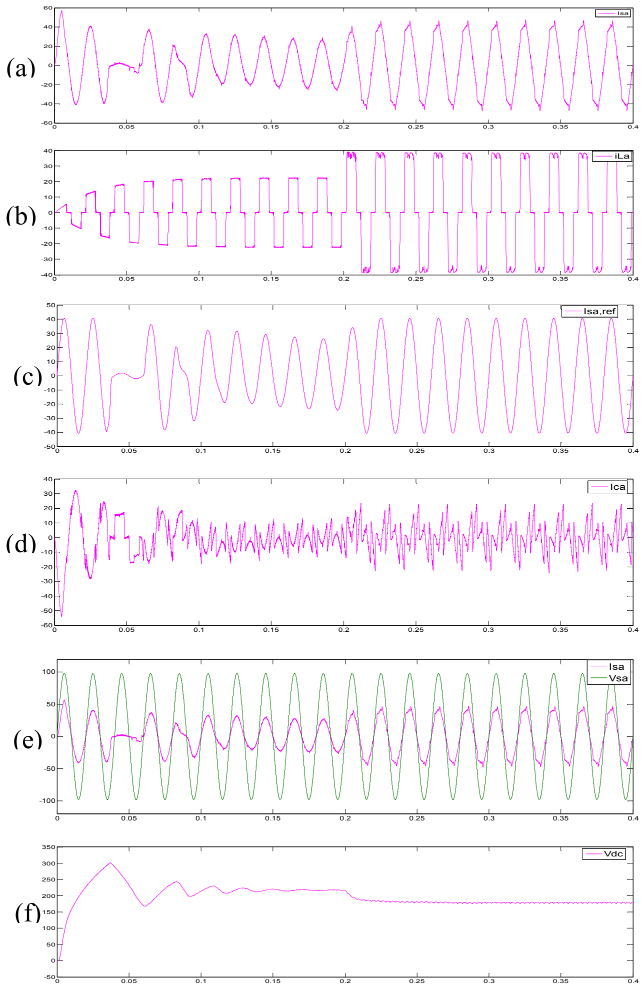


Fig.6 Simulation results for three-phase active-power-filter under the steady state condition (a) Source current after APF, (b) Load currents, (c)Reference currents by the Fuzzy logic algorithm, (d) Compensation current by APF, (e) source voltage per current for unity power factor and (f) DC capacitor voltage

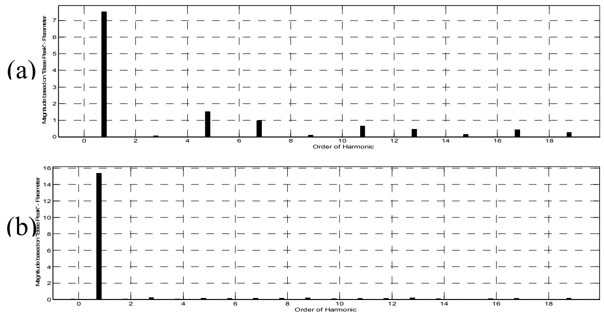


Fig 7 Simulation under the steady state condition (a) FFT analys of Sourcecurrent without APF(THD=26.53%) (b) with APF(THD=3.64%)

Total Harmonic distortion (THD) measurement is a good measure of the effectiveness of the APF. THD of the source current without and with APF are THD=26.53% and THD=3.64% respectively. This cleerly satisfioes the IEEE standards and hence the fuzzy controller can act as a good candidate for APF application.

<u>*Case 2: Transient condition:*</u>

First for simulation time T=0 to T=0.4 with load of rectifier with R L parameter values of 7 ohms and 200mH respectively and after T=0.4 switch on load with R L value of 3.5 ohms and 100 mH. Similar waveforms are obtained in transient conditions and presented in Fig. 8 ((a) through (f)) and in Fig, 9 (THD after and before APF). These sketches are self explanatory.

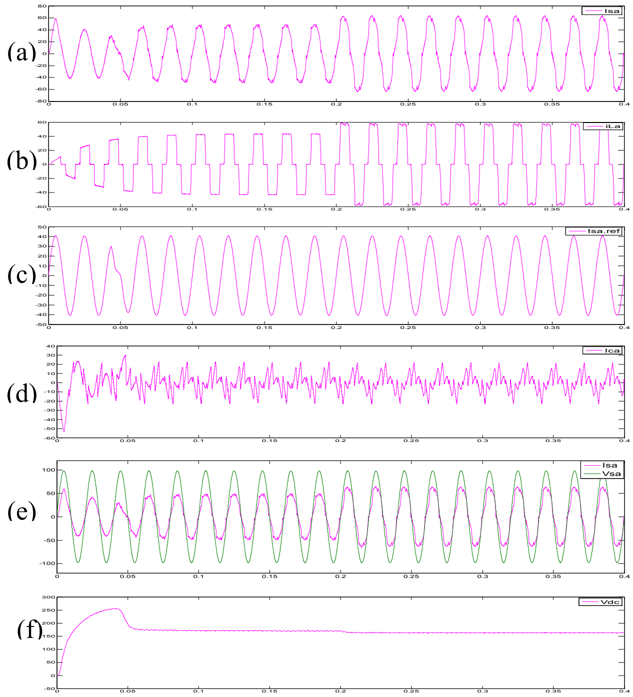
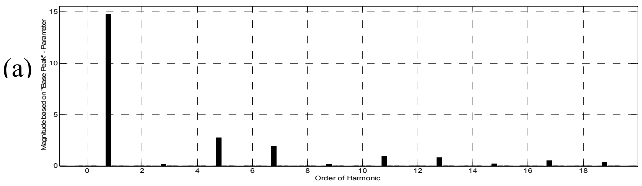


Fig.8 Simulation results for three-phase active-power-filter under the Transient condition (a) Source current after APF, (b) Load currents, (c)Reference currents by the Fuzzy logic algorithm, (d) Compensation current by APF, (e) source voltage per current for unity power factor and (f) DC capacitor voltage



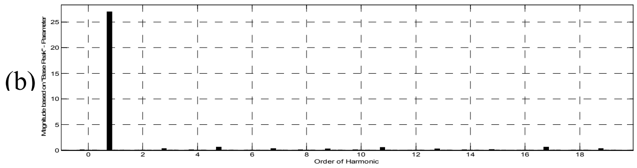


Fig 9 Simulation under the Transient condition (a) FFT analys of Source current without APF (THD=25.71%) (b) with APF(THD=3.86%)

These simulation done various steady state and transient conditions. The obtained result shows the source current and load current is small variation in steady state and transient conditions. The compensator filter made balance responsibility in steady state and transient response. FFT analysis of the active filter brings the THD of the source current into compliance with IEEE-519 standards harmonic.

5 CONCLUSION

A fuzzy logic controller is implemented for three phase shunt active power filter to obtain dc capacitor voltage and the reference currents. This facilitates to improve the power quality parameters such as reactive power and harmonics due to nonlinear load. The obtained results indicate that DC capacitor voltage and the harmonic current control can be adapted easily even under unbalance conditions. The performance of *a* fuzzy logic controlled shunt active power is verified the simulation results. The fuzzy logic controller compares the transient response and steady state performance in various conditions. The THD of the source current after compensation is 3.64% which is less than *5%,* the harmonic limit imposed by the IEEE-519 standard. The fuzzy logic controller is a good candidate for controlling active power filter to solve power quality issues.

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