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A Fuzzy Controlled APF for Compensation of Harmonics in Distribution Micro Grid

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Abstract

This paper presents the harmonics and reactive power compensation from 3P4W micro-grid distribution system by IP controlled shunt active. Micro grid became one of the key spot in research on distributed energy systems. Since the definition of the micro grid is paradigm of the first time, investigation in this area is growing continuously and there are numerous research projects in this moment all over the world. The increased infiltration of nonlinear loads and power electronic interfaced distribution generation system creates power quality issues in the distributed power system. In this project, a comprehensive survey on micro grid to improve the power quality parameters is taken as the main objective. Shunt active filter based on current controlled PWM converters are seen as a most viable solution. Furthermore, the detailed investigations are explored in this paper for the enhancement of power quality issues with the help of an optimization technique, filters, controllers, FACTS devices, compensators, and battery storage. The technique which is used for generate desired compensation current extraction based on offset command instantaneous currents distorted or voltage Signals in the time domain because compensation time domain response is quick, easy implementation and lower computational load compared to the frequency domain. In distribution systems, the load has been a sudden increase or decreases and it is like as nonlinear loads so the load draws non-sinusoidal currents from the AC mains and causes the load harmonics and reactive power, and excessive neutral currents that give pollution in power systems. Most pollution problems created in power systems are due to the nonlinear characteristics and fast switching of power electronic devices. The proposed concept can be implemented with fuzzy based APF using MATLAB/SIMULINK software and the results are verified.

I. INTRODUCTION

With the development of power electronics technology, nonlinear loads in power system are increasing which generate reactive current and harmonics. Harmonic has some impacts on the safe operation of a variety of electrical equipments and can cause severe damage to the equipment and power system.

Active power filter can play role on changing frequency and amplitude of harmonic and reactive current compensation it is an important trend in both harmonic suppression and the current research focus in the field of power electronics technology. In recent years, shunt active power filter (SAPF) is an effective device to implement the harmonic current in the grid and attracts more and more attention in the modern society; research studies on the APF including harmonic detection, topology studies, system modeling, and control methods become promising topics; the new type of intelligent control and adaptive control methods get a lot of development. There are many current tracking control methods, such as single cycle control, hysteresis current control, space vector control, sliding mode control, deadbeat control, repetitive control, predictive control, fuzzy control, adaptive control, iterative learning control and

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artificial neural network control. Rahmani et al. [1] introduced a comparative study of shunt hybrid and shunt active power filters for single phase applications both in simulation and experimental validations.

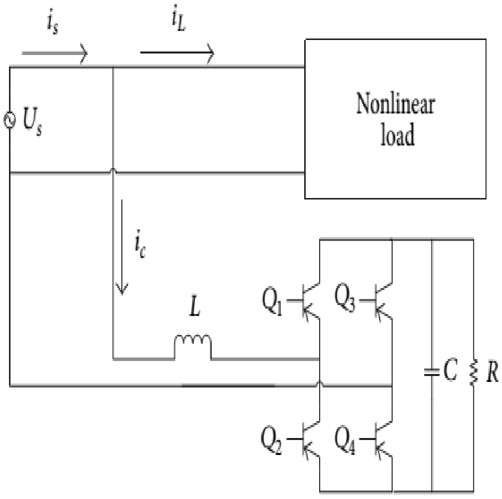

Figure 1: Basic circuit structure of shunt APF.

Proposed a model reference adaptive controller to control the circuit, improve the current, and reduce the current harmonics by using the approximate dynamic model of single-phase shunt APF. Matas et al showed a feedback linearization approach of a single-phase APF via sliding mode control. Hua et al gave control analysis of an APF using Lyapunov analysis. Montero et al. compared different control strategies for shunt APF in three-phase four-wire systems.

Valdez et al. designed an adaptive controller for shunt active filter in the presence of a dynamic load and the line impedance. Marconi et al. developed robust nonlinear controller to compensate harmonic current for shunt active filters. Sriram et al. proposed indirect current control of a single-phase voltage-sourced boost-type bridge converter operated in the rectifier mode. Some other control methods and harmonic suppression approaches for APF have been investigated. Singh et al. presented a simple fuzzy logic based robust APF for harmonics minimization under random load variation. Bhende et al. Developed a TS-fuzzy controller for load compensation of APF.

II. VOLTAGE SOURCE CONVERTERS

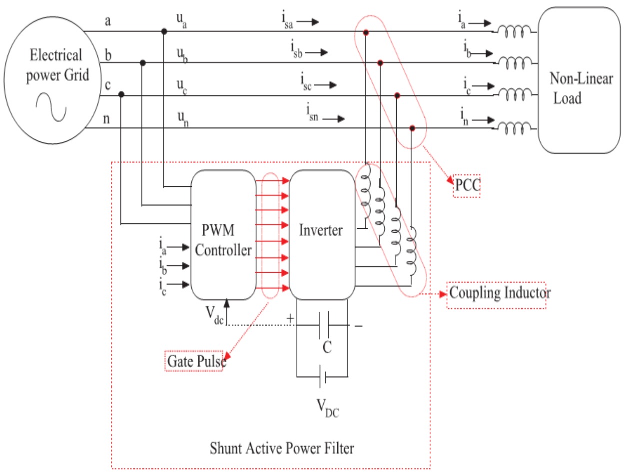

Fig.2.Shunt active power filters topology.

The active power filter topologies mostly use as voltage source converters. This topology, shown in Figure 2, converts a dc voltage into an ac voltage by appropriately gating the power semiconductor switches. A single pulse for each half cycle can be applied to synthesize an ac voltage. For these purposes most applications requiring dynamic performance, pulse width modulation is the most commonly used for active power filter. PWM techniques applied to control the VSI for consist of chopping the dc bus voltage to produce an ac voltage of an arbitrary waveform.

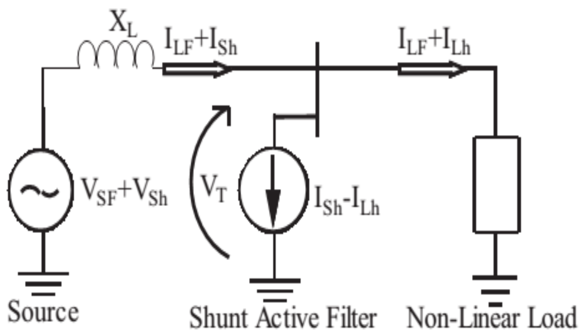

Fig.3.Principle of Shunt Current Compensation.

Voltage source converters are preferred over current source converter because it has higher efficiency and lower initial cost than the current source converters [3, 4, 9]. They can be readily expanded in parallel to increase their combined rating and their switching rate

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can be increased if they are carefully controlled so that their individual switching times do not coincide. Therefore, higher-order harmonics can be eliminated by using converters without increasing individual converter switching rates. Because of non linear load current will have harmonics, so load current will be the summation of fundamental and all other harmonics, all harmonics will be integer multiple of fundamental frequency. Load current can be written as

$$i_L(t) = \sum_{n-1}^{\infty} i_n \sin(n\omega t + \varphi_n) = i_l \sin(\omega t + \varphi_l) + \sum_{n=2}^{\infty} \sin(n\omega t + \varphi_n) \quad (1)$$

Instantaneous Load can be written as

$$p_L(t) = v_s(t) \times i_L(t) \quad (2)$$

Putting value of $i_L(t)$ from equation (1) in equation (2)

$$p_A(t) + p_R(t) + p_H(t) \quad (3)$$

Here $P_A(t)$ is active or fundamental power. Only fundamental component of voltage and current can deliver power to the load and $P_R(t)$ is reactive power. Harmonic power denoted by $P_H(t)$. So active or real power drawn by the load from the source is

$$p_A(t) = v_m i_1 sin^2\omega t \times cos\varphi_1 = v_s(t) \times i_s(t) \quad (4)$$

Therefore, source current after compensation will be given by equation (5)

$$i_s(t) = p_A(t) / v_s(t) = i_1 cos\varphi_1 \times sin\omega t = i_m sin\omega t \quad (5)$$

Where $i_m = i_1 cos\varphi_1$

In a practical converter, there are switching, conducting and capacitor leakage losses. So that losses must be supplied by the supply or by the grid itself. So total current supplied by supply will be given as

$$i_{SP} = i_m + i_{slo} \quad (6)$$

Where isp= peak current supplied by source. where i_{slo} = loss current of converter supplied by the source.

If total harmonic and reactive power of the load is supplied, by the Active Power Filter then there will not be any harmonic in source current and source current will be in phase with the source voltage. Therefore, the total source current including losses will be given as $i_s^*(t) = i_{sp}\, sin\omega t$ So compensating current will be given as

$$i_c(t) = i_L(t) - i_S^*(t) \quad (7)$$

It is obvious from above discussion that for instantaneous compensation of reactive power in addition, harmonic power, source (grid) should be able to supply current $i_S^*(t)$. Therefore, it is necessary to find $i_S^*(t)$ which is known as reference current.

III.ESTIMATION OF REFERENCE SOURCE CURRENT

The instantaneous currents can be written as

$$i_s(t) = i_l(t) - i_c(t) \quad (8)$$

Source voltage is given by

$$v_s(t) = v_m\, sin\omega t \quad (9)$$

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

$$i_L = \sum_{n-1}^{\infty} I_n \sin(n\omega t + \phi_n) \quad (10)$$

$$i_L = \sum_{n-1}^{\infty} I_n \sin(n\omega t + \phi_n) = I_n \sin(n\omega t + \phi_1) + \sum_{n-2}^{\infty} \sin(n\omega t + \phi_n) \quad (11)$$

The instantaneous load power can be given as

$$\begin{aligned} P_L(t) &= v_s(t) \times i_L(t) \\ &= V_m I_1 sin^2\omega t \times cos\phi_1 + v_m I_1 sin\omega t \times cos\omega t \times sin\phi_1 + V_m sin\omega t \times \sum_{n-2}^{\infty} I_n \sin(n\omega t + \phi_n) \\ &= P_f(t) + P_r(t) + P_h(t) \end{aligned} \quad (12)$$

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

$$P_f(t) = V_m I_1 sin^2\omega t \times cos\phi_1 = v_s(t) \times i_s(t) \quad (13)$$

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

$$i_s(t) = P_f(t)/v_s(t) = I_1 cos\phi_1 sin\omega t = I_m sin\omega t \quad (14)$$

Where $I_{sm} = I_1 cos\Phi 1$.

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There are also some switching losses in the PWM converter, and 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. The total peak current supplied by the source is therefore

$$I_{sp} = I_{sm} + I_{s1} \quad (15)$$

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

$$i_c(t) = i_L(t) - i_s(t) \quad (16)$$

Hence, for accurate and instantaneous compensation of reactive and harmonic power it is necessary to estimate, i.e. the fundamental component of the load current as the reference current. The design of the power circuit includes three main parameters: Lc, Vdc, ref and Cdc.

A. SELECTION OF L_c, $V_{dc,ref}$ and C_{dc}

The design of these components is based on the following assumptions:

- The AC source voltage is sinusoidal.
- To design of Lc, the AC side line current distortion is assumed to be 5%.
- Fixed capability of reactive power compensation of the active filter.
- The PWM converter is assumed to operate in the linear modulation mode (i.e. 0≤ma≤1).

As per the compensation principle, the active filter adjusts the current ic1 to compensate the reactive power of the load [2]. If the active filter compensates all the fundamental reactive power of the load, is1 will be in phase and ic1 should be orthogonal to Vs. The three-phase reactive power delivered from the active filter can be calculated from a vector diagram

$$Q_{c1} = 3V_s I_{c1} = \frac{3V_s V_{c1}}{\omega L_c\left(1-\left(\frac{V_s}{V_{c1}}\right)\right)} \quad (17)$$

i.e. the active filter can compensate the reactive power from the utility only when Vc1 > Vs. If the PWM converter is assumed to operate in the linear modulation mode (i.e. 0≤ma≤1), the amplitude modulation factor ma is

$$m_a = v_m/(V_{dc}/2) \quad (18)$$

Where $v_m=\sqrt{2}\ V_c$, and hence $V_{dc} = 2\sqrt{2}\ V_{c1}$ for ma=1. The filter inductor Lc is also used to filter the ripples of the converter current, and hence the design of Lc is based on the principle of harmonic current reduction. The ripple current of the PWM converter can be given in terms of the maximum harmonic voltage, which occurs at the frequency mfω:

$$I_{ch(mfw)} = \frac{V_{ch(mfw)}}{m_f \omega L_c} \quad (19)$$

IV. PI CONTROL SCHEME

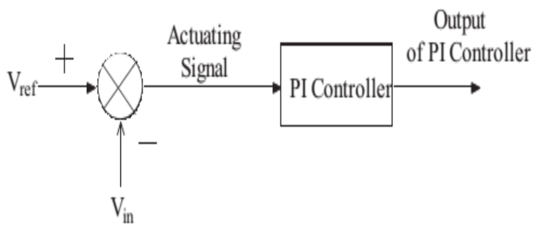

Fig.4 APF Control scheme with PI controller.

The error signal is fed to PI controller. The output of PI controller has been considered as peak value of the reference current. It is further multiplied by the unit sine vectors (usa, usb, and usc) in phase with the source voltages to obtain the reference currents (i_{sa}^*, i_{sb}^*, and i_{sc}^*). These reference currents and actual currents are given to a hysteresis based, carrier less PWM current controller to generate switching signals of the PWM converter [5]. The difference of current template and actual current decides the operation of switches. These switching signals after proper isolation and amplification are given to the switching devices. Due to these switching actions current flows through the filter inductor Lc, to compensate the harmonic current and reactive power of the load, so that only active power drawn from the source.

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V. DESIGN AND IMPLEMENTATION OF FUZZY CONTROLLER

There has been a significant and growing interest in the application of artificial intelligence type control techniques such as neural network and fuzzy logic to control the complex, nonlinear systems. Fuzzy logic is applied in applications like washing machines, subway systems, video cameras, sewing machines, biomedical, and finance. Having understood the general behavior of the system, fuzzy logic enables the designer to describe the general behavior of the system in a linguistic manner by forming IF–THEN rules that are in the form of statements. The great challenge is to design and implement the FLC quickly by framing minimum number of rules based on the knowledge of the system. The general FLC [4], [10] consists of four parts as illustrated in Fig.3. They are fuzzification, fuzzy rule base, fuzzy inference engine, and defuzzification. The design steps are as follows.

Step 1 (Define inputs, outputs, and universe of discourse):

The inputs are error E and change in error CE and the output is change in duty cycle ΔDC. The error is defined as the difference between the reference speed Nref and actual speed Nact and the change in error is defined as the difference between the present Error e(k)and previous error e(k−1). The output, change in duty cycle ΔDC is the new duty cycle DC new that is used to control the voltage applied across the phase windings. The inputs and new duty cycle are described by

$$E = e(k) = N_{\text{ref}} - N_{\text{act}} \quad (20)$$

$$\text{CE} = e(k) - e(k-1) \quad (21)$$

$$DC_{\text{new}} = \Delta DC. \quad (22)$$

The speed range of the motor is taken as 0–4000 r/min based on the specifications of BLDC servomotor. The possible range of error is from−4000 to+4000 r/min. Therefore, the universe of discourse for error can be defined to span between−4000 and+4000 r/min. Based on the study of PID controller-based BLDC servomotor drive system, the universe of discourse for change in error is chosen as+/−500 r/min.

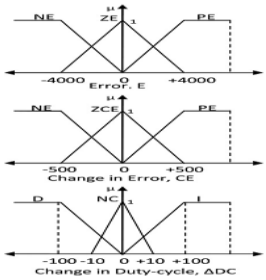

Fig.5. Membership functions for Error E, Change in Error CE, and Change in Duty Cycle ΔDC.

The maximum and minimum value for the change in duty cycle are defined as −100% and+100%, respectively. To easily handle the large values of error and change in error and reduce the computation time so as to achieve faster control action, the inputs and output are normalized.

Step 2 (Defining fuzzy membership functions and rules):

To perform fuzzy computation, the inputs must be converted from numerical or crisp value into fuzzy values and the output should be converted from fuzzy value to crisp value. The fuzzy input variables “error” and “change in error” are quantized using the following linguistic terms Negative N, Zero Z, and Positive P.

The fuzzy output variable “change in duty cycle” is quantized using the following linguistic terms Decrease D, No-change NC, and Increase I. Fuzzy membership functions are used as tools to convert crisp values to linguistic terms. A fuzzy variable can contain several fuzzy subsets within, depending on how many linguistic terms are used. Each fuzzy subset represents one linguistic term. Each fuzzy subset allows its members to have different grade of membership; usually the membership value lies in the interval [0, 1]. In order to define fuzzy membership function, the designer can choose many different shapes based on their preference and experience. The

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popular shapes are triangular and trapezoidal because these shapes are easy to represent designer's ideas and they require less computation time. Therefore, triangular membership functions are used for inputs and output and are shown in Fig.5. In order to fine tune the controller for improving the performance, the adjacent fuzzy subsets are overlapped by about 25% or less. Instead of using mathematical formula, FLC uses fuzzy rules to make a decision and generate the control action. The rules are in the form of IF–THEN statements. There are nine rules framed for this system and they are illustrated in Fig. 6.

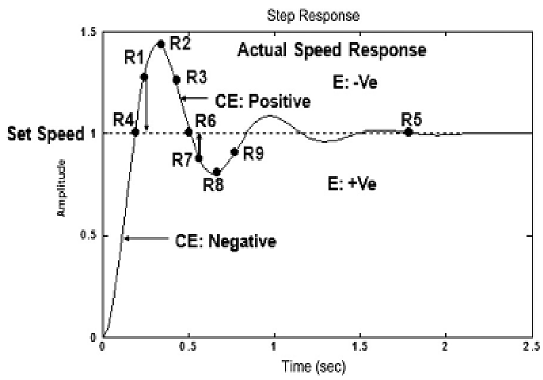

Fig.6. Illustration for the formation of rules for a typical under damped BLDC servomotor drive system.

TABLE I

3 × 3 FAM MATRIX

E / CE	NE	ZE	PE
NCE	D	D	I
ZCE	D	NC	I
PCE	D	I	I

The number of rules to be used to describe the system behavior is entirely based on the designer's experience and the previous knowledge of the system. The performance of the controller can be improved by adjusting the membership function and rules. A fuzzy associative memory (FAM) expresses fuzzy logic rules in tabular form. A FAM matrix maps antecedents to consequents and is a collection of IF–THEN rules. Each composition involves three fuzzy variables and each fuzzy variable is further quantized into three. This has resulted in nine possible two inputs and single output FAM rules as illustrated in the Table I. The nine rules formulated for the proposed fuzzy logic control system are listed below.

R_1. IF Error E is Negative NE and Change in Error CE is Negative NCE THEN Change in duty-cycle ΔDC is Decrease D.

This rule implies that when the system output is at R_1, then the actual speed is greater than the reference speed (or set speed) and the motor is accelerating, so the duty cycle of the IGBTs of the Inverter module should be decreased so as to reduce the average voltage applied across the phase windings and bring the actual speed of the system close to the reference speed.

R_2. IF E is Negative NE and CE is Zero ZCE THEN ΔDC is Decrease D.

R_3. IF E is Negative NE and CE is Positive PCE THENΔDC is Decrease D.

R_4. IF E is Zero ZE and CE is Negative NCE THENΔDC is Decrease D.

R_5. IF E is Zero ZE and CE is Zero ZCE THENΔDC is No-Change NC.

This rule implies that when the system output is at R_5, then there should be a no change in the duty cycle as the actual speed has already reached steady state.

R_6. IF E is Zero ZE and CE is Positive PCE THENΔDC is Increase I.

R_7. IF E is Positive (PE) and CE is Negative (NCE) THEN ΔDC is Increase (I).

This rule implies that when the system output is at R7, then the actual speed is lesser than the reference speed and the motor is decelerating, so the duty cycle of the IGBTs of the Inverter module should be increased so as to increase the average voltage applied across the phase windings and bring the actual speed of the system close to the reference speed.

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R_8. IF E is Positive PE and CE is Zero ZCE THENΔDC is Increase I.
R_9. IF E is Positive PE and CE is Positive PCE THENΔDC is Increase I.

Finally, the fuzzy output is converted into real value output, i.e., crisp output by the process called defuzzification. Even though many defuzzification methods are available, the most preferred one is centroid method because this method can easily be implemented and requires less computation time when implemented in digital control systems using microcontrollers or DSPs. The formula for the centroid defuzzification method is given by

$$z = \sum_{x=1}^{n} \mu(x)x / \sum_{x=1}^{n} \mu(x) \quad (23)$$

Where z is the defuzzified value and μ(x)is the membership value of memberx. This crisp value is used to control the duty cycle of the switching devices in the power inverter module so as to control the average voltage applied across the phase windings, hence the speed of the motor.

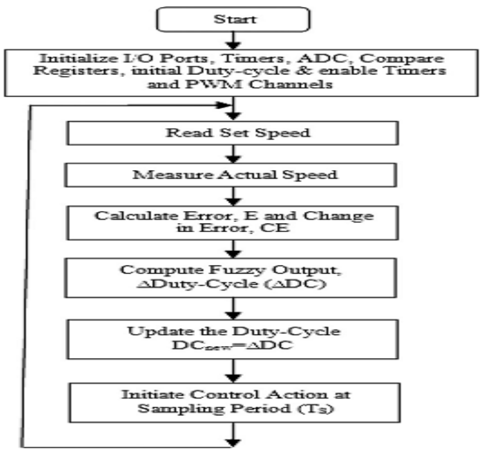

Fig.7. Flowchart of a fuzzy controller program.

PWM1-PWM6 pins of Event Manager-A (EVA) module are used to generate gating signals. The program is written for DSP using Code Composer Studio 3.0 software and the output file generated is downloaded from personal computer to the DSP.

The PWM control technique is used to control the voltage applied across the windings in order to control the speed of the motor. The choice of 20-kHz PWM signal is made because of the absence of acoustic noise during the motor operation. The duty cycle of the 20-kHz signal generated by the DSP is varied to control the average current and average voltage of the phase windings, and hence the torque produced by the motor. The duty cycle of the devices is controlled based on the fuzzy controller output. The expression for the average voltage applied across the winding is given by (20). The dc signal output of F/V converter is given as one of the input to analog-to-digital converter (ADC) of the DSP processor to determine the actual speed of the motor. The reference speed is set through a potentiometer and voltage follower and it is given as another input to the ADC converter to determine the reference speed. The other provisions to set the reference speed are by changing the value of the reference speed in the program or from watch window of code composer studio software. The function of the DSP processor is to compute the error and change in error, store these values, compute the fuzzy controller output, determine the new duty cycle for the switching devices, and perform electronic commutation. The PWM signals are generated for the IGBT switching devices using EVA module components such as timers, PWM channels, etc. The flowchart for the fuzzy controller program is shown in Fig. 7. The steps involved are: Initialize, ADC to read actual and reference speeds, I/O ports to read hall senor signals and generate commutation signals for IGBT switches, Timer1 to generate control action time and sampling time to measure speed, Timer 2 to generate 20-kHz PWM signal, measure the reference and actual speeds, compute controller output, and initiate control action by changing the duty cycle of the IGBT switches. The control signals for the IGBTs are generated by AND ing commutation signals with PWM signal. The driver circuits are designed to operate at high frequencies. The duty cycle of the IGBTs is varied so as to vary the average voltage applied across the winding, and hence the speed of the motor. The duty cycle is initially set

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more than 50% so as to allow sufficient current through the motor windings to start and run the motor with load. The time period of the PWM signal is chosen such that it is greater than the time constant of the motor so as to allow sufficient current through the windings and to produce the required torque during the normal operation [3], [4]. The PWM control signal of 20 kHz is generated at PWM_1–PWM_6 pins of EVA module of DSP processor. The control action is initiated at every 1.5 ms using Timer1

$$V_o(\text{avg}) = \text{Duty} - \text{cycle} \times V_{dc} \quad (24)$$

$$\% \text{ Duty} - \text{cycle} = (t_{on}/T) \times 100 \quad (25)$$

Where ton is turn-on time, T is total time period of PWM signal, V_{dc} is the dc input voltage applied to the inverter, and Vo (avg) is the average dc voltage applied across the phase windings.

VI.MATLAB/SIMULATIONS RESULTS

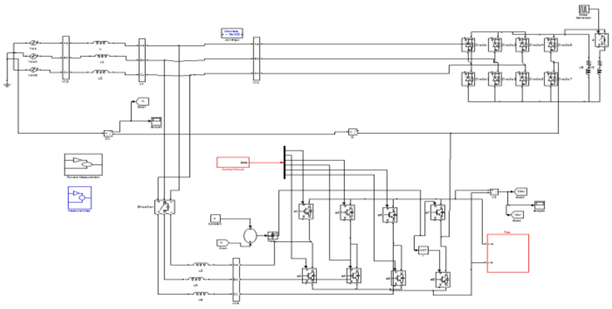

FIGURE.8. MATLAB/SIMULINK Model of Shunt Active Power Filters

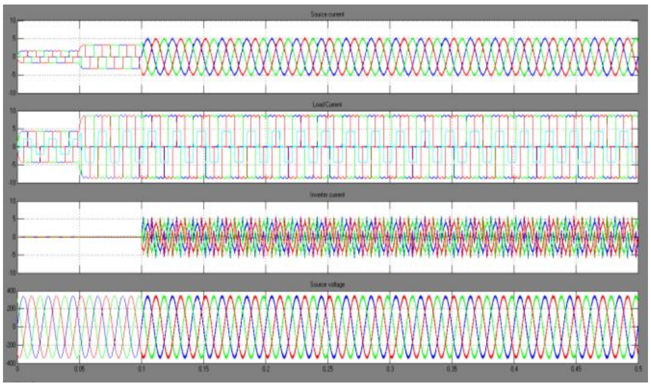

Figure.9.Source current, load current, inverter current and source voltage wave forms of the systems.

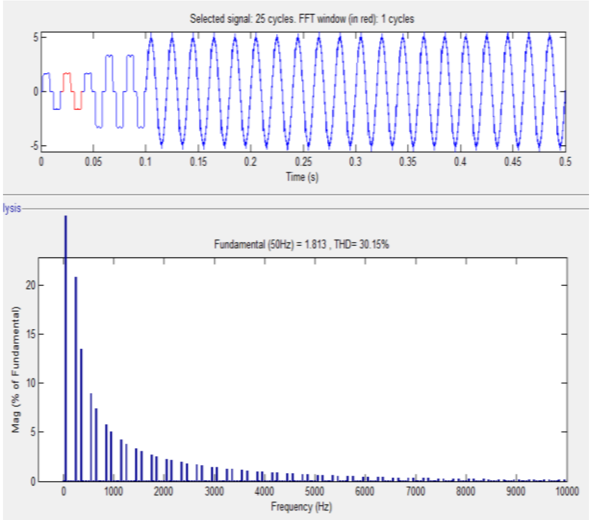

Fig.10. total harmonics distortions of source current with pi control.

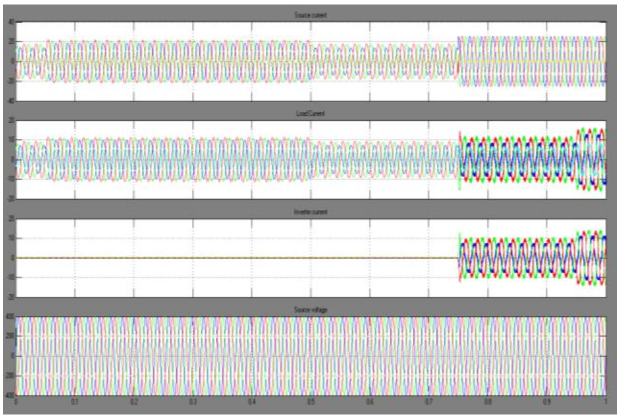

Figure.11.Source current, load current, inverter current and source voltage wave forms of the systems with fuzzy logic controller.

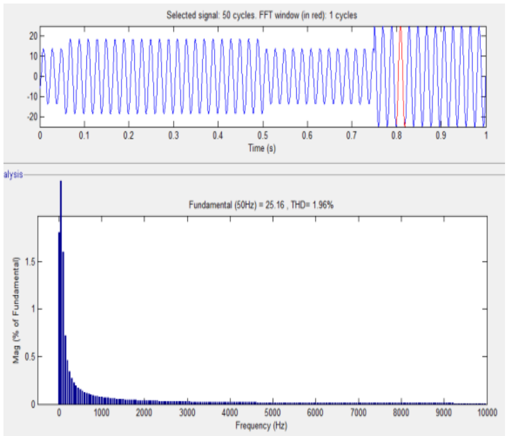

Fig.12.Total harmonics distortions of source current with fuzzy logic controller.

VII. CONCLUSION

PI controller based shunt active power filter simulated n MATLAB are implemented for harmonic and reactive power compensation of the non-linear load at PCC. It is found from the simulation results that shunt active power filter improves power quality of the distribution system by eliminating harmonics and reactive power compensation of non-linear load. It is found from simulation results that shunt active power filter improves power quality of the power system by eliminating harmonics and reactive current of the load current, which makes the load current sinusoidal and in phase with the source voltage.

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