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Minimization of Harmonic Distortion using Fuzzy based Shunt Active Power Filter

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Abstract: In this paper study and designing of intellect controller by using speed as feedback for considerably improving the dynamic performance of active power filter, and the comparative analysis of several control strategies fed APF for power quality improvement features is presented. Due to the sensitivity of consumers on power quality and also development in power electronics may accomplish the power quality concerns. Active power filter technology is the most capable way to balance reactive power and reduce lower order harmonics generated by nonlinear loads. An active power filter is a device that is connected in parallel to and minimizes the reactive and harmonic currents from the group of nonlinear loads so that the resulting total current drawn from the ac main is sinusoidal. The shunt active power filter was measured to be the most basic configuration for the APF. This paper describes the basic concept of shunt active power filter, along with the current tracking circuit based on the instantaneous reactive power theory and the main circuit performing as an inverter with PWM hysteresis control. The proposed concept can be implemented by using MATLAB/SIMULINK software and the results are verified.

Keywords: Power quality, Shunt Active Power Filter, Current Tracking, Fuzzy logic Controller, Hysteresis Control, Reactive Power, Total Harmonic Distortion (THD).

I. INTRODUCTION

In recent years, there has been an improved use of non-linear loads which has resulted in an increased portion of non-sinusoidal currents and voltages in Electric Network. Because of these non-linear loads power quality problems will occur due to harmonics, transients etc. Power quality is defined as to maintaining a sinusoidal waveform of bus voltages at rated voltage and frequency [1]. The shape of the waveform of electric power at generation stage is merely sinusoidal and free from any distortion. A lot of the Power conversion and consumption equipment are also designed to function under pure sinusoidal voltage waveforms. However, there are several devices that distort the waveform. These distortions may spread all over the electrical network. Categorization of power quality areas may be made according to the source of the problem such as converters, magnetic circuit non linearity, arc furnace or by the wave shape of the signal such as harmonics, flicker or by the frequency spectrum means EMI problems. The wave shape phenomena associated with power quality may be classified into synchronous and non synchronous. A synchronous phenomenon refers to those in synchronism with A.C waveform at power frequency [2]. Advances in semiconductor device technology have fuelled a revolution in power electronics over the past decade, and there are indications that this trend will continue. However, these power electronics equipment which include adjustable-speed motor drives (ASDs), electronic power supplies, direct current (DC) motor drives, battery chargers, electronic ballasts are responsible for the increase in related PQ problems.

All these nonlinear loads are manufactured by nonlinear devices, in which the current is not proportional to the applied voltage. So as to reduce the power quality problems conventional passive filters are the earliest solution to mitigate power quality problems drawn by the non-linear loads, but due to its bulky in size and resonance with the impedance [3], its applications have becomes very restricted in use. To minimize the power quality problems in electric network active power filters are introduced. With the development of shunt active power filter, the harmonics distortion created by the non-linear loads can be therefore compensated, and the total harmonic distortion can be minimized to it smallest distorted level. To control the shunt active power filters various algorithms are proposed in the literature, but instantaneous power theory in [4] which has been mostly preferred by various researchers because of its characteristics. The p-q theory offers better results compared to other algorithms, but it is very complex technique due to its involvement in complex equations and mathematical analysis in order to reach realistic results. Another technique is the synchronous reference frame (SRF) detection method for the harmonic reduction in water pump station for an accurate harmonic damping.

The p-q theory or instantaneous power theory is based on time domain. This is most widely accepted control algorithm in this control mode is to initially detect and calculate the harmonics in the load current, then the negative value of which represents as the reference current that triggers the control of inverter by PWM current tracking method. Time domain based theory makes the operation in steady-state or transient state, as well as for common voltage and current waveforms, allowing to control the active power filters in real-time. Another important characteristic of this theory is the simplicity of the calculations, which involves only algebraic calculation. Finally achieve minimum THD value by the comparative performance analysis of several intelligence control techniques with fuzzy logic control technique, the proposed techniques are implemented by using Matlab/Simulink platform and results are conferred.

II. THE PRINCIPLE OF SHUNT ACTIVE POWER FILTER

A. Basic Structure

The shunt active filter approach is based on the principle of injection of harmonic currents into the ac system, of the same amplitude but opposite in phase to that of the load harmonic currents.

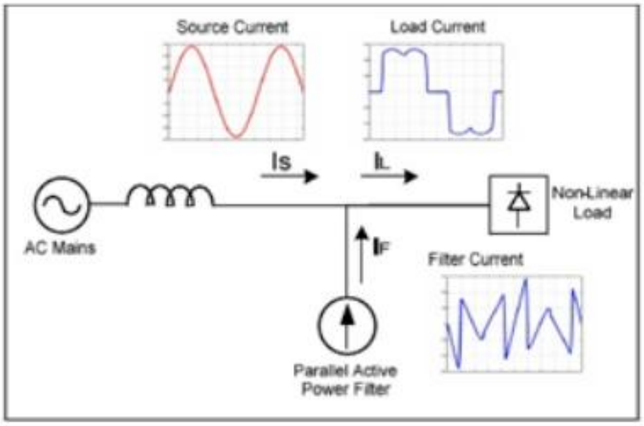

Fig.1. Basic Principle of SAPF System.

Fig.1 shows the active power filter compensation principle, which is controlled in a closed loop manner to actively shape the source current into sinusoid. Fig.2 demonstrates the simplified configuration of shunt APF [5], which could be dichotomized into reference current calculation section and its counterpart—compensating current generator (consisting of current control, drive and main circuit). The core function of the reference current calculation circuit is to detect the harmonics as well as the reactive power contributed by the non-linear load.

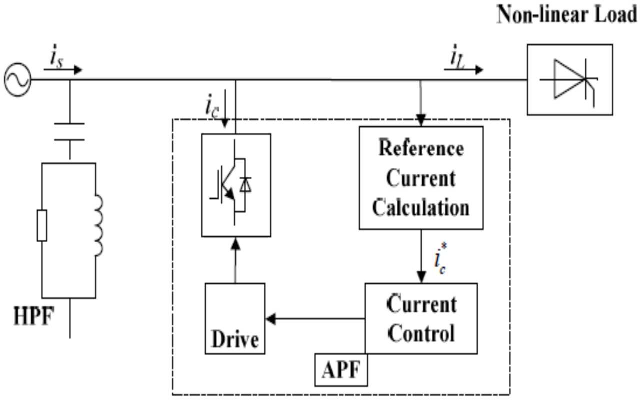

Fig.2. Simplified shunt APF configuration.

B. The Calculation of Reference Current

The circuit of reference current calculation is essentially based on three-phase instantaneous reactive power theory [5], which suggests a novel approach to detect the three-phase harmonic current. As shown in Fig 3, i_a, i_b and i_c are initially detected and then served as the input for the next stage of algorithm, which involves specific calculation of instantaneous active current i_p as well as reactive current i_q.

$$\begin{bmatrix} i_p \\ i_q \end{bmatrix} = C \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (1)$$

Where

$$C = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin \omega t & \sin\left(\omega t - \frac{2\pi}{3}\right) & \sin\left(\omega t + \frac{2\pi}{3}\right) \\ -\cos \omega t & -\cos\left(\omega t - \frac{2\pi}{3}\right) & -\cos\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix} \qquad (2)$$

In addition, a three-phase PLL section is prerequisite in order to grasp the angle of phase A. When i_p and i_q flow through the low-pass filter (LPF), the harmonics contained could be eliminated, and thus give rise to the DC component of the load current known as $\overline{i_p}$ and $\overline{i_q}$. With inverse transformation of the transpose matrix of CT, hence the three phase fundamental current of i_{af}, i_{bf} and i_{cf} could be readily obtained. Therefore, the reference current i_a^*, i_b^* and i_c^* is obviously the subtraction of those fundamental three-phase currents with the correspondingly original load currents [6].

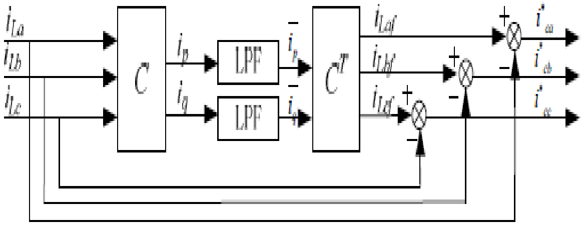

Fig.3. Algorithm of the reference current calculation circuit.

C. Current Tracking Control Circuit

Current tracking is the first step for the production of targeted compensating current, under the basic function of obtaining the PWM signals that are responsible for the switch modes of each device in the main circuit. In addition, the PWM signal is generated by the comparison between the reference current and the real compensating current. The current-tracking-controlled PWM inverters possess various forms, the most common of which is the hysteresis current tracking control shown in Fig 4. i_a^* represents the reference value and meanwhile the tracking target of the load current. A hysteresis error h is intentionally established in case of the high frequency of switches in inverters. While $i_a^* - i_a \geq h$, the hysteresis controller produces high level which drives the upper bridge arm S_1 in working mode condition, and thus increasing load current i_a even when i_a is outstripping i_a^*. The increase of load current will not be affected unless i_a is exactly greater by h comparing with the reference current, then follows the reverse working mode of hysteresis controller by switching off S_1 and simultaneously acting on S_4, which may not be necessarily switched on, for the current flows through diode D_4 is not reversed in direction but rather begin decreasing [7]. When the hysteresis control is applied, the real output of the current from inverters could maintain a fluctuation value only within h and –h, bouncing up and down in zigzag forms, as one of the examples illustrated in Fig.5.

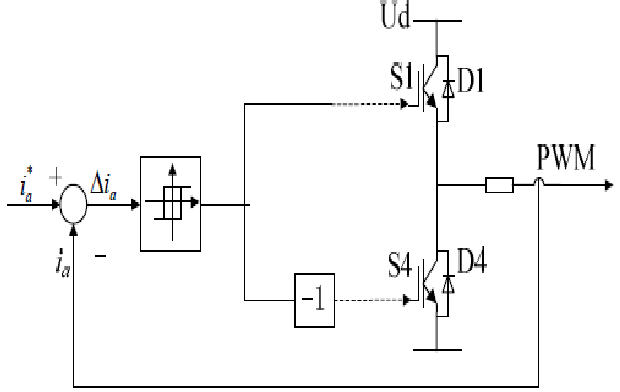

Fig.4.Circuit of current tracking control.

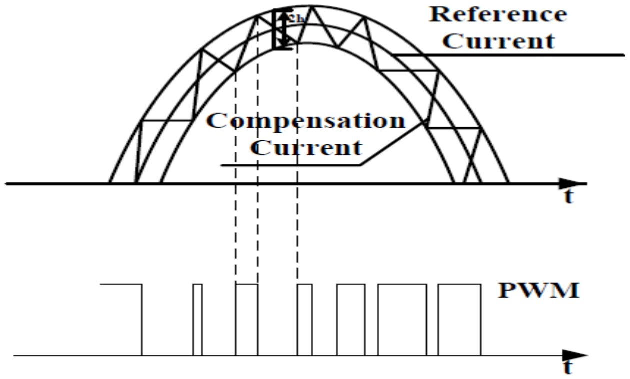

Fig.5. One example of the hysteresis control of the reference and compensating current.

D. Main Circuit Parameter Design

The working mode of the main circuit is determined by the condition of its six switches. Generally speaking, there is always a single device switched on in all three groups (S_1/S_4, S_3/S_6 or S_2/S_5), constructing six different combinations all together. The main circuit is shown in Fig.6.

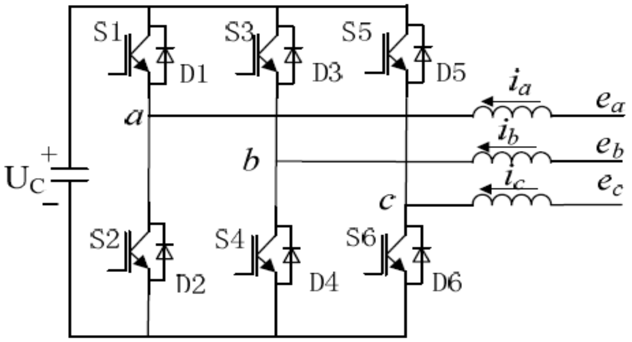

Fig.6. Main circuit.

Suppose the sum of three-phase voltage source $e_a+e_b+e_c=0$ along with the current $i_a+i_b+i_c=0$, then the differential equation of phase A could be described as

$$L\frac{di_a}{dt} = e_a + K_a U_c \tag{3}$$

In which K_a denotes the switching coefficient, while e_a represents as the instantaneous value of the ac side voltage and i_a as the compensating current. In addition, when the upper bridge arm of phase A is switched on, the absolute value of K_a is -2/3; similarly, K_a is 1/3 when the lower bridge arm is working. Provided that the sample working time is long enough, the average effect of AC voltage e_a in (2) would be zero [8]-[10]. As the possibility of K_a=1/3 is 66.7% while that of K_a=2/3 is 33.3%, the mean of K_a is hence 4/9. Within one period of time, (2) could be reshaped as:

$$L\lambda\frac{i^*_{c\max}}{t_c} = \frac{4}{9}U_c \tag{4}$$

Signal of compensating current; the most appropriate value of coefficient λ varies from 0.3 to 0.4 in terms of the overall effect of compensation, which could be obtained by simulation. Taking function (3) and safety concerns into consideration, the prerequisite of $U_c \geq 3E_m$ should be granted, in which E_m is the peak value of phase voltage. Assuming that the DC side capacitor is always in transition from charging to discharging states within a single switching cycle, the maximum acceptable deviation of DC side capacitor voltage is [4]:

$$\Delta U_{c\max} = \frac{\left|i^*_{c\max}\right|}{Ct_c} \tag{4}$$

III. FUZZY CONTROLLER

The control scheme consists of Fuzzy controller, limiter, and three phase sine wave generator for reference current generation and generation of switching signals. The peak value of reference currents is estimated by regulating the DC link voltage. The actual capacitor voltage is compared with a set reference value. The error signal is then processed through a Fuzzy controller, which contributes to zero steady error in tracking the reference current signal, Fig. 7 shows the internal structure of the control circuit. A fuzzy controller converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed by expert experience or knowledge database. Firstly, input voltage V_{dc} and the input reference voltage $V_{dc\text{-}ref}$ have been placed of the angular velocity to be the input variables of the fuzzy logic controller. Then the output variable of the fuzzy logic controller is presented by the control Current Imax. To convert these numerical variables into linguistic variables, the following seven fuzzy levels or sets are chosen as: NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), and PB (positive big) as shown in Fig.8 as proposed in [4]. The fuzzy controller is characterized as follows:

- Seven fuzzy sets for each input and output;
- Fuzzification using continuous universe of discourse;

- Implication using Mamdani's ‘min’ operator;
- De-fuzzification using the ‘centroid’ method.

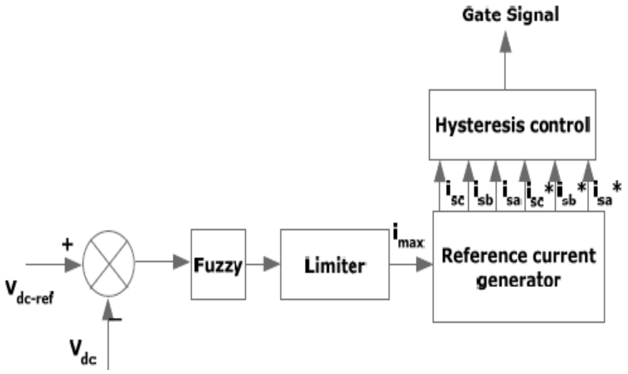

Fig.7.Conventional fuzzy controller.

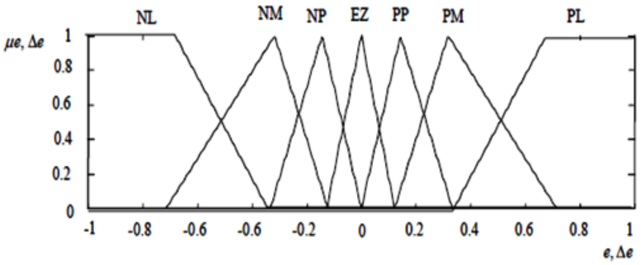

Fig.8. Membership functions for Input, Change in input, Output.

Fuzzification: the process of converting a numerical variable (real number) convert to a linguistic variable (fuzzy number) is called fuzzification.

De-fuzzification: 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).

TABLE I: Input/Output Variables

Δe \ e	NL	NM	NS	EZ	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	EZ
NM	NL	NL	NL	NM	NS	EZ	PS
NS	NL	NL	NM	NS	EZ	PS	PM
EZ	NL	NM	NS	EZ	PS	PM	PL
PS	NM	NS	EZ	PS	PM	PL	PL
PM	NS	EZ	PS	PM	PL	PL	PL
PL	NL	NM	NS	EZ	PS	PM	PL

Database: the Database stores the definition of the membership Function required by fuzzifier and defuzzifier.
Rule Base: the elements of this rule base table are determined based on the theory that in the transient state, large errors need coarse control, which requires coarse in-put/output variables; in the steady state, small errors need fine control, which requires fine input/output variables. Based on this the elements of the rule table are obtained as shown in Table 1, with ‘V_{dc}’ and ‘V_{dc-ref}’ as inputs.

IV. MATLAB/SIMULINK RESULTS

Here simulation is carried out in different cases 1). Implementation of Shunt Active Power Filter using Inverter 2). Implementation of Shunt Active Power Filter with Fuzzy Logic Controller.

Case1: Implementation of Shunt Active Power Filter using Inverter

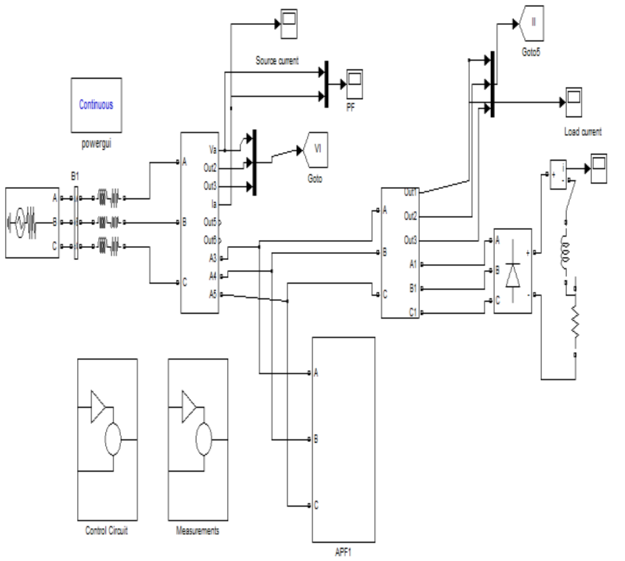

Fig.9. Matlab/Simulink Model of Proposed Shunt Active Power Filter.

Fig.9 shows the Matlab/Simulink Model of Proposed Shunt Active Power Filter using Matlab/Simulink Platform.

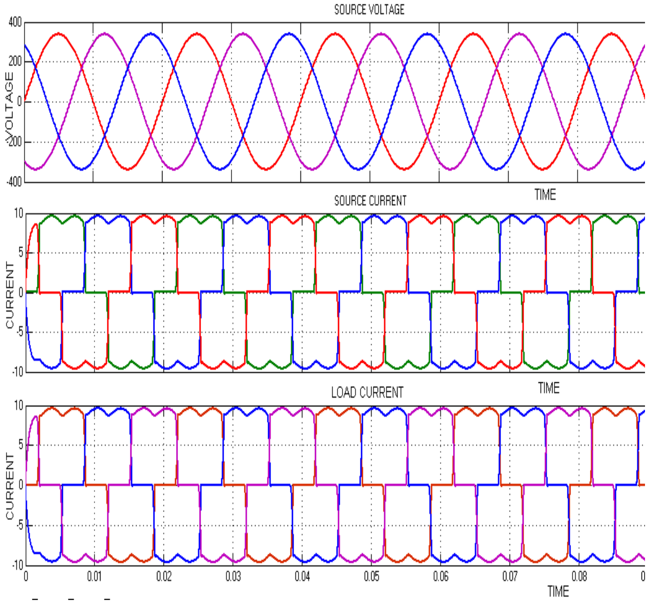

Fig. 10. Source voltage, current and load current without APF.

Fig. 10 shows the three phase source voltages, three phase source currents and load currents respectively without APF. It is clear that without APF load current and source currents are same.

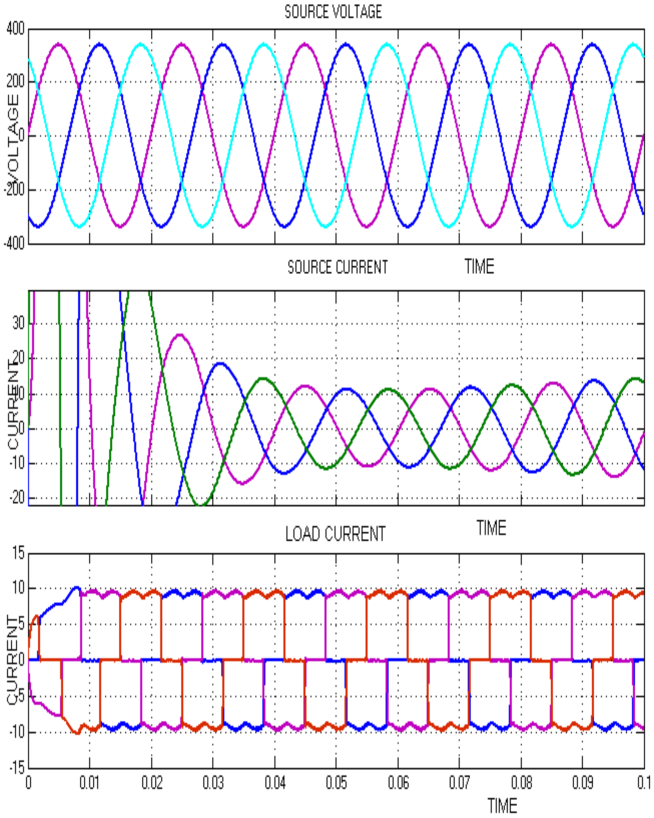

Fig. 11. Source voltage, current and load current with APF.

Fig. 11 shows the three phase source voltages, three phase source currents and load currents respectively with APF. It is clear that with APF even though load current is non sinusoidal source currents are sinusoidal.

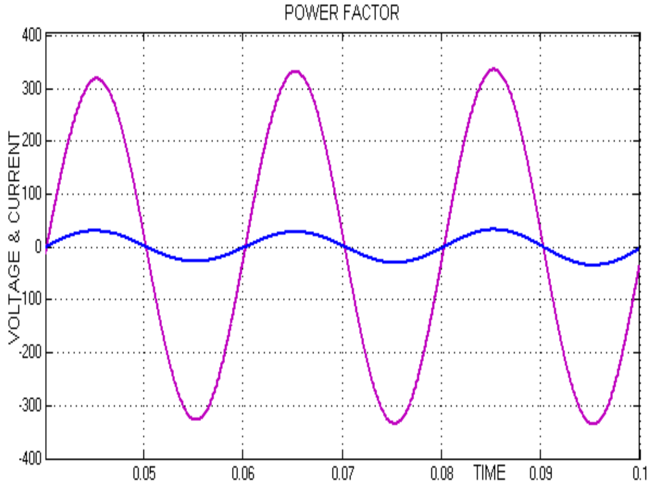

Fig. 12. Phase-A source voltage and current.

Fig.12 shows the phase-A source voltage and current, even though the load is non linear RL load the source power factor is unity.

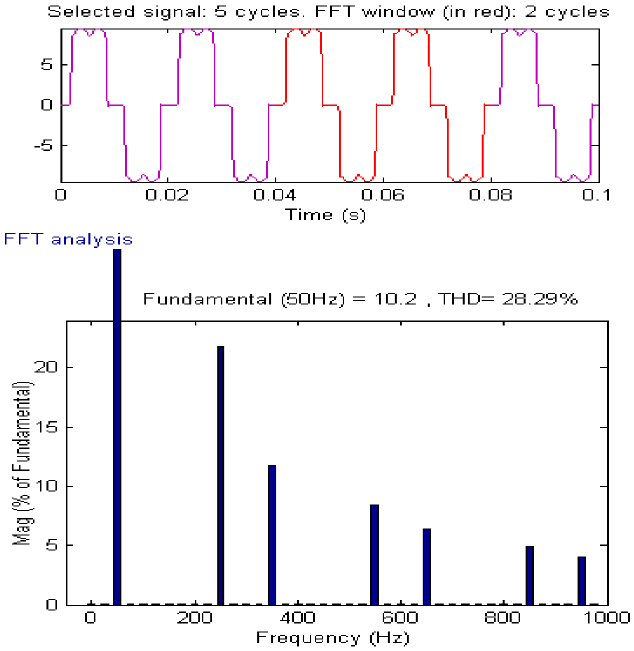

Fig. 13. Harmonic spectrum of Phase-A Source current without APF.

Fig. 13 Shows the harmonic spectrum of Phase –A Source current without APF. The THD of source current without APF is 28.29%.

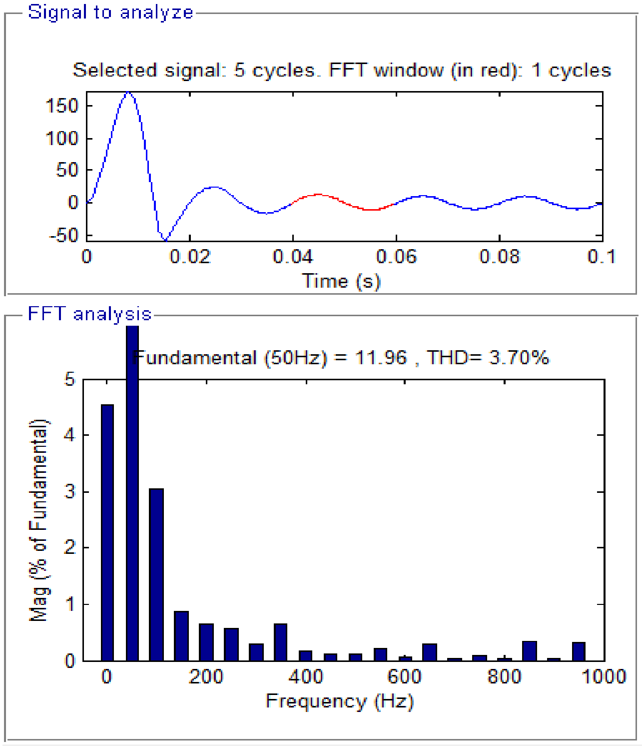

Fig. 14. Harmonic spectrum of Phase-A Source current with APF.

Fig14 Shows the harmonic spectrum of Phase –A Source current with APF. The THD of source current without APF is 3.70%.

Case 2: Implementation of Shunt Active Power Filter with Fuzzy Logic Controller.

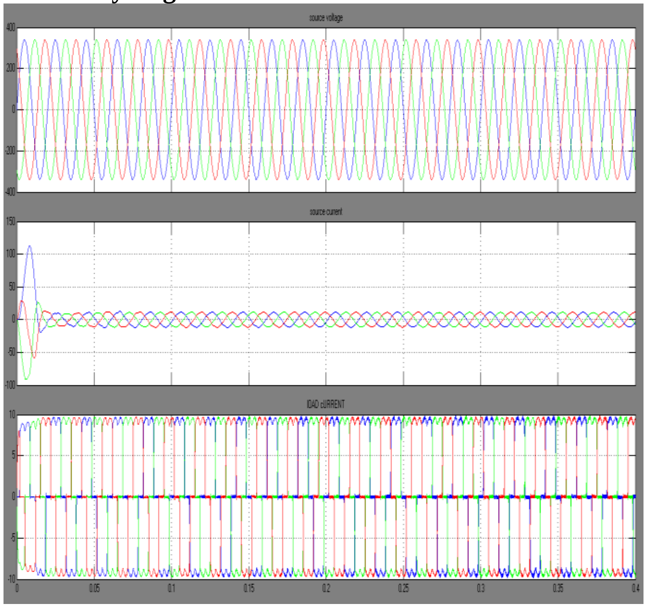

Fig. 15. Source voltage, current and load current with FLC Based APF.

Fig. 15 shows the three phase source voltages, three phase source currents and load currents respectively with FLC Based APF.

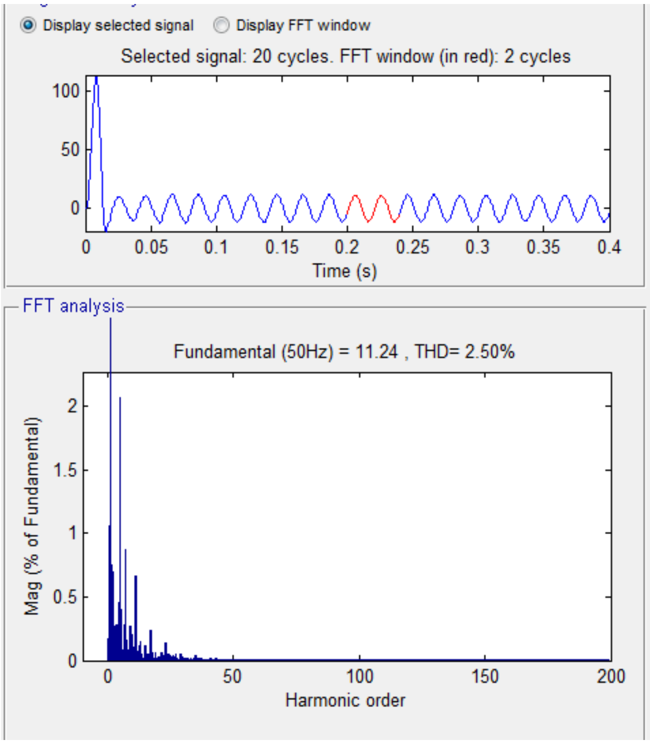

Fig. 16. Harmonic spectrum of Phase-A Source current with FLC Based APF.

Fig16 Shows the harmonic spectrum of Phase –A Source current with FLC Based APF. The THD of source current without APF is 2.50%.

TABLE II: Comparative Analysis of Intelligence Control Techniques Based Shunt Active Power Filter for PQ features

THD (%)	Without APF	With PI	With Fuzzy
Source Current	29.28%	3.70%	2.50%

As above Table II depict the comparative analysis of the several intelligence control techniques based shunt active power filter for PQ features, with the help of different control strategies attain low THD values and fast response with low error values and system may operate under good stability factor.

V. CONCLUSION

Shunt active power filter(SAPF) with the proposed fuzzy logic controller reduces harmonics and provides better reactive power compensation due to non-linear load currents; as a result source currents become sinusoidal and unity power factor is also achieved under both transient and steady state conditions.This proposed model is implemented using Matlab/Simulink software and the obtained resultant waveforms were evaluated and the effectiveness of the system stability and performance of power system have been established. Total harmonic distortion without shunt APF is 29.28%. By using shunt APF with PI controller the THD value is 3.50%, whereas by using APF with Fuzzy logic controller the THD value is 2.50% only. Finally fuzzy logic controller based shunt APF gives better performance than PI controller and also minimal THD value as per IEEE standards; this will also increase the stability of the system.

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