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A Comparative Analysis of PI Controller and Fuzzy Logic Controller for Hybrid Active Power Filter Using Dual Instantaneous Power Theory

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Abstract*- This paper presents a fuzzy logic, PI controlled shunt active power filter used to compensate for harmonic distortion in three-phase systems. The Hybrid active power filter employs a simple method for the calculation of the reference compensation current based on Fast Fourier Transform. The presented Hybrid Active Power filter is able to operate in balanced, load conditions. Classic filters may not have satisfactory performance in fast varying conditions. But auto tuned active power filter gives better results for harmonic minimization, and THD improvement. The proposed auto tuned hybrid active power filter maintains the THD well within IEEE-519 standards. The proposed methodology is extensively tested and with improved dynamic behavior of hybrid active power filter using fuzzy logic, PI controllers. The results are found to be quite satisfactory to mitigate harmonic Distortions, and improve quality. The detailed simulations are carried out on MATLAB environment to validate the performance.*

Keywords*- Fuzzy Logic Controller (FLC), Hybrid Active Power Filter (HAPF), THD, load compensation, power factor, power quality (PQ), voltage-source inverter (VSI), Proportional-Integral (PI) control.*

I. INTRODUCTION

With the development of power electronic devices and these related control technologies, more and more power electronic equipment has been installed in power system network. However, many power electronic consumers, such as arc furnaces and rectifiers, because of these special operation characteristics, would cause serious voltage fluctuation, harmonic current pollution, low power factor (PF), less qualitated power etc. Therefore, a lot of specialists have given attention to improving such power quality problems. Power quality conditioners, such as static var compensators (SVCs) and active power filters (APFs), which locally mitigate the harmonic current, can effectively improve voltage quality and PF and suppress harmonic pollution

Although passive power filters (PPFs) can suppress limited characteristic frequency harmonic current, this dynamic filtering performance is not good enough to avoid that the harmonic current from passive power filter causes series–parallel resonance between the filter and the system. Recently, APFs have been developed quickly because of this good filtering performance, but the limitations of capacity and voltage level of power electronic devices prevent APFs from applying in medium–high-voltage systems. Hybrid APFs (HAPFs) combine the advantages of APFs and PPFs and are suitable to be equipped in medium–high-voltage system.

The increased severity of power quality problems and other problems associated with the passive filters such as large size and weight, higher cost, fixed compensation, and resonance problems with loads and networks have required a focus on a power electronic solution, that is, active power filters (APF) as shown in Fig.1. In recent years, many publications have also appeared on the harmonics suppression using active power filters. Selection of a control method and proper topology of harmonic suppression, best suited to particular conditions, requires that advantages, disadvantages and limitations of these devices, which exhibit a very broad range of properties.

The control strategy for a hybrid active power filter generates the reference current, that must be provided by the power filter to compensate reactive power and harmonic currents demanded by the load [4]-[6] This involves a set of currents in the phase domain, which will be tracked generating the switching signals applied to the electronic converter by means of the appropriate closed-loop switching control technique such as hysteresis or deadbeat control. Several methods including dual instantaneous real and reactive power theory have been proposed for extracting the harmonic content [2-5].

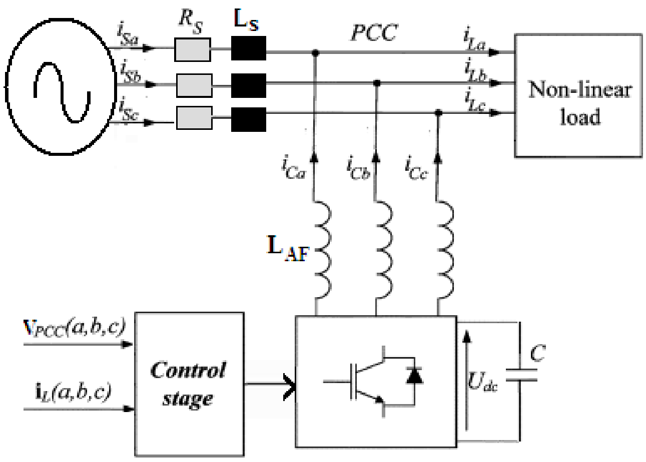

Fig.1. Basic principal of shunt current compensation in active filter

All these methods work well under steady state, balanced and Sinusoidal conditions of supply voltage. Among all the methods presented in the literature, the dual instantaneous active and reactive power (P-Q) theory is one of the most common and probably it is the best method[4].

Recently, to avoid the inherent undesirable characteristics of conventional control approaches, Fuzzy Logic Controller (FLC) is being developed. FLC offers a linguistic approach to develop control algorithms for any system. It maps the input-output relationship based on human expertise and hence, does not require an accurate mathematical model of the system and can handle the nonlinearities that are generally difficult to model [2]. This consequently makes the FLC tolerant to parameter variation and more accurate and robust.

II. DESIGN OF APF

A. Principle of APF

A APF, which is schematically depicted in Fig. 2, consists of a two-level Voltage Source Converter (VSC), a dc energy storage device, a coupling transformer connected in shunt to the distribution network through a coupling transformer. The VSC converts the dc voltage across the storage device into a set of three-phase ac output voltages[7]. These voltages are in phase and coupled with the ac system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the APF output voltages allows effective control of active and reactive power exchanges between the APF and the ac system. Such configuration allows the device to absorb or generate controllable active and reactive power[8].

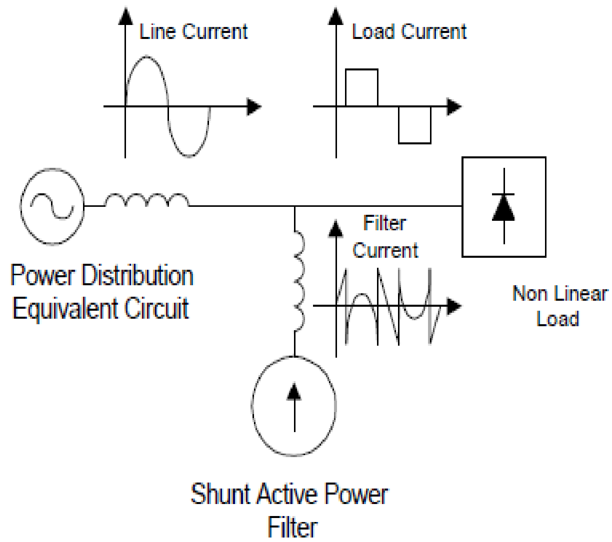

Fig. 2. Schematic Diagram of a APF

The VSC connected in shunt with the ac system provides a multifunctional topology which can be used for up to three quite distinct purposes:
1. Voltage regulation and compensation of reactive power;
2. Correction of power factor
3. Elimination of current harmonics.

Here, such device is employed to provide continuous voltage regulation using an indirectly controlled converter [9]. As shown in Fig. 3 the shunt injected current I_{sh} corrects the voltage sag by adjusting the voltage drop across the system impedance Z_{th}. The value of I_{sh} can be controlled by adjusting the output voltage of the converter. The shunt injected current I_{sh} can be written as,

$$I_{sh} = I_L - I_S = I_L - (V_{th} - V_L) / Z_{th} \quad (1)$$

$$I_{sh} \angle \eta = I_L \angle -\theta \quad (2)$$

It may be mentioned that the effectiveness of the APF in correcting voltage sag depends on the value of Z_{th} or fault level of the load bus. When the shunt injected current I_{sh} is kept in quadrature with V_L, the desired voltage correction can be achieved without injecting any active power into the system. On the other hand, when the value of I_{sh} is minimized, the same voltage correction can be achieved with minimum apparent power injection into the system [10].

B. Principle of HAPF

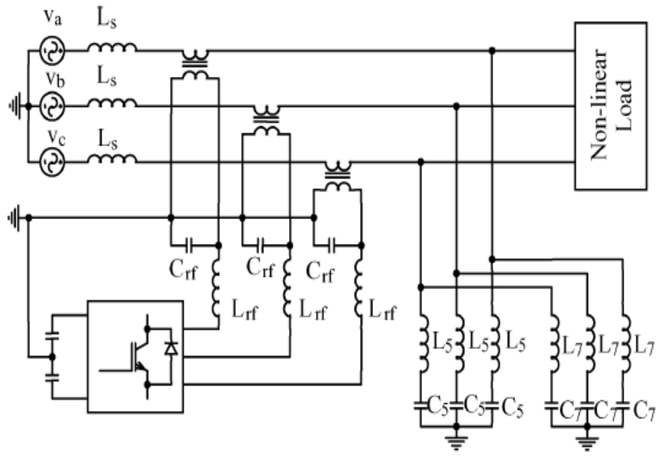

Fig. 3. Schematic Diagram of a HAPF

An active power filter, APF, typically consists of a three phase pulse width modulation (PWM) voltage source inverter [11]. When this equipment is connected in series to the ac source impedance it is possible to improve the compensation characteristics of the passive filters in parallel connection [12]. This topology is shown in Fig. 3, where the active filter is represented by a controlled source, where is the voltage that the inverter should generate to achieve the objective of the proposed control algorithm.

III. CONCEPT OF DUAL INSTANTANEOUS POWER THEORY

A. The Dual Instantaneous Reactive Power Theory For Hybrid Active Power Filter:

The instantaneous reactive power theory is the most widely used as a control strategy for the APF. It is mainly applied to compensation equipment in parallel connection. This theory is based on a Clarke coordinate transformation from the phase coordinates Shown in Fig. 4

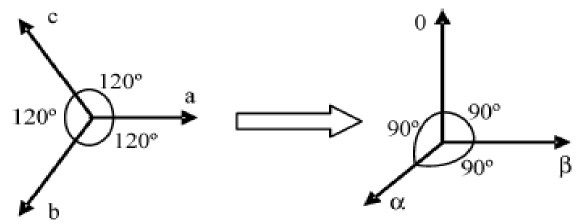

Fig. 4. Transformation from the phase reference system (abc) to the 0αβsystem.

In a three-phase system such as that presented in Fig. 4 voltage and current vectors can be defined by

$$v = [v_a \quad v_b \quad v_c]^T \quad i = [i_a \quad i_b \quad i_c]^T \qquad (3)$$

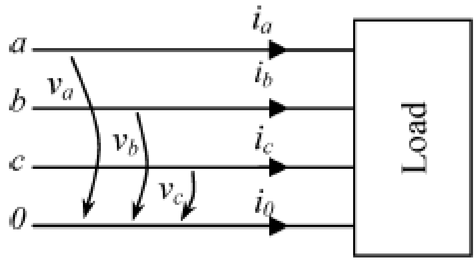

Fig. 5. Three-phase system.

The vector transformations from the phase reference system a-b-c to αβ0 coordinates can be obtained, thus

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3/2} & -\sqrt{3/2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad (4)$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3/2} & -\sqrt{3/2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (5)$$

The instantaneous real power in the α- β- 0 frame is calculated as follows:

$$P_{3\emptyset}(t) = v_\alpha i_\alpha + v_\beta i_\beta + v_0 i_0 \qquad (6)$$

This power can be written as

$$P_{3\emptyset}(t) = p + p_0 \qquad (7)$$

Where p is the instantaneous real power without zero sequence component and given by

$$p = v_\alpha i_\alpha + v_\beta i_\beta \qquad (8)$$

It can be written in vectorial form by means of dot product

$$p = i_{\alpha\beta}^T v_{\alpha\beta} \qquad (9)$$

Where $i_{\alpha\beta}^T$ the transposed current vector in α-β is coordinates

$$i_{\alpha\beta} = [i_\alpha \quad i_\beta]^T \qquad (10)$$

In the same way, $v_{\alpha\beta}$ is the voltage vector in the same coordinates

$$v_{\alpha\beta} = [v_\alpha \quad v_\beta]^T \qquad (11)$$

is the zero sequence instantaneous power, calculated as follows:

$$p_0 = v_0 i_0 \qquad (12)$$

In a three-wire system there are no zero-sequence current components, that is, $i_0 = 0$ .In this case, only the instantaneous power defined on the $\alpha - \beta$axes exists, because the product $v_0 i_0$ is always zero.

The imaginary instantaneous power is defined by the equation

$$q \triangleq v_\alpha i_\beta - v_\beta i_\alpha \qquad (13)$$

In accordance with (20), this can be expressed by means of the dot product

$$q = i_{\alpha\beta}^T \perp v_{\alpha\beta} \qquad (14)$$

Where $i_{\alpha\beta}^T \perp$ is the transposed current vector perpendicular to $i_{\alpha\beta}$ and it can be defined as follows:

$$i_{\alpha\beta} \perp = [i_\beta \quad -i_\alpha]^T \qquad (15)$$

Both power variables previously defined can be expressed as

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} i_{\alpha\beta}^{T} \\ i_{\alpha\beta\perp}^{t} \end{bmatrix} v_{\alpha\beta} \quad (16)$$

In the $\alpha\beta$ plane$i_{\alpha\beta}$ and $i_{\alpha\beta\perp}$vectors establish two coordinates' axes. The voltage vector $v_{\alpha\beta}$ can be decomposed in its orthogonal projection on the axis defined by the currents vectors, Fig. 6. By means of the current vectors and the real and imaginary instantaneous power, the voltage vector can be calculated

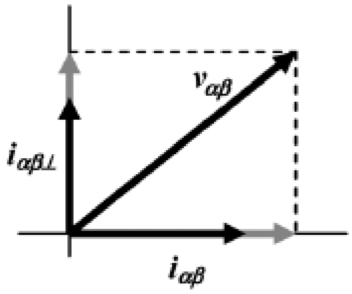

Fig. 6. Decomposition of the voltage vector

$$\boldsymbol{v_{\alpha\beta}} = \frac{\boldsymbol{p}}{\boldsymbol{i_{\alpha\beta}^2}} \boldsymbol{i_{\alpha\beta}} + \frac{\boldsymbol{q}}{\boldsymbol{i_{\alpha\beta}^2}} \boldsymbol{i_{\alpha\beta\perp}} \quad (17)$$

In a four-wire system, the zero sequence instantaneous power is not null. In this case, (17) would have to include an additional term with the form$(\frac{p_0}{i_0^2})i_0$, where $i_0$is the zero sequence current vector.

B. Compensation Strategy:

Electric companies try to generate electrical power as sinusoidal and balanced voltages so it has been obtained as a reference condition in the supply. Due to this fact, the compensation target is based on an ideal reference load which must be resistive, balanced and linear. It means that the source currents are collinear to the supply voltages and the system will have unity power factor. If, in Fig 6, voltages are considered as balanced and sinusoidal, ideal currents will be proportional to the supply voltages[1].

$$v = R_e i \quad (18)$$

R_e is the equivalent resistance $\boldsymbol{v}$ the load voltage vector and $\boldsymbol{i}$ the load current vector.

The average power supplied by the source will be

$$Ps = I_1^2 R_e \quad (19)$$

In this equation, I_1^2 is the square rms value of the fundamental harmonics of the source current vector. It must be supposed that when voltage is sinusoidal and balanced, only the current fundamental component transports the power consumed by the load. Compensator instantaneous power is the difference between the total real instantaneous power required by the load and the instantaneous power supplied by the source

$$P_C(t)=P_L(t)- Ps(t) \quad (20)$$

In this equation, the average power exchanged by the compensator has to be null, that is

$$P_C = \frac{1}{T}\int P_C(t)dt = 0 \quad (21)$$

When average values are calculated in (19), and (20) and (21) are taken into account

$$0 = \frac{1}{T}\int P_L(t)dt - I_1^2 R_e \quad (22)$$

Therefore, the equivalent resistance can be calculated as

$$R_e = P_L / I_1^2 \quad (23)$$

Where P_L is the load average power, defined a

$$P_L = \frac{1}{T}\int P_L(t)dt \quad (24)$$

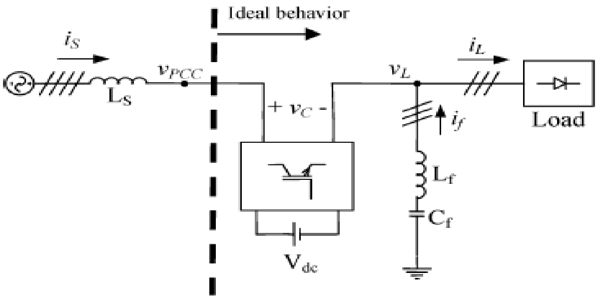

Fig. 7. System with compensation equipment.

Fig. 7 shows the system with series active filter, parallel passive filter and unbalanced and non-sinusoidal load. The aim is that the set compensation equipment and load has an ideal behavior from the PCC. The voltage at the active filter connection point in $0\alpha\beta$ coordinates can be calculated as follows:

$$V_{PCC\alpha\beta} = \frac{P_L}{I_1^2}\, i_{\alpha\beta} \tag{25}$$

$i_{\alpha\beta}$ is the source current in $0\alpha\beta$ coordinates. In this equation, the restriction of null average power exchanged by the active filter is imposed.

The load voltage is given according to (17) by

$$V_{L\alpha\beta} = \frac{P_L}{i_{\alpha\beta}^2} i_{\alpha\beta} + \frac{q_L}{i_{\alpha\beta}^2} i_{\alpha\beta\perp} \tag{26}$$

Where P_L is the real instantaneous power and $q_L$is the load imaginary instantaneous power. The reference signal for the output voltage of the active filter

$$V_{C\alpha\beta}^{*} = V_{PCC\alpha\beta} - V_{L\alpha\beta} \tag{27}$$

Considering (25) and (26), the compensation voltage is

$$V_{C\alpha\beta}^{*} = \left(\frac{P_L}{I_1^2} - \frac{P_L}{i_{\alpha\beta}^2}\right) i_{\alpha\beta} - \frac{q_L}{i_{\alpha\beta}^2} i_{\alpha\beta\perp} \tag{28}$$

When the active filter supplies this compensation voltage, the set load and compensation equipment behaves as a resistor Re**.** Finally, if currents are unbalanced and non sinusoidal, a balanced resistive load is considered as ideal reference load. Therefore, the equivalent resistance must be defined by the equation

$$R_e = \frac{P_L}{I_1^{+2}} \tag{29}$$

Here, I_1^{+2} is the square rms value of the positive sequence fundamental component. In this case, (30) is modified, where I_1 is replaced by I_1^{+} , that is

$$V_{C\alpha\beta}^{*} = \left(\frac{P_L}{I_1^{+2}} - \frac{P_L}{i_{\alpha\beta}^2}\right) i_{\alpha\beta} - \frac{q_L}{i_{\alpha\beta}^2} i_{\alpha\beta\perp} \tag{30}$$

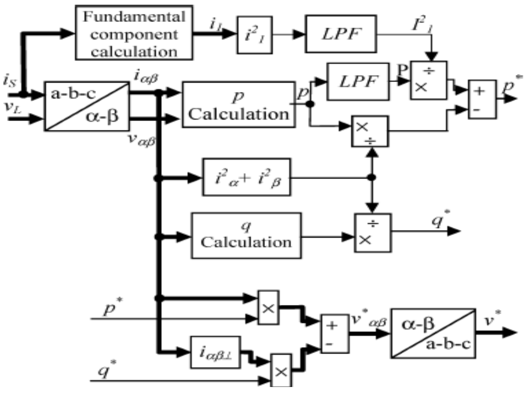

Fig. 8. Control Scheme

Reference signals are obtained by means of the reference calculator shown in Fig. 8 and Fig.9. In the case of unbalanced loads, the block “fundamental component calculation”

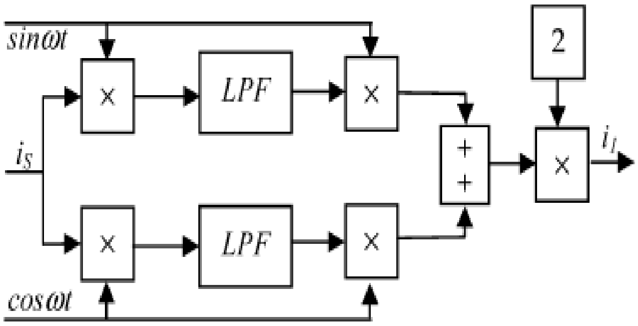

Fig. 9. Calculation Fundamental Component

The compensation target imposed on a four-wire system is the one presented in (16). However, a modification in the control scheme of Fig. 8 is necessary. This consists in including a third input signal from the zero sequence power P_0 in the control block where $V^{*}_{0\alpha\beta}$ is generated. The proposed control strategy may be suitable in a stiff feeder, where voltage could be considered undistorted [2].

IV. FUZZY LOGIC CONTROLLER

FLC is a technique to embody human-like thinking into a control system. FLC can be designed to emulate human deductive thinking, that is, the process people use to infer conclusions from what they know. FLC has been primarily applied to the control of processes through fuzzy linguistic descriptions [2]. FLC is utilized to design controllers for plants with complex dynamics and high nonlinearity model. In a motor control system, the function of FLC is to convert linguistic control rules into control strategy based on heuristic information or expert knowledge. FLC has a fixed set of control rules, usually derived from expert’s knowledge. The membership function (MF) of the associated input and output linguistic variables is generally predefined on a common universe of discourse. For the successful design of FLC’s proper selection of input and output scaling factors (gains) or tuning of the other controller parameters are crucial jobs, which in many cases are done through trial and error to achieve the best possible control performance. The structure of FLC is shown in Fig.10. The structure shows four functions, each one materialized by block.

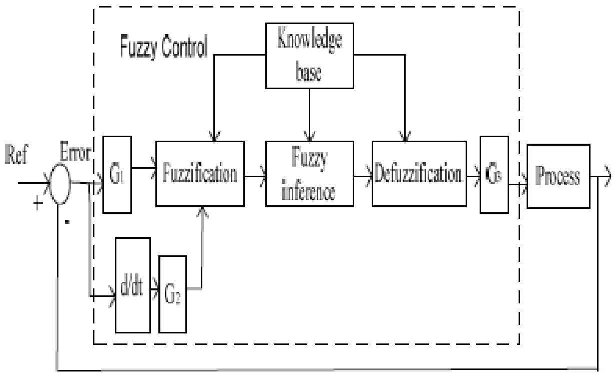

Fig.10. Structure of fuzzy controller

A fuzzification interface, the fuzzy control initially converts the crisp error and its rate of change in displacement into fuzzy variables; then they are mapped into linguistic labels. Membership functions are defined within the normalized range (-1, 1), and associated with each label: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). Seven MFs are chosen for *e(pu)* and *ce(pu)* signals and seven for output. All the MFs are symmetrical for positive and negative values of the variables. Thus, maximum 7x7 = 49 rules can be formed as in Fig.12.

The membership functions for the inputs (error and change of error) and output of fuzzy control for hybrid active power filter are shown in Fig.11.

• A knowledge base (a set of If-Then rules), which contains the definition of the fuzzy subsets, their membership functions, their universe discourse and the whole of the rules of inference to achieve good control.

• An inference mechanism (also called an "inference engine" or "fuzzy inference" module), which is heart of a fuzzy control, posses the capacity of feign the human decisions and emulates the expert's decision making in interpreting and applying knowledge about how best to control the plant.
• A de-fuzzification interface, which converts the conclusions of the inference mechanism into actual inputs for the process.

A. Fuzzy Logic Membership Functions:

Fuzzy controllers do not require an exact mathematical model. Instead, they are designed based on general knowledge of the plant. Fuzzy controllers are designed to adapt to varying operating points. Fuzzy Logic Controller is designed to control the change in voltage of the converter using Mamdani style fuzzy inference system. Two input variables, error (e) and change of error (de) are used in this fuzzy logic system. The single output variable (u) is steady state signal of the converter, nothing but error free response is directly fed to the system.

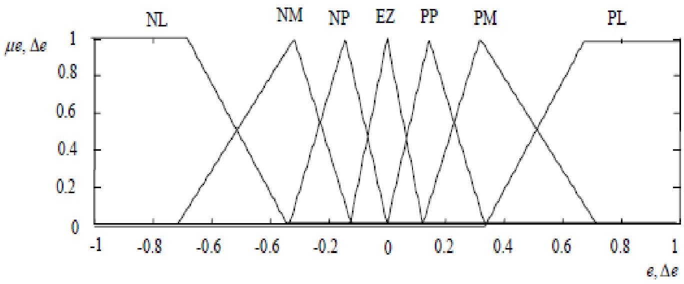

Fig.11.. Membership functions for Input, Change in input, Output.

Fig.11. Shows the membership functions for input (error (e)), Change in input (change of error (de)), Output variable (u).

B. Fuzzy Logic Rules

The objective of this dissertation is to control the output voltage of the converter. The error and change of error of the output voltage will be the inputs of fuzzy logic controller. These 2 inputs are divided into seven groups; NL: Negative Large, NM: Negative Medium, NS: Negative Small, ZO: Zero Area, PS: Positive small, PM: Positive Medium and PL: Positive Large and its parameter [10]. These fuzzy control rules for error and change of error can be referred that is shown as below:

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

Fig.12. Rules for fuzzy logic controller

V. MATLAB/SIMULINK MODELING AND SIMULATION RESULTS

Here the Simulation is carried out in two cases.

1. Improvement of Power Quality by using Hybrid Active Power Filter using conventional PI controller.
2. Improvement of Power Quality by using Hybrid Active Power Filter using Fuzzy Logic Controller.

Case 1: Improvement of Power Quality by using Hybrid Active Power Filter using conventional pi controller:

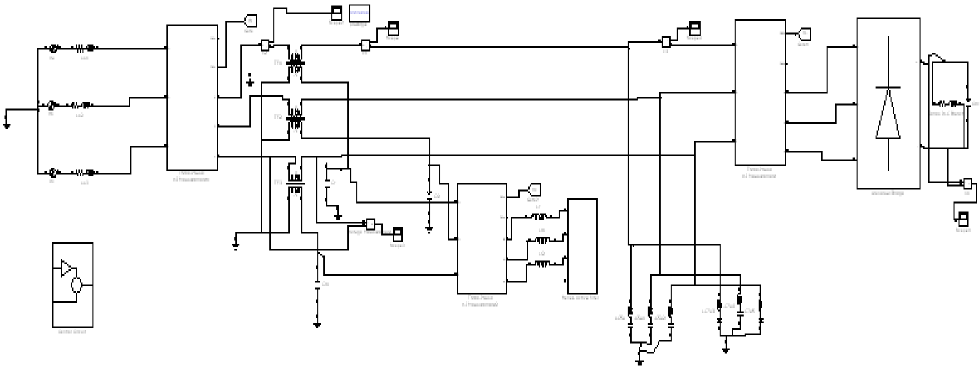

Fig. 13. Matlab/Simulink Model Power Circuit of Hybrid APF

Fig. 13 shows the Matlab/Simulink power circuit model of HAPF. It consists of five blocks named as source block, non linear load block, control block, HAPF block and measurements block.

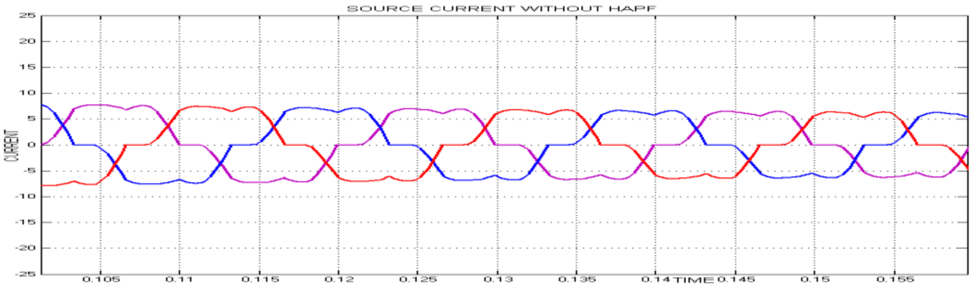

Fig. 14. Source Current Without Hybrid Active Power Filter

Fig. 14 Shows the Source Current Without Hybrid Active Power Filter

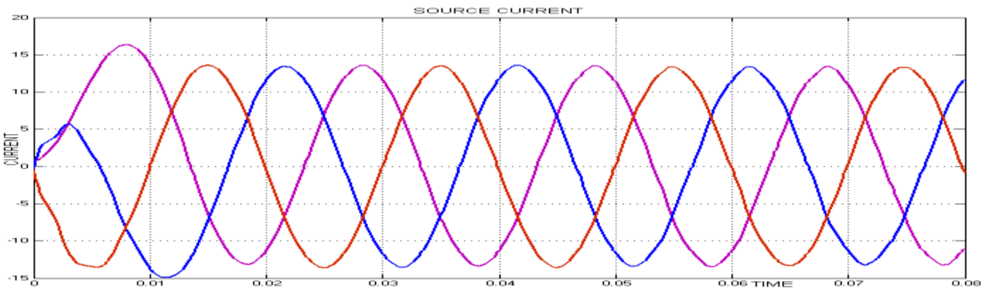

Fig. 15. Source Current of Hybrid Active Power Filter using conventional pi controller

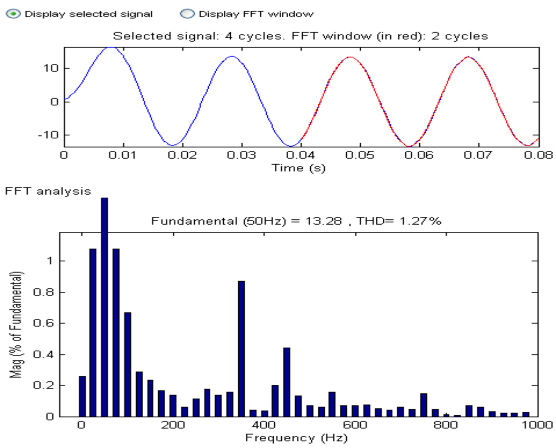

Fig. 16. Harmonic Spectrum of Phase – A Source Current With Hybrid Active Power Filter using conventional pi controller.

Fig. 15. Shows the Source Current of Hybrid Active Power Filter and Fig 16 Shows the Harmonic Spectrum of Phase – A Source Current With Hybrid Active Power Filter. The THD of source current with HAPF using conventional pi controller is 1.27%.

Case 2: Improvement of Power Quality by using Hybrid Active Power Filter using fuzzy logic controller:

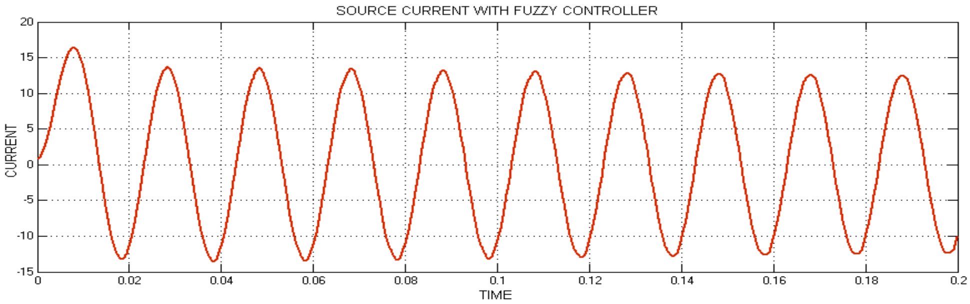

Fig .17. Source Current of Hybrid Active Power Filter using fuzzy logic controller

Fig.17. Shows the Source current of Hybrid Active Power Filter using fuzzy logic controller.

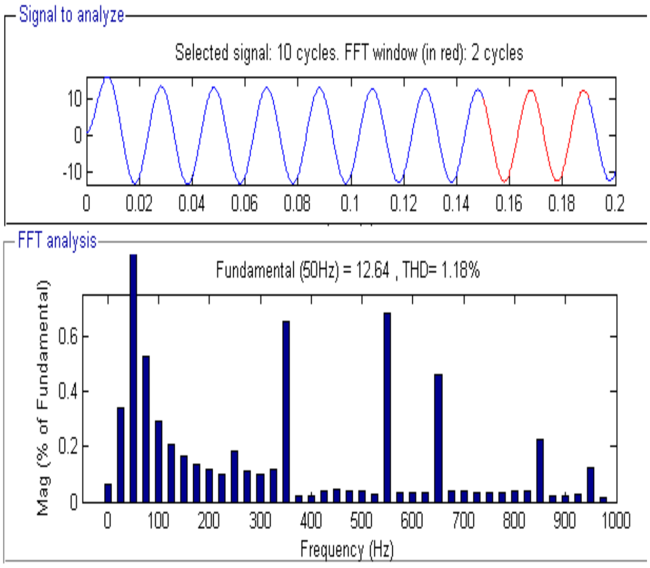

Fig.18. Harmonic Spectrum of Phase – A Source Current with Hybrid Active Power Filter using fuzzy logic controller.

Fig.18. Harmonic Spectrum of Phase – A Source Current with Hybrid Active Power Filter using fuzzy logic controller, the THD of source current With Hybrid Active Power Filter. The THD of source current with HAPF using conventional pi controller is 1.18 %.. Table I Shows the THD comparative analysis of conventional pi controller & fuzzy logic controller.

Table I A Comparative Analysis

	PI CONTROLER	FUZZY LOGIC CONTROLLER
THD	1.27%	1.18%

VI. CONCLUSION

The objective of this paper is to compare the time specification performance between conventional controller and artificial intelligence controller (FLC) controlling the dc link voltage. A VSI topology for HAPF compensating ac balanced nonlinear loads and a dc load supplied by the dc link of the compensator is presented. A control algorithm for conventional pi controller and fuzzy logic controller constituted by a hybrid active power filter, this topology we developed a series active power filter and a passive filter connected in parallel with the load is investigated. Finally Matlab/Simulink based model is developed and simulation results are presented.

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