PI and Fuzzy Controller based SHAF for Mitigation of Current Harmonics with I_d-I_q Control Strategy

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Abstract— *Commencing with incandescent light bulb, every load today creates harmonics. Unfortunately, these loads vary with respect to their amount of harmonic content and response to problems caused by harmonics. The prevalent difficulty with harmonics is voltage & current waveform distortion. Additional, Electronic equipment like, computers, battery chargers, electronic ballasts, variable frequency drives, and switching mode power supplies generate perilous harmonics. Issue of Harmonics are of a greater concern to engineers and building designers because they do more than distort voltage waveforms, they can overheat the building wiring, cause nuisance tripping, overheat transformer units, and cause random end-user equipment failures. Thus power quality has become more and more serious with each passing day. As a result active power filter (APF) gains much more attention due to excellent harmonic compensation. But still the performance of the active filter seems to be in contradictions with different control techniques. The main objective of this paper is to analyse shunt active filter with fuzzy and pi controllers. To carry out the analysis, we consider active and reactive current method (i_d-i_q). Extensive simulations were carried out; simulations were performed with balance, unbalanced and non sinusoidal conditions. Simulation results validate the dynamic behaviour of fuzzy logic controller over pi controller.*

Index Terms— *Harmonic compensation, Shunt Active power filter (SHAF), i_d-i_q control strategy, PI controller, fuzzy controller.*

I. INTRODUCTION

In recent years power quality has been an important and growing problem because of the proliferation of nonlinear loads such as power electronic converters in typical power distribution systems. Particularly, voltage harmonics and power distribution equipment problems result from current harmonics [1-2] produced by nonlinear loads.

As nonlinear currents flow through a facility's electrical system and the distribution-transmission lines, additional voltage distortions are produced due to the impedance associated with the electrical network. Thus, as electrical power is generated, distributed, and utilized, voltage and current waveform distortions are produced. It is noted that non-sinusoidal current results in many problems for the utility power supply company, such as: low power factor, low energy efficiency, electromagnetic interference (EMI), distortion of line voltage etc.

Eminent issues always arises in three-phase four-wire system, it is well-known that zero line may be overheated or causes fire disaster as a result of excessive harmonic current

[4] going through the zero line three times or times that of three. Thus a perfect compensator is necessary to avoid the consequences due to harmonics. Though several control techniques and strategies had developed but still performance of filter in contradictions, these became primarily motivation for the current paper.

In i_d-i_q method [4] angle 'θ' is calculated directly from main voltages and thus enables the method to be frequency independent. Thus large numbers of synchronization problems with un-balanced and non-sinusoidal voltages are also avoided.

The PI controller [5] requires precise linear mathematical models, which are difficult to obtain and may not give satisfactory performance under parameter variations, load disturbances, etc. Recently, fuzzy logic controllers have received a great deal of interests in APF. The advantages of fuzzy controllers over conventional controllers are that they do not need an accurate mathematical model, can work with imprecise inputs, can handle non-linearity, and are more robust than conventional controllers. The Mamdani type of fuzzy controller [6] used for the control of APF gives better results compared with the PI controller, but it has the drawback of a larger number of fuzzy sets and 49 rules.

Present paper mainly focused on two controllers i.e., fuzzy and pi. Additionally we developed a filter with instantaneous active and reactive currents (i_d–i_q) method which is prominent one with this we analysed the performance of filter under different main voltages. On observing fuzzy controller shows some superior performance over pi controller. To validate current observations, Extensive simulations were performed and adequate results were presented.

II. SHUNT ACTIVE FILTER CONFIGURATION

The active filter currents are achieved from the instantaneous active and reactive powers *p* and *q* of the non-linear load. Fig. 1 shows a three-leg structure with the neutral conductor being connected to midpoint of dc-link capacitor.

The three-leg six-switch split-capacitor configuration of shunt APF suffers from several shortcomings viz.

- (*a*) Control circuit is somewhat complex
- (*b*) Voltages of the two capacitors of split-capacitor need to be properly balanced
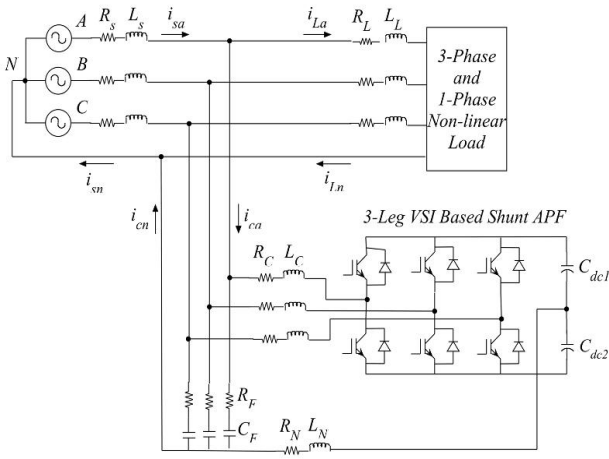- (*c*) Large dc-link capacitors are required.

Fig.1. Three-leg split capacitor Shunt APF with Non-linear load.

a. *Compensation principle*

The active power filter is controlled to draw/supply the a compensating current i_f from/to the load to cancel out the current harmonics on AC side and reactive power flow from/to the source there by making the source current in phase with source voltage. Figure 2 shows the basic compensation principle of the active power filter.
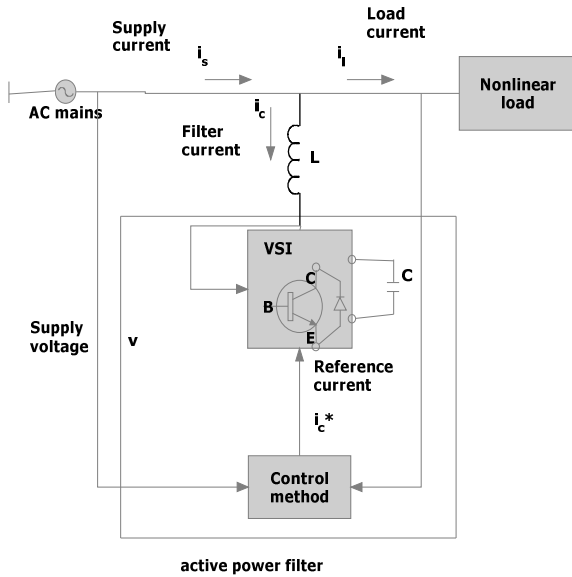

Fig 2. Compensation Characteristics of a Shunt Active power filter

III. INSTANTANEOUS ACTIVE AND REACTIVE CURRENT THEORY

In Fig. 3, the entire reference current generation scheme has been illustrated. The load currents i_{La}, i_{Lb} and i_{Lc} are tracked upon which Park's transformation is performed to obtain corresponding d-q axes currents i_{Ld} and i_{Lq} as given in (1), where ω is rotational speed of synchronously rotating d-q frame. According to i_d-i_q control strategy, only the average value of d-axis component of load current should be drawn

from supply. Here i_{Ld1h} and i_{Lq1h} indicate the fundamental frequency component of i_{Ld} and i_{Lq}. The oscillating components i_{Ld} and i_{Lq} i.e., i_{Ldnh} and i_{Lqnh} are filtered out using low-pass filter.
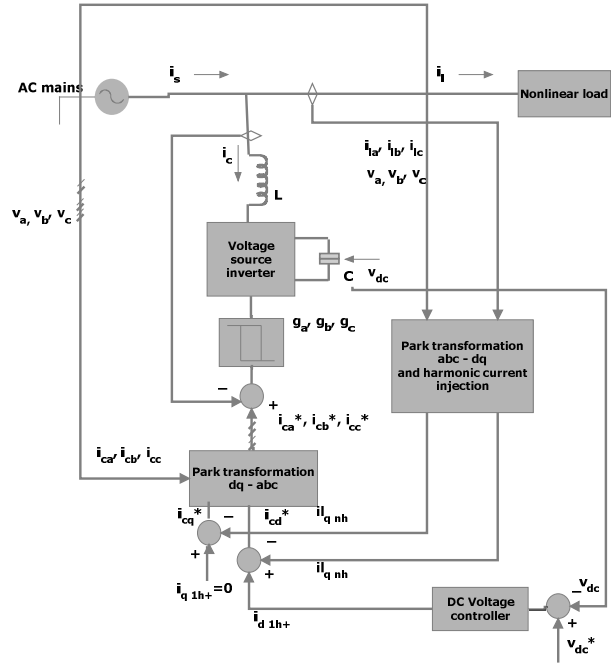

Fig.3. Active powers filter control circuit.

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} i_{Ld1h} + i_{Ldnh} \\ i_{Lq1h} + i_{Lqnh} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} \sin wt & \cos wt \\ -\cos wt & -\sin wt \end{bmatrix} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix}$$

The currents i_{Ldnh} and i_{Lqnh} along with i_{d1h} are utilized to generate reference filter currents $i_{cd}*$ and $i_{cq}*$ in d-q coordinates, followed by inverse Park transformation giving away the compensation currents $i_{ca}*$, $i_{cb}*$, $i_{cc}*$ and $i_{cn}*$ in the four wires as described in (2) and (3).

$$\begin{bmatrix} i_{ca}* \\ i_{cb}* \\ i_{cc}* \end{bmatrix} = \begin{bmatrix} \sin wt & \cos wt & 1 \\ \sin(wt - 2\pi/3) & \cos(wt - 2\pi/3) & 1 \\ \sin(wt + 2\pi/3) & \cos(wt + 2\pi/3) & 1 \end{bmatrix} \begin{bmatrix} i_{cd}* \\ i_{cq}* \\ i_{c0}* \end{bmatrix} \tag{2}$$

$$i_{cn}* = i_{ca}* + i_{cb}* + i_{cc}* \tag{3}$$

The reference signals thus obtained are compared with the actual compensating filter currents in a hysteresis comparator, where the actual current is forced to follow the reference and provides instantaneous compensation by the APF [9] on account of its easy implementation and quick prevail over fast current transitions. This consequently provides switching signals to trigger the IGBTs inside the inverter. Ultimately, the filter provides necessary compensation for harmonics in the source current and

reactive power unbalance in the system. Fig.3 shows voltage and current vectors in stationary and rotating reference frames. The transformation angle 'θ' is sensible to all voltage harmonics and unbalanced voltages; as a result $d\theta/dt$ may not be constant.
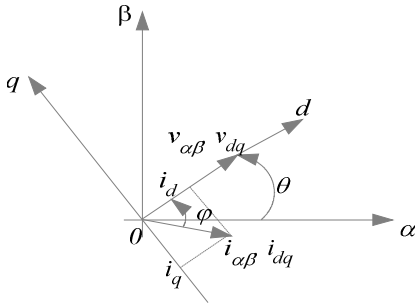

Fig.4. Instantaneous voltage and current vectors.

One of the advantages of this method is the angle θ is calculated directly from the main voltages and thus makes this method frequency independent; Consequently synchronizing problems with unbalanced and distorted conditions of main voltages are also evaded. Thus with $i_d - i_q$ one can achieves large frequency operating limit essentially by the cut-off frequency of the voltage source inverter (VSI). After the load currents i_d and i_q are obtained from park transformation, they are allowed to pass through the high pass filter to eliminate dc components in the nonlinear load currents. Filters used in the circuit are Butterworth type and to reduce the influence of high pass filter an alternative high pass filter (AHPF) can be used in the circuit. It can be obtained through the low pass filter (LPF) of same order and cut-off frequency simply by calculating the difference between the input signal and the filtered one, which is clearly shown in Fig.6. Butterworth filters used in harmonic injecting circuit have a cut-off frequency equal to one half of the main frequency ($f_c=f/2$), with a small phase shift in

harmonics a sufficiently high transient response can be obtained.

a. DC Voltage regulator (I_d-I_q):

The function of the voltage regulator at the dc side is performed by a proportional – integral (PI) controller. Inputs to the PI controller are, the change in dc link voltage (V_{dc}) and the reference voltage ($V_{dc}*$). By controlling the first harmonic active current of the positive sequence $i_{d1h}{}^+$ it is possible to control the active power flow in the VSI and thus the capacitor voltage V_{dc}.

In similar fashion reactive power flow is controlled by the first harmonic reactive current of the positive sequence $i_{q1h}{}^+$. On the contrary the primary end of the active power filters is just the exclusion of the harmonics caused by nonlinear loads hence the current $i_{q1h}{}^+$ is always set to zero.

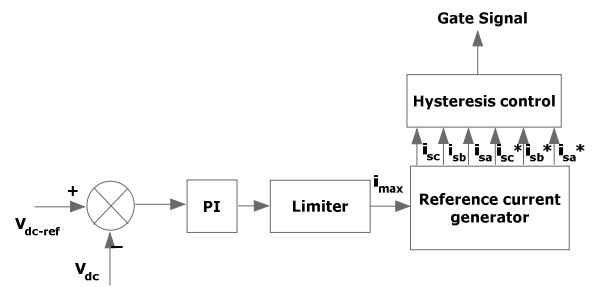## IV. CONSTRUCTION OF PI CONTROLLER

Fig.5 Conventional PI Controller

Fig.5 shows the internal structure of the control circuit. The control scheme consists of PI 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 [10].
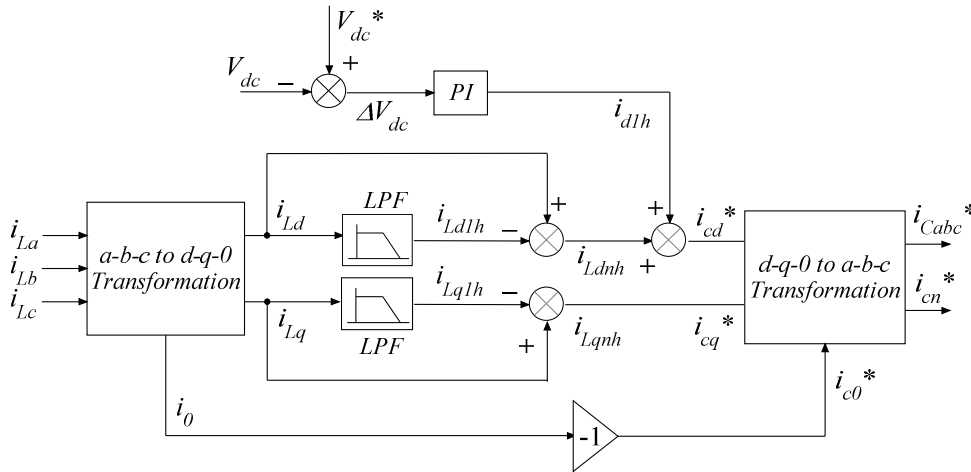

Fig.6. Reference current extraction with i_d-i_q method with PI controller

The error signal is then processed through a PI controller, which contributes to zero steady error in tracking the reference current signal. The output of the PI controller is considered as peak value of the supply current (I_{max}), which is composed of two components: (a) fundamental active power component of load current, and (b) loss component of APF; to maintain the average capacitor voltage to a constant value. Peak value of the current (I_{max}) so obtained, is multiplied by the unit sine vectors in phase with the respective source voltages to obtain the reference compensating currents. These estimated reference currents ($I_{sa}*$, $I_{sb}*$, $I_{sc}*$) and sensed actual currents (I_{sa}, I_{sb}, I_{sc}) are compared at a hysteresis band, which gives the error signal for the modulation technique. This error signal decides the operation of the converter switches. In this current control circuit configuration, the source/supply currents I_{sabc} are made to follow the sinusoidal reference current I_{abc}, within a fixed hysteretic band. The width of hysteresis window determines the source current pattern, its harmonic spectrum and the switching frequency of the devices.

The DC link capacitor voltage [11] is kept constant throughout the operating range of the converter. In this scheme, each phase of the converter is controlled independently. To increase the current of a particular phase, the lower switch of the converter associated with that particular phase is turned on while to decrease the current the upper switch of the respective converter phase is turned on. With this one can realize, potential and feasibility of PI controller.

V. CONSTRUCTION OF FUZZY CONTROLLER

The bock diagram of Fuzzy logic controller is shown in **Fig 7**. It consists of blocks

- Fuzzification Interface
- Knowledge base
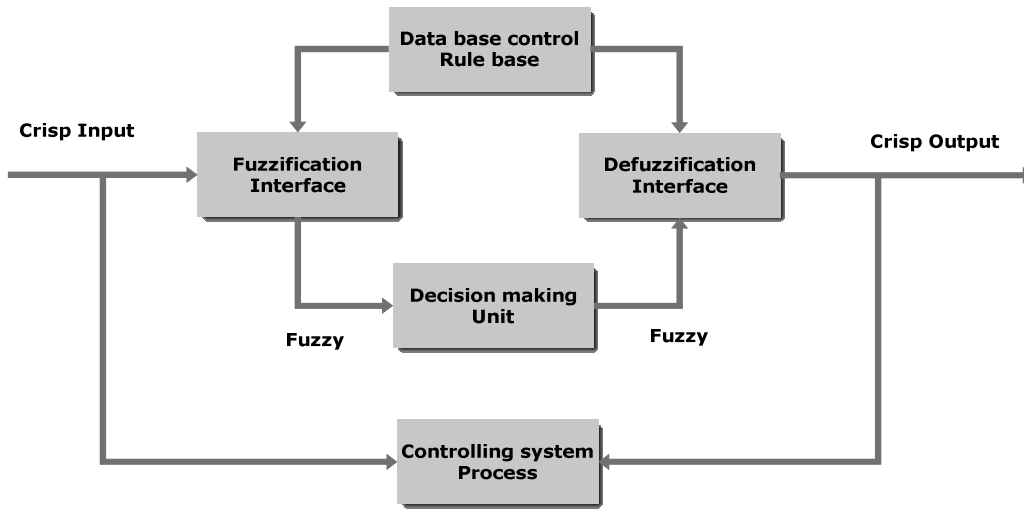- Decision making logic
- Defuzzification

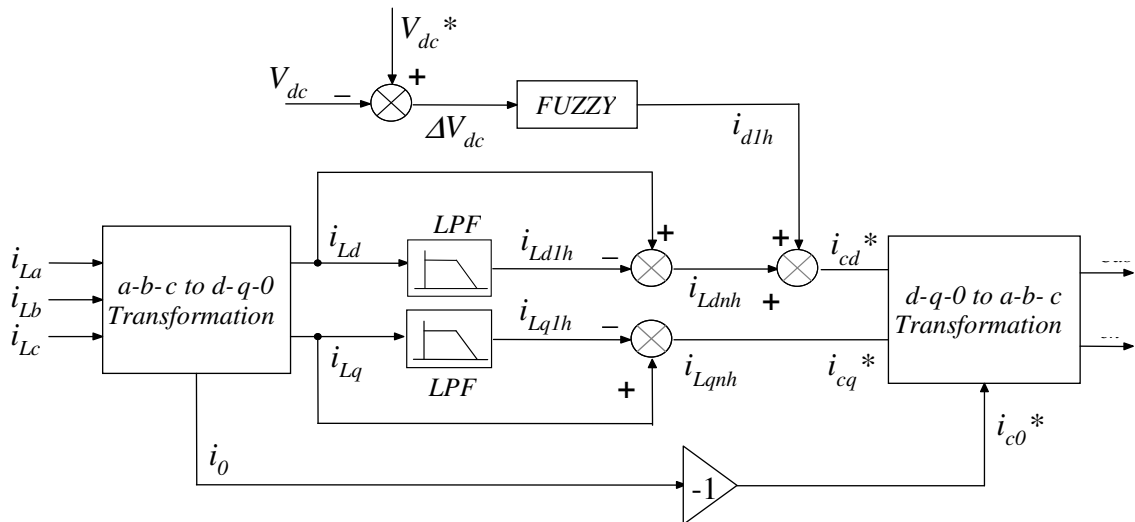**Fig.7** Block Diagram of Fuzzy Inference System

Fig.8. Reference current extraction with i_d-i_q method with Fuzzy controller
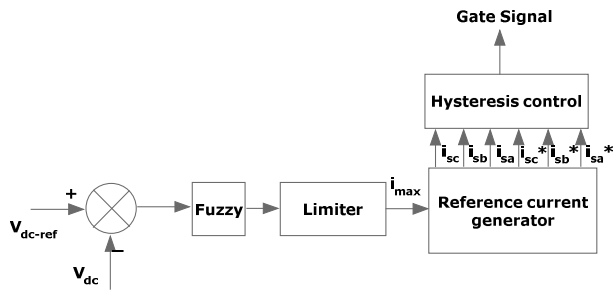
Fig.9 Conventional Fuzzy Controller

The concept of Fuzzy Logic (FL) was proposed by Professor Lotfi Zadeh in 1965, at first as a way of processing data by allowing partial set membership rather than crisp membership. Soon after, it was proven to be an excellent choice for many control system applications since it mimics human control logic.

Fig.9 shows the internal structure of the control circuit. The control scheme consists of Fuzzy controller [12], 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.

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-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 I_{max}. 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 Figure 10.
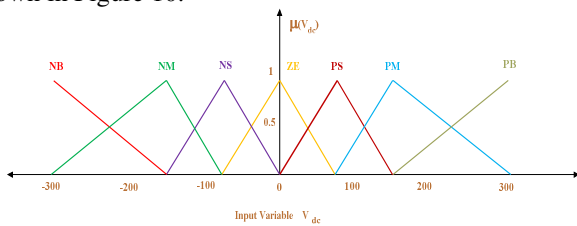

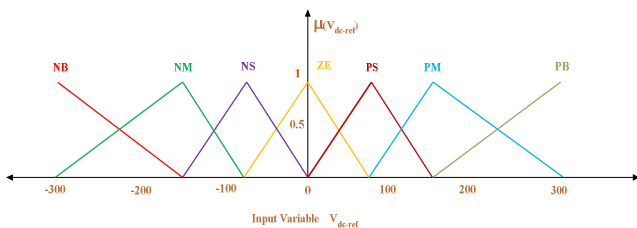**Fig. 10(a)** Input V_{dc} Normalized Membership Function.

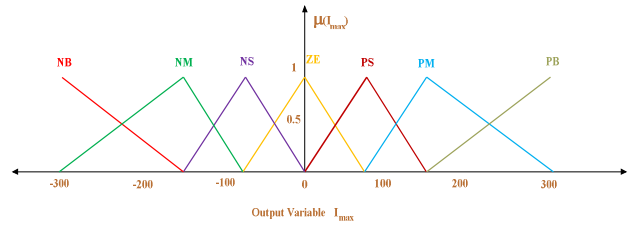**Fig. 10(b)** Input V_{dc-ref} Normalized Membership Function.

Fig.10 (c) Output I_{max} Normalized Membership Function.

The fuzzy controller [13] is characterized as follows:
   (i) Seven fuzzy sets for each input and output.
   (ii) Fuzzification using continuous universe of discourse.
   (iii) Implication using Mamdani's 'min' operator.
   (iv) De-fuzzification using the 'centroid' method.

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).

Database: The Database stores the definition of the membership Function required by fuzzifier and defuzzifier.

Rule Base: The elements of this rule base [14] table are determined based on the theory that in the transient state, large errors need coarse control, which requires coarse input/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.

TABLE 1. RULE BASE

V_{dc} / V_{dc-ref}	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

VI. SYSTEM PERFORMANCE

Fig.11 and Fig.12 illustrates the performance of shunt active power filter under different main voltages, as load is highly inductive, current draw by load is integrated with rich harmonics.
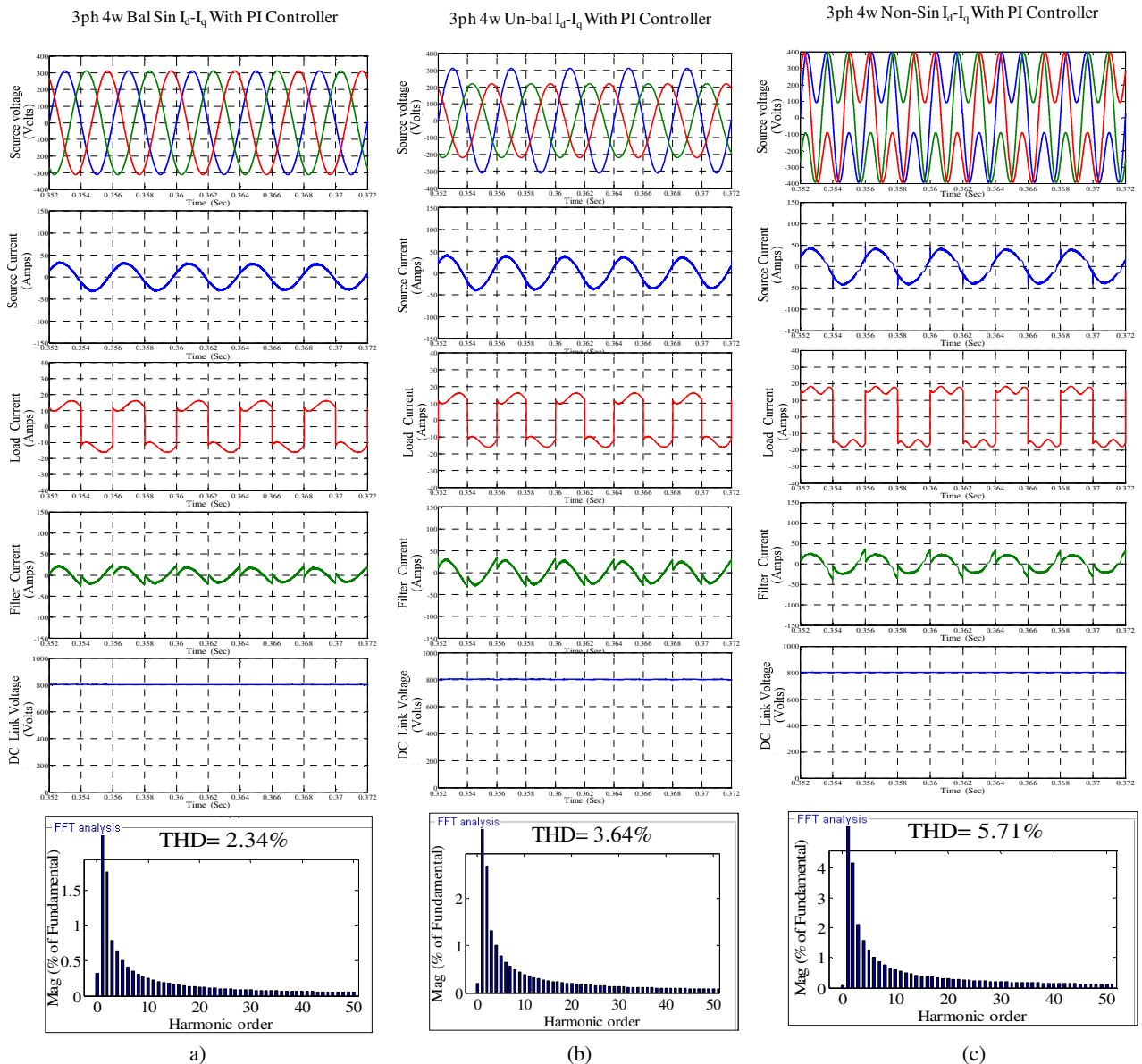
Fig 11. 3ph 4wire Shunt ative filter using I_d-I_q Control Strategy response with PI controller Under
(a) Balanced Sinusoidal (b)Un-balanced Sinusoidal and (c) Balanced Non-Sinusoidal

Numerical simulations:

Above simulation is carried out with only AHPF (alternative high pass filter) of 2nd order with a cut-off frequency f_c=f_c/2, it is also assumed that currents are independent of main voltages and there is no ripple on the rectifier dc current. Active power filter performance is analysed under several main voltage conditions. In addition simulation is also extended to different kinds of filters like HPF (high pass filter) with 2nd order, AHPF with 4th order and HPF with 4th order. In all those, Alternative high pass filter shows good performance and it is easy to obtain with LPF (low pass filter) of same order and cut-off frequency, simply by difference between the input and filter signal which is shown in Fig.4. Graphs shown in Fig.10 and Fig.11 summarize the total performance of the shunt active filter with different filters. Results presented confirm superior performance of Fuzzy controller. But performance of shunt active filters with both controllers under sinusoidal conditions performance same. Generally speaking in all the filters, HPF gives best filtering action under any voltage conditions.

Initially system performance is analysed with balanced sinusoidal conditions, on owing PI and Fuzzy are good enough in suppressing harmonics and THD is about 2.34% and 1.14%, but under unbalanced and non-sinusoidal conditions fuzzy shows superior performance over pi controller and THD at this instant with PI are 3.64% and 5.71 %, where as in fuzzy it is about 2.27% and 4.09%. On observation the PI controller fails to respond quickly because

of its non-linear nature in the system, but fuzzy shows an outstanding performance under any voltage conditions. Frankly, fuzzy is the more sensitive controller in all the controllers, but it have also some drawbacks like redundancy and iteration problems. So one has to choose the membership function on the bases system complexity. Extensive simulation is carried out to validate both controllers, on over all with combination of i_d-i_q strategy and fuzzy controller, there is possibility of building novel shunt active filter for 3 phase 4 wire system.
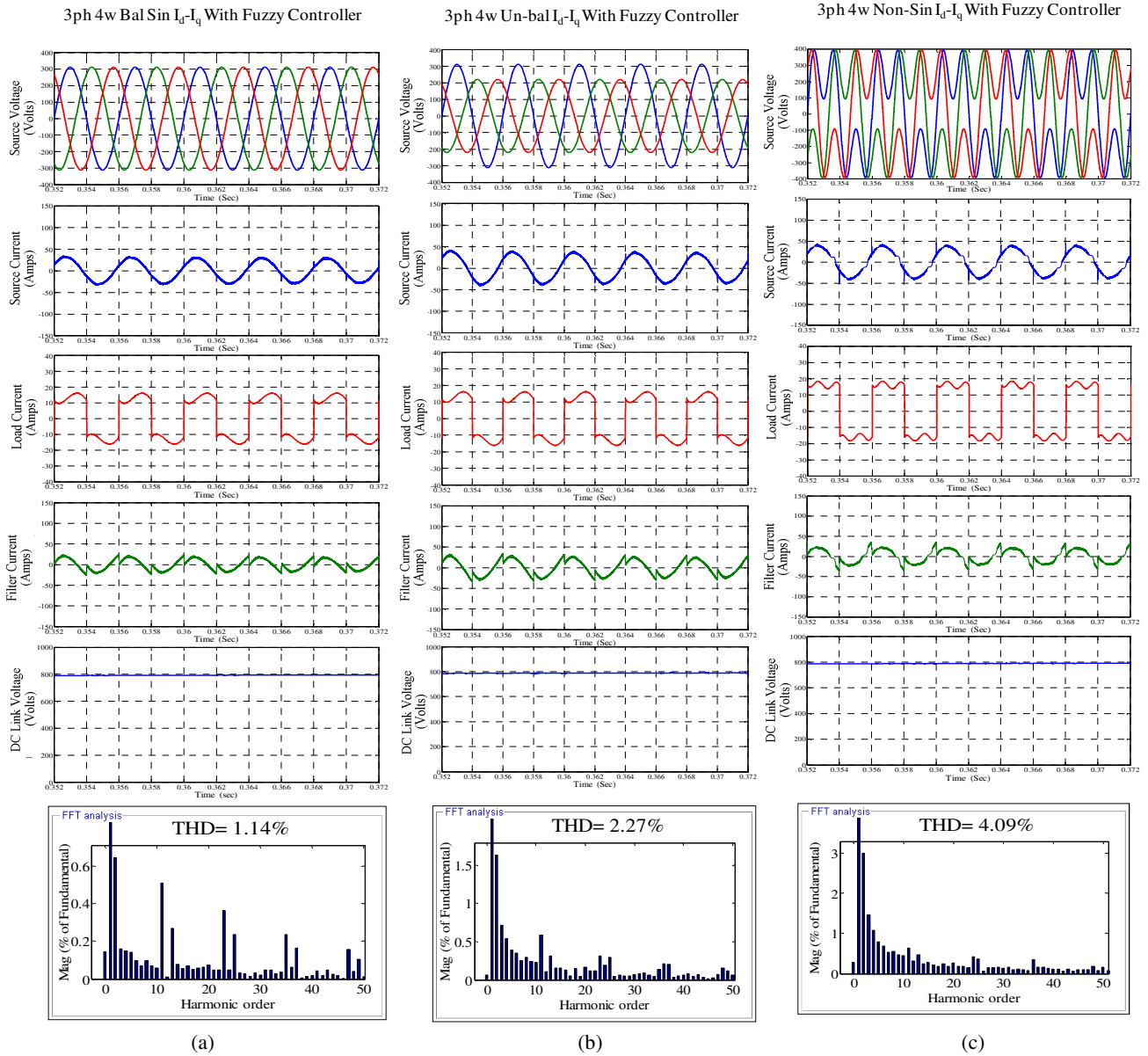

(a) (b) (c)

Fig 12. 3ph 4wire Shunt ative filter using I_d-I_q Control Strategy response with Fuzzy controller Under
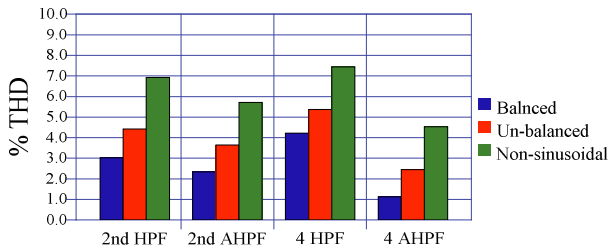(a) Balanced Sinusoidal (b)Un-balanced Sinusoidal and (c) Balanced Non-Sinusoidal
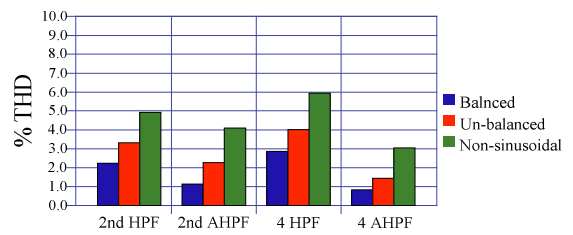

Fig.13 THD for i_d-i_q method with PI controller.
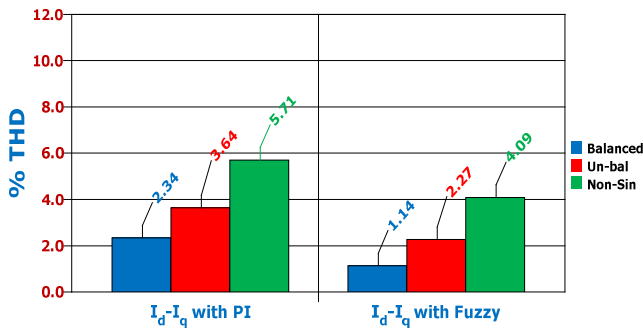

Fig.14 THD for i_d-i_q method with Fuzzy controller.

Fig.15 THD for i_d-i_q method with PI and Fuzzy controllers.

Table 1. System parameters

Parameter	Value
Supply Voltage	V_s = 311.12 V
Source Resistance	R_s=0.1 Ω
Source Inductance	L_s=1 mH
Filter Phase-branch Resistance	R_f=0.01 Ω
Filter Phase-branch Inductance	L_f=0.1 mH
DC Link Capacitance	C_{dc}=3000 μf
DC Link Voltage	V_{dc} = 800 V
Hysterisis band	± 0.2 A
Load	Diode rectifier Snubber Resistance R_{sn} = 500 Ω Snubber Capacitance L_{sn} = 250 e-9 f
Load Resistance	R_L=15 Ω
Load Inductance	L_L=60 mH

VII.CONCLUSION

In the present paper two controllers are developed and verified with three phase four wire system. Even though both presented controllers are capable to compensate current harmonics in the 3 phase 4-wire system, it is observed that a Fuzzy Logic controller has a better dynamic performance than a conventional PI controller. PWM pattern generation based on carrier less hysteresis current control is used for quick response. Additionally, in contrast of different control strategies; i_d-i_q method is used for obtaining the reference currents in the system, because in this strategy the angle 'θ' is calculated directly from the main voltages and enables an operation which is frequency independent, so this technique avoids large numbers of synchronization problems. It is also observed that the DC voltage regulation system is a stable

and a steady-state error free system. Thus with fuzzy logic and *(id-iq)* approach a novel shunt active filter can be developed. Essential simulation results are presented to validate the performance of shunt active filter.

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