PI and Fuzzy Logic Controller based 3-phase 4-Wire Interleaved Buck Active Power Filter for Mitigation of Harmonics with the I_d-I_q Control Strategy

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***Abstract*—The "shoot-through" failure glossary define as the rush of current that occurs while both the devices are ON at the same time of a particular limb, which is one of the most perilous failure modes encountered in conventional inverter circuits of the active power filter (APF). Shoot-through results in reduced efficiency, typical ringing, increased temperature in power switches and higher Electromagnetic Interference (EMI). However, these conventional inverters suffer from "shoot-through". To avert the "shoot-through", dead time control could be added but it deteriorates the harmonic compensation level. A novel 3-phase 4-wire active power filter based on interleaved buck (IB) DC-to-AC converters with the instantaneous active and reactive current component (i_d-i_q) control strategy is proposed here to mitigate the harmonics having PI and fuzzy logic (FLC) controllers. This interleaved buck (IB) DC-to-AC converter is augmented conventional phase leg configuration and is innately immune to "shoot-through" phenomenon, with the elimination of special protection features required in conventional inverter circuits. Here in this paper, a comparison has been made on the compensation capabilities of the 3-phase IB-APF with the PI and fuzzy logic controller (FLC) used by i_d-i_q control strategy under different supply voltage condition.**

Keywords—shoot-through; three-phase interleaved buck (IB) inverter; active power filter; harmonic compensation, i_d-i_q control strategy; PI and fuzzy logic controller.

I. INTRODUCTION

In recent years, with the proliferation of power electronic equipment, the problems of harmonics are most serious. The importance of active power filter has grown over the years because of good compensation and finds attention of researchers for its outstanding performance [1]. Particularly, voltage harmonics and power distribution equipment problems are result of current harmonics produced by power electronic equipment [2].

In 3-phase 4-wire system some eminent issues always arise as a result of excessive harmonic current flowing through the neutral wire. It is known that neutral wire may cause a fire due to overheating. Thus a consummate filter is required to avert the negative consequences of the harmonics [3].

In general, the main APF circuit is a conventional phase leg based voltage source inverter (VSI). However "shoot-through" failures, one of the most hazardous modes encountered in these conventional inverter circuits. To avoid the "shoot-through" dead time control is added and this deteriorates the harmonic compensation performance. Several researches have been done to overcome dead time effects. Interleaved buck (IB) inverter topology is special and it receives more attention since its proposal in [4-7].These issues became the primary motivation.

Now days, various control strategies are there, out of which the i_d-i_q control method is the most advantageous, because it eliminates synchronization problems and a frequency independent filter is achieved [8].

The PI controller design used in i_d-i_q control strategy needs precise linear mathematical models which are tough to get and may not give suitable results under parameter variations, load disturbances, etc. Only just, fuzzy logic controllers have acknowledged a great deal of attention in regards to their application to active power filters. The advantages of fuzzy logic controllers over PI controllers are that they do not necessitate any precise linear mathematical models, can handle non-linearity with inaccurate inputs, and are more robust. Out of Sugeno and Mamdani types of fuzzy controllers, the Mamdani type controller gives better result for the control of an active power filter, but it has the drawback of a large number of fuzzy sets and 49 rules [9-12]. The referred papers [10-11] present the harmonic minimization of the source current in 3-phase 4-wire system with non-linear load by using the conventional inverter based active power filter. This conventional inverter suffers from shoot-through phenomenon and it has been abolished in this proposed APF, which shows the novelty of the developed circuit.

Hence a novel 3-phase 4-wire interleaved buck based active power filter (IB-APF) with i_d-i_q control strategy using PI and FLC is presented with an end to the "shoot-through" phenomenon. We developed an 3-phase 4-wire interleaved buck based active power filter with the i_d-i_q control method using PI and FLC which is prominent one, with this we analyzed the performance of filter under different main voltages. On observing the performances of i_d-i_q method with FLC, it is concluded that, under balanced and unbalanced supply it presents better results. To validate the observations, extensive simulations were performed and verified.

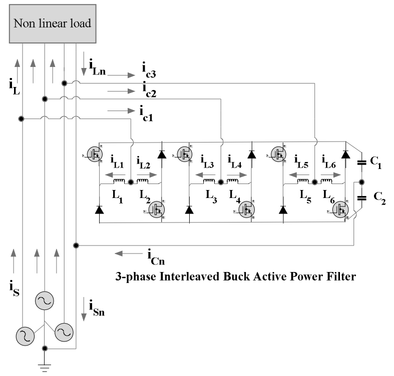

Fig.1. Three phase four wire interleaved buck active power filter

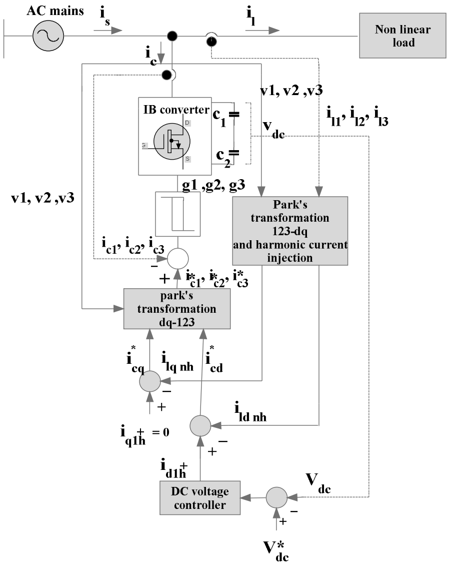

Fig.2. Current control method for Shunt current compensation based on i_d-i_q theory

II. SHUNT ACTIVE FILTER CONFIGURATION

A. Interleaved buck circuit description

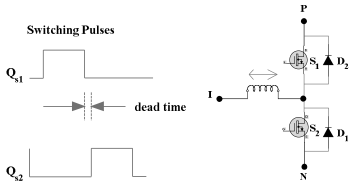

Fig.3. Conventional inverter phase limb

The conventional inverter phase limb with dead time effect is shown in fig.3 [6-7]. The power switches in a limb are normally operated in a proper sequence with the assumption that each MOSFET conducts for the duration, its switching pulse is present and is commutated as soon as this pulse is removed. For an inductive load, the load current cannot change immediately with the output voltage. If S_1 is turned off, the load current continue to flow through D_1 and similarly, when S_2 is turned off, the load current flows through D_2. When diode D_1 or D_2 conducts, energy is fed back to the DC source and these diodes are known as feedback diodes.

So, in the conventional inverter phase limb has an integral fault path with a heavy short circuit current when both switches are empowered at the same time. Therefore, a time delay has to be added between the turn off time of one power switch in a limb of an inverter, and the corresponding turn on time of the another power switch in the same limb to reduce the short circuit or shoot-through currents as shown in fig.3. Dead time introduction has also some limitation, cannot go for too long or too short. Too short dead time can cause shoot-through and it again gives complexity. The inclusion of dead time state creates an innate nonlinearity in the output voltage and current and this behavior does not give good harmonic compensation. In other words, the conventional phase leg can be divided into high side power switch and low side power switch according to the direction of inductor current with the respective diodes as shown in fig.4. So a three phase in which the conventional inverter two switches leg is replaced by one switch bridge leg [7] is here to eliminate the “shoot- through” used to compensate the harmonics generated by non-linear load as shown in fig.1.

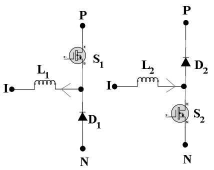

Fig.4. Equivalent circuit cells of conventional inverter phase limb

The three phase interleaved buck converter with split capacitor configuration suffers from following shortcomings:

- The control circuit is somewhat complex due to the split capacitor configuration.
- The voltages of the two capacitors of a split capacitor need to be properly balanced.

B. Compensation principle

An active power filter is implemented to draw /supply the compensating current in order to make the source current sinusoidal, which flows from/to the load by removing the higher order harmonics than the fundamental with the injection of same but opposite in phase harmonic components as shown in fig.2. This principle is valid for all non-linear loads which generate harmonic components.

III. INSTANTANEOUS ACTIVE AND REACTIVE CURRENT $(I_d\text{-}I_q)$ THEORY

In this method [10], only the magnitudes of currents are transformed and hence the p-q formulation is done on the instantaneous active i_d and instantaneous reactive i_q components. If the d-axis has the same direction as the voltage space vector $\bar{v}$, then the zero-sequence component of the current remains invariant. Therefore, the i_d-i_q method can be expressed as follows:

$$\begin{bmatrix} i_{ld}\\ i_{lq}\\ i_{l0}\end{bmatrix} = \frac{1}{v_{\alpha\beta}} \begin{bmatrix} v_{\alpha} & v_{\beta} & 0\\ -v_{\beta} & v_{\alpha} & 0\\ 0 & 0 & v_{\alpha\beta}\end{bmatrix}\begin{bmatrix} i_{L\alpha}\\ i_{L\beta}\\ i_{L0}\end{bmatrix} \tag{1}$$

In this control strategy (for harmonic reduction and reactive power compensation) assumes that the source must only deliver the mean value of the direct axis component of the load current. Therefore, the reference current will be:

$$i_{sdref} = \overline{i_{Ld}}\ ,\ i_{sqref} = i_{s0ref} = 0 \tag{2}$$

$$i_{Ld} = \frac{v_{\alpha} i_{L\alpha} + v_{\beta} i_{L\beta}}{v_{\alpha\beta}} = \frac{P_{L\alpha\beta}}{\sqrt{v_{\alpha}^{2} + v_{\beta}^{2}}} \tag{3}$$

The dc component of the above equation will be:

$$\overline{i_{Ld}} = \left(\frac{P_{L\alpha\beta}}{v_{\alpha\beta}}\right)_{dc} = \left(\frac{P_{L\alpha\beta}}{\sqrt{v_{\alpha}^{2} + v_{\beta}^{2}}}\right)_{dc} \tag{4}$$

Where, the subscript "dc" means the average value of the expression within the parentheses.

Since the reference source current must be in phase with the voltage at the PCC (and have no zero-sequence component), it will be calculated (in α-β-0 coordinate) by multiplying the above equation by a unit vector in the direction of the PCC voltage space vector (excluding the zero-sequence component):

$$i_{sref} = \overline{i_{Ld}}\ \frac{1}{v_{\alpha\beta}} \begin{bmatrix} v_{\alpha}\\ v_{\beta}\\ 0\end{bmatrix} \tag{5}$$

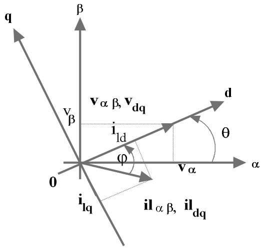

Fig.5. Instantaneous voltage and current vectors

$$\begin{bmatrix} i_{s\alpha ref}\\ i_{s\beta ref}\\ i_{s0ref}\end{bmatrix} = \left(\frac{P_{L\alpha\beta}}{v_{\alpha\beta}}\right)_{dc} \frac{1}{v_{\alpha\beta}} \begin{bmatrix} v_{\alpha}\\ v_{\beta}\\ 0\end{bmatrix} \tag{6}$$

$$\begin{bmatrix} i_{s\alpha ref}\\ i_{s\beta ref}\\ i_{s0ref}\end{bmatrix} = \left(\frac{P_{L\alpha\beta}}{\sqrt{v_{\alpha}^{2} + v_{\beta}^{2}}}\right)_{dc} \frac{1}{\sqrt{v_{\alpha}^{2} + v_{\beta}^{2}}} \begin{bmatrix} v_{\alpha}\\ v_{\beta}\\ 0\end{bmatrix} \tag{7}$$

The reference signals thus obtained are compared with the compensating current in a hysteresis comparator, where the actual compensating current is forced to follow the reference and the APF provides instantaneous harmonic compensation. The main advantages of this are its easy implementation and its quick response to fast current transitions. This consequently provides the switching signals to the MOSFETS present in the IB inverter. Ultimately, the filter provides the harmonic compensation to the source current. Fig.5 shows the voltage and current vectors in the stationary and rotating reference frames. The transformation angle 'θ' is sensible for all voltage harmonics and unbalanced voltages. As a result dθ/dt may not be constant.

Here in this method, the angle 'θ' is calculated directly from the main voltages which is one of the advantages, making this method frequency independent. Consequently, the synchronizing problems with the unbalanced and distorted conditions of the main voltages are also avoided.

After the load currents i_d and i_q are obtained from the Park's transformation, the currents are allowed to pass through high pass filter to eliminate the dc components in the non-linear load currents. Here an alternative high pass filter (AHPF) is used to reduce the influence of high pass filter. This can be obtained through a low pass filter (LPF) of the same order as that of high pass filter and cut-off frequency simply by calculating the difference between the input signal and the filtered one. The Butterworth filters used in the harmonic compensation 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.

IV. CONSTRUCTION OF CONTROLLERS

A. PI controller

The internal structure of the control circuit with PI controller is shown in Fig.6. The conventional PI controller control strategy consists of a PI controller with a limiter, and a three phase sine wave generator for the generation of reference current and switching signal. The peak value of the reference current is estimated by adjusting the DC link voltage. The actual capacitor voltage value is compared with the set reference DC voltage value and the error signal is processed through a PI controller which contributes to the zero steady state error in tracking the reference current signal. As we know, the design of PI controller needs precise linear mathematical model. Here, the tuning of PI controller has been done by Ziegler-Nichols method [10-12].

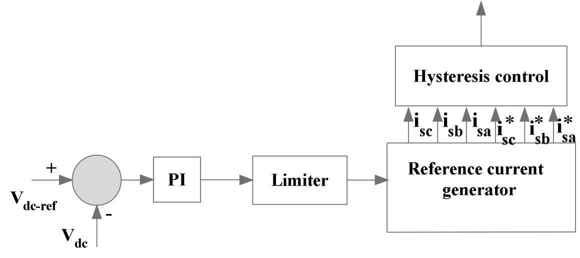

Fig.6. Conventional PI controller

The output of the PI controller is considered as the peak value of the supply current (I_{max}) composed of two components, one is fundamental active power component of the load and another is the loss component of the APF. To maintain the average capacitor voltage at a constant value, the obtained peak value of the current (I_{max}) is multiplied by the unit sine vectors in phase with the respective source voltages to obtain the reference compensating currents. These estimated reference currents and the actual sensed compensating current are compared in a hysteresis band, which gives error signal for the modulation technique. This error signal decides the operation of the IB converter switches. In this current control circuit configuration, the source currents I_{sabc} are made to follow the sinusoidal reference current I_{abc}, within a fixed hysteretic band.

B. *Fuzzy Logic controller*

Fig.7 shows the internal structure of the control circuit. The control scheme consists of Fuzzy logic controller, a limiter, and a three phase sine wave generator for the generation of reference currents and switching signals.

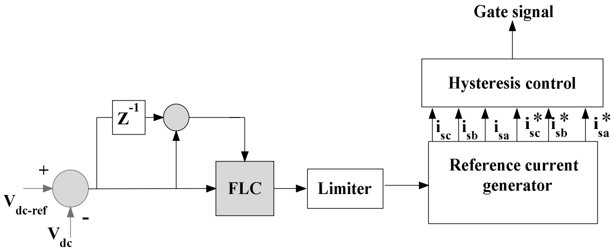

Fig.7. Fuzzy Logic controller

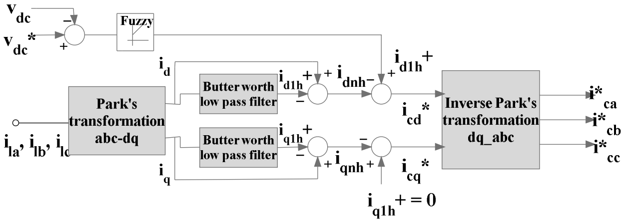

Fig.8. Reference current extraction with id-iq method with Fuzzy Logic controller

The peak value of the reference current is estimated by adjusting the DC link voltage. The actual capacitor voltage is compared with the set reference dc voltage. The error signal is then processed through a fuzzy controller, which contributes to the zero steady state 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 either by expert or with a knowledge data base. The fuzzy inference process consists of following five steps. They are fuzzification; application of fuzzy operator in the antecedent part of the rule; implication from the antecedent to the consequent; aggregation of the consequents across the rules and finally defuzzification. So here the Mamdani fuzzy inference type based FLC characteristics comprise of seven fuzzy sets for each of the two inputs i.e. error and change in error, seven fuzzy sets for the output with triangular membership function. The following seven fuzzy levels or sets are chosen: NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), and PM (positive medium), PB (positive big) is shown in fig.9. The fuzzification gives the corresponding universe of discourse of the crisp input variables performing a scale mapping, implication using the “min” operator, aggregation using the “max” operator, defuzzification using the “center of area (COA)” method [9]. At first, the input error (E) and change in error (ΔE) have been placed with the angular velocity to be used as input variables of the fuzzy logic controller. The fuzzy inference system is a popular computing framework based on the concepts of fuzzy set theory. Then the output variable of the fuzzy logic controller is current

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 input/output variables, while 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. I [9]

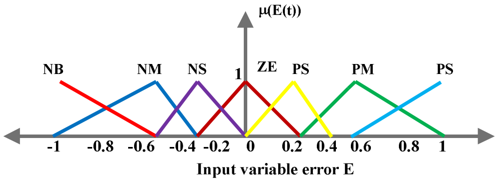

Fig.9. Input variable Error ‘E’ Membership Function

TABLE I RULE BASE

E \ ΔE	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

V. SIMULATION RESULTS

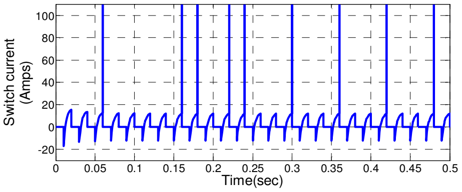

Fig.10. Switch current of the conventional inverter

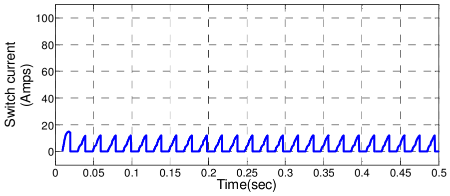

Fig.11. Switch current of the interleaved buck inverter

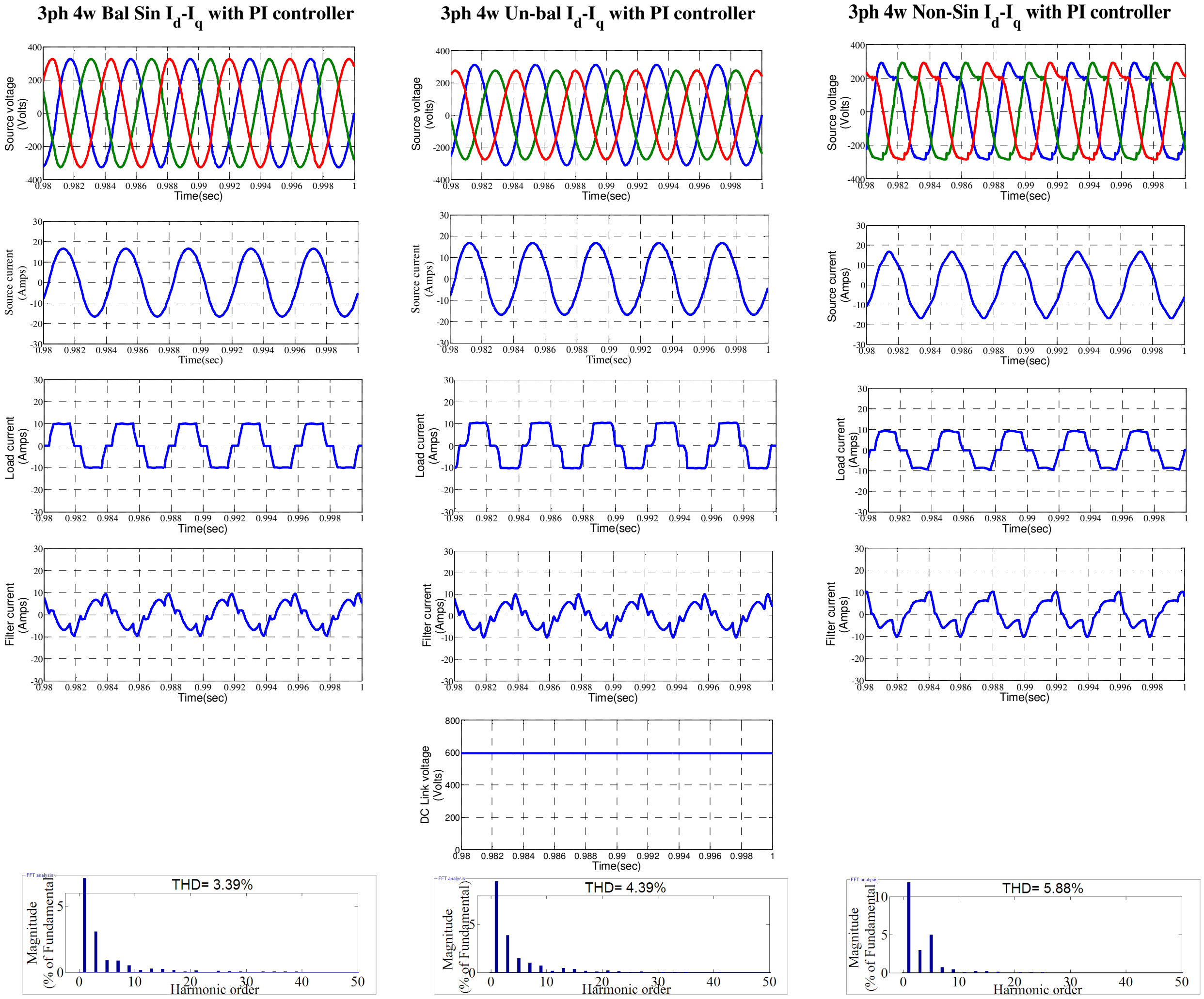

Fig.12. 3-ph 4-wire IB-APF using i_d-i_q control strategy response with PI controller under (a) Balanced Sinusoidal. (b). Unbalanced sinusoidal. (c). Non-Sinusoidal.

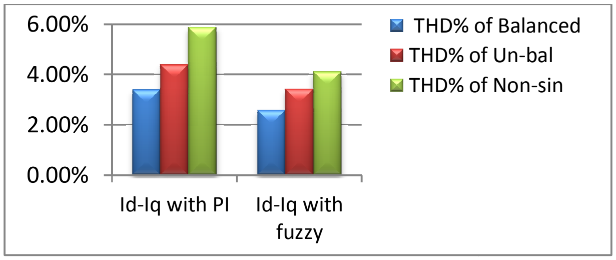

Fig.13. THD of sinusoidal source current fot the I_d-I_q method with PI and Fuzzy controllers

The results presented confirm the superior performance of the fuzzy controller. Initially the system performance is analyzed under balanced sinusoidal conditions in which the PI and fuzzy controller are good enough to mitigate the harmonics and THD results about 3.39% and 2.57%. However, under un-balanced and non-sinusoidal conditions the fuzzy controller gives superior performance over the PI controller. With the PI controller the THD are 4.39% and 5.88% while with fuzzy controller they are about 3.42% and 4.11% respectively for un-balanced and non-sinusoidal voltage condition as graphed in fig.13.

VI. CONCLUSION

In the present paper, an extensive simulation analysis of novel 3-phase 4-wire IB-APF has been done focusing on the inherent elimination of shoot-through current with a good harmonic compensation to the disturbances generated by the non-linear loads. The proposed module contributes the elimination of shoot-through path improving the reliability of the system. Eventhough both of the presented controllers are capable to compensate the harmonics, it is concluded that FLC has a better dynamic performance over PI controller. Under sinusoidal supply voltage condition, both the controllers can provide good compensation but in non-sinusoidal supply voltage condition PI fails to have that much of good compensation. The THD of the source current have been limited to within IEEE-519 standard.

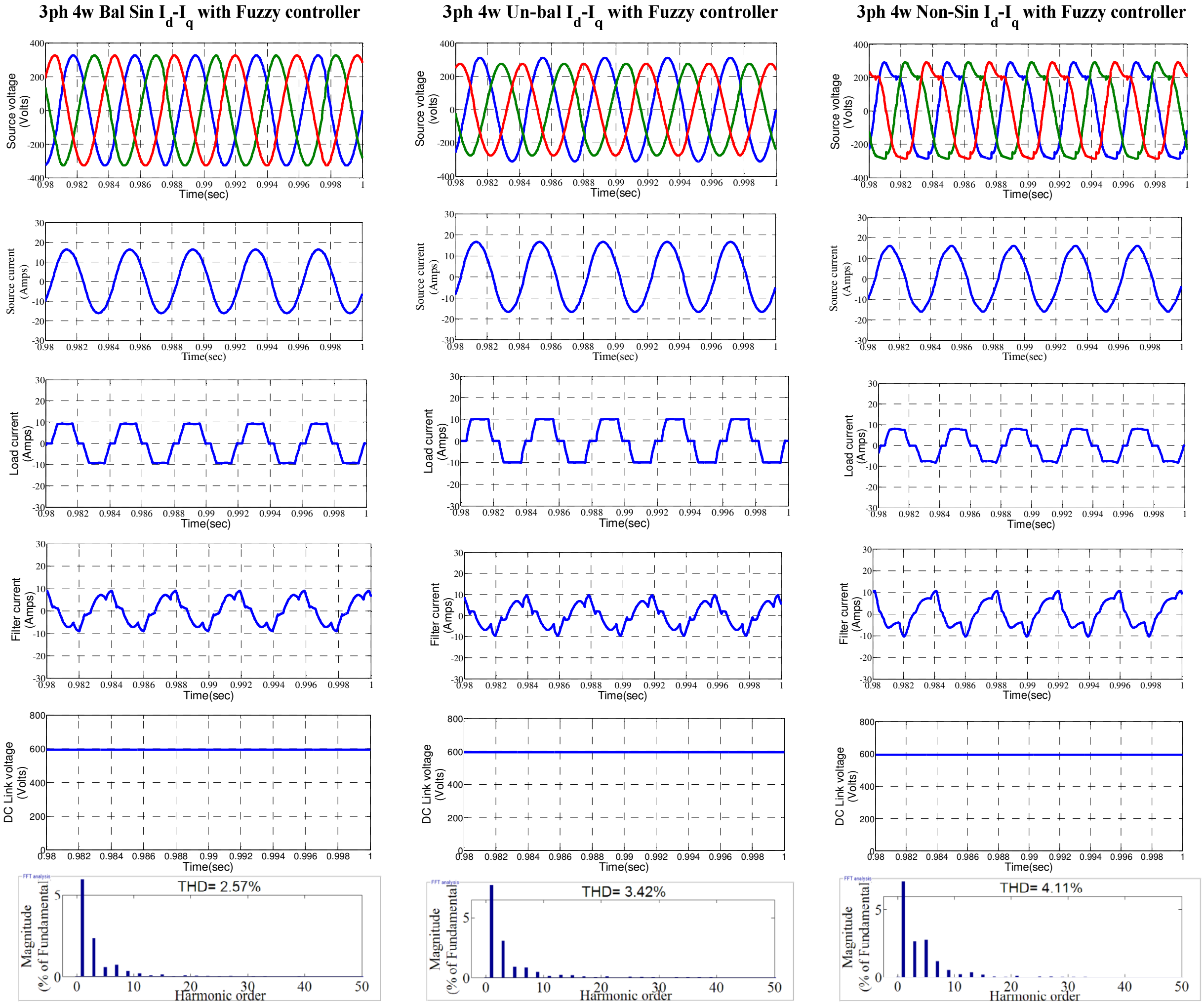

Fig.14. 3-ph 4-wire IB-APF using i_d-i_q control strategy response with fuzzy logic controller under (a) Balanced Sinusoidal. (b). Unbalanced sinusoidal. (c). Non-Sinusoidal.

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