Trends in Electrical Engineering
Volume 1, Issue 1-3 Compilation 2011

APF for Mitigation of Current Harmonics with p–q and I_d–I_q Control Strategies using PI Controller

Suresh.Mikkili and Prof. A. K. Panda*
Department of Electrical Engineering, National Institute of Technology Rourkela, India.

ABSTRACT

Due to a large amount of non-linear power electronic equipments, impact and fluctuating loads (such as that of arc furnace, heavy merchant mill and electric locomotive, etc), problems of power quality have 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 strategies. This paper presents detailed analysis to compare and elevate the performance of two control strategies for extracting reference currents of shunt active filters under balanced, un-balanced and non-sinusoidal conditions by using PI controller. The well known methods, instantaneous real active and reactive power control strategy (p–q) and active and reactive current control strategy (i_d–i_q) are two control strategies which are extensively used in active filters. Extensive Simulations are carried out with PI controller for both p–q and I_d–I_q control strategies for different voltage conditions and adequate results were presented. Simulation results validate the superior performance of active and reactive current control strategy (i_d – i_q) with PI controller over active and reactive power control strategy (p–q) with PI controller.

Keywords: *Harmonic compensation, Shunt Active power filter, p–q control strategy, i_d–i_q control strategy, PI Controller*

***Author for Correspondence** E-mail: msuresh.ee@gmail.com, Tel. No: 919178797867, 918143674574

INTRODUCTION

Over the past few years, the growth in the use of nonlinear loads has caused many power quality problems like high current harmonics, low power factor and excessive neutral current. Nonlinear loads appear to be current sources injecting harmonic currents into the supply network through the utility's Point of Common Coupling (PCC). This results in distorted voltage drop across the source impedance, which causes voltage distortion at the PCC. Other customers at the same PCC will receive distorted supply voltage, which may cause overheating of power factor correction capacitors, motors, transformers and cable, and mal-operation of some protection devices. Therefore, it is important to install compensating devices to eliminate the harmonic currents produced by the nonlinear loads. In fact, many publications have already proposed innovative techniques to alleviate the current harmonics produced by these nonlinear loads [1] and major research have been carried out on control circuit designs for active filters.

In recent years, single-phase electronic equipments have been widely used in domestic, educational and commercial appliances. These equipments include computers, communication equipments, electronic lighting ballasts etc. Also, a large number of computers are turned on at the same time. Each computer and its related devices have a diode rectifier to convert AC electricity to DC one. In other words, those equipments draw non-sinusoidal currents which pollute the utility line due to the current harmonics generated by the nonlinear loads. 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. and it is noted that, in three-phase four-wire system, zero line may be overheated or causes fire disaster as a result of excessive harmonic current 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 [2].

Though several control strategies have been developed but still two control theories, instantaneous active and reactive currents (i_d–i_q) method and instantaneous active and reactive power (*p*–*q*) methods [3, 4] are always dominant. Present paper mainly focused on two control strategies (*p*–*q* and I_d–I_q) with PI controller. To validate current observations, Extensive Simulations are carried out with PI controller for both p–q and I_d–I_q methods for different voltage conditions like sinusoidal, non-sinusoidal, and un-balanced conditions and adequate results were presented. On observing the performance of i_d–i_q control strategy with PI controller is quite good over p–q control strategy with PI controller.

SHUNT ACTIVE FILTER

In this section two control strategies are discussed in detail. Ideal analysis has done in steady state conditions of the active power filter. The active filter currents are achieved from the instantaneous active and reactive powers *p* and *q* of the non-linear load. Figure 1 shows a basic architecture of three-phase - four wire shunt active filter.

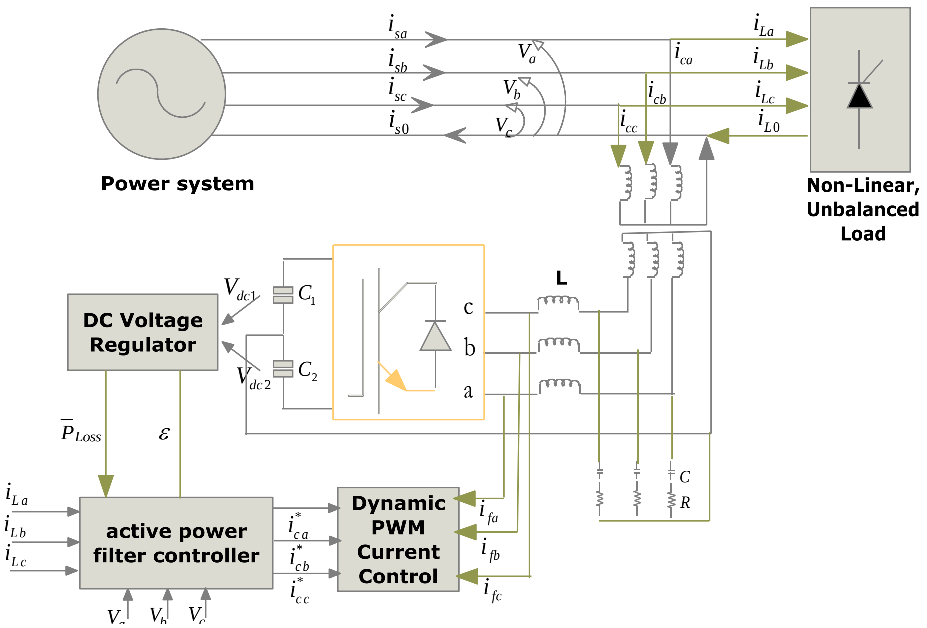


Fig. 1 Basic Architecture of Three-Phase - Four Wire Shunt Active Filter.

ISSN 2249 –4774

Compensation principle

The active power filter is controlled to draw/supply the a compensating current if 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.

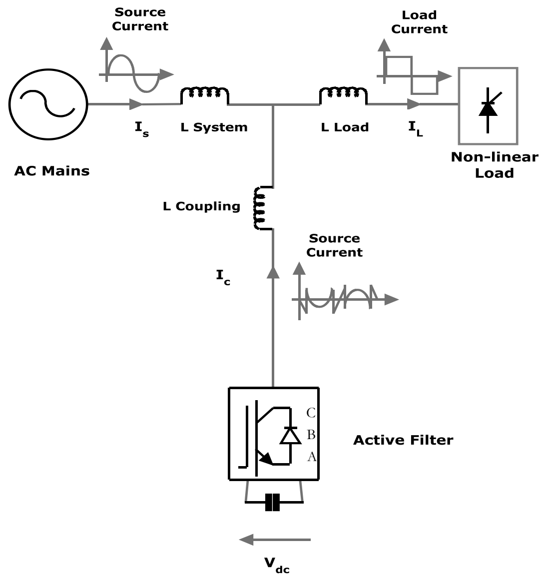


Fig. 2 Compensation Characteristics of Shunt Active Power Filter.

Instantaneous real and reactive power method (*p* – *q*):

Transformation of the phase voltages v_a, v_b, and v_c and the load currents i_{La}, i_{Lb}, and i_{Lc} into the α–β orthogonal coordinates are given in equation (1–2). The compensation objectives of active power filters are the harmonics present in the input currents. Present architecture represents three phase four wire and it is realized with constant power controls strategy [5]. Figure 3 illustrates control block diagram and Inputs to the system are phase voltages and line currents of the load. It was recognized that resonance at relatively high frequency might appear between the source impedance. So a small high pass filter is incorporated in the system. The power calculation is given in detail form in equation (3).

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

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (3)$$

STM JOURNALS

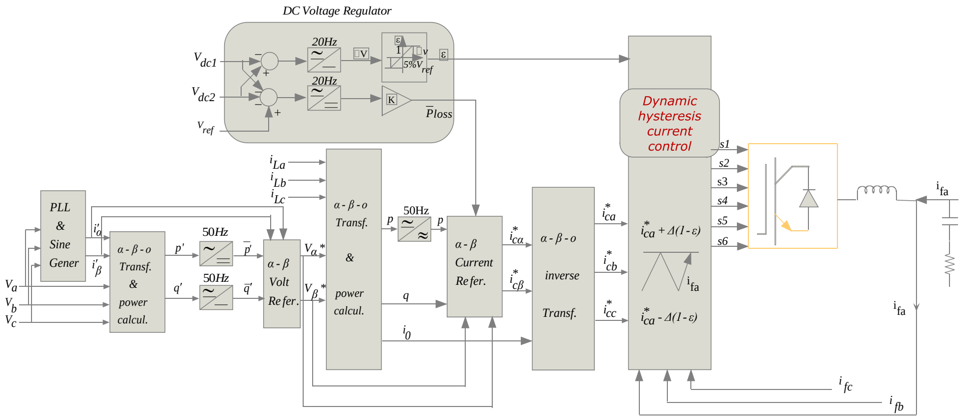


Fig. 3 Control Block Diagram of Shunt Active Power Filter.

From Figure 3 we can observe a high pass filter with cut off frequency 50 Hz separates the powers $-p$ from p and a low-Pass filter separates $\bar{p}_0$ from p_0. The powers p and p_0 of the load, together with q, should be compensated to provide optimal power flow to the source. It is Important to note that system used is three phase four wire, so additional neutral currents has to be supplied by the shunt active power filter thus P_{loss} is incorporated to correct compensation error due to feed forward network unable to suppress the zero sequence power. Since active filter compensates the whole neutral current of the load in the presence of zero-sequence voltages, the shunt active filter eventually supplies p_o. Consequently if active filter supplies p_o to the load, this make changes in dc voltage regulator, hence additional amount of active power is added automatically to P_{loss} which mainly provide energy to cover all the losses in the power circuit in the active filter [6]. Thus, with this control strategy shunt active filter gains additional capability to reduce neutral currents and there-by supply necessary compensation when it is most required in the system. Thus the $\alpha\beta$ reference currents can be found with following equation.

$$\begin{bmatrix} i_{c\alpha}{}^* \\ i_{c\beta}{}^* \end{bmatrix} = \frac{1}{v_\alpha{}^2 + v_\beta{}^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} -p + \Delta\bar{p} \\ -q \end{bmatrix} \qquad (4)$$

$$\Delta\bar{p} = \bar{p}_0 + \bar{p}_{Loss}$$

Where p is the ac component / oscillating value of p

$\bar{p}_0$ is the dc component of p_0

P_{loss} are the losses in the active filter

$\bar{P}_{loss}$ is the average value of P_{loss}

$\Delta\bar{p}$ Provides energy balance inside the active power filter and using equation (5) inverse transformation can be done.

$$\begin{bmatrix} i_{ca}{}^* \\ i_{cb}{}^* \\ i_{cc}{}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} -i_0 \\ i_{c\alpha}{}^* \\ i_{c\beta}{}^* \end{bmatrix} \qquad (5)$$

Where $i_{ca}*$, $i_{cb}*$, $i_{cc}*$ are the instantaneous three-phase current references.

In addition PLL (Phase locked loop) employed in shunt filter tracks automatically, the system frequency and fundamental positive–sequence component of three phase generic input signal [7].

Appropriate design of PLL allows proper operation under distorted and unbalanced voltage conditions. Controller includes small changes in positive sequence detector as harmonic compensation is mainly concentrated on three phase four wire [8]. As we know in three- phase three wire, v_a', v_b', v_c' are used in transformations which resemble absence of zero sequence component and it is given in equation (6). Thus in three phase four wire it was modified as v_α', v_β' and it is given in equation (7).

$$\begin{bmatrix} v_a' \\ v_b' \\ v_c' \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_\alpha' \\ v_\beta' \end{bmatrix} \qquad (6)$$

$$\begin{bmatrix} v_\alpha' \\ v_\beta' \end{bmatrix} = \frac{1}{i_\alpha'^2 + i_\beta'^2} \begin{bmatrix} i_\alpha' & -i_\beta' \\ i_\beta' & i_\alpha' \end{bmatrix} \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} \qquad (7)$$

DC voltage regulator (*p–q*)

The dc capacitor voltages V_{dc1} and V_{dc2} may be controlled by a dc voltage regulator. A low-pass filter with cut-off frequency 20Hz is used to render it insensitive to the fundamental frequency (50Hz) voltage variations.

The filtered voltage difference $\Delta V = V_{dc2} - V_{dc1}$ produces voltage regulation ε according to the following limit function generator:

$$\varepsilon = -1; \qquad \Delta V < -0.05V_{ref}$$

$$\varepsilon = \frac{\Delta V}{-0.05V_{ref}}; \quad -0.05V_{ref} \le \Delta V \le 0.05V_{ref}$$

$$\varepsilon = 1; \qquad \Delta V > 0.05V_{ref}$$

Where V_{ref} is a pre-defined dc voltage reference and $0.05V_{ref}$ was arbitrarily chosen as an acceptable tolerance margin for voltage variations.

If $(V_{dc1} + V_{dc2}) < V_{ref}$, the PWM inverter should absorb energy from the ac network to charge the dc capacitor. The inverse occur if $(V_{dc1} + V_{dc2}) > V_{ref}$.

The signal $\overline{P_{loss}}$ generated in the dc voltage regulator is useful for correcting voltage variations due to compensation errors that may occur during the transient response of shunt active filter.

Instantaneous active and reactive current method ($i_d - i_q$):

In this method reference currents are obtained through instantaneous active and reactive currents i_d and i_q of the nonlinear load [9, 10]. Calculations follows Similar to the instantaneous power theory, however *dq* load currents can be obtained from equation (8). Two stage transformations give away relation between the stationary and rotating reference frame with active and reactive current method. Figure 4 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. Arithmetical relations are given in equation (8) and (9); finally reference currents can be obtained from equation (10).

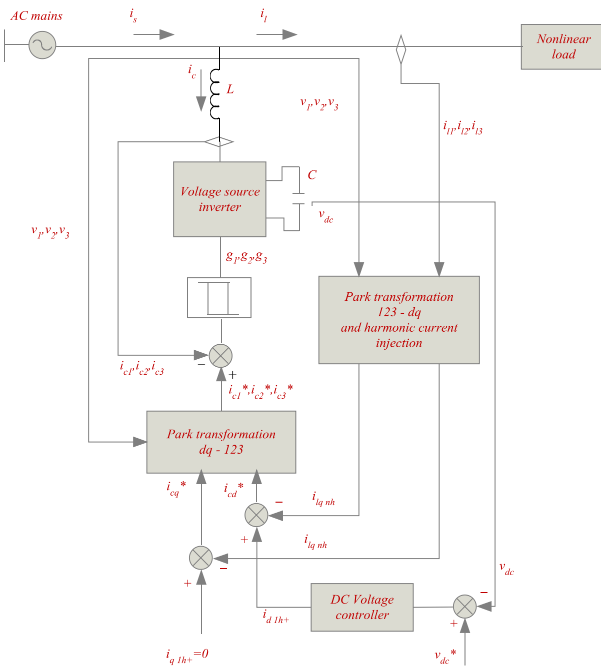


Fig. 4 Active Powers Filter Control Circuit.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{1}{\sqrt{v_\alpha^2 + v_\beta^2}} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (8)$$

Where i_α , i_β are the instantaneous α–β axis current references

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} ic_\alpha \\ ic_\beta \end{bmatrix} = \frac{1}{\sqrt{v_\alpha^2 + v_\beta^2}} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} ic_d \\ ic_q \end{bmatrix} \quad (10)$$

where i_{cd} ,i_{cq} are compensation currents.

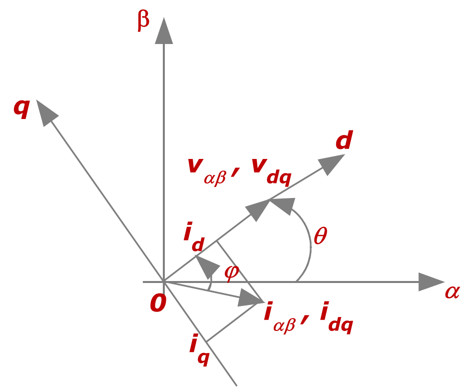


Fig. 5 Instantaneous Voltage and Current Vectors.

One of the advantages of this method is that angle θ is calculated directly from main voltages and thus makes this method frequency independent by avoiding the PLL in the control circuit. Consequently synchronizing problems with unbalanced and distorted conditions of main voltages are also evaded. Thus $i_d - i_q$ achieves large frequency operating limit essentially by the cut-off frequency of voltage source inverter (VSI) [11]. Figure 4 and 6 show the control diagram for shunt active filter and harmonic injection circuit. On owing load currents i_d and i_q are obtained from park transformation then 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 difference between the input signal and the filtered one, which is clearly shown in Figure 6. Butterworth filters used in harmonic injecting circuit have cut-off frequency equal to one half of the main frequency ($f_c=f/2$), with this a small phase shift in harmonics and sufficiently high transient response can be obtained.

DC voltage regulator (I_d–I_q):

The function of voltage regulator on dc side is performed by proportional – integral (PI) controller, inputs to the PI controller are, change in dc link voltage (V_{dc}) and reference voltage (V_{dc}*), on regulation of first harmonic active current [12] of 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 first harmonic reactive current of 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.

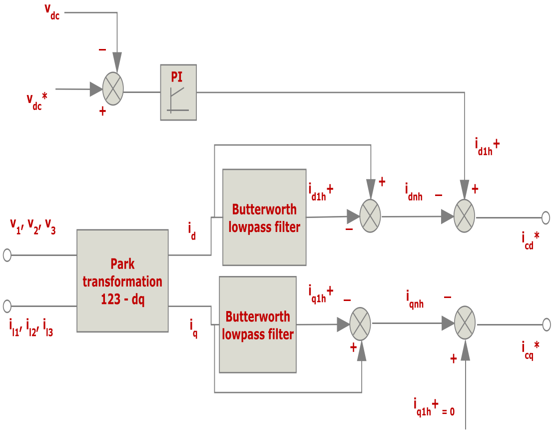


Fig. 6 Park transformation and harmonic current injection circuit.

CONSTRUCTION OF PI CONTROLLER

Figure 7 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.

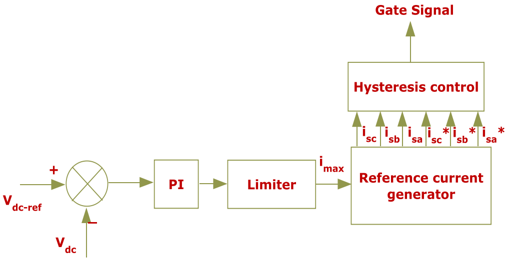


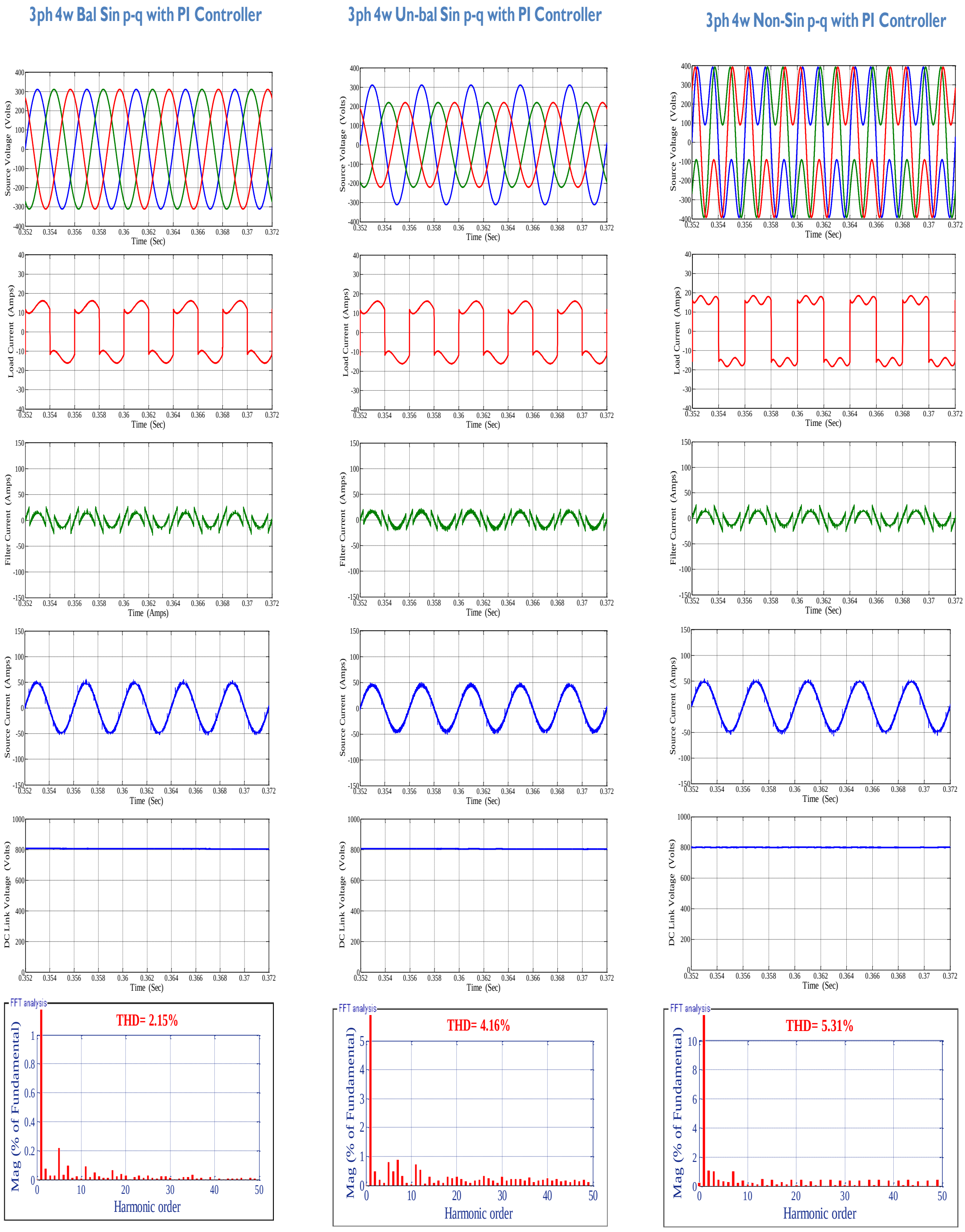
Fig. 7 Conventional PI Controller.

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 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 (*Isa*, *Isb*, *Isc*) 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 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.

SIMULATION RESULTS

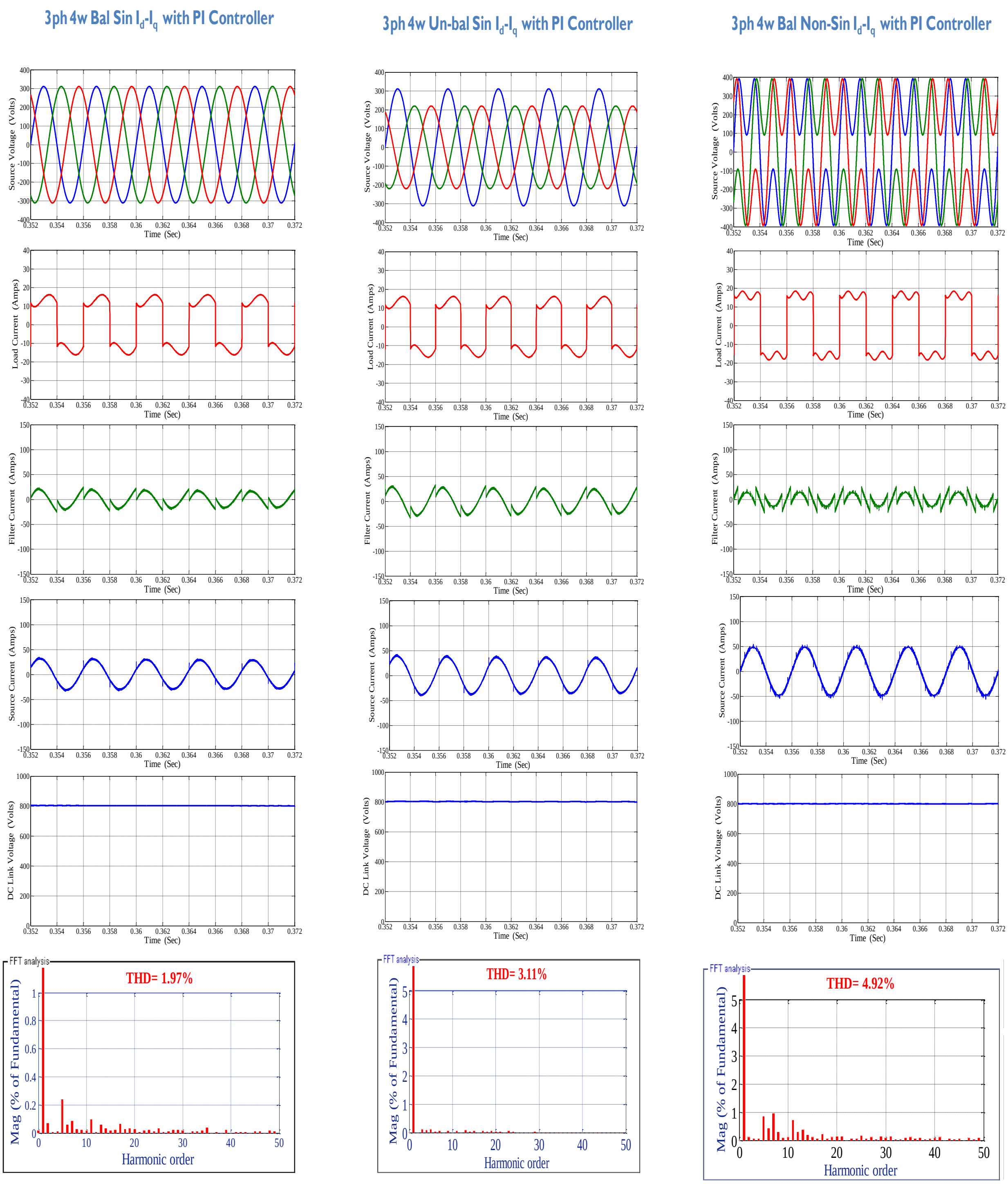
In this section 3 phase 4 wire shunt active power filter responses are presented in transient and steady state conditions. In the present simulation AHPF (alternative high pass filter) were used in Butterworth filter with cut-off frequency f_c=f/2. Simulation shown here are for different voltage conditions like sinusoidal, non-sinusoidal, and unbalanced conditions. Simulation is carried out with PI controller for both instantaneous real active and reactive power control strategy (p–q) and active and reactive current control strategy (i_d–i_q).

When the supply voltages are balanced and sinusoidal, the two control strategies (Instantaneous Active and Reactive power control strategy and Instantaneous Active and Reactive current control strategy) are converge to the same compensation characteristics; However, the supply voltages are distorted and/or un-balanced sinusoidal, these control strategies result in different degrees of compensation in harmonics. The compensation capabilities are not equivalent, with p–q control strategy unable to yield an adequate solution when source voltages are not ideal.Figure 8 and Figure 9 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. Initially system performance is analysed with balanced sinusoidal conditions, on owing p–q and I_d–I_q methods with PI controller are good enough in suppressing harmonics and THD is about 2.15% and 1.97%, but under un-balanced and non-sinusoidal conditions I_d–I_q method with PI controller shows superior performance over p–q method with PI controller and THD at this instant with p–q method using PI controller are 4.16% and 5.31 %, where as in I_d–I_q method with PI controller it is about 3.11% and 4.92%. Extensive simulation is carried out to validate both p–q and I_d–I_q methods with PI controller; on over all with combination of i_d–i_q strategy and PI controller, there is possibility of building novel shunt active filter for 3 phase 4 wire system.



(a) **(b)** **(c)**

Fig (8). 3ph 4wire Shunt ative filter using p–q Control Strategy response with PI controller Under (a) Balanced Sinusoidal (b)Un-balanced Sinusoidal and (c) Balanced Non-Sinusoidal.



(a) **(b)** **(c)**

Fig. 9 3ph 4wire Shunt ative filter using I_d–I_q Control Strategy response with PI controller Under (a) Balenced Sinusoidal (b)Un-balanced Sinusoidal and (c) Balanced Non-Sinusoidal.

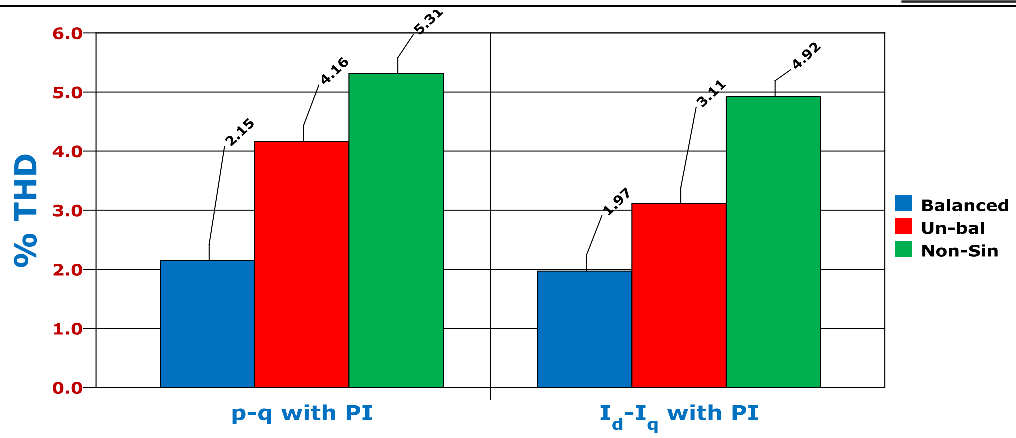


Fig. 10 THD for p–q and i_d–i_q Methods with Pi Controller.

CONCLUSION

In the present paper two control strategies are developed and verified with three phase four wire system. Though the two strategies are capable to compensate current harmonics in the 3 phase 4-wire system, but it is observed that instantaneous active and reactive current (i_d–i_q) control strategy with PI controller leads always better result under un-balanced and non-sinusoidal voltage conditions over the instantaneous active and reactive power (p–q) control strategy. On contrast p–q theory needs additional PLL circuit for synchronization so p–q method is frequency variant, where as in i_d–i_q method 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. Addition to that DC voltage regulation system valid to be a stable and steady-state error free system was obtained. Over all, performance of i_d–i_q theory with PI controller is quite good over p–q theory with PI controller.

REFERENCES

1. Akagi H. in *IEEE Transactions on Industrial Applications* Nov./Dec.1996. 32(6) 1312–1322p.
2. Peng Z. et al. *IEEE Transactions on Power Electronics* Nov. 1998. 13(5) 1174–1181p.
3. Gyugyi L. and Strycula E. C. *IEEE IIAS Annual Meeting* 1976. 529p.
4. S. Mikkili, A.K. Panda, S. Yellasiri, *Journal of Power Electronics & Power Systems* March, 2011. 1(1) 13–23p.
5. S. Mikkili, A.K. Panda, *Inter. Journal of Eng. Technol. Appl. Sci. Res,* 2011. 1(3), 54–62p.
6. Montero M. I. M. et al. *IEEE Transactions On Power Electronics* January 2007. 22(1).
7. Akagi H. et al. "Instantaneous Power Theory and Applications to Power Conditioning" New Jersey. *IEEE Press/Wiley-Inter-science* 2007 ISBN: 978-0-470-10761–4.
8. Vodyakho O. and Chris C. Mi Senior. "Three-Level Inverter-Based Shunt Active

Power Filter in Three-Phase Three-Wire and Four-Wire Systems" *IEEE Transactions On Power Electronics* May 2009. 24(5).

9. Soares V. et al. "Active Power Filter Control Circuit Based on the Instantaneous Active and Reactive Current $i_d - i_q$ Method" *IEEE Power Electronics Specialists Conference* 1997. 2. 1096–1101p.
10. Aredes M. et al. *IEEE Transactions on Power Electronics* March 1997. 12(2).
11. S. Mikkili, A.K. Panda, S. Yellasiri, *Journal of Energy and Power Engineering (Scientific Research Publisher)* February 2011. 3(1) 43–52p.
12. Salmeron P. and Herrera R. S. *IEEE Transactions on Power Delivery* Jul. 2006. 21(3) 1655–1662p.