Comparison of Two Compensation Control Strategies for Shunt Active Power Filter in Three-Phase Four-Wire System

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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 distorted and unbalanced conditions. The well known methods, instantaneous real active and reactive power method (p-q) and active and reactive current method (i_d-i_q) are two control methods which are extensively used in active filters. On owing i_d - i_q method gives away an outstanding performance under any voltage conditions (balanced, un-balanced, balanced non-sinusoidal and balanced sinusoidal with different main frequencies). Extensive simulations were carried out; simulation results validate the superior performance of active and reactive method ($i_d - i_q$).*

Index Terms— *Harmonic compensation, Shunt Active power filter, p-q control strategy, i_d-i_q control strategy.*

1. INTRODUCTION

Harmonics surfaced as a buzz word from 1980's which always threaten the normal operation of power system and user equipment [1]. Highly automatic electric equipments, in particular, cause enormous economic loss every year. Owing both power suppliers and power consumers are concerned about the power quality problems and compensation techniques [2]. 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 [3]. 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 [4]. Though several control strategies had 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 are always dominant.

2. CONTROL STRATEGY

In this section two control strategies are discussed in detail. Ideal analysis has done in steady state conditions of the active power filter. Steady state analysis using Fast Fourier Transform (FFT) for the two control methods that are presented are now briefly enlightened.

A. Instantaneous real and reactive power method ($p - q$):

The active filter currents are achieved from the instantaneous active and reactive powers p and q of the non-linear load. Fig.1 shows the block diagram to attain reference currents from load.

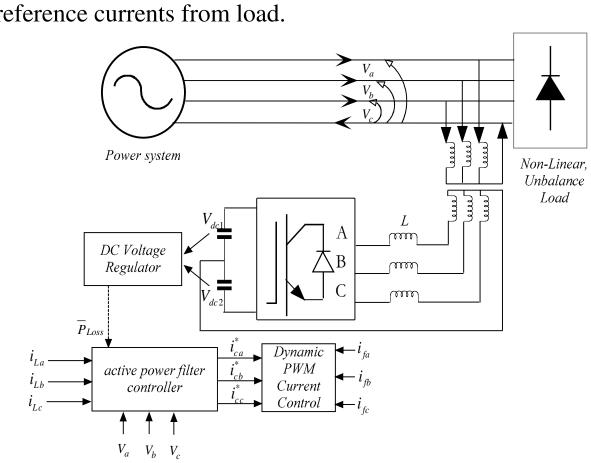

Fig.1. shows a basic architecture of three-phase - four wire shunt active filter.

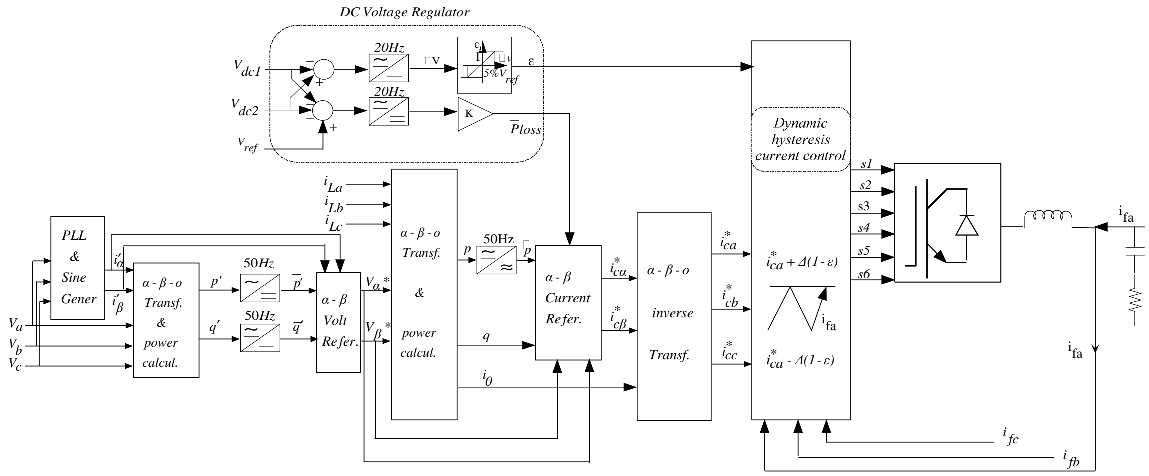

Fig.2. control block diagram of shunt active power filter.

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. Fig.2 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).

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

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

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

From Fig.2 we can observe a high pass filter with cut off frequency 50 Hz separates the powers $-\tilde{p}$ from p and a low - Pass filter separates $\bar{p}_0$ from p_0. The powers $\tilde{p}$ 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. 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.

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

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

Where $\tilde{p}$ is the ac component / oscillating value of p

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

P_{loss} is 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.

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

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 [5]. 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 [6-8]. 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).

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

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

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.

B. 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 non linear load [9-11]. 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. Fig.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).

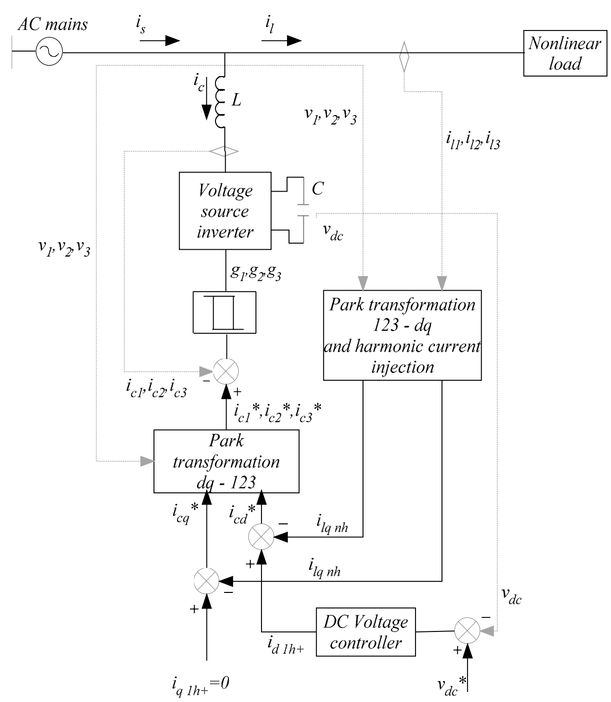

Fig.3. Active powers filter control circuit.

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

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 .

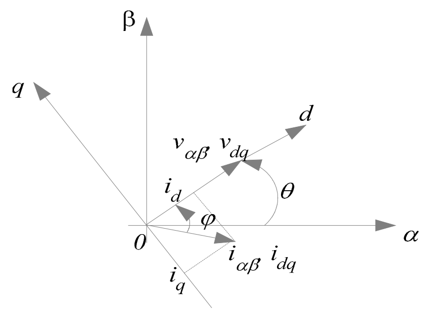

Fig.4. Instantaneous voltage and current vectors.

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). Fig.3 and 5 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 Fig.5. 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 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.

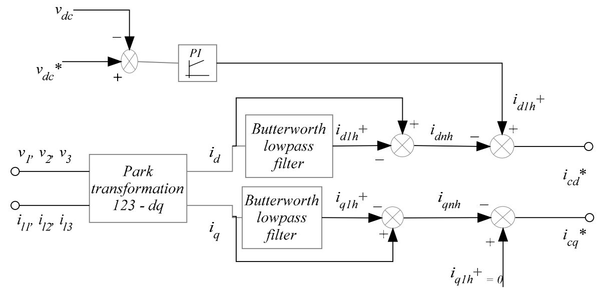

Fig. 5. Park transformation and harmonic current injection circuit.

3. SYSTEM PERFORMANCE

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, unbalanced, and with different main frequencies. Simulation is carried out for both instantaneous power theory (p-q) and instantaneous active and reactive current theory (i_d- i_q).

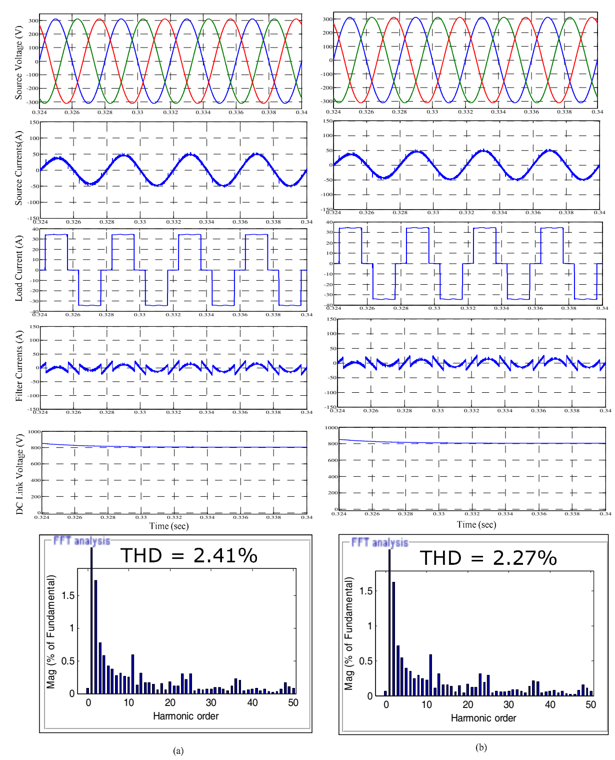

Fig.6. Shunt active power filter response under balanced sinusoidal voltage conditions for (a) p-q method (b) i_d-i_q method.

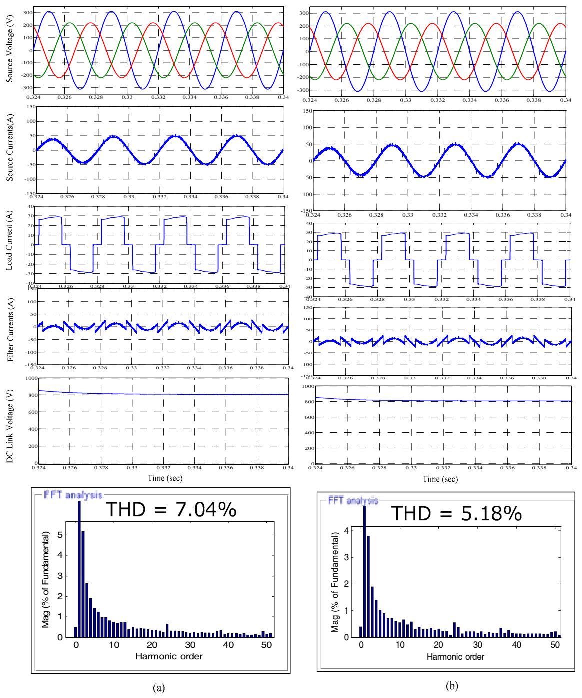

Fig.7. Shunt active power filter response under Un-balanced sinusoidal voltage conditions for (a) *p-q* method (b) i_d-i_q method.

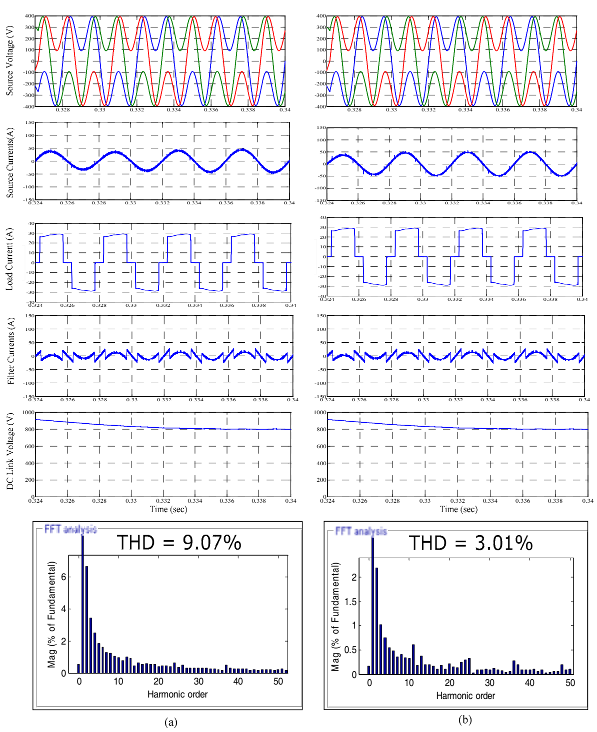

Fig.8. Shunt active power filter response under balanced non-sinusoidal voltage conditions for (a) *p-q* method (b) i_d-i_q method.

Fig.6 illustrates the performance of shunt active power filter under sinusoidal condition, as load is highly inductive current draw by load is integrated with rich harmonics. Under this circumstance both control schemes seems to work in similar nature and respective Harmonic distortions are shown in Fig.6. Simulation is extended to un-balanced sinusoidal conditions with same AHPF. It is observed that rather than *p-q* theory, i_d-i_q performance is quite good. FFT spectrum gives about 7.04% in *p-q* theory and 5.18% in i_d-i_q which is shown in Fig.7. Similar fashion both controllers are subjected to balanced non-sinusoidal voltage conditions with same AHPF by cut off frequency $f_c/2$, on owing i_d-i_q performance is outstanding(9.07% in *p-q* theory and 3.01% in i_d-i_q theory) which is shown in Fig.8, though the system is three-phase four-wire, i_d-i_q supplies sufficient neutral currents. Thus i_d-i_q behaviour is robust in nature.

Numerical simulations:

Above simulation is carried out with only AHPF (alternative high pass filter) of 2nd order with 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.5. Graphs shown in Fig.9 and Fig.10 summarize the total performance of the shunt active filter with different filters. Results presented confirm superior performance of i_d-i_q method. But performance of both filters under sinusoidal conditions seems to be same. Generally speaking in all the filters, AHPF gives best filtering action under any voltage conditions.

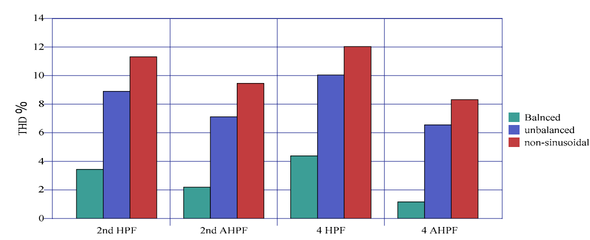

Fig.9 Total harmonic distortion for *p-q* control method

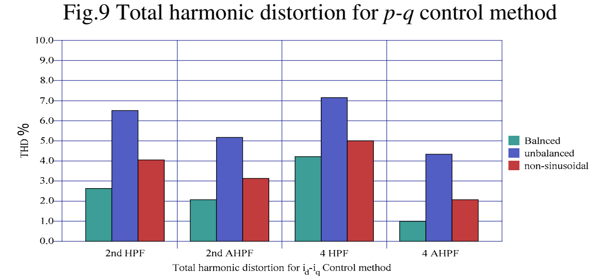

Fig.10 Total harmonic distortion for i_d-i_q control method

4. 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 method lead always better result under un-balanced and non-sinusoidal voltage conditions over the instantaneous active and reactive power *p-q* method. 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 is quite good over *p-q* theory.

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