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Design of Shunt Active Power Filter for Power Quality

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ABSTRACT

The power quality of the system can be expressed by the three physical characteristics Voltage, current and frequency. and a power quality issue is defined as "any occurrence disturbance in current, voltage, or frequency that results in damage, upset or failure of end-use equipments". The higher switching frequency and the non-linearity in the properties of the power electronics devices are mostly responsible for the power quality issue. So importance is being given to the development of Active Power Filters to solve these problems to improve power quality among which shunt active power filter is used to eliminate voltage and load current harmonics and for reactive power compensation. The shunt active power filters have been developed based on control strategies like instantaneous active and reactive power compensation scheme (p-q control) and instantaneous active and reactive current scheme (Id-Iq control). Considering its superior nature, a study on the Id-Iq control scheme based shunt active filter is brought out in this project. The compensation is carried out by the use of PI based controllers. A theoretical study based on both the compensation schemes is done in this paper and then the theory of Id-Iq control scheme is implemented in simulation work and its harmonic compensation results are analyzed.
Keywords : Power Quality, Shunt Active Power Filter, harmonics, P-Q theory.

I. INTRODUCTION

In recent years, the increasing use of power semi-conductor technology and non linear loads, industrial machines and automation devices in industries, commerce and households, have led to a significant increase in disturbances, which affect power quality in power systems. Therefore, it is necessary to develop and implement solutions to improve power quality in electrical power systems[1-2]. Conventionally passive L-C filters were employed to reduce harmonics and capacitors were used to improve the power factor of the loads. But passive filters have the demerits of fixed compensation, large size and resonance. The increased severity of harmonic pollution in power distribution network has attracted the attention to develop dynamic and adjustable solutions to the power quality problems giving rise to active filter.[3]

Now days, three-phase four-wire shunt active power filters have appeared as an effective method to solve the problem of harmonics, unbalanced load currents together with reactive power compensation. Active power filters are connected to AC mains in order to eliminate voltage variations and harmonic components. Shunt active power filter eliminates the current harmonic components working as a source with only the harmonic components and power factor correction, so that only the fundamental component is supplied in the AC mains.

The Shunt Active Power Filter is connected in parallel with the line through a coupling inductor. Its main power circuit consists of a three phase three-leg current controlled voltage source inverter with a DC link capacitor. An active power filter operates by generating a compensating current with 180 degree phase opposition and injects it back to the line so as to cancel out the current harmonics introduced by the nonlinear load. This will thus suppress the harmonic content present in the line and make the current waveform sinusoidal. So the process comprises of detecting the harmonic component present in the line current, generating the reference current, producing the switching pulses for the power circuit, generating a compensating current and injecting it back to the line.[12]

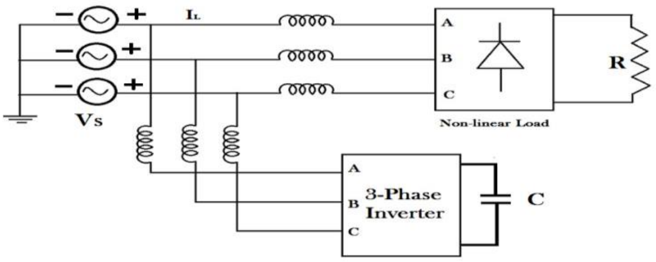

Fig.1. Three phase shunt active power filter

II. MATHEMATICAL ANALYSIS OF P-Q METHOD

A. Clarke's Transformation

The term instantaneous reactive power is defined as a unique value for arbitrary three-phase voltage and current waveforms including all distorted waveforms, by using instantaneous imaginary power. An instantaneous reactive power compensator eliminates the harmonic currents having the frequencies of f ± f0.

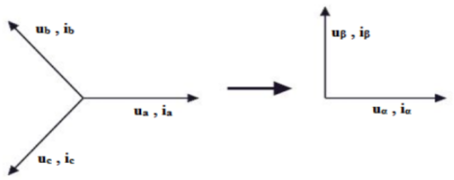

Fig. 2. a – b – c to α – β co-ordinates transformation

For dealing with the instantaneous mathematical values of the voltage and current waveforms in 3 – phase circuits, it is adequate to express their quantities as the instantaneous space vectors. In a-b-c coordinate-axis system, all the three axes are fixed on the same plane, phase separated from each other by 2π/3, as shown in Fig.2. The instantaneous space vectors, ua and ia are set on the a axis, and their amplitude and (±,-) direction vary with the passage of time. In the same way, ub and ib are on the b axis, and uc and ic are on the c axis. These space vectors are easily transformed into α – β coordinates as follows:

$$\begin{bmatrix} u_\alpha \\ u_\beta \\ u_o \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_o \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2)$$

If we assume a balanced 3-phase system with $i_o = 0$ then (1) and (2) reduce to:

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (4)$$

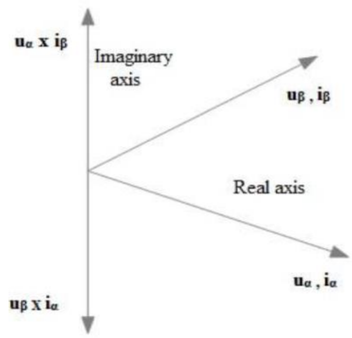

Fig. 3. Instantaneous space vectors

B. Compensation Current Determination

As shown in fig.3. the product of instantaneous voltage in one axis and the instantaneous current in the same gives us the instantaneous real power (p). Similarly the product of instantaneous voltage in one axis and instantaneous current in the perpendicular axis gives the instantaneous imaginary power (q) as shown in (5) and (6).

$$\text{In } \alpha - \beta \text{ co-ordinates}, \quad p = u_\alpha \cdot i_\alpha + u_\beta \cdot i_\beta \quad (5)$$

$$\text{In } \alpha - \beta \text{ co-ordinates}, \quad q = u_\alpha \times i_\beta + u_\beta \times i_\alpha \quad (6)$$

From above equation we get the following matrix equation:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (7)$$

Now iα and iβ can be determined from (7) and decomposed into components as shown in (8) and (9).

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p \\ 0 \end{bmatrix} + \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ q \end{bmatrix}$$

(8)

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} i_{\alpha p} \\ i_{\beta p} \end{bmatrix} + \begin{bmatrix} i_{\alpha q} \\ i_{\beta q} \end{bmatrix}$$

(9)

where,

α – axis instantaneous active current , $i_{\alpha p} = \frac{u_\alpha}{u_\alpha^2 + u_\beta^2} p$

α – axis instantaneous reactive current , $i_{\alpha q} = \frac{-u_\beta}{u_\alpha^2 + u_\beta^2} q$

β – axis instantaneous active current , $i_{\beta p} = \frac{u_\beta}{u_\alpha^2 + u_\beta^2} p$

β – axis instantaneous reactive current , $i_{\beta q} = \frac{u_\alpha}{u_\alpha^2 + u_\beta^2} q$

p and q from (7) can be average and oscillatory terms :

$p = \bar{p} + \tilde{p}$ and $q = \bar{q} + \tilde{q}$

where $\bar{p}$ and $\bar{q}$ are average terms and $\tilde{p}$ and $\tilde{q}$ are the oscillatory term

The oscillatory components represent the higher order harmonics. Thus, the oscillatory power should be compensated by active power filter so that the average power components remain in the mains and by this way rating of the active filter can be minimized.

The average power component will be eliminated by using high pass filter (HPF). The power to be compensated which is given as follows:

$pc = -\tilde{p}$ and $qc = \tilde{q}$

The compensation current in α – β co-ordinates can be found by eq. (9)

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{u_\alpha^2 + u_\beta^2} \begin{bmatrix} u_\alpha & -u_\beta \\ u_\beta & u_\alpha \end{bmatrix} \begin{bmatrix} pc \\ qc \end{bmatrix}$$

(10)

Applying Clarke's transformation on eq. (10) we can determine the compensation currents ica, icb and icc:

$$\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \cdot \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

(11)

Thus eq. (11) shows the converter reference current that must be fed back to the power line via a appropriate controller based on PI control or Fuzzy Logic control to eliminate the harmonic current.

III. MATHEMATICAL ANALYSIS OF ID – IQ METHOD

A. Park's Transformation

In this method the currents ic_i are obtained from the instantaneous active and reactive current components id and iq of the nonlinear load. In the same way, the mains voltages u_i and the polluted currents il_i in αβ components must be calculated as in the previous method by (3) and (4). However, the dq load current components are derived from a synchronous reference frame based on the Park's transformation, where θ represents the instantaneous voltage vector angle.

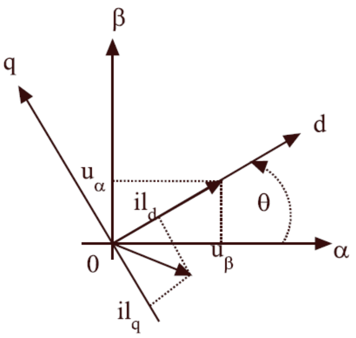

Fig.4. Voltage and current space vectors in stationary frame and synchronous rotating frame

$$\begin{bmatrix} il_d \\ il_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} il_\alpha \\ il_\beta \end{bmatrix}, \theta = \tan^{-1}\frac{u_\beta}{u_\alpha}$$

(12)

If the d axis is in the direction of the voltage space vector, since the zero-sequence component is invariant, the transformation is given by

$$\begin{bmatrix} il_d \\ il_q \end{bmatrix} = S.\begin{bmatrix} il_\alpha \\ il_\beta \end{bmatrix}, \qquad S = \frac{1}{\sqrt{u_\alpha 2 + u_\beta 2}} \cdot \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix}$$

(13)

Where the transformation matrix, S satisfies:

$\|S\| = 1; S^{-1} = S^T$

B. Compensation Current Determination

Each current (id, iq), component has an average value or dc component and an oscillating value or ac component:

$$il_d = \overline{il_d} + \widetilde{il_d}$$

$$il_q = \overline{il_q} + \widetilde{il_q}$$

(14)

As the id – iq theory states, the first harmonic component of the positive sequence current gives the dc component, il^{+}_{dq1h} . This average component does not go any frequency shift due to the harmonics. The non-dc quantities give the remaining higher order harmonics as well as the first harmonic current of the negative sequence, $il^{-}_{dqnh} + il^{+}_{dq1h}$. All these assumptions are made under the assumption of balanced load condition. The average and the oscillating components can be separated by passing through a Butterworth LPF which gives the average component and hence subtracting it from the actual signal we get the high frequency oscillating component. So in this method we obtain the compensating currents as $iC_d = -il_d$ and $iC_q = -il_q$. From the d – q components the α – β co-ordinates of the compensation current can be found out by the following mathematical relation:

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{\sqrt{u_\alpha^2 + u_\beta^2}} \begin{bmatrix} u_\alpha & -u_\beta \\ u_\beta & u_\alpha \end{bmatrix} \begin{bmatrix} ic_d \\ ic_q \end{bmatrix} \tag{15}$$

From the α – β co-ordinates of the compensation current the abc axis components can be determined by the inverse Clarke's transformation as stated in (11).

IV. DESIGN OF CONTROL CIRCUIT BASED ON Id – Iq METHOD

For supplying the compensation current to the line, a three phase IGBT based Voltage Source Inverter (VSI) is used. This makes the design simple, robust and has good dynamics in spite of some of its well-known disadvantages. The current controller used is composed of three independent two-level hysteresis comparators operating on a three leg VSI. This provides the compensation harmonic current to be injected by the control circuit which consists of two units namely Harmonic Current Generator and DC Voltage Regulator.

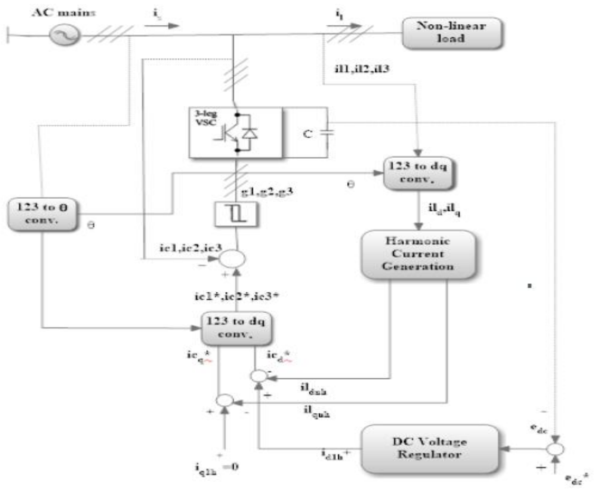

Fig.5. AF Control system based on id – iq method

A. Harmonic Current Generator

The currents iC_d* and iC_q* are obtained from the Park Transformation and harmonic current injection circuit and from the dc voltage regulator. As shown in Fig.4 , at first 123-dq axis conversion is done by the Park Transformation block which is executed according to (15). Thus the load currents ild and ilq are obtained. The first harmonic load current of positive sequence are transformed to dc quantities. The first harmonic load currents of negative sequence and all other harmonics are transformed to non-dc quantities and undergo a frequency shift in the spectrum. Consequently, the dc quantities that must be preserved in the mains are the first harmonic currents of the positive sequence $-il_{d1h}$ and il_{q1h} .

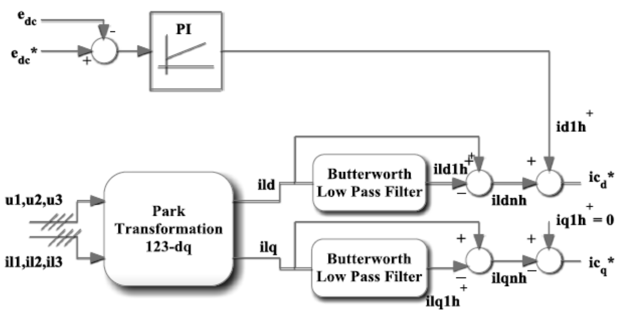

Fig.6. Park Transformation and Harmonic Current Generator circuit

So, the signal is passed through a fourth order Butterworth Low Pass Filter resulting in the currents il_{d1h} and il_{q1h}. Now subtracting this filtered signal from the input signal we obtain the higher order dq harmonic components il_{dnh} and il_{qnh}. This has been shown in Fig.6.

B. DC Voltage Regulator

The voltage regulation of the VSI dc side is done by the DC Voltage regulator part. It contains a PI controller to do the job. The input received by it is capacitor voltage error, e_{dc}^{*}- e_{dc} . By the regulation of the positive sequence first harmonic d-axis component il_{d1h}, the active power flow to the VSI is controlled and hence the capacitor voltage, e_{dc}. This control is done with a proportional-integral (PI) controller. The expected d – axis reference current is obtained by subtracting the higher order d-axis components (obtained from the harmonic current generator) from the output of the DC voltage regulator. Similarly the q-axis reference current is obtained by subtracting the higher order q-axis component (obtained from the harmonic current generator) from the first harmonic q-axis component,

$$ic_d^* = il_{d1h}^{+} - il_{dnh} \tag{16}$$

$$ic_q^* = il_{q1h}^{+} - il_{qnh} \tag{17}$$

However considering that the primary end of the AF is simply the elimination of the current harmonics caused by non-linear load, the current, $il_{q1h}^{+} = 0$.

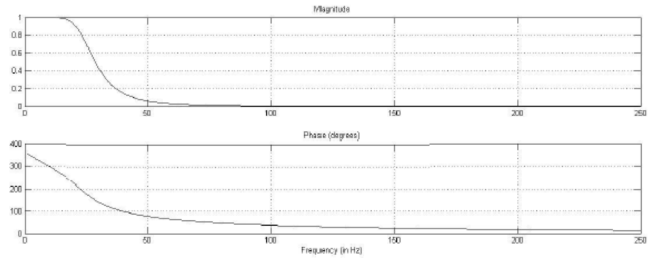

Fig.7. Magnitude and Phase plot of a fourth order Butterworth LPF

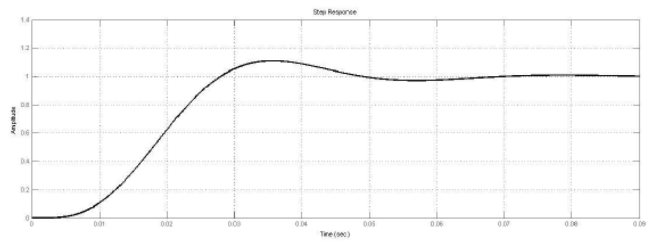

Fig.8. Step response of the fourth order Butterworth LPF

For the purpose of filtering out the higher order harmonic components a Butterworth LPF of fourth order has been used. The magnitude and phase plot of this filter with cut-off frequency = f/2 = 25 Hz has been shown in Fig.7 and Fig.8.

The voltage component u_d can be calculated from the mains voltage U under balanced sinusoidal voltage conditions by the given relation (this relation has been derived from (3) and (14),

$$u_d = \overline{u}_{dq} = |\overline{u}_{\propto\beta}| = \sqrt{\frac{3}{2}}(\sqrt{2}U) \tag{18}$$

Taking into consideration that the active power flow from the mains to the VSI is equal to the active power in the DC side, i.e., neglecting the losses in the inductances and the switching devices we get,

$$p = u_d ic_d \approx e_{dc} i_{dc} \tag{19}$$

Where i_{dc} is the current in the capacitor C. Now we can find out the state equation of the capacitor voltage to be,

$$\frac{de_{dc}}{dt} = \frac{u_d}{C}\frac{ic_d}{e_{dc}} - \frac{i_{load}}{C} \tag{20}$$

The current i_{Load} is an extra load current in the DC side of the VSI. The above shown equation results in a non-linear solution. So, we can perform linearization on it about the operating point defined by e_{dc}^{0} and ic_d^{0} to get the following equation:

$$\Delta E_{dc} = \frac{1}{s + \frac{u_d}{C}\frac{ic_d{}^0}{e_{dc}{}^{02}}}\left(\frac{u_d}{Ce_{dc}{}^0}\Delta Ic_d - \frac{1}{C}\Delta I_{load}\right)$$

(21)

This above shown equation represents the linearized model of the voltage regulation system which has been shown in Fig.9.

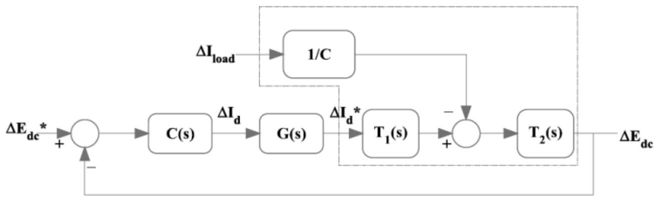

Fig.9. Block diagram of the DC voltage regulator system with unity feedback

$$T_1(s) = \frac{u_d}{C \cdot e_{dc}{}^0}$$

$$T_2(s) = \frac{1}{s + \frac{u_d}{C} \cdot \frac{ic_d{}^0}{e_{dc}{}^{02}}}$$

The transfer functions represented by C(s) and G(s) are the transfer functions of the PI controller and the VSI. Based on this linearized model the DC voltage regulator is synthesized assuming a unitary transfer function for the VSI and without disturbance, i.e. , absence of the extra load at the capacitor.

From this the closed loop transfer function of the entire system can be determined to be,

$$\frac{\Delta E_{dc}}{\Delta E_{dc}^{*}} = \frac{\frac{k_p u_d}{C e_{dc}^{0}}\left(s + \frac{k_I}{k_p}\right)}{s^2 + \frac{u_d}{C e_{dc}^{0}}\left(\frac{i c_d^{0}}{e_{dc}^{0}} + k_p\right) s + \frac{k_I u_d}{C e_{dc}^{0}}}$$

(22)

Here the variables Kp and Ki are the proportional and the integral control constants. If we assume a null active power flow in the converter then the above-mentioned equation can be simplified as the following

$$\frac{\Delta E_{dc}}{\Delta E_{dc}^{*}} = \frac{\frac{k_p u_d}{C e_{dc}^{0}}\left(s + \frac{k_I}{k_p}\right)}{s^2 + \frac{k_p u_d}{C e_{dc}^{0}} s + \frac{k_I u_d}{C e_{dc}^{0}}}$$

(23) The above-mentioned PI controller is realized using a prototype of a second-order system. For the above system PI controller was designed such that the real part of the poles was sufficiently negative for the closed loop equation with the values of different parameters being:

Capacitance $C = 4\ mF$

$e_{dc}^{0} = e_{dc}^{*} = 381.05\ V$

$u_d = 220\ V$

The values of proportional and integral constants were found to be:

$k_p = 1.96$ *and* $k_i = 392$

The bode plot and pole zero plot of the closed loop transfer function for these values of k_p and k_i is shown in Fig. 10 and Fig. 11.

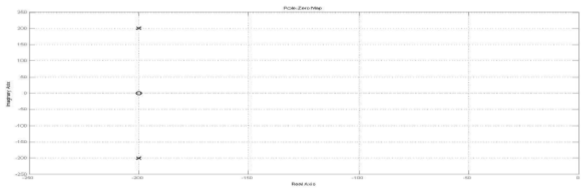

Fig.10. Pole zero location of the closed loop transfer function of DC Voltage Regulator

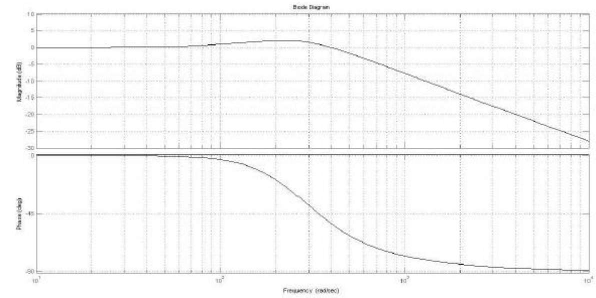

Fig.11. Bode plot of the closed loop transfer function of the dc voltage regulator

V. SIMULATION RESULTS AND DISCUSSION

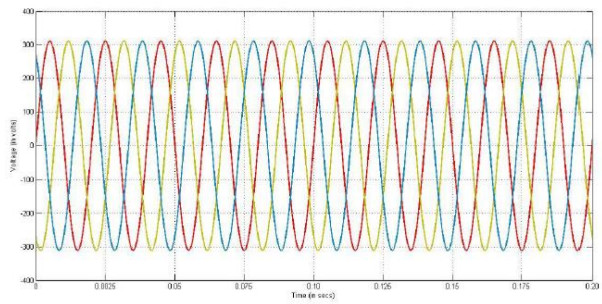

Fig.12. Phase Source Voltage waveform

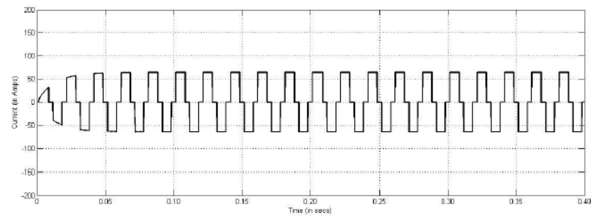

Fig.13. Load current waveform with harmonics introduced to it by non-linear load

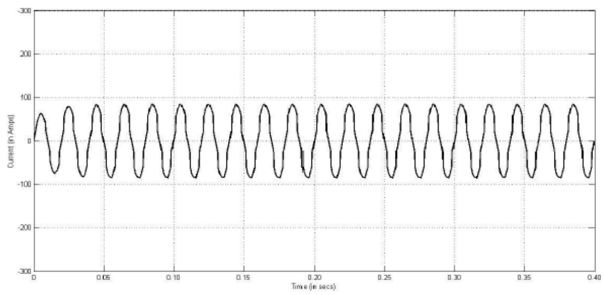

Fig.14. Compensated Source Current waveform

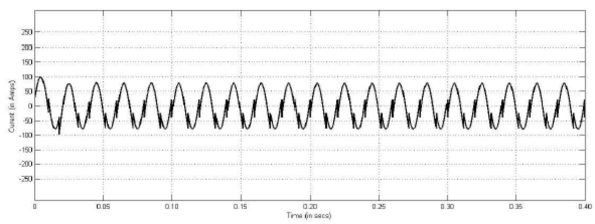

Fig.15. Filter current or Compensation current introduced by VSC

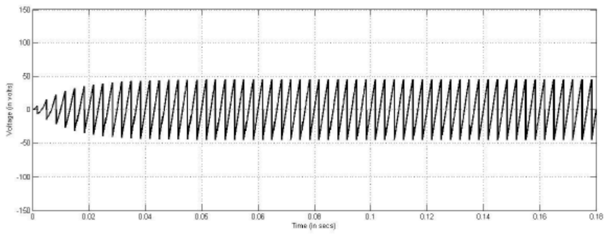

Fig.16. Load current waveform after Park's Transformation (il_d)

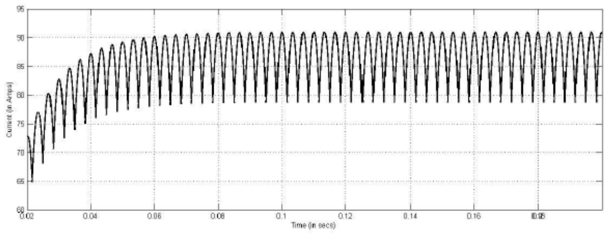

Fig.17. Load current waveform after Park's Transformation (id_q)

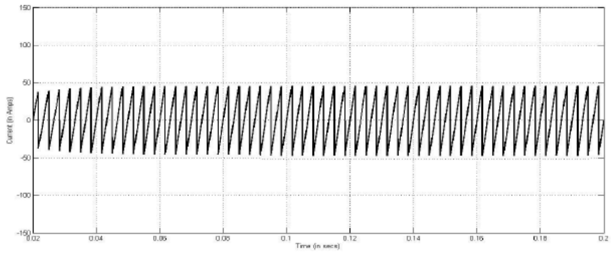

Fig.18. Filtered Load current waveform (id_{nh})

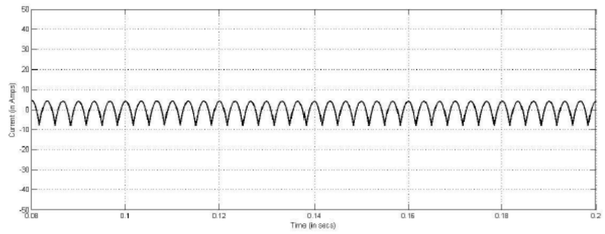

Fig.19. Filtered Load current waveform (iq_{nh})

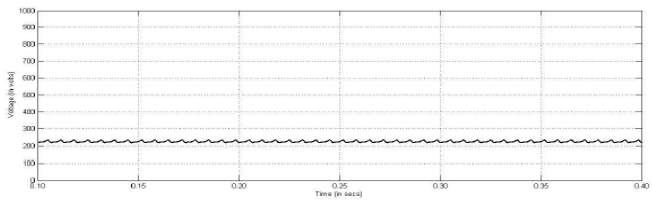

Fig.20. DC Link Voltage waveform

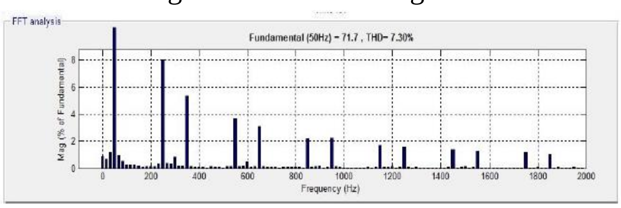

Fig.21. Magnitude vs. Frequency plot of source current waveform

VI. CONCLUSION

An active filter based on the principle of instantaneous active and reactive current (id – iq method) compensation has been proposed in this paper. A mathematical analysis of both instantaneous active and reactive power (p – q method) as well as id – iq method has been carried out to understand both the control scheme. Since the id – iq control method is based on a synchronous rotating frame derived from mains voltages without the phase locked loop (PLL) and has superior harmonic compensation performance, so simulation was carried out based on this control scheme. Under balanced and sinusoidal voltage conditions the id – iq control scheme is found to have satisfactory harmonic compensation performance. Here the active harmonic currents have been generated by three – leg VSC and the use of Hysteresis controller. A control system that enables current harmonics to be generated and the dc voltage to be regulated is implemented in Park coordinates. Expressions for the synthesis of the dc voltage regulator are derived and a stable and steady-state error free system is obtained. The - control method proposed allows the operation of the AF in variable frequency conditions without adjustments.

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