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Three Phase Active Power Filter Design using Instantaneous Reactive Power Compensation Theory for Harmonics Mitigation

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Abstract: *In single-phase or three-phase circuits,the conventional reactive power has been defined on the basis of mean value concept for sinusoidal voltage and current waveforms for steady state conditions. Various types of reactive power compensators have been developed to provide correction of power factor. However, it has been found that the compensator can eliminate the fundamental reactive power in steady states only. The generalized control strategy including the compensation of the fundamental reactive power in transient states has not been discussed yet. In the cases of non-linear loads the explanations are not sufficient and with increasing use of power electronics devices, the power sources had to start supplying power to a large number of thesenon-linear loads. In this paper Instantaneous Reactive Power Compensation Theory is presented for Harmonics Mitigation and Power Factor Correction.*

I. Introduction

Today power electronic loads like computers, uninterrupted power supplies (UPS), variable speed drives, switch mode power supplies (SMPS) etc. are deteriorating the power quality. The main problem with such loads is that, their switching characteristics (like of thyristors) gives rise to harmonic currents that flow in transmission lines. It causes considerable losses and voltage distortion, nuisance tripping of circuit breakers, premature failure of electronic equipment and other problems. Thus it is disturbing quality of power. Conventional methods like fixed compensation techniques, series and shunt passive filters have been used but every method has limitations.

The *p-q* theory is basically a set of instantaneous power defined in the time domain. There are no restrictions imposed on the current or voltage waveforms, and it can be applied with a neutral wire or without a neutral wire for three phase generic voltage and current waveformsto three-phase systems. Thus it is valid also in the transient state. This theory is very efficient and flexible in designing controller for power conditioning based on power electronics devices comparative to other three phase active filter design techniques [1]-[9]. The *p-q* theory transforms voltage and current from the *abc* to $\alpha\beta 0$ coordinates, and defines instantaneous power on these coordinates. Hence, this theory does not consider the three-phase system asa superposition or sum of three single-phase circuits but consider as aunit.

II. The Clarke Transformation

The $\alpha\beta 0$ transformation or Clarke transformation [10] maps the three-phase instantaneous voltage in the *abc*phase v_a, v_b and v_c into the instantaneous voltages on the $\alpha\beta 0$-axes v_α, v_β, and v_0. The Clarke transformation and the inverse of Clarke transformation of three phase voltages are given by

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

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

III. The *p-q* Theory in Three Phase, Three Wire Systems

Another way to introduce the *p-q* theory for three phases, three wire systems is to use the instantaneous voltage and current vector [10]. An instantaneous voltage vector is in space can be defined from the instantaneous α and βvoltage components, that is,

$$e = v_\alpha + jv_\beta \quad \text{….(2)}$$

Similarly, the instantaneous current vector is defined as

$$i = i_\alpha + ji_\beta \quad \text{….(3)}$$

In case of a three-phase balanced sinusoidal system the voltage and current have constant amplitude and rotate in the anticlockwise direction, at the angular frequency ω, as shown in Fig. 1.

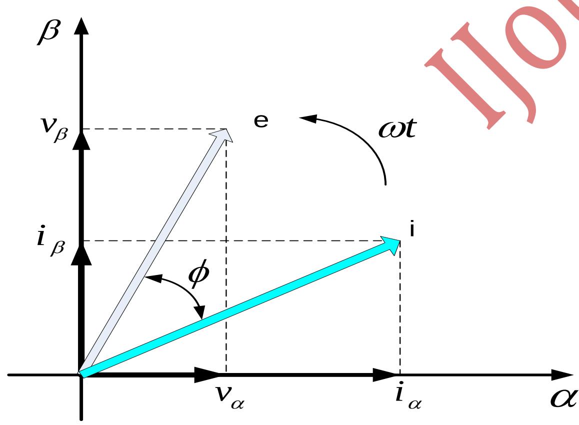

Fig. 1Vector representation of voltages and current on the *α-β* reference frames.

The original definition of *p* and *q* was based on the following equation:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad \text{….(4)}$$

From (4), it is possible to write

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{v^2{}_\alpha + v^2{}_\beta} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \quad \text{….(5)}$$

The right-hand side of (5) can have its terms expanded as

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{v^2{}_\alpha + v^2{}_\beta} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} p \\ 0 \end{bmatrix} + \frac{1}{v^2{}_\alpha + v^2{}_\beta} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} 0 \\ q \end{bmatrix}$$

….(6)

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

The above current components can be defined as shown below.

Instantaneous active current on the α axis $i_{\alpha p}$:

$$i_{\alpha p} = \frac{v_\alpha}{v^2{}_\alpha + v^2{}_\beta} p \quad \text{….(7)}$$

Instantaneous reactive current on the αaxis $i_{\alpha q}$:

$$i_{\alpha q} = \frac{v_\beta}{v^2{}_\alpha + v^2{}_\beta} q \quad \text{….(8)}$$

Instantaneous active current on the β axis $i_{\beta p}$:

$$i_{\beta p} = \frac{v_\beta}{v^2{}_\alpha + v^2{}_\beta} p \quad \text{….(9)}$$

Instantaneous reactive current on the β axis $i_{\beta q}$:

$$i_{\beta q} = \frac{-v_\alpha}{v^2{}_\alpha + v^2{}_\beta} q \quad \text{….(10)}$$

The instantaneous power on the α and β coordinates are defined as p_α and p_β, respectively, and are calculated from the instantaneous voltages and currents on the $\alpha\beta$ axes as follows:

$$\begin{bmatrix} p_\alpha \\ p_\beta \end{bmatrix} = \begin{bmatrix} v_\alpha i_\alpha \\ v_\beta i_\beta \end{bmatrix} = \begin{bmatrix} v_\alpha i_{\alpha p} \\ v_\beta i_{\beta p} \end{bmatrix} + \begin{bmatrix} v_\alpha i_{\alpha q} \\ v_\beta i_{\beta q} \end{bmatrix} \quad (11)$$

Instantaneous active power on the α axis $p_{\alpha p}$

$$p_{\alpha p} = v_\alpha . i_{\alpha p} = \frac{v^2{}_\alpha}{v^2{}_\alpha + v^2{}_\beta} p \ \ldots (12)$$

Instantaneous reactive power on the α axis $p_{\alpha q}$:

$$p_{\alpha q} = v_\alpha . i_{\alpha q} = \frac{v_\alpha v_\beta}{v^2{}_\alpha + v^2{}_\beta} q$$

….(13)

Instantaneous active power on the β axis $p_{\beta p}$

$$p_{\beta p} = v_\beta . i_{\beta p} = \frac{v^2{}_\beta}{v^2{}_\alpha + v^2{}_\beta} p \ \ldots .(14)$$

Instantaneous reactive power on the β axis $p_{\beta q}$:

$$p_{\beta q} = v_\beta . i_{\beta q} = \frac{-v_\alpha v_\beta}{v^2{}_\alpha + v^2{}_\beta} q \ \ldots .(15)$$

If the $\alpha\beta$ variable of the instantaneous imaginary power q as defined in (11) are replaced by their equivalent expressions to the *abc* axes using (4) and similarly for the current, the following relation can be found:

$$q = v_\beta i_\alpha - v_\alpha i_\beta = \frac{1}{\sqrt{3}}\left[(v_a - v_b)i_c + (v_b - v_c)i_a + (v_c - v_a)i_b\right]$$

$$= \frac{1}{\sqrt{3}}\left(v_{ab} i_c + v_{bc} i_a + v_{ca} i_b\right)$$

….(16)

IV. Selection of Power Components to be Compensated

One significant advantage of using the *pq* Theory in designing controller for active power-line conditioners is the possibility of independently selecting the portions of real, imaginary, and zero-sequence power to be compensated. Sometimes, it is convenient to separate these powers into their average and oscillating parts, that is,

Real power:

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

Imaginary power:

$$q = \bar{q} + \tilde{q} \quad \ldots .(17)$$

Zero- sequence power:

$$p_0 = \bar{p}_0 + \tilde{p}_0$$

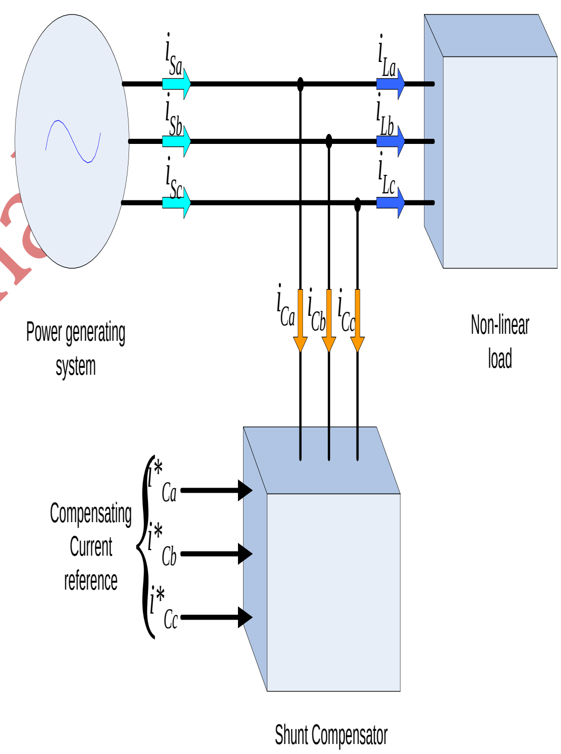

Fig. 2 Basic principle of shunt current compensation.

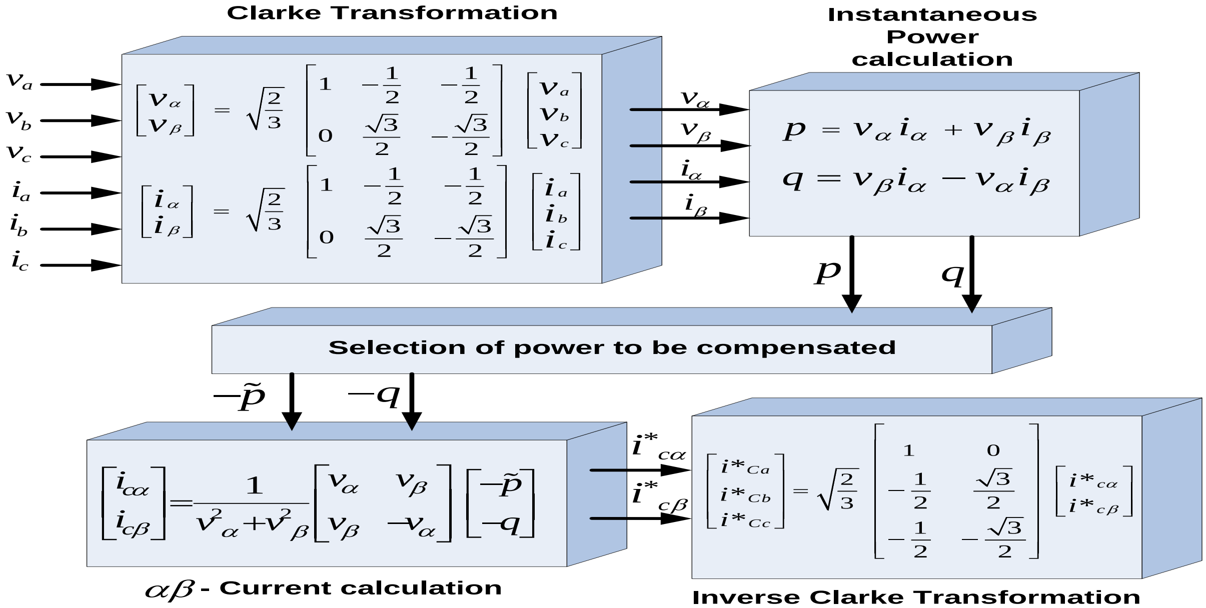

Fig. 3 Control method for shunt current compensation based on the *p-q* Theory

V. Software Simulation

The active filter controller consists of four functional blocks:

i) Instantaneous-power calculation
ii) Power-compensating selection
iii) Current reference calculation
iv) Hysteresis current control

Test System

Simulation parameters selected in circuit of three-phase, three-wire APF for different types of load are given below.

For RL Load

Voltage (Vs) = 200 (V peak value)
Current (I)= 15 Amp (peak value)
Frequency (f)= 50 Hz
Load Resistance (R_L)= 25Ω
Load Inductance (L)= 200 mH
DC Link Capacitor (C_{dc}) =5000 μF
Filter Inductor = 2.5 mH

For RC Load

Voltage (Vs) = 200 (V peak value)
Current (I) = 15 Amp (Peak value)
Frequency (f) = 50 Hz
Load Resistance (R_L)= 25Ω
Load Capacitance C=200 μF
DC Link Capacitance (C_{dc}) =5000 μF
Filter Inductor = 2.5 mH

For Inverter fed Induction Motor Load

Power= 5 kVA
Voltage (rms)= 400 V
Frequency= 50 Hz
Stator resistance= 14.85e-3 Ω
Stator leakage inductance= 0.3027e-3 H
Mutual inductance= 10.46e-3 H
Rotor resistance=9.295e-3 Ω
Rotor leakage inductance= 0.3027e-3 H

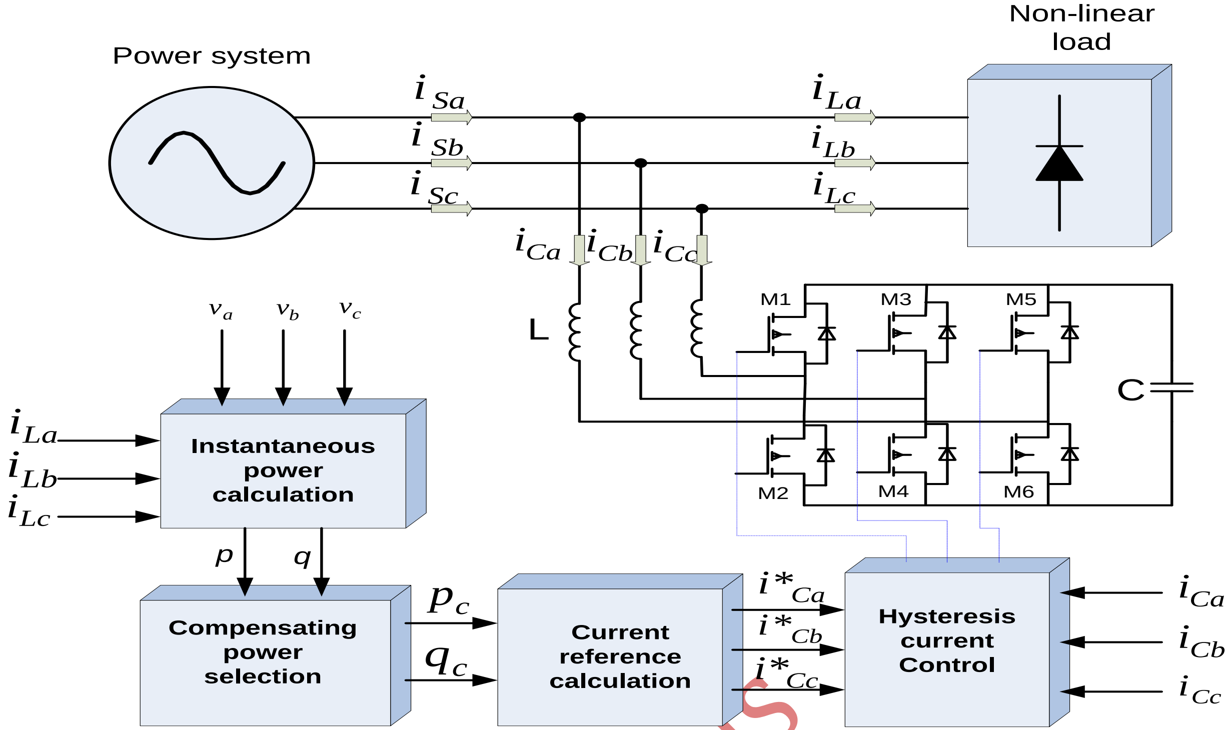

Fig 4 Block Diagram

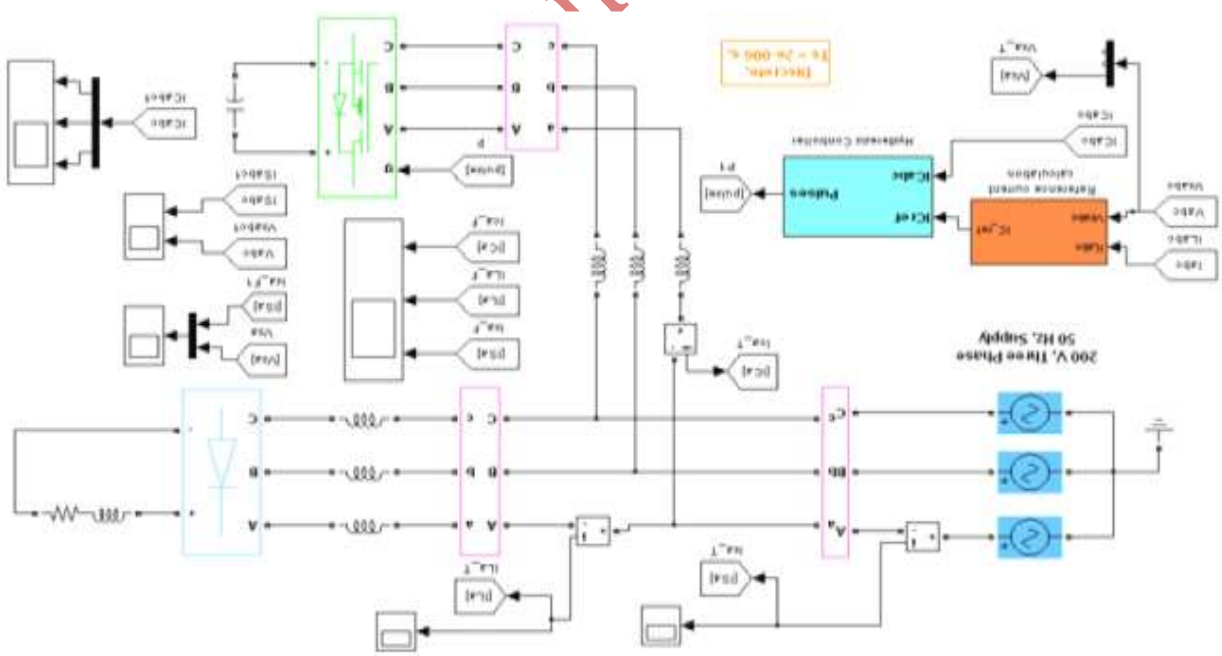

Fig 5 Simulation Model

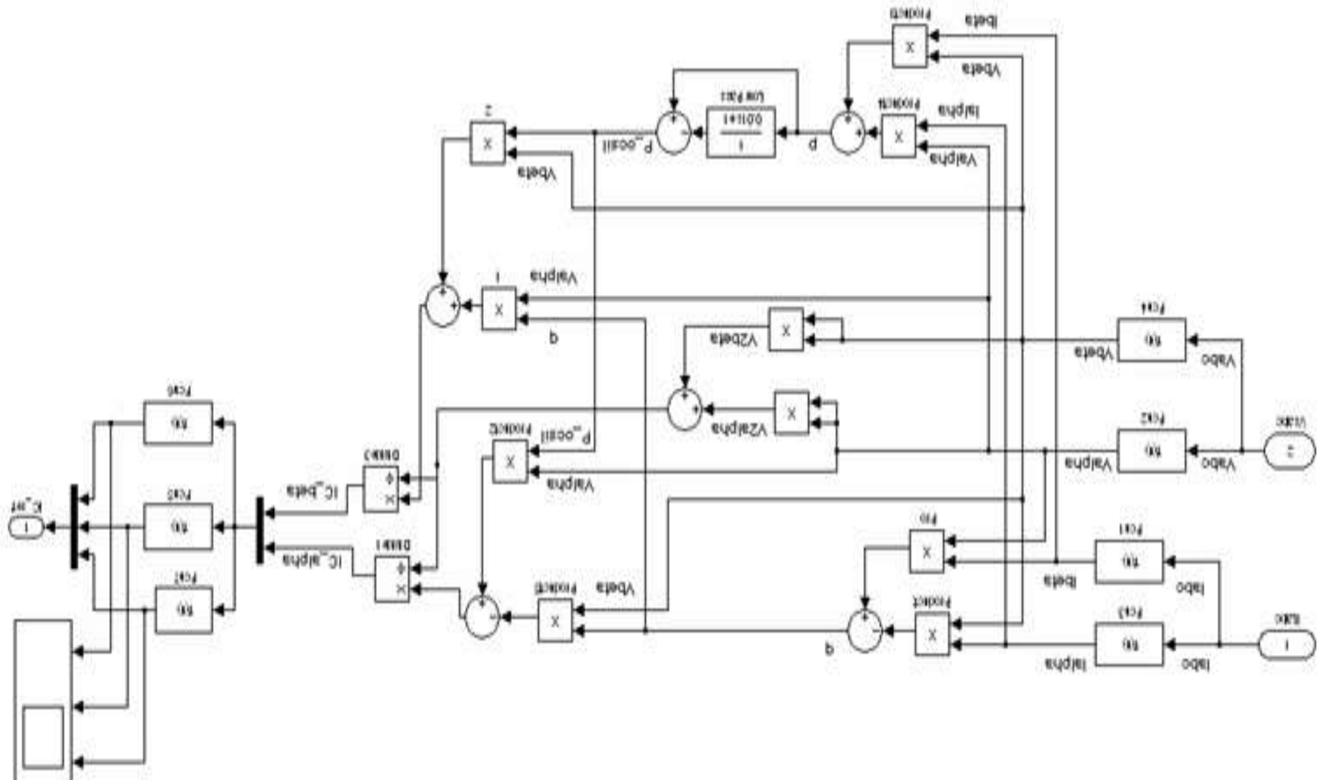

Fig 6 Simulation circuit for Reference current calculation of APF

VI. Simulation Result

For RL Load : Simulation of RL load is carried out and the results are shown in Fig 7-9.

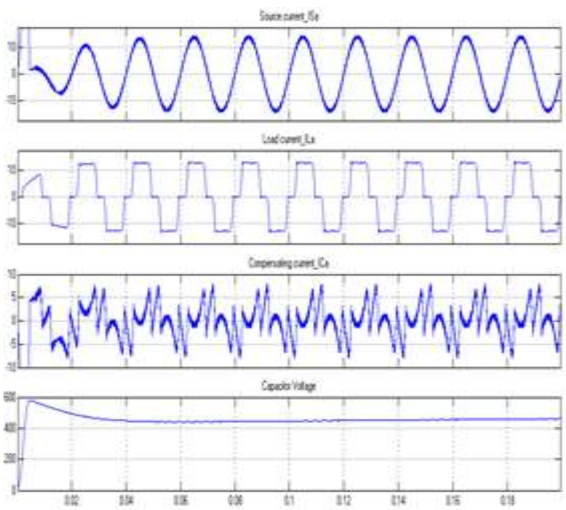

Fig. 7 Simulation waveform of source, Load, Compensation Current and Capacitor voltage for RL Load.

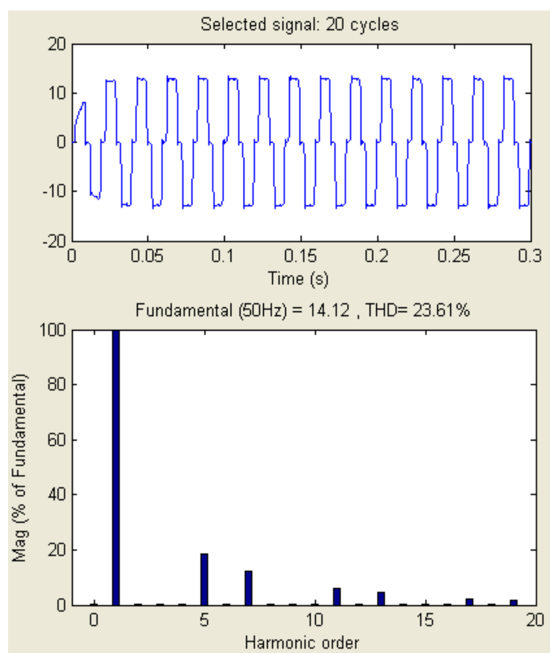

Fig. 8 Harmonic Spectrum of Load current for RL Load.

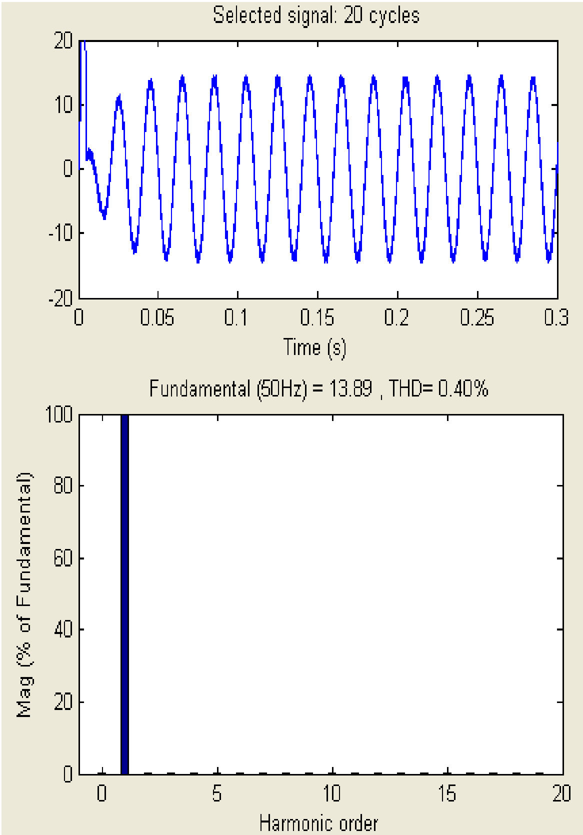

Fig 9 Harmonic Spectrum of Source current RL Load.

For RC Load

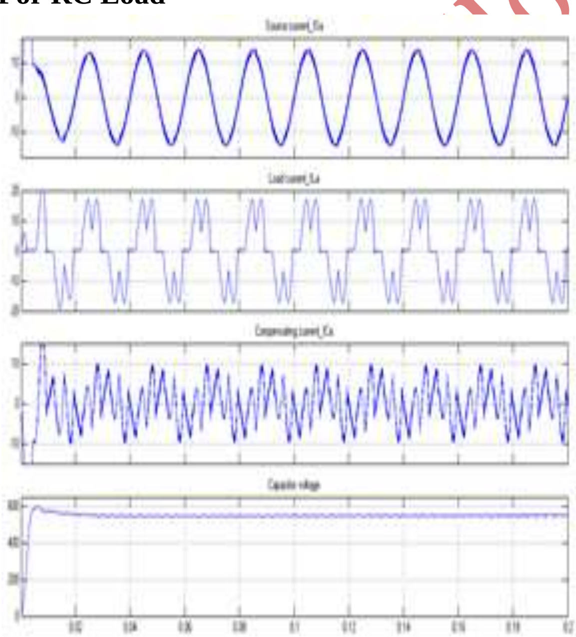

Fig. 10 Simulation waveform of source, Load, Compensation Current and Capacitor voltage for RC Load.

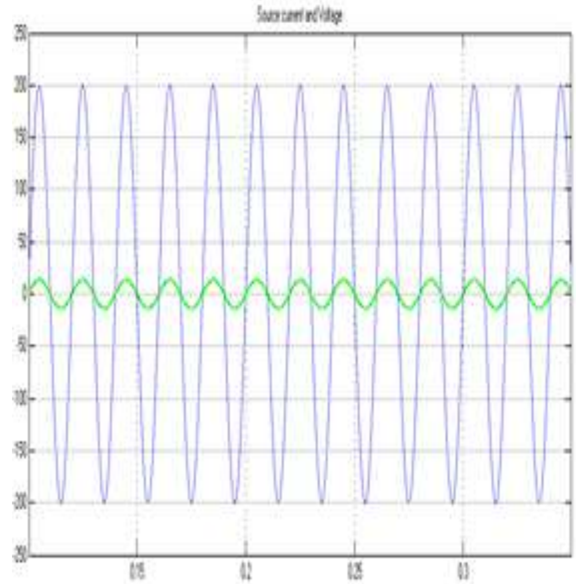

Fig. 11 Simulation waveform of source voltage and source current for RC Load.

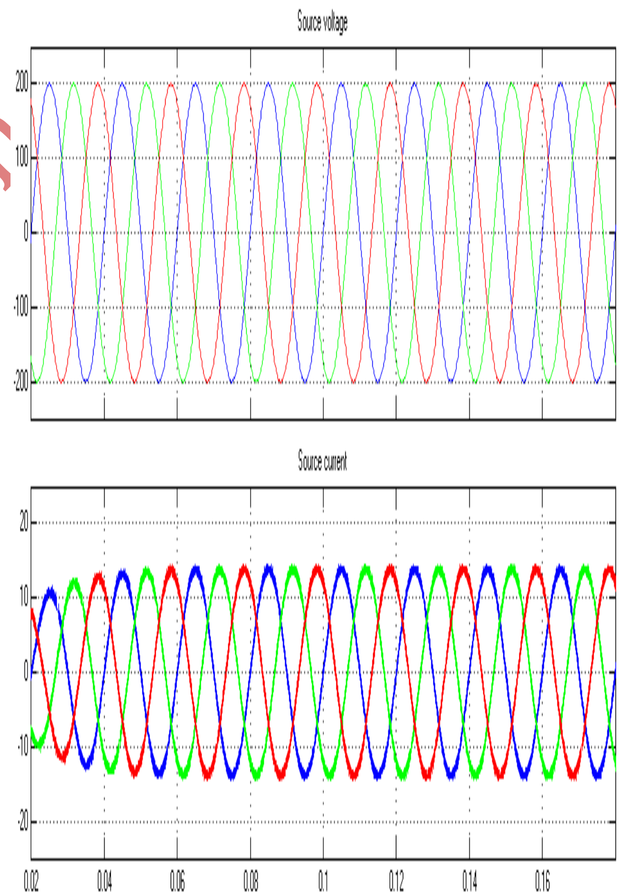

Fig. 12 Simulation waveform of three phase source voltage and source current for RC Load.

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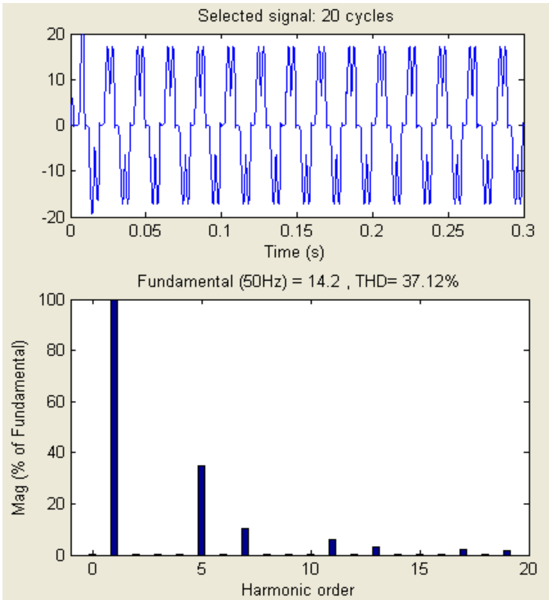

Fig. 13 Harmonic Spectrum of Load current for RC Load.

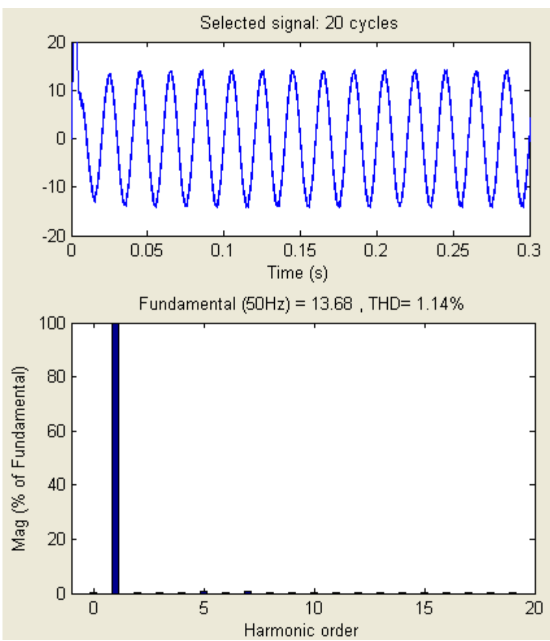

Fig. 14 Harmonic Spectrum of Source current for RC Load

VI. Conclusion

Simulation of RL Load with and without APF is carried out and the results are shown in Fig 7-9. Simulation result of these Load shows that the total harmonic distortion of source current using APF is improved from 23 % to less than 5%. From fig. 11 it is clear that both source voltage and source current are in phase so the power factor is improved.Simulation of RC Load with and without APF is carried out and the results are shown in Fig 10-14. Simulation result of these Load shows that the total harmonic distortion of source current using APF is improved from 37.12 % to 1.14%.

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