Performance Investigation of Shunt Active Power Filter Using Hysteresis Current Control Method

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ABSTRACT

The simulation study of PI Controlled, three phase shunt active power filter to improve power quality by compensating harmonics and reactive power required by a non-linear load is presented. The shunt active filter employs a simple method for the reference compensation current based on Fast Fourier Transform. Classic filters may not have satisfactory performance in fast varying conditions. But auto tuned active power filters give better results for harmonics minimization, reactive power compensation and power factor improvement. This paper has proposed an auto tuned shunt active filter, which maintains the THD well within the IEEE-519 standards. The results are found to be quite satisfactory to mitigate harmonic distortion, reactive power compensation and power factor improvement.

KEYWORDS

Power System, Shunt Active Filter, PI Controller, Hysteresis Current Pulse Width Modulation.

1. INTRODUCTION

Harmonics contamination is a serious and a harmful problem in Electric Power System. Active Power filtering constitutes one of the most effective proposed solutions. A shunt active power filter that achieves low current total harmonic distortion (THD), reactive power compensation and power factor correction is presented. Hence, it is necessary to reduce the dominant harmonics below 5% as specified in IEEE-519-1992 harmonic standard [1].

Harmonic Amplification is one the most serious problem. It is caused by harmonic resonance between line inductance and power factor correction (PFC) capacitors installed by consumers. Active filters for damping out harmonic resonance in industrial and utility power distribution systems have been researched [1]-[5].

Traditionally based, passive L-C filters were used to eliminate line harmonics in [2]-[4]. However, the passive filters have the demerits of fixed compensation, bulkiness and occurrence of resonance with other elements. The recent advances in power semiconductor devices have resulted in the development of Active Power Filters (APF) for harmonic suppression. Various topologies of active filters have been proposed for harmonic mitigation. The shunt APF based on Voltage Source Inverter (VSI) structure is an attractive solution to harmonic current problems. The SAF is a pulse width modulated (PWM) VSI that is connected in parallel with the load. It has the capability to inject harmonic current into the AC system with the same amplitude but opposite phase than that of the load [1]-[2]. The principal components of the APF are the VSI, a DC energy storage device that in this case is capacitor, a coupling transformer and the associated control circuits. The performance of an active filter depends mainly on the technique used to compute the reference current and the control method used to inject the desired compensation current into the line.

There are two major approaches that have emerged for the harmonic detection [2], namely, time domain and the frequency domain methods. The frequency domain methods include, Discrete Fourier Transform (DFT), Fast Fourier Transform (FFT), and Recursive Discrete Fourier Transform (RDFT) based methods. The frequency domain methods require large memory, computation power and the results provided during the transient condition may be imprecise [4]. On the other hand, the time domain methods require less calculation and are widely followed for computing the reference current.

There are several current control strategies proposed in the literature [5]-[7], [8]-[9], namely, PI control, Average Current Mode Control (ACMC), Sliding Mode Control (SMC) and hysteresis control. Among the various current control techniques, hysteresis control is the most popular one for active power filter applications. Hysteresis current control [6] is a method of controlling a voltage source inverter so that the output current is generated which follows a reference current waveform in this paper. Generally, PI controller [7] is used to control the DC bus voltage of SAF. The PI controller based approach requires precise linear mathematical model.

This chapter basically deals with the modeling and design of shunt active power filter for compensation of harmonics and reactive power. Designs of different parameters like power circuit, control circuit, control strategies, EMI/ Ripple factor are discussed.

2. Basic Compensation Principle

Fig.1 shows the basic compensation principle of shunt active power filter. A voltage source inverter (VSI) is used as the shunt active power filter. This is controlled so as to draw or supply a compensating current I_c from or to the utility, such that it cancels current harmonics on the AC side i.e. this active power filter (APF) generates the nonlinearities opposite to the load nonlinearities [3].

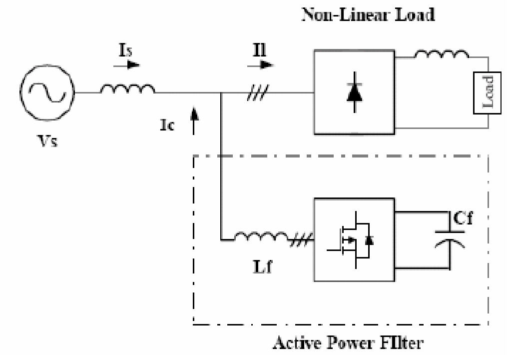

Fig.1 Basic compensation principle

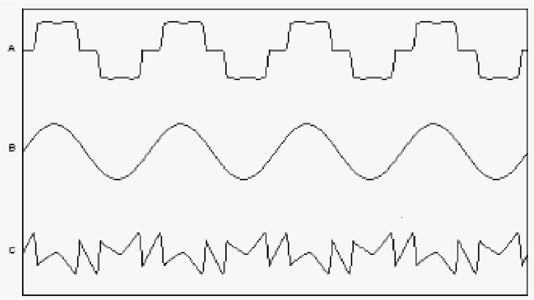

Fig.2 Waveform for actual load current (A), desired source current (B) and the compensating filter current (C).

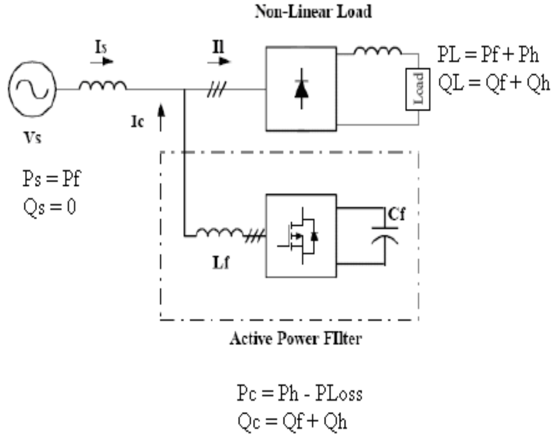

Fig.3 Single line diagram of the shunt active power filter showing power flow

Total instantaneous power drawn by the nonlinear load can be represented as:-

$$p_L(t) = p_f(t) + p_r(t) + p_h(t)$$

Where,

$p_f(t)$ - instantaneous fundamental (real) power absorbed by the load,

$p_r(t)$ – instantaneous reactive power drawn by the load, and

$p_h(t)$ – instantaneous harmonic power drawn by the load.

In order to achieve unity power factor operation and drawing sinusoidal currents from the utility, active power filter must supply all the reactive and harmonics power demand of the load. At the same time, active filter will draw real component of power (P_{Loss}) from the utility, to supply switching losses and to maintain the DC link voltage unchanged.

Power components (reactive and the harmonic) should be supplied by the active power filters i.e.

$$p_c(t) = p_r(t) + p_h(t)$$

2.1 Estimation of Reference Source Current

From the single line diagram shown in fig.3

$$i_s(t) = i_L(t) - i_c(t) \quad (1)$$

Where,

$i_s(t)$, $i_L(t)$, $i_c(t)$ are the instantaneous value of source current, load current and the filter current.

And the utility voltage is given by

$$v_s(t) = V_m \sin\omega t \quad (2)$$

Where,

$v_s(t)$ – is the instantaneous value of the source voltage,

V_m - is the peak value of the source voltage.

If non-linear load is connected then the load current will have a fundamental component and the harmonic components which can be represented as –

$$i_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \phi_n)$$

$$= I_1 \sin(\omega t + \phi_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n) \qquad (3)$$

Where, I_1 and ϕ_1 are the amplitude of the fundamental current and its angle with respect to the fundamental voltage, and

I_n and ϕ_n are the amplitude of the nth harmonic current and its angle.

Instantaneous load power $p_L(t)$ can be expressed as–

$$p_L(t) = v_s(t)\, i_L(t)$$

$$= V_m \sin\omega t \; I_1 \sin(\omega t + \phi_1) +$$

$$V_m \sin\omega t \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n)$$

$$= p_f(t) + p_r(t) + p_h(t) \qquad (4)$$

$$= p_f(t) + p_c(t) \qquad (5)$$

In the equation (4) and (5)

$p_f(t)$ is the real power (fundamental),

$p_r(t)$ represents the reactive power and

$p_h(t)$ represents the harmonic power drawn by the load.

For ideal compensation only the real power (fundamental) should by supplied by the source while all other power components (reactive and the harmonic) should be supplied by the active power filters i.e. $p_c(t) = p_r(t) + p_h(t)$

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The total peak current supplied by the source

$$I_{max} = I_{sm} + I_{sL} \qquad (6)$$

Where, $I_{sm} = I_1 \cos\phi_1$

and I_{sL} is the loss component of current drawn from the source.

If active power filter provide the total reactive and harmonic power, then $i_s(t)$ will be in phase with the utility and pure sinusoidal. At this time, the active filter must provide the following compensation current:

$$I_c(t) = I_L(t) - i_s(t) \qquad (7)$$

Hence, for the accurate and instantaneous compensation of reactive and harmonic power it is very necessary to calculate the accurate value of the instantaneous current supplied by the source.

$$I_s(t) = I_{max} \sin\omega t \qquad (8)$$

Where, I_{max} (= $I_1 \cos\phi_1 + I_{sL}$) is the amplitude of the desired source currents. The phase angles can be obtained from the source voltages. Hence, the waveform and phases of the source currents are known and only the magnitude of the source currents needs to be determined.

The peak value or the reference current I_{max} is estimated by regulating the DC link voltage of the inverter. This DC link voltage is compared by a reference value and the error is processed in a PI controller. The output of the PI controller is considered as the amplitude of the desired source currents and the reference currents are estimated by multiplying this peak value with the unit sine vectors in phase with the source voltages.

2.2 Design of Shunt Active Power Filter

The shunt active power filter mainly consists of DC link capacitor, filter inductor, PI controller and the hysteresis controller.

2.2.1 DC Link Capacitor

The DC link capacitor mainly serves two purposes-

(a) It maintains almost a constant DC voltage.

(b) It serves as an energy storage element to supply real power difference between load and source during transients.

In this scheme the role of the DC link capacitor is to absorb/supply real power demand of the load during transient. Hence the design of the DC link capacitor is based on the principle of instantaneous power flow.

Equalizing the instantaneous power flow on the DC and AC side of the inverter considering only fundamental component [3].

$$V_{dc} I_{dc} = v_{ca}(t)\, i_{ca}(t) + v_{cb}(t)\, i_{cb}(t) + v_{cc}(t)\, i_{cc}(t) \qquad (9)$$

Assuming that three phase quantities are displaced by 120^0 with respect to each other, ϕ is the phase angle by which the phase current lags the inverter phase voltage, and $\sqrt{2}\, V_c$ and $\sqrt{2}\, I_c$ are the amplitudes of the phase voltage and current, respectively of the input side of the inverter.

$$V_{dc} I_{dc} = 2V_{ca} I_{ca} \sin \omega_1 t \sin (\omega_1 t - \phi_a) + 2V_{cb} I_{cb} \sin (\omega_1 t - 120^0) \sin (\omega_1 t - 120^0 - \phi_b) + 2V_{cc} I_{cc} \sin (\omega_1 t + 120^0) \sin (\omega_1 t + 120^0 - \phi_c) \qquad (10)$$

Case I: If the three phase system is balanced-

Then, $V_{ca} = V_{cb} = V_{cc} = V_c$

$I_{ca} = I_{cb} = I_{cc} = I_c$, and

$\phi_a = \phi_b = \phi_c = \phi$

Hence,

$$V_{dc} I_{dc} = 3 V_c I_c \cos\phi \qquad (11)$$

i.e. the DC side capacitor voltage is a DC quantity and ripple free.

Case II: If the three phase system is unbalanced-

$$V_{dc} I_{dc} = (V_{ca} I_{ca} \cos\phi_a + V_{cb} I_{cb} \cos\phi_b + V_{cc} I_{cc} \cos\phi_c) - [V_{ca} I_{ca} \cos(2\omega_1 t - \phi_a) + V_{cb} I_{cb} \cos(2\omega_1 t - 240^0 - \phi_b) + V_{cc} I_{cc} \cos(2\omega_1 t + 240^0 - \phi_c)] \qquad (12)$$

The above equation shows that the first term is a dc component, which is responsible for the power transfer from dc side to the AC side. Here it is responsible for the loss component of the inverter and to maintain the DC side capacitor voltage constant.

The peak to peak ripple voltage is given by–

$$V_{pp} = \pi * I_{pp} * X_c = (\pi * I_{pp}) / (\omega * C_f) \qquad (13)$$

Where, I_{pp} is the peak to peak second harmonic ripple of the DC side current. Assuming that V_{pp} is much less than V_{dc} then using equations (14) and (15) the maximum value of the V_{pp} can be obtained as-

$$V_{pp} = (\pi * I_{c1,\,rated}) / (\sqrt{3}\,\omega * C_f) \qquad (14)$$

Case III: Since the total load power is sum of the source power and compensator power (i.e. $P_L = P_c + P_s$), so that when load change takes place, the changed load power must be absorbed by the active power filter and the utility i.e.

$$\Delta P_L = \Delta P_c + \Delta P_s \qquad (15)$$

Hence, selection of capacitor value C_f can be governed by reducing the voltage ripple. As per the specification of $V_{pp,\,max}$ and $I_{c1,\,rated}$ the value of the capacitor can be found from the following equation –

$$C_f = (\pi * I_{c1,\,rated}) / (\sqrt{3}\,\omega * V_{pp,\,max}) \qquad (16)$$

It is observed that the value of C_f depends on the maximum possible variation in load and not on the steady state value of the load current. Hence, proper forecasting in the load variation reduces the value of C_f.

2.2.2 Selection of Lc and Reference Capacitor Voltage ($V_{dc,ref}$)

The design of these components is based on the following assumptions:

(a) The AC source voltage is sinusoidal.
(b) For Lc, the AC side line current distortion is assumed to be 5%.
(c) Reactive power compensation capability of the active filter.
(d) The PWM converter is assumed to operate in the linear modulation mode (i.e $0 \leq m_a \leq 1$).

For satisfactory operation the magnitude of $V_{dc,ref}$ should be higher than the magnitude of the source voltage V_s. By suitable operation of switches a voltage V_c having fundamental component V_{c1} is generated at the ac side of the inverter. This results in flow of fundamental frequency component I_{s1}, as shown in fig.4.The phasor diagram for $V_{c1}>V_s$ representing the reactive power flow is also shown in this figure. In this I_{s1} represent fundamental component [3]-[11].

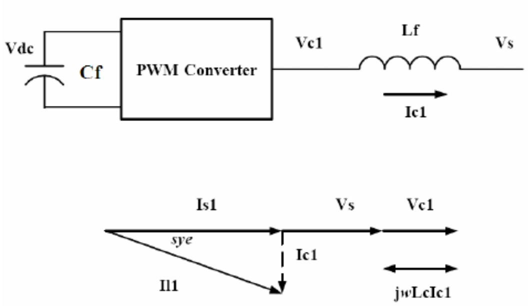

Fig.4 Single line and vector diagrams for shunt APF

As per the compensation principle active power filter adjusts the current I_{c1} to compensate the reactive power of the load. In order to maintain I_{s1} in phase with V_s, active filter should compensate all the fundamental reactive power of the load. The vector diagram represents the reactive power flow in which I_{s1} is in phase with V_s and I_{c1} is orthogonal to it.

Form the vector diagram,

$$V_{c1} = V_s + j\omega L_f I_{c1} \qquad (17)$$

i.e. to know V_{c1} it is necessary to know I_{c1}

$$I_{c1} = \frac{V_{c1} - V_s}{\omega L_f} = \frac{V_{c1}}{\omega L_f}\left(1 - \frac{V_s}{V_{c1}}\right) \qquad (18)$$

Now the three phase reactive power delivered from the active power filter can be calculated from the vector diagram as –

$$Q_{c1} = Q_{L1} = 3 V_s I_{c1} = 3 V_s \frac{V_{c1}}{\omega L_f}\left(1 - \frac{V_s}{V_{c1}}\right) \qquad (19)$$

From these equations

If $V_{c1} > V_s$, Q_{c1} is positive.

If $V_{c1} < V_s$, Q_{c1} is negative.

i.e. active power filter can compensate the lagging reactive power from utility only when$V_{c1}>V_s$.

From[11], If the inverter is assumed to operate in the linear modulation mode i.e. modulation index varies between 0 and 1, then the amplitude modulation index is given by-

$$m_a = \frac{2\sqrt{2}V_{c1}}{V_{dc}} \quad \text{(where, } V_m=\sqrt{2}\,V_c\text{)} \qquad (20)$$

And the value of V_{dc} is taken as

$$V_{dc} = 2\sqrt{2}\;V_{c1} \quad \text{(for } m_a=1\text{)} \qquad (21)$$

The filter inductor L_f is also used to filter the ripples of the inverter current,and hence the design of L_f is based on the principle of harmonic current reduction.The ripple current of the inverter can be given in terms of the maximum harmonic voltage, which occurs at the frequency $m_f\omega$.

$$I_{ch}(m_f\omega) = \frac{V_{ch}\;(m_f\omega)}{m_f\omega L_c} \qquad (22)$$

Where,m_f is the frequency modulation ratio of PWM converter.

On solving (19) and (22) simultaneously, the value of L_f and V_{c1}(i.e V_{dc}) can be calculated. V_{c1} and $V_{dc\ ref}$, must be set according to the capacity requirement of the system (i.e $V_s< V_{c1} \leq 2V_s$).As the switching frequency is not fixed with the hysteresis controller, a practically feasible value of 10kHz has been assumed.

2.3 PI Controller

The controller used is the discrete PI controller that takes in the reference voltage and the actual voltage and gives the maximum value of the reference current depending on the error in the reference and the actual values. The mathematical equations for the discrete PI controller are:

The voltage error V (n) is given as:

V (n) =V*(n) - V (n)

The output of the PI controller at the nth instant is given as:

I(n)=I(n-1) + Kp[V(n)-V(n-1)] + Ki V(n)

2.4 Hysteresis Current Controller

With the hysteresis control, limit bands are set on either side of a signal representing the desired output waveform. The inverter switches are operated as the generated signals within limits. Hysteresis-band PWM is basically an instantaneous feedback control method of PWM where the actual signal continually tracks the command signal within a hysteresis band [10].

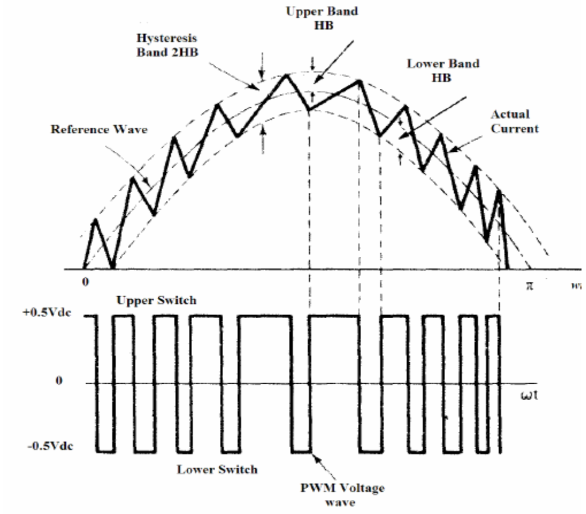

Fig.5 Basic principle of hysteresis band control

The rate of change of inductor current is then given by

$$\frac{di}{dt} = \frac{V_c \pm V_{1m}\sin(\omega t)}{L_f} \qquad (23)$$

Making assumption that the ac supply does not change during a cycle of switch operations, the time taken t_m taken to cross a dead band is

$$t_m = \frac{L\Delta I}{V_{c1} - V_{s1}\sin(\omega t)} \qquad (24)$$

The switching frequency f_{sw} is, therefore variable. Combining above two equations (23) and (24) to obtain the switching period, and inverting, gives

$$f_{sw} = \frac{V_c^2 - V_{s1}^2\sin^2(\omega t)}{2L\Delta I V_c}$$

3. Simulation And Performance Investigation Of Shunt APF

In this section the simulation analysis of shunt APF is described, first for R-L load and then for DC machine load and the FFT analysis has been carried out simultaneously.

3.1 Operation of Simulation Model

The operation of the simulation model shown below is described as – first the capacitor voltage is sensed which is compared with the reference voltage and the error signal is given to the PI controller for processing to obtain the maximum value (I_m) of the reference current which is multiplied with the unit vector template i.e. sinωt to get the reference current I_m sinωt for phase a. This signal is now delayed by 120^0 for getting the reference current for phase b, which is further delayed by 120^0 to get the reference current for the phase c. these reference currents are now compared with the actual source currents and the error is processed in the hysteresis controller to generate the firing pulses for the switches of the inverter. And the switches are turned on and off in such a way that if the reference current is more than the actual source current then the lower switch is turned on and the upper switch is turned off and if the reference current is less than the actual source current then the upper switch of the same leg is turned on and the lower switch is turned off. The output of the shunt active power filter is such that the source current is purely sinusoidal and the harmonic current is drawn or supplied by the filter.

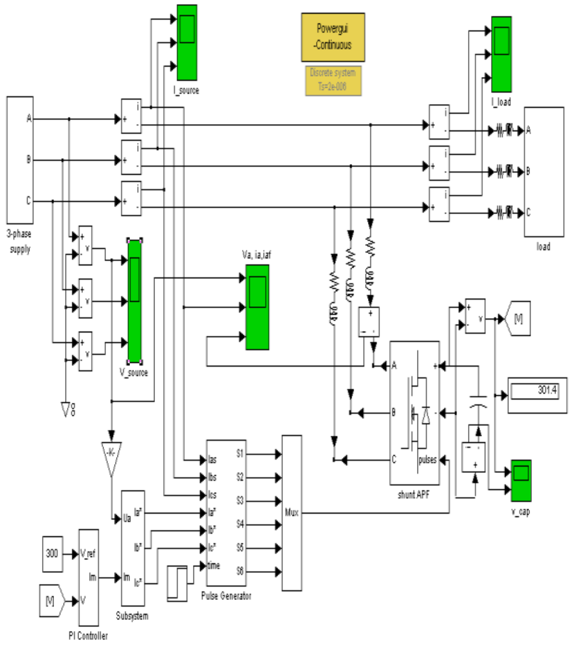

Fig.6 MATLAB model for Shunt active power filter

3.2 Simulation Result And Discussion

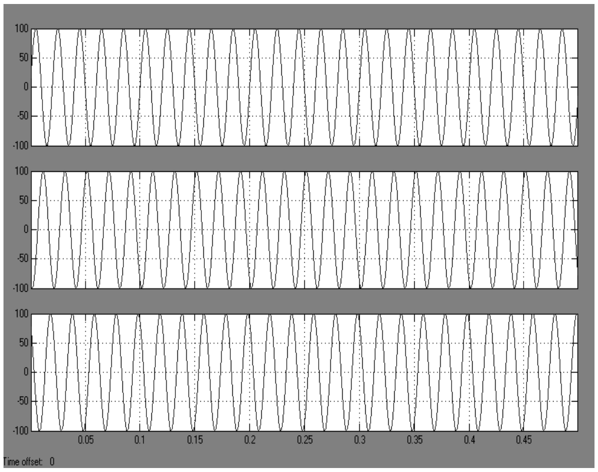

Fig.7   Three phase supply voltages

The waveform shown in fig.7 demonstrates that supply voltage is almost sinusoidal of V_{peak}=100 volt in phase 0,-120 and +120 degree of a, b and c phase respectively.

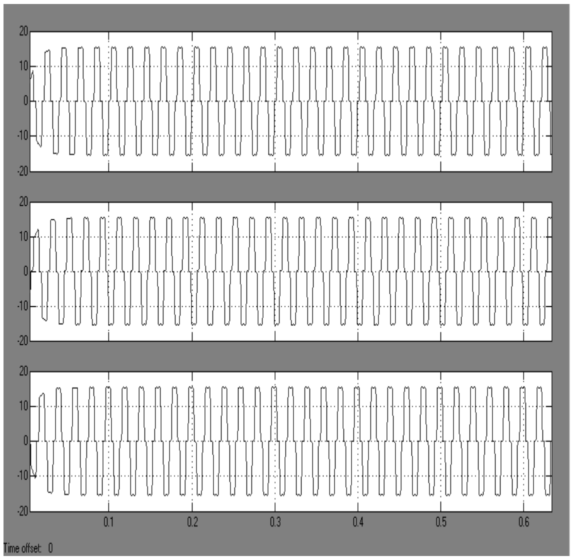

Fig.8   Load current

The waveform shown in fig.8 demonstrates that load current is in sinusoidal nature with containing small amount harmonic .

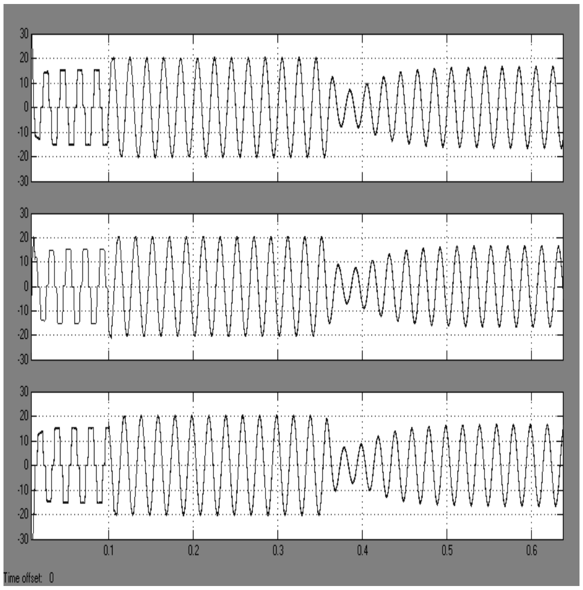

Fig.9   Source current before and after compensation

The waveform shown in fig.9 demonstrates that source current before compensation (i.e from 0 to 0.1 sec.) and after compensation (i.e from 0.1 sec.), it is almost sinusoidal with reduced harmonic content.

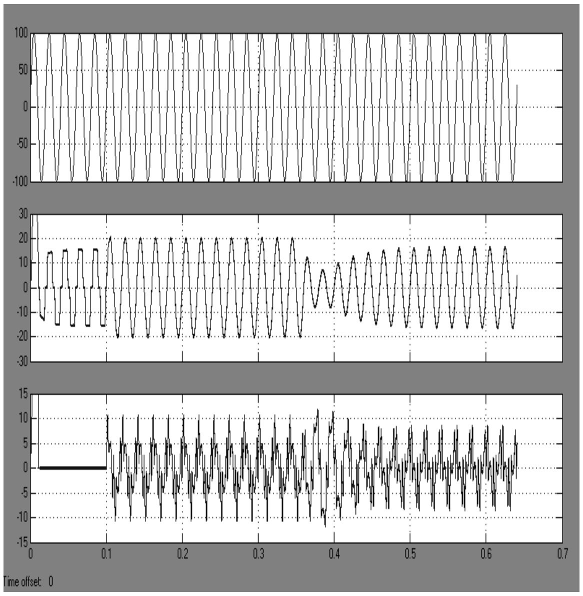

Fig.10 Source voltage, source current and filter current for phase A

The waveform shown in fig.10 demonstrates that source voltage, source current before and after compensation and filter current for phase A.

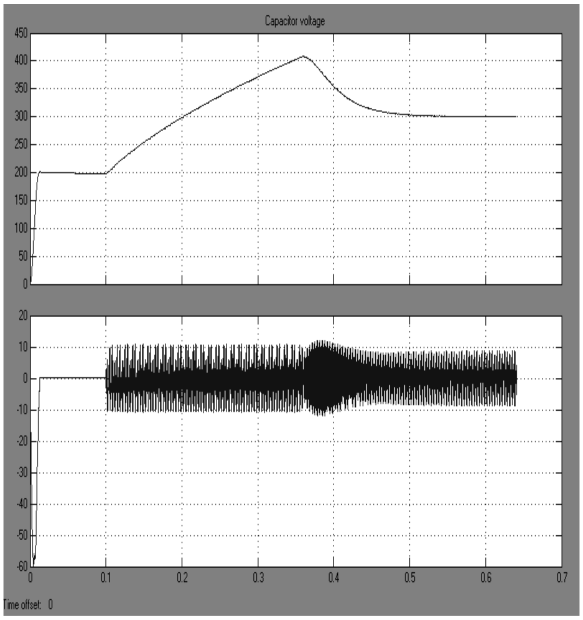

Fig.11 Capacitor voltage and capacitor current

The waveform shown in fig.11 demonstrates that capacitor voltage settles at nearly constant value of $V_{dc\ ref.}$ and capacitor current settles at almost equal to the value of filter current.

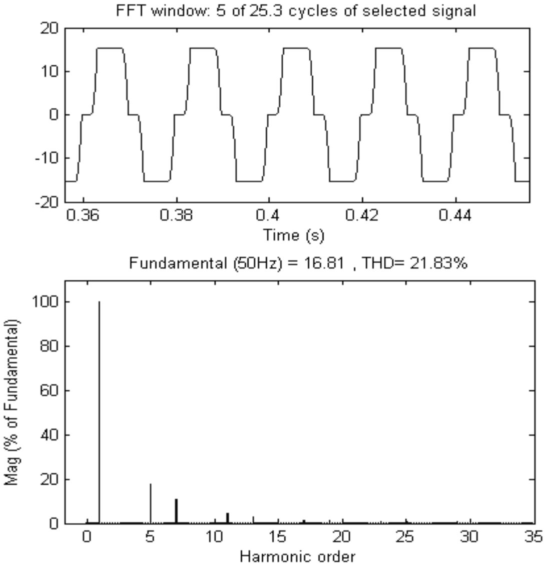

Fig.12 FFT Analysis for load current

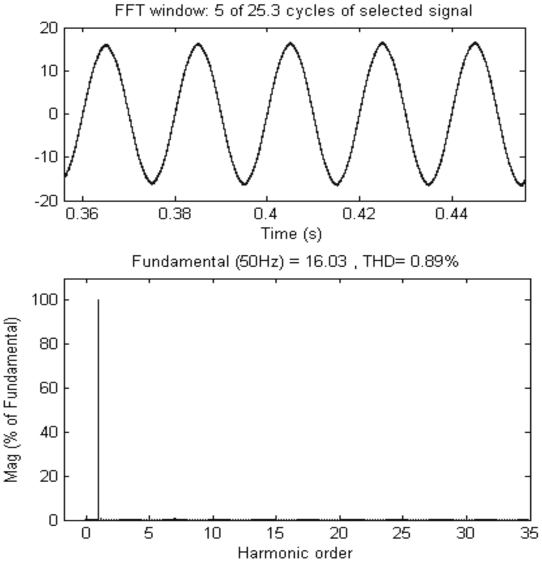

Fig.13 FFT Analysis for source current

The waveform shown in fig.12 and fig.13 demonstrates that source current is reduced THD from 21.83% to 0.89%.

THD analysis of shunt active power filter for RL-Load is shown in table 1.

Load type	THD(%) Load Current	THD(%) Source Current
R-L Load	21.83 %	0.89 %

Table 1

4. Conclusion

The performance of the system improves and the THD is reduced up to very large extent. Also, it is seen from the simulation results that the source current and the source voltages are in same phase i.e. the input power factor is unity and there is no reactive power from the source.

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Appendix

The values of the different parameters used for shunt active power filter.

- Source voltage:3-phase, 100V, 50Hz
- Proportional gain K_p: 0.5
- Integral gain K_i : 10
- Capacitor reference voltage: 300V
- RL load parameters: 10 Ω, 100mH
- line parameters : 0.2 Ω, 1.5mH
- Filter inductor : 5mH
- Hysteresis band gap : -0.01 to 0.01