Simulation And Performance Investigation Of Series Active Power Filter Using Hysteresis Current Control Method

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ABSTRACT

The simulation study of Hysteresis Current Controlled, three phase series active power filter to improve power quality by compensating harmonics and reactive power required by a non-linear load is presented. The series active filter employs a simple method for the reference compensation voltage based on p-q theory. Classic filters may not have satisfactory performance in fast varying conditions. But auto tuned active power filters give better result for harmonic minimization, reactive power compensation and power factor improvement. This paper has proposed an auto tuned series active filter 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.
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KEYWORDS

Power System, Series Active Power Filter, 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 series active power filter that achieves low voltage 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 [9].
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 [9]-[7].

Traditionally based, passive L-C filters were used to eliminate line harmonics in [1]-[13]. 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.
There are two major approaches that have emerged for the harmonic detection [1], 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 [13].
There are several current control strategies proposed in the literature [7]-[2], [12]-[3], 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 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[10].
In this paper, the proposed control algorithm for series active power filters is applicable to harmonic voltage source loads as well as to harmonic current source loads. This control algorithm is applied under the basic concept of the generalized p–q theory. However, this generalized p–q theory is valid for compensating for the harmonics and reactive power using the parallel active power filter in the three-phase power system. To overcome such limits, a revised p–q theory is proposed. This revised algorithm may be effective not only for the three-phase three-wire series active power filter with harmonic current voltage loads, but also for the combined system of parallel passive filters and active filter[14].

This chapter basically deals with the modeling and design of series active power filter for compensation of harmonics and reactive power. Designs of different parameters like power circuit, ontrol circuit, control strategies, PLL circuit are discussed.

2. Series Active Power Filter

Series active power filters are operated mainly as a voltage regulator and as a harmonic isolator between the nonlinear load and the utility system. The series connected filter protects the consumer from an inadequate supply voltage quality. This type of approach is especially recommended for compensation of voltage unbalances and voltage sags from the AC supply and for low power applications and represents economically attractive alternatives to UPS, since no energy storage (battery) is necessary and the overall rating of the components is smaller. The series active filter injects a voltage component in series with the supply voltage and therefore can be regarded as a controlled voltage source, compensating voltage sags and swells on the load side[11].

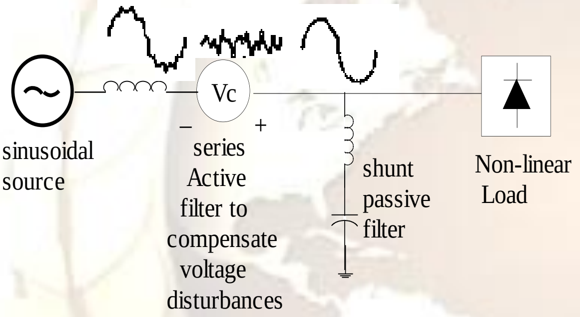

Fig.1 Filter voltage generation to compensate voltage disturbances

2.1 Basic Compensation Principle

Fig.2 shows the basic compensation principle of series active power filter. A voltage source inverter (VSI) is used as the series active power filter. This is controlled so as to draw or inject a compensating voltage V_c from or to the supply, such that it cancels voltage harmonics on the load side i.e. this active power filter (APF) generates the distortions opposite to the supply harmonics[4].

Fig.3 shows the different waveforms i.e. source voltage, desired load voltage and the compensating voltage injected by the series active power filter which contains all the harmonics, to make the load voltage purely sinusoidal. This is the basic principle of series active power filter to eliminate the supply voltage harmonics.

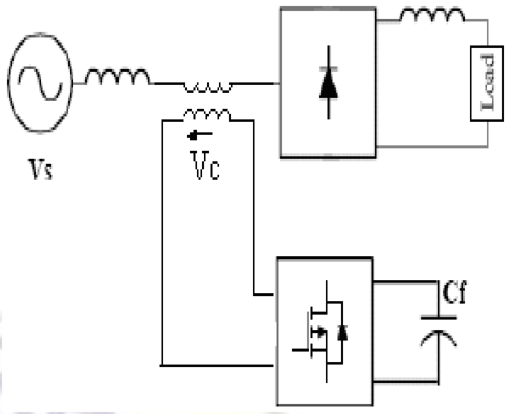

Fig.2 Basic compensation principle

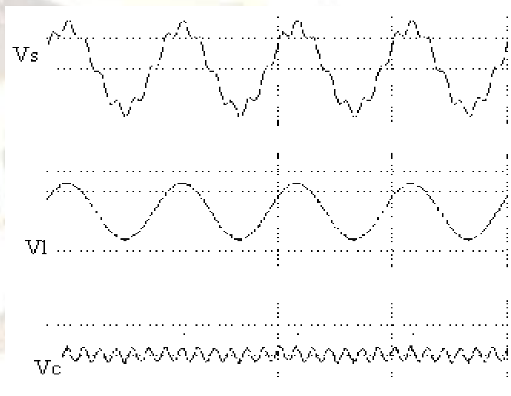

Fig.3 Waveforms for the supply voltage (V_S), Desired load voltage (V_l) and the Compensating voltage (filter voltage-V_C

2.2 Estimation Of Reference Voltage

This Section introduces the control algorithm of the series active power filter, which compensates for harmonics and reactive power. The three-phase voltages v_a, v_b and v_c and currents i_a, i_b and i_c for the three-phase three-wire power distribution system is shown in Fig.4[14]-[11]-[4].

The three-phase load voltages $v_{L(a,b,c)}$ and the three-phase source currents $i_{s(a,b,c)}$ are represented as:

$$v_{L(a,b,c)} = \begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix}, \quad i_{s(a,b,c)} = \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \tag{1}$$

The load voltage vector $v_{L(a,b,c)}$ and the source current vector $i_{s(a,b,c)}$ of (1) are transformed into $\alpha\beta 0$ co-ordinates by the substituting (3) into (2) as

$$v_{L(\alpha,\beta,0)} = [T]\begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix} = \begin{bmatrix} q_{L\alpha} \\ q_{L\beta} \\ q_{L0} \end{bmatrix},$$

$$i_{s(\alpha,\beta,0)} = [T]\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ i_{s0} \end{bmatrix} \qquad (2)$$

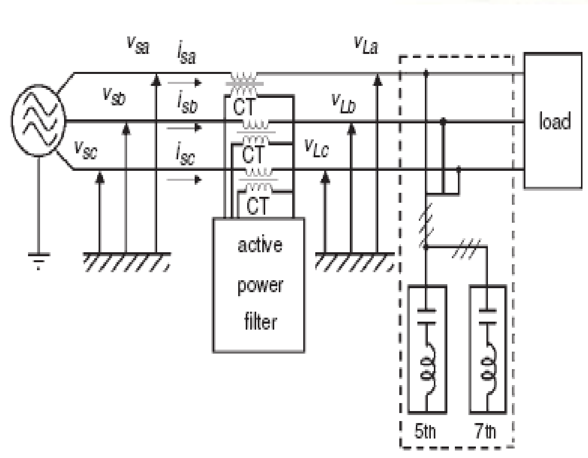

Fig.4 Circuit *configuration for series active power filter*

Where,

$$[T] = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \qquad (3)$$

The active power p can be expressed as (4) by the inner product of the load voltage vector $v_{L(\alpha,\beta,0)}$ and the source current vector $i_{s(\alpha,\beta,0)}$ of (2), where the active power p is the instantaneous active power at the load side of the CT in Fig. 4.

$$p = v_{L(\alpha,\beta,0)}\, i_{s(\alpha,\beta,0)} = v_{L\alpha} i_{s\alpha} + v_{L\beta} i_{s\beta} + v_{L0} i_{s0} \qquad (4)$$

Also, the reactive power $q_{L(\alpha,\beta,0)}$ is represented as (5) by the cross product of $v_{L(\alpha,\beta,0)}$ and $i_{s(\alpha,\beta,0)}$

$$q_{L(\alpha,\beta,0)} = v_{L(\alpha,\beta,0)} \times i_{s(\alpha,\beta,0)} \qquad (5)$$

$$q = \left\| q_{L(\alpha,\beta,0)} \right\| = \left\| v_{L(\alpha,\beta,0)} \times i_{s(\alpha,\beta,0)} \right\| \qquad (6)$$

Where, q is the instantaneous reactive power at the load side of the CT in Fig.4.

For a three-phase system without zero sequence voltage and current, i.e.

$v_a + v_b + v_c = 0$ and $i_a + i_b + i_c = 0$

$v_{L0} = \frac{1}{3}(v_a + v_b + v_c) = 0$ and

$i_{s0} = \frac{1}{3}(i_a + i_b + i_c) = 0$),

Equ. (4) and (5) can be expressed as follows:

$$p = v_{L(\alpha,\beta,0)} i_{s(\alpha,\beta,0)} = v_{L\alpha} i_{s\alpha} + v_{L\beta} i_{s\beta} \qquad (7)$$

$$q_{L(\alpha,\beta,0)} = v_{L(\alpha,\beta,0)} \times i_{s(\alpha,\beta,0)} = \begin{bmatrix} q_{L\alpha} \\ q_{L\beta} \\ q_{L0} \end{bmatrix} = \begin{bmatrix} |0| \\ |0| \\ \begin{vmatrix} v_{L\alpha} & v_{L\beta} \\ i_{s\alpha} & i_{s\beta} \end{vmatrix} \end{bmatrix} \qquad (8)$$

From (1)–(5), the active voltage vector $v_{p(\alpha,\beta,0)}$ and the reactive voltage vector $v_{q(\alpha,\beta,0)}$ are defined as follows:

$$v_{p(\alpha,\beta,0)} = \frac{p}{i_{(\alpha,\beta,0)} \cdot i_{(\alpha,\beta,0)}}\, i_{(\alpha,\beta,0)} \qquad (9)$$

$$v_{q(\alpha,\beta,0)} = \frac{q_{(\alpha,\beta,0)} \times i_{(\alpha,\beta,0)}}{i_{(\alpha,\beta,0)} i_{(\alpha,\beta,0)}} \qquad (10)$$

The $v_{p(\alpha,\beta,0)}$ represents the parallel component of the load voltage vector $v_{L(\alpha,\beta,0)}$ to the current vector $i_{s(\alpha,\beta,0)}$; $v_{q(\alpha,\beta,0)}$ represents the perpendicular component of the load voltage vector $v_{L(\alpha,\beta,0)}$ to the current vector $i_{s(\alpha,\beta,0)}$. As a result, the load voltage vector is represented by the sum of the active voltage vector $v_{p(\alpha,\beta,0)}$ and the reactive voltage vector $v_{q(\alpha,\beta,0)}$ as follows:

$$v_{L(\alpha,\beta,0)} = v_{p(\alpha,\beta,0)} + v_{q(\alpha,\beta,0)} \qquad (11)$$

The active voltage vector $v_{p(\alpha,\beta,0)}$ is induced as follows, using the projection of the load voltage vector $v_{L(\alpha,\beta,0)}$ onto the current vector $i_{s(\alpha,\beta,0)}$:

$$v_{p(\alpha,\beta,0)} = \mathrm{proj}_i v_{L(\alpha,\beta,0)} = \frac{v_{L(\alpha,\beta,0)} i_{s(\alpha,\beta,0)}}{\left\| i_{s(\alpha,\beta,0)} \right\|^2}\, i_{s(\alpha,\beta,0)} \qquad (12)$$

The reactive voltage vector $v_{q(\alpha,\beta,0)}$, which is perpendicular to the active voltage vector $v_{p(\alpha,\beta,0)}$, is also induced through (13)–(16):

$$q_{L(\alpha,\beta,0)} = v_{L(\alpha,\beta,0)} \times i_{s(\alpha,\beta,0)}$$
$$i_{s(\alpha,\beta,0)} \times q_{L(\alpha,\beta,0)} = i_{s(\alpha,\beta,0)} \times \left(v_{L(\alpha,\beta,0)} \times i_{s(\alpha,\beta,0)}\right) \tag{13}$$

$$v_{L(\alpha,\beta,0)} = \frac{i_{s(\alpha,\beta,0)} \times q_{L(\alpha,\beta,0)}}{\left\|i_{s(\alpha,\beta,0)}\right\|^2} + \frac{p}{\left\|i_{s(\alpha,\beta,0)}\right\|^2} i_{s(\alpha,\beta,0)} \tag{14}$$

The second term of the right-hand side of (15) is the active voltage vector $v_{p(\alpha,\beta,0)}$ and the first term of the right-hand side of (14) becomes the reactive voltage vector $v_{q(\alpha,\beta,0)}$:

$$v_{q(\alpha,\beta,0)} = \frac{i_{s(\alpha,\beta,0)} \times q_{L(\alpha,\beta,0)}}{\left\|i_{s(\alpha,\beta,0)}\right\|^2} = \frac{i_{s(\alpha,\beta,0)} \times q_{L(\alpha,\beta,0)}}{i_{s(\alpha,\beta,0)} i_{s(\alpha,\beta,0)}} \tag{15}$$

Where $q_{L(\alpha,\beta,0)}$ is equal to the reactive power, which is defined in the instantaneous reactive power theory. The voltage compensation reference of the series active power filter can be represented as (16), using $v_{p(\alpha,\beta,0)}$ and $v_{q(\alpha,\beta,0)}$ in (9) and (10):

$$v^*_{C(\alpha,\beta,0)} = \frac{\tilde{\rho}}{i_{s(\alpha,\beta,0)} i_{s(\alpha,\beta,0)}} i_{s(\alpha,\beta,0)} + \frac{i_{s(\alpha,\beta,0)} \times q_{L(\alpha,\beta,0)}}{i_{s(\alpha,\beta,0)} i_{s(\alpha,\beta,0)}} \tag{16}$$

The active power and the reactive power can be divided into DC components $\tilde{p}$ and $\tilde{q}$, which are generated from the fundamental components of the load voltages and the source currents, and AC components $\tilde{p}$ and $\tilde{q}$, which are generated from the negative sequence components and the harmonic components of the load voltages and the source currents. If the reactive power q is replaced by the AC component of reactive power $\tilde{q}$, a new voltage compensation reference compensates for the AC component of the active power $\tilde{p}$ and the reactive power $\tilde{q}$.

The compensation voltage reference in αβ0 co-ordinates is obtained from (16) and the final compensation voltage reference by transforming this compensation voltage reference in αβ0 co-ordinates into the compensation voltage reference of three-phase co-ordinates.

$$v^*_{C(a,b,c)} = [T]^{-1} \begin{bmatrix} v^*_{C\alpha} \\ v^*_{C\beta} \\ v^*_{C0} \end{bmatrix} = \begin{bmatrix} v^*_{Ca} \\ v^*_{Cb} \\ v^*_{Cc} \end{bmatrix} \tag{17}$$

2.3 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 [5].

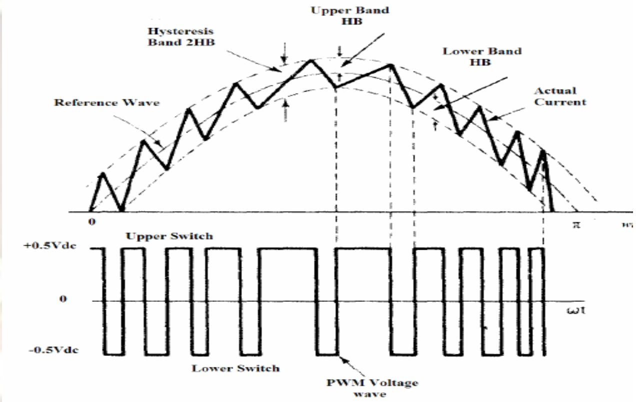

Fig.5 Basic principle of hysteresis band control

The rate of change of inductor current is then given by

$$\frac{di}{dt} = \frac{V_c \pm V_{1m}\sin(\omega t)}{L_f} \tag{18}$$

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

$$t_m = \frac{L\Delta I}{V_{c1} - V_{s1}\sin(\omega t)} \tag{19}$$

The switching frequency f_{sw} is, therefore variable. Combining above two equations (18) and (19) 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 Series APF

In this section the simulation analysis of series APF is described for R-L 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 reference voltages are generated and then these reference voltages are compared with the actual load voltages and the error signal is given to the hysteresis controller to generate the firing pulses for the switches of the inverter. The switches are turned on and off in such a way that if the reference voltage is more than the actual load voltage then the lower switch is turned on and the upper switch is turned off and if the reference voltage is less than the actual load voltage then the upper switch of the same leg is turned on and the lower switch is turned off. The output of the series active power filter is fed to the main lines through series transformers so as to make the load voltage purely sinusoidal the harmonic voltage is absorbed or injected by the filter [6].

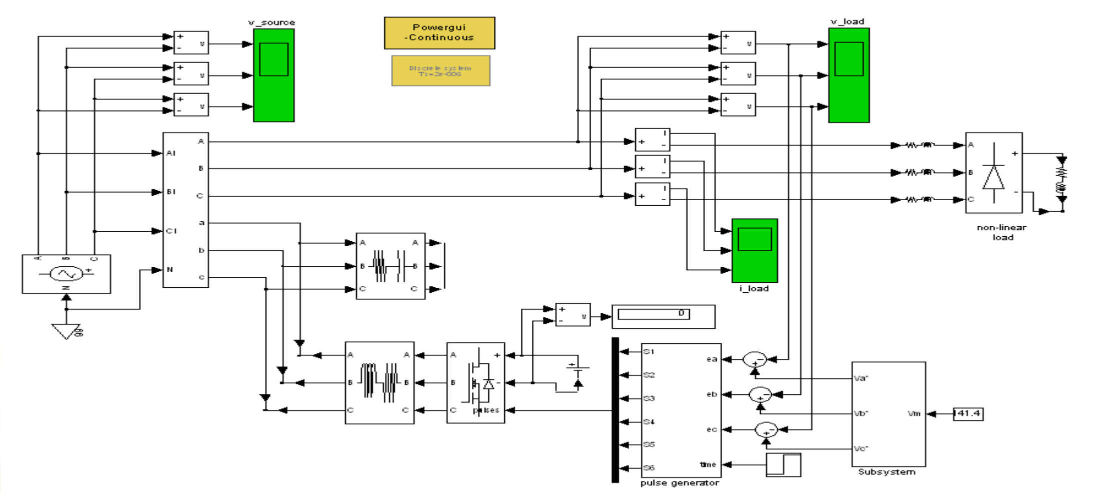

*Fig.6 MATLAB model for **Series** active power filter*

3.2 Simulation Result

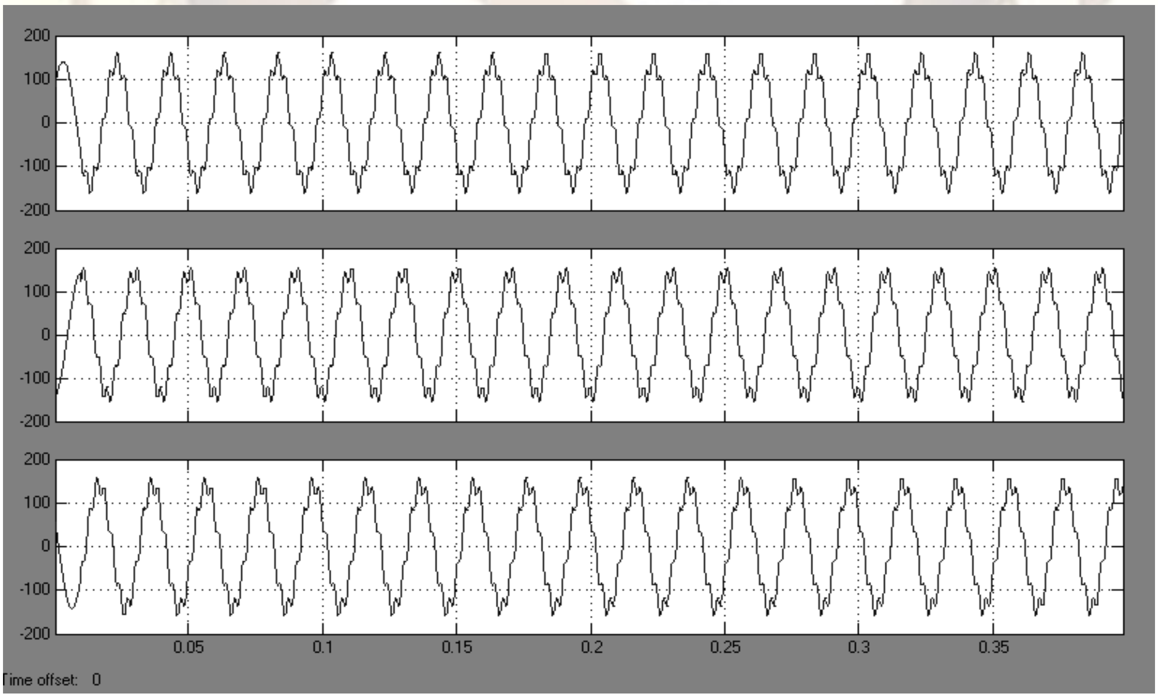

Fig.7 Source voltage containing harmonics

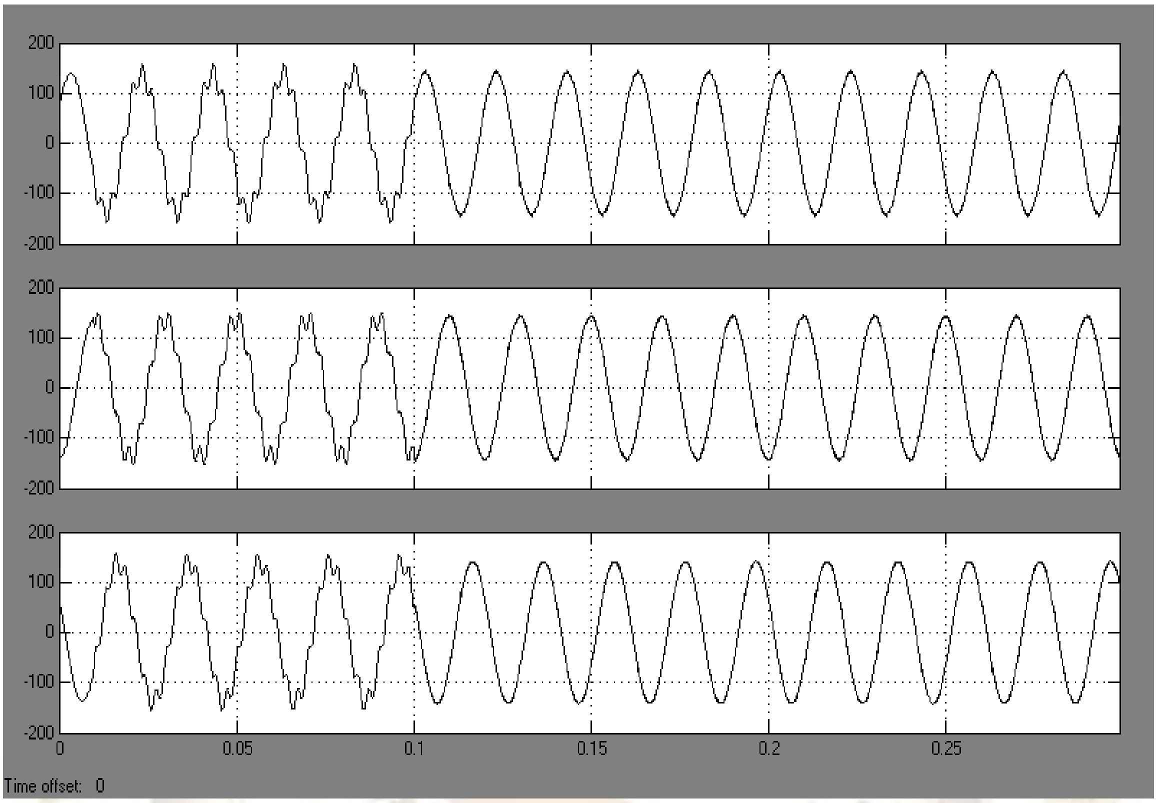

Fig.8 Load voltage before and after compensation

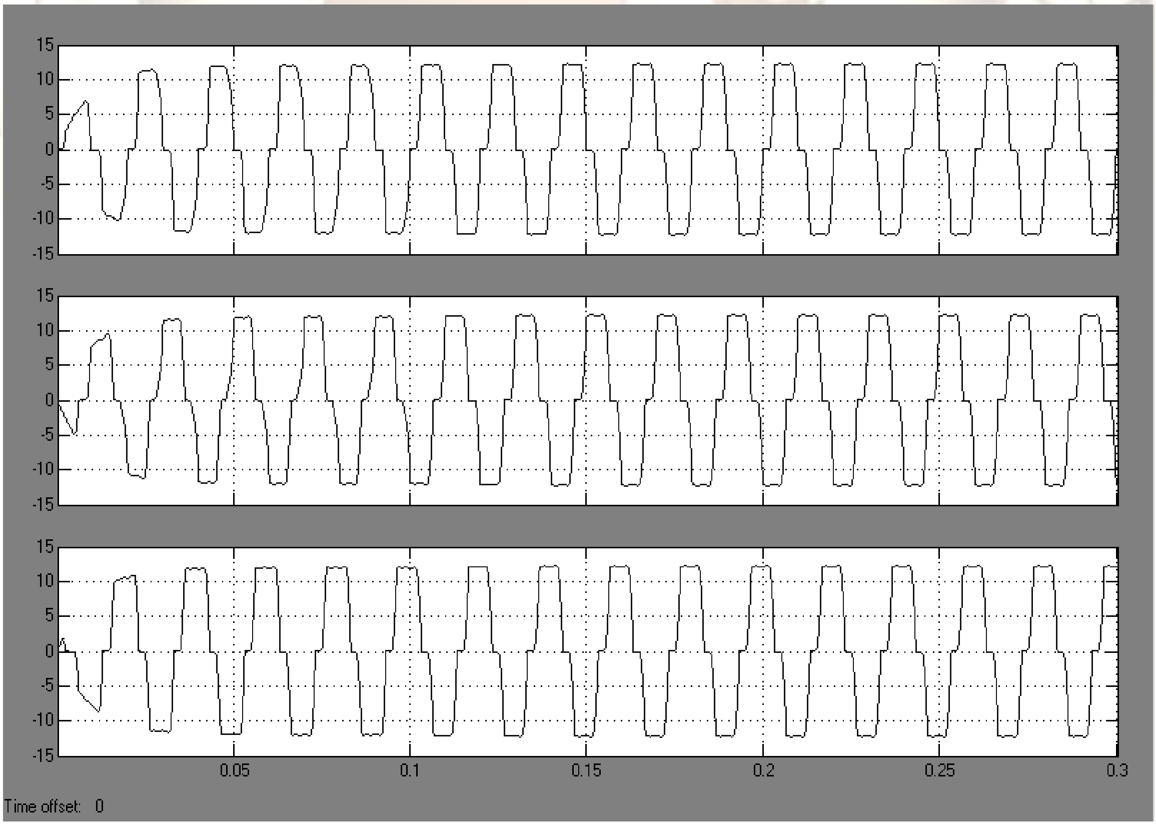

Fig.9 Load current

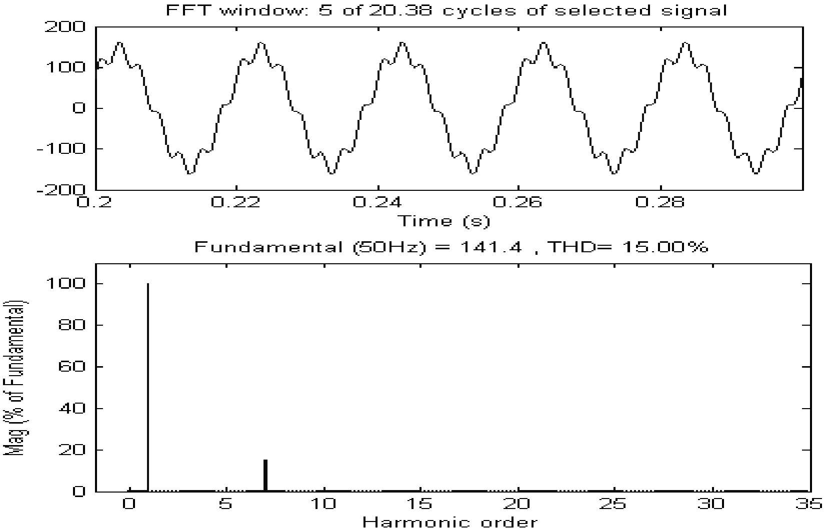

Fig.10 FFT Analysis for source voltage

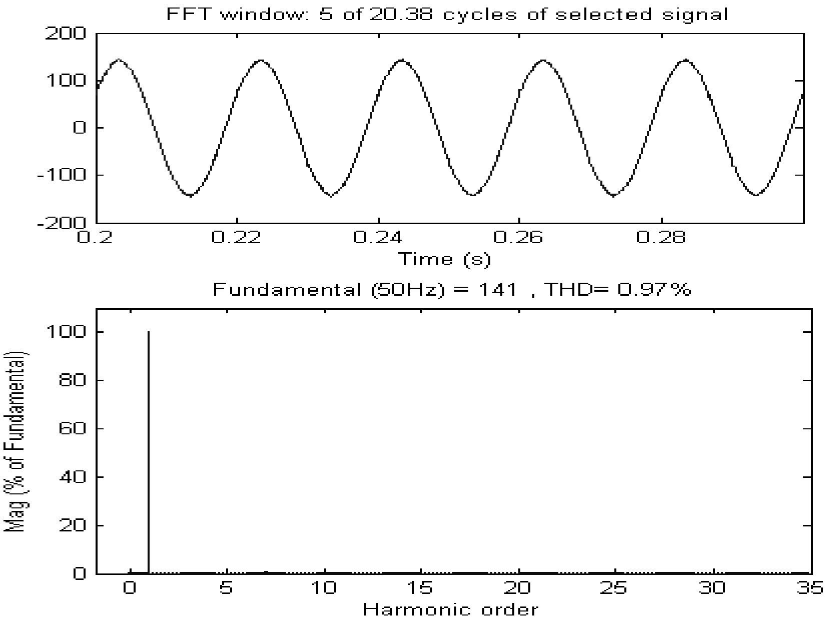

Fig.11 FFT Analysis for load voltage

Load type	THD (%) source voltage	THD (%) load voltage
R-L load	15	0.97

Table 1 THD analysis of series active power filter for R-L load

The table 1 shows the THD analysis for the source voltage and the load voltage. It is clear from the table that the performance of the system improves and the THD is reduced from 15 % to 0.97 %. The values of different parameters used for this model have been given in appendix.

4. Conclusion

A MATLAB based model of the series active power filter has been simulated for RL load using the hysteresis control technique. The simulation results show that the input voltage harmonics are compensated very effectively by using the series active power filter.

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Appendix

The values of the different parameters used for series active power filter

- Source voltage: 3-phase, 100V, 50Hz.
- Harmonics in the supply voltage: 5^{th}, 0.2pu and 7^{th}, 0.15pu.
- Series transformer rating: 1KVA, 50Hz, 240/240V
- RL load parameters : 10 Ω, 100mH
- Line parameters : 0.2 Ω, 1.5mH
- Line parameters : 0.2 Ω, 1.5mH
- RC filter parameters : 16 Ω, 199.04µF
- Hysteresis band gap : -0.01 to 0.01