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A MATLAB Model of Hybrid Active Filter Based on SVPWM Technique

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Abstract

A method for active filter having hybrid feature is discussed in this paper. The method uses space vector pulse width modulation (SVPWM). In the proposed control method, the Active Power Filter (APF) reference voltage vector is generated instead of the reference current, and the desired APF output voltage is generated by SVPWM. The whole power system block set model of the proposed scheme is developed in MATLAB environment. A MATLAB code is developed to generate the SVPWM switching pulses fed to the two-level inverter topology. The developed control algorithm is simple. The APF based on the proposed method can eliminate harmonics, compensate reactive power and balance load asymmetry.

Keyword: SVPWM, Mathematical Modeling, Active Power Filter

Introduction

The growing use of non-linear and time-varying loads has led to distortion of voltage and current waveforms and increased reactive power demand in ac mains. Harmonic distortion is known to be source of several problems, such as increased power losses, excessive heating in rotating machinery, significant interference with communication circuits, flicker and audible noise, incorrect operation of sensitive loads [1-2]. Passive filters are traditional method to eliminate harmonics, but with recent developments in power semiconductor switches and converters, coupled with developments in control techniques and analog and digital implementations, active filters are becoming an effective and commercially viable alternative to passive filters. [3]. The performance of active power filters depends on the adoptive control approaches. Various current detection methods, such as instantaneous reactive power theory [5], synchronous reference frame method [6], supplying current regulation [7] and etc., are presented. The commonness of these methods is the request for generating reference current of

APF, either with the load current or the mains current. The second is that controls the VSI to inject the compensating current into AC mains. The proposed method differs from previously discussed approaches in the following ways: a) To generate APF reference voltage vector instead of reference current; b) to generate desired APF output voltage by space vector modulation based on generated reference voltage at step a).

Mathematical Modelling of Svpwm Technique with APF

This literature is briefly discusses the theory and operation of Space Vector Pulse Width Modulation (SVPWM) explains the implementation of SVPWM for the two level inverter topology.

Philosophy of SVPWM Technique

SVPWM technique was originally developed as a vector approach to pulse width modulation for three-phase inverters. The SVPWM method is frequently used in vector controlled applications. In vector controlled applications this technique is used for reference voltage generation when current control is exercised. The SVPWM technique is more popular than conventional technique because of its excellent features.

- More efficient use of DC supply voltage.
- 15% more output voltage then conventional modulation.
- Lower Total Harmonic distortion (THD).
- Prevent un-necessary switching hence less commutation losses.

Principle of SVPWM

Firstly model of a three-phase inverter is presented on the basis of space vector representation. The three-phase VSI is reproduced in Fig.1. $S_{1,}$ to $S_{6,}$ are the six power switches that shape the output, which are controlled by the switching variables a, a', b, b' c and c' When an upper transistor is switched on, i.e., the corresponding a', b', or c' is 0. Therefore, the on and off states of the upper switches $S_{1,}$ $S_{3,}$ $S_{5,}$ can be used to determine the output voltage.

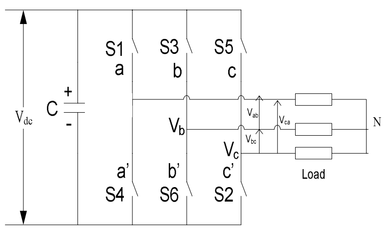

Figure 1: Power circuit of a three-phase VSI

The relationship between the switching variable vector $[a\ b\ c\ ]^t$ and line-to-line voltage vector $[V_{ab,}\ V_{bc,}\ V_{ca}\ ]$ is given by (1) in the following:

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{1}$$

Also, the relationship between the switching variable vector $[a\ b\ c\ ]^t$ and the phase voltage vector $[V_{ab,}\ V_{bc,}\ V_{ca}\ ]^t$ can be expressed below.

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{2}$$

As illustrated in Fig.1, there are eight possible combinations of on and off patterns for the three upper power switches. The on and off states of the lower power devices are opposite to the upper one and so are easily determined once the states of the upper power transistors are determined. Table 1 and shows the eight inverter voltage vectors (V_0 to V_7).

Table 1: Switching vectors, phase voltages and output line to line voltages

Voltage vectors	Switching vectors			Line to neutral voltage			Line to line voltage		
	a	b	c	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
Vo	0	0	0	0	0	0	0	0	0
V1	1	0	0	2/3	-1/3	-1/3	1	0	-1
V2	1	1	0	1/3	1/3	-2/3	0	1	-1
V3	0	1	0	-1/3	2/3	-1/3	-1	1	0
V4	0	1	1	-2/3	1/3	1/3	-1	0	1
V5	0	0	1	-1/3	-1/3	2/3	0	-1	1
V6	1	0	1	1/3	-2/3	1/3	1	-1	0
V7	1	1	1	0	0	0	0	0	0

To implement SVPWM, the voltage equations in the abc reference frame can be transformed into the stationary $d-q$ reference frame that consists of the horizontal (d) and vertical (q) axes as depicted in Fig.2.

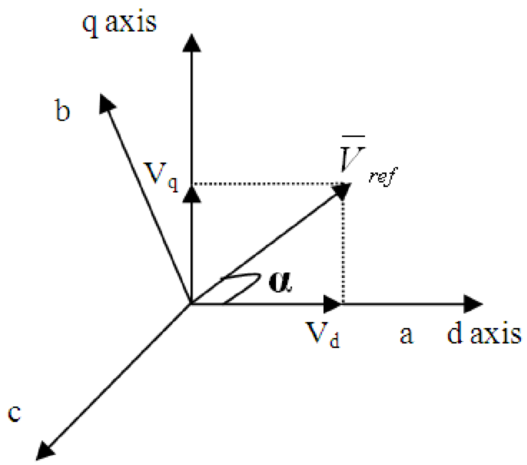

Figure 2: Voltage Space Vector and its components in (d, q)

From this figure, the relation between these two reference frames is given as
$f_{dq0} = [\ f_d\ f_q\ f_0]^T,\ f_{abc} = [\ f_a\ f_b\ f_c\ ]^T,$ (3)

where, f denotes either a voltage or a current variable.

Therefore, space vector PWM can be implemented by the following steps
Step 1: Determination of V_d, V_q, V_{ref} an angle(α)
Step 2: Determination of time duration T_1, T_2, T_0
Step 3: Determination of the switching time of each switch (S_1 to S_6)

Step 1: Determination of V_d, V_q, V_{ref} and angle (α)

$$\therefore \begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix}$$

$$\therefore \left| \overline{V}_{ref} \right| = \sqrt{V_d^2 + V_q^2}$$

$$\therefore \alpha = \tan^{-1}\left(\frac{V_q}{V_d} \right) = \omega t = 2\pi f t\ ,$$

where f =fundamental frequency.

Step 2: Determination of time duration T_1, T_2, T_0

From Fig.2, the switching time duration can be calculated as follows:

$$\Rightarrow T_z \cdot \left|\overline{V}_{ref}\right| \cdot \begin{bmatrix} \cos\alpha \\ \sin\alpha \end{bmatrix} = T_1 \cdot \frac{2}{3} . V_{dc} \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} + T_2 \cdot \frac{2}{3} \cdot V_{dc} \cdot \begin{bmatrix} \cos\left(\pi/3\right) \\ \sin\left(\pi/3\right) \end{bmatrix}$$

(Where, $0 \leq \alpha \leq 60°$)

$$\therefore T_1 = T_z \cdot a \cdot \frac{\sin(\pi/3 - \alpha)}{\sin(\pi/3)}$$

$$\therefore T_2 = T_z \cdot a \cdot \frac{\sin(\alpha)}{\sin(\pi/3)}$$

$$\therefore T_0 = T_z - (T_1 + T_2) \quad \left(where\, T_z = \frac{1}{f_z} \;\; and \;\; a = \frac{\left|\overline{V}_{ref}\right|}{\frac{2}{3} V_{dc}} \right)$$

Block Diagram of Control System

The main section of the APF shown in Fig.3 is a forced-commutated VSI connected to dc capacitor. Considering that the distortion of the voltage in public power network is usually very low, it can be assumed that the supply voltage is ideal sinusoidal and three-phase balanced as shown below

It is known that the three-phase voltages $[V_{sa,} V_{sb,} V_{sc}]$ in $a - b - c$ can be expressed as two-phase representation in $d - q$ frame by Clark's transformation and it is given by

$$\overline{V_s} = \begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \tag{4}$$

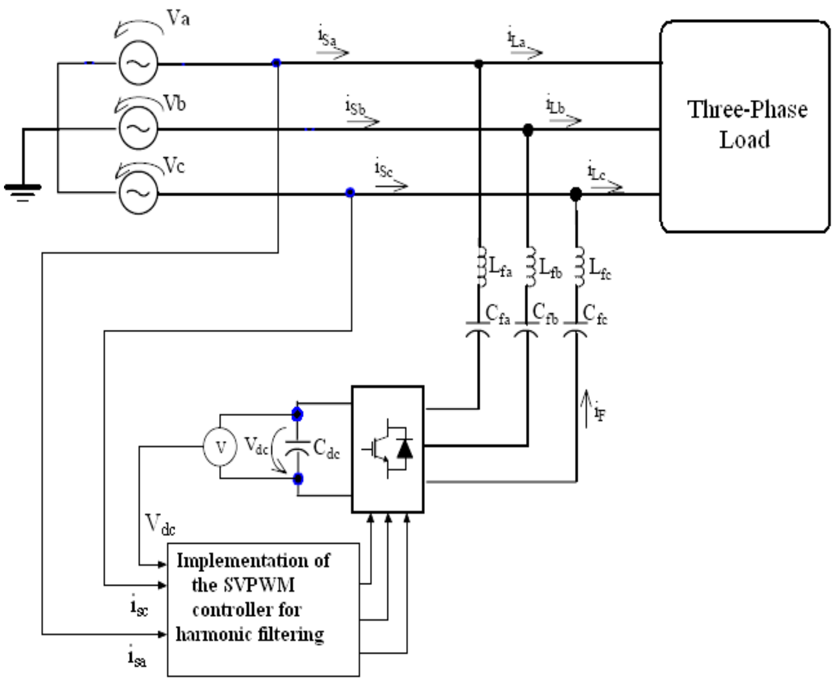

Figure 3: Configuration of a Hybrid APF using SVPWM

As shown in Fig. 3, the shunt APF takes a three-phase voltage source inverter as the main circuit and uses capacitor as the energy storage element on the dc side to maintain the dc bus voltage V_{dc} constant.

Compensation Principle

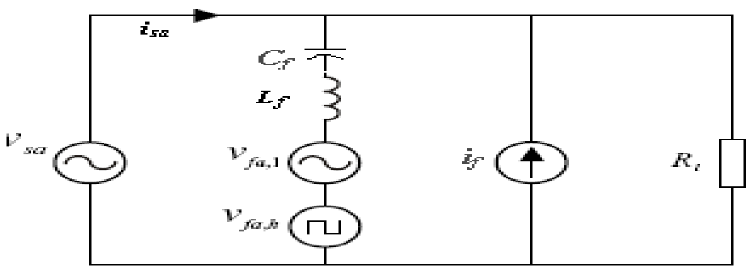

Figure 4: Equivalent circuit of a simple power system together with the Hybrid APF

In the Fig.2.5, V_{fa1} and V_{fah} denote the output fundamental and harmonic voltages of the inverter, respectively. These voltage sources are connected to a supply source $V_{sa,}$ in parallel via a link inductor L_f and capacitor C_f .The supply current $i_{sa,}$ is forced to be free of harmonics by appropriate voltages from the APF and the harmonic current emitted from the load is then automatically compensated.

It is known from Fig.4, that only fundamental component is taken into account, the voltages of the ac supply and the APF exist the following relationship in the steady state

$$\overline{V}_s = L_f \cdot \frac{d\overline{I}_{f1}}{dt} + \frac{1}{C_f}\int \overline{I}_{f1} dt + \overline{V}_{f1} \tag{5}$$

Where $\overline{V}_s$ is the supply voltage, $\overline{I}_{f1}$ is the fundamental current of APF, $\overline{V}_{f1}$ is the fundamental voltage of APF, and above variables are expressed in form of space vector. The APF is joined into the network through the inductor L_f and C_f the function of these is to filter higher harmonics nearly switching frequency in the current and to link two ac voltage sources of the inverter and the network. So the required inductance and capacitance can just adopt a small value. Then the total reactance caused by inductor and capacitor for the frequency of 50Hz, and the fundamental voltages across the link inductors and capacitors are also very small, especially compared with the mains voltages. Thus the effect of the voltage of the link inductor and capacitor is neglected. So the following simplified voltage balanced equation can be obtained from equation (5).

$$\overline{V}_s = \overline{V}_{f1} \tag{6}$$

The control object of APF is to make the supply current sinusoidal and in phase with the supply voltage. Thus the nonlinear load and the active power filter equals to a pure resistance load R_s, and the supply voltage and the supply current satisfy the following equation:

$$\overline{V}_s = R_s \cdot I_s \tag{7}$$

Where $\overline{I}_s = \frac{2}{3}\left(i_{sa}a^0 + i_{sb}a^1 + i_{sc}a^2\right) = I_{sd} + jI_{sq} = I_s\angle\theta_i$. Then the relationship between I_s and the supply voltage amplitude V_s is

$$\overline{V}_{f1} = \frac{V_s}{I_s} \cdot \overline{I}_s \tag{8}$$

Equation (8) describes the relationship between the output fundamental voltage of APF, the supply voltage and the supply current, which ensure that the APF operate normally. However, for making the APF normally achieving the required effect, the dc bus voltage V_{dc} has to be high enough and stable. In the steady state, the power supplied from the supply must be equal to the real power demanded by the load, and no real power passes through the power converter for a lossless APF system. On the contrary, the average voltage of the dc capacitor rises, and the supply current must be decreased.

Therefore, the average voltage of the dc capacitor can reflect the real power flow information. In order to maintain the dc bus voltage as constant, the detected dc bus voltage is compared with a setting voltage. The compared results are fed to a PI controller, and amplitude control of the supply current i_s can be obtained by output of PI controller

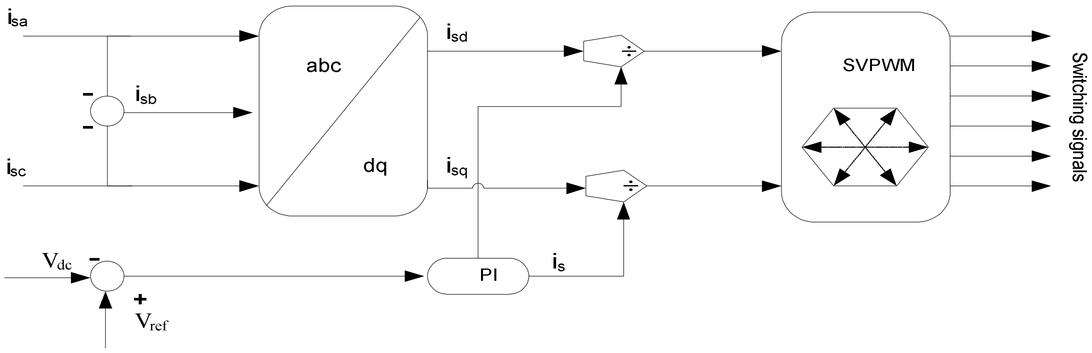

Figure 5: Control block diagram of proposed algorithm

The fig.5 shows the block diagram of active filter controller implemented for reducing the harmonics with hybrid active filter system. In each switching cycle, the controller samples the supply currents $i_{sa,}$ i_{sc} and the supply current i_{sc} is calculated. These three-phase supply currents are measured and transformed into synchronous reference frame (d-q axis). The generated switching actions are applied to the APF and power balancing of the filter takes place.

Simulation and Results

The developed control method for three-phase hybrid APF is simulated in MATLAB/Simulink. Firstly, the three-phase supply currents are sensed and transformed into synchronous reference frame (d-q) axis. The obtained d-q axis components generate voltage command signal. By using Fourier magnitude block, voltage magnitude and angle is calculated from the obtained signal. These values are fed to the developed code and generated switching actions are applied to the hybrid APF. Thus, power balancing of the filter takes place. The complete simulation model of APF with different type of loads is shown in further diagrams. For an input supply voltage of 230V (rms) and switching frequency of 5 kHz, the simulation results before and after power balancing are shown.

Table 2: Parameter values

System parameters	Values of parameters
Supply system	$220\ V_{rms},\ 50\ H_z,$ three phase supply
Balanced linear load	$Z_1 = 50 + j6.28\Omega,$
APF	$C_{dc} = 450\mu f, V_{ref} = 900V, C_f = 70\mu f,$ $L_f = 25mH$

Linear load

Case 1: Balance RL load condition without APF

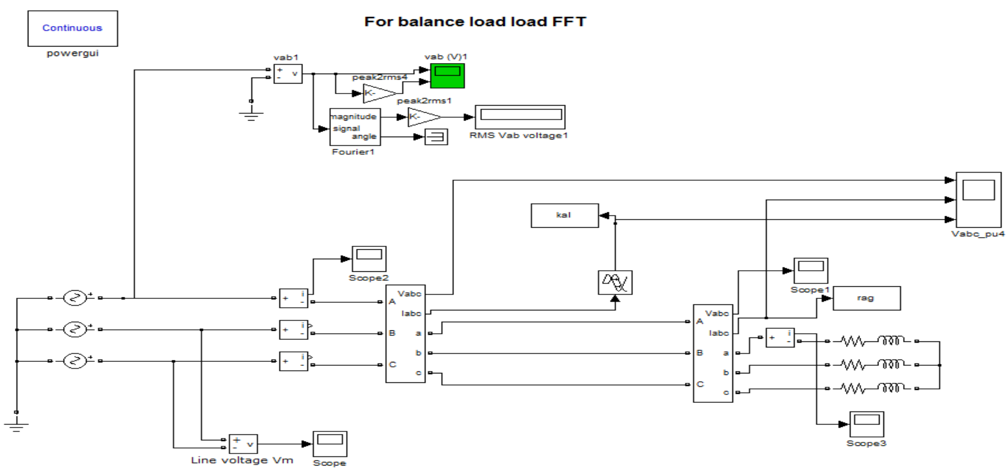

Figure 6: Simulation model of three phase balance RL-load condition without APF.

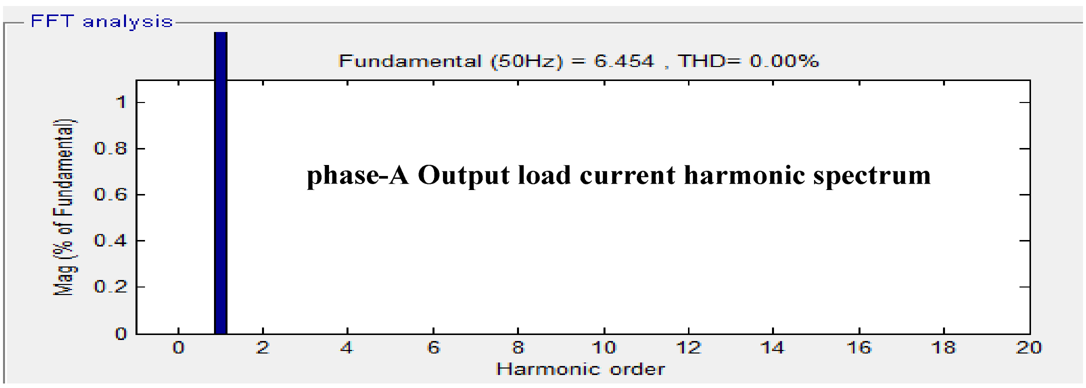

Figure (a): Phase-A load current harmonic spectrum

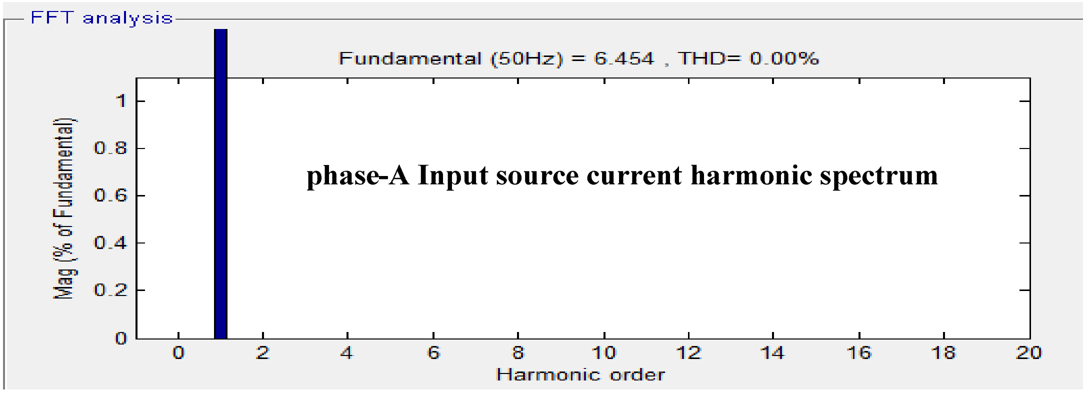

Figure (b): Phase-A source current harmonic spectrum

Figure 7: Harmonic spectrum of linear balance load without APF

Case 2: SVPWM Technique for Linear balance RL load condition with APF

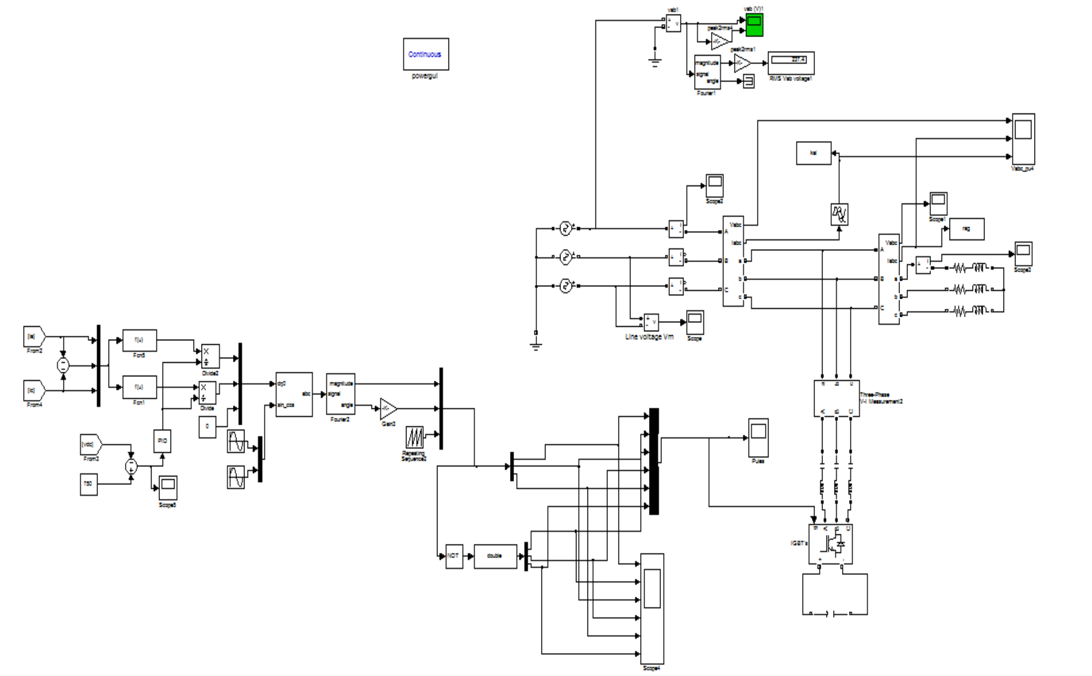

Figure 8: SVPWM Technique for linear balance RL-load condition with APF.

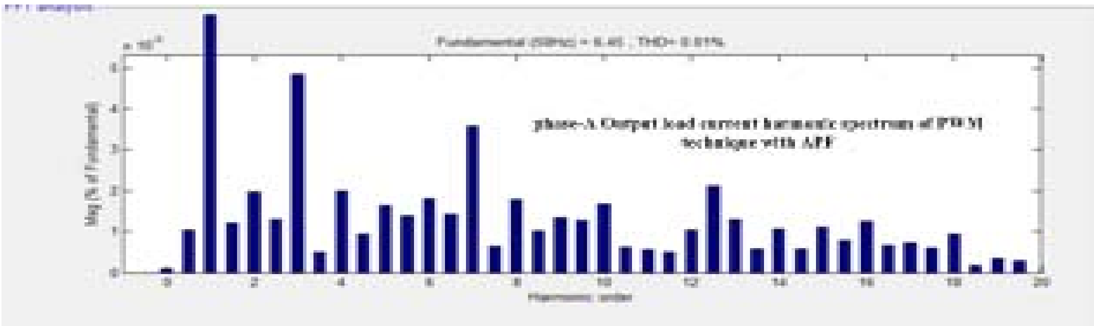

Figure (a): Output load current harmonic spectrum

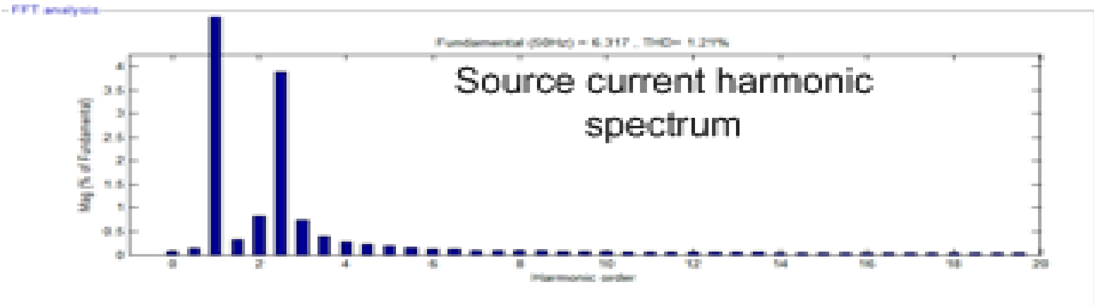

Figure (b): Input source current harmonic spectrum

Figure 9: Harmonic spectrum of SVPWM Technique for linear balance RL-load condition with APF

Result Analysis

Table 3: Simulation of harmonic spectrum

Types of load	Without APF		SVPWM Technique with APF	
	THD Load Side	THD Source side	THD Load Side	THD Source side
Linear Balance RL load	0.00%	0.00%	0.02%	1.21%
Nonlinear Rectifier with R load	30.28%	30.2%	30.28%	5.47%

From Table 3 shows the simulation of harmonic spectrum of linear three phase balance load is the harmonic spectrum of the current before compensation on the load side. When the APF is used the harmonic generate at the source side the value of supply current THD is 1.21% when SVPWM Technique used. And the value of supply current THD is 1.21% when SVPWM Technique used.

When the APF is used for non linear loads, the harmonic generate at the source side, the value of supply current THD is 1.31% when SVPWM Technique used.

From Table 3 shows the simulation of harmonic spectrum of APF with SVPWM Technique used for non linear load used. When the non-linear is a three-phase diode bridge rectifier with resistance load is very large. The harmonic spectrum of the source current shows that magnitude of the 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonics are evidently reduced after compensation. The load current Total Harmonic Distortion (THD) is 30.28%, while the supply current THD is 5.47%.when SVPWM Technique is used.

Conclusion

The active power filter controller has become the most important technique for reduction of current harmonics in electric power distribution system. In this thesis a model for three-phase active power filter for balanced non-linear load is made and simulated using MATLAB/Simulink software package for the reduction harmonics in source current. The conclusions of the manuscript such as:

- During this paper work the performance of the hybrid active power filter is analyzed using SVPWM technique for minimizing harmonics, and improving the power factor in the power system.
- The performance of the hybrid active power filter is verified with the simulation results. Form the results; it clearly indicates that, the current ripple is less by using SVPWM.
- In case of non linear load the THD response of the source current before compensation is 30.28%
- The THD of the source current after compensation is 5. 47% by using SVPWM technique.

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