ANALYSIS OF DISCRETE & SPACE VECTOR PWM CONTROLLED HYBRID ACTIVE FILTERS FOR POWER QUALITY ENHANCEMENT

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ABSTRACT

It is known from the fact that Harmonic Distortion is one of the main power quality problems frequently encountered by the utilities. The harmonic problems in the power supply are caused by the non-linear characteristic based loads. The presence of harmonics leads to transformer heating, electromagnetic interference and solid state device mal-functioning. Hence keeping in view of the above concern, research has been carried out to mitigate harmonics. This paper presents an analysis and control methods for hybrid active power filter using Discrete Pulse Width Modulation and Space Vector Pulse Width Modulation (SVPWM) for Power Conditioning in distribution systems. The Discrete PWM has the function of voltage stability, and harmonic suppression. The reference current can be calculated by'd-q' transformation. In SVPWM technique, 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 THD will be decreased significantly by SVPWM technique than the Discrete PWM technique based Hybrid filters. Simulations are carried out for the two approaches by using MATLAB, it is observed that the %THD has been improved from 1.79 to 1.61 by the SVPWM technique.

KEYWORDS: *Discrete PWM Technique, Hybrid Active Power Filter, Reference Voltage Vector, Space Vector Pulse Width Modulation (SVPWM), Total Harmonic Distortion (THD), Voltage Source Inverter (VSI).*

I. INTRODUCTION

High power non-linear and time varying loads, such as rectifiers, office equipments like computers and printers, and also adjustable speed drives causes undesirable phenomena in the operation of power systems like harmonic pollution and reactive power demand [1-2]. The application of passive tuned filters creates new system resonances which are dependent on specific system conditions. In addition, passive filters often need to be significantly overrated to account for possible harmonic absorption from the power system. Passive filter ratings must be co-ordinate with reactive power requirements of the loads and it is often difficult to design the filters to avoid leading power factor operation for some load conditions [3-4]. Parallel active filters have been recognized as a viable solution to current harmonic and reactive power compensation. Various active power filter configurations and control strategies have been proposed and developed in the last decade in order to reduce these undesirable phenomena. Active filters have the advantage of being able to compensate for harmonics without fundamental frequency reactive power concerns. This means that the rating of the active power can be less than a comparable passive filter for the same non-linear load and the active filter will not introduce system resonances that can move a harmonic problem from one frequency to another. The active filter concept uses power electronics to produce harmonic current components that cancel the harmonic current components from the non-linear loads.
The active filter uses power electronic switching to generate harmonic currents that cancel the harmonic currents from a non-linear load. The active filter configuration investigated in this paper is

based on a discrete pulse-width modulation and pulse-width modulated (PWM) voltage source inverter based filters.

Among the various topologies the shunt active filter based on Voltage Source Inverter (VSI) is the most common one because of its efficiency [5]. The performance of active filter depends on the adoptive control approaches. There are two major parts of an active power filter controller. The first is that determines the reference current of APF and maintains a stable DC bus voltage. Various current detection methods, such as instantaneous reactive power theory, synchronous reference frame method, supplying current regulation, etc., are presented. The commonness of these methods is the request for generating reference current of Active Power Filter (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 commonness of these methods is to control VSI with the difference between real current and reference current.

In discrete PWM technique based hybrid filters, the system has the function of voltage stability, and harmonic suppression. The reference current can be calculated by 'd-q' transformation [6-7]. In pulse-width modulated (PWM) voltage source inverter based filter differs from previously discussed approach 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 Pulse Width Modulation (SVPWM) [8-9] based on generated reference voltage. Therefore, the proposed method is simple and easy to carry out. This paper discussed the basic principle of this method in detail and proved its validity by simulation results.

II. PROPOSED CONTROL METHODS

2.1. Using Discrete PWM Technique Based Hybrid Filter

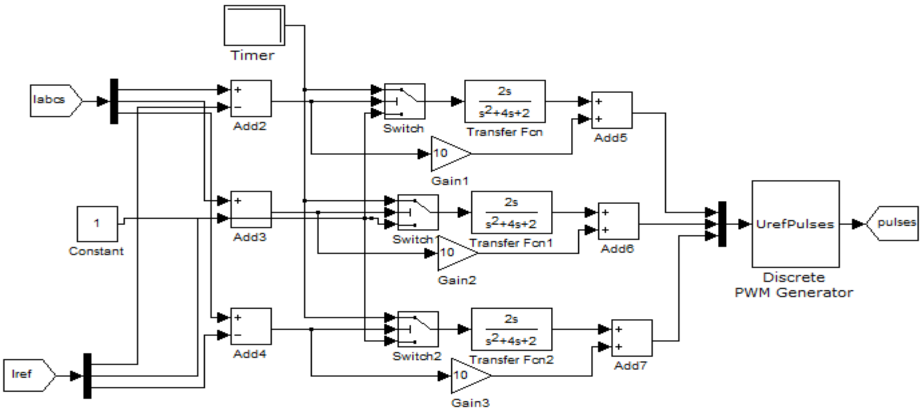


Figure 2.1. Simulation circuit of integral controller with Discrete PWM Generator

The Figure 2.1 is the integral controller used to generate the PWM pulses, which are generated based on the error produced by comparing the reference current and the source current. The differences calculated along with the gains are sent to discrete PWM generator and the resultant PWM pulses are given to the IGBT bridge for controlling.

2.2. d-q Transformation

The abc_to_dq0 Transformation block computes the direct axis, quadratic axis, and zero sequence quantities in a two-axis rotating reference frame for a three-phase sinusoidal signal. The following transformation is used

$$V_d = \frac{2}{3}(V_a \sin(\omega\, t) + V_b \sin(\omega\, t - {}^{2\pi}/_{3}) + V_c \sin(\omega\, t + {}^{2\pi}/_{3} \quad (2.1)$$

$$V_q = \frac{2}{3}(V_a \cos(\omega\, t) + V_b \cos(\omega\, t - {}^{2\pi}/_{3} + V_c \cos(\omega\, t + {}^{2\pi}/_{3}) \quad (2.2)$$

$$V_o = \frac{1}{3}(V_a + V_b + V_c) \quad (2.3)$$

Where ω = rotation speed (rad/s) of the rotating frame.

The transformation is the same for the case of a three-phase current; which can be obtained by replacing the V_a, V_b, V_c, V_d, V_q, and V_0 variables with the I_a, I_b, I_c, I_d, I_q, and I_0 variables.This block can be used in a control system to measure the positive-sequence component V_1 of a set of three-phase voltages or currents. The V_d and V_q (or I_d and I_q) then represent the rectangular coordinates of the positive-sequence component.

2.3. Control Method Using SVPWM Based Hybrid Filter

The main section of the APF shown in Figure 2.2 is a forced-commutated VSI connected to D.C capacitor [10]. 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:

$$V_{sa} = V_s \sin(wt)$$
$$V_{sb} = V_s \sin(wt - 2\pi/3)$$
$$V_{sb} = V_s \sin(wt + 2\pi/3) \qquad (2.4)$$

Where Vs is the supply voltage amplitude.

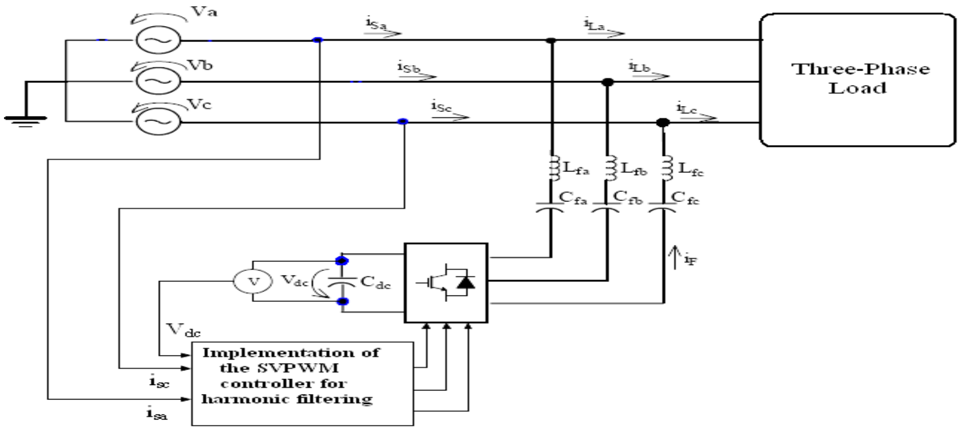


Figure 2.2. Configuration of an APF using SVPWM

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

$$\overline{Vs} = \begin{bmatrix} Vd \\ Vq \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} Vsa \\ Vsb \\ Vsc \end{bmatrix} \qquad (2.5)$$

It is possible to write equation (1.2) more compactly as

$$[\overline{Vs}] = {}^{2}/_{3}\,(V_{sa}\, a^0 + V_{sb}a^1 + V_{sc}a^2\,) = V_{sd} + jV_{sq} = V_s\angle\theta^s \qquad (2.6)$$

Where $a\ = e^{j\frac{2}{3}\pi}$, so balanced three-phase set of voltages is represented in the stationary reference frame by a space vector of constant magnitude, equal to the amplitude of the voltages, and rotating with angular speed $w\ = 2\pi f$.

As shown in Figure 2.2, 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. Figure 2.3 shows the per-phase (Phase A) equivalent circuit of the system.

2.4. Compensation Principle

In the Figure 2.3, $v_{fa,1}$ and $v_{fa,h}$ 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 Figure 2.3, 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

$$\overline{V_s} = L_f.\frac{d\overline{I_{f1}}}{dt} + \frac{1}{C_f}\int \overline{I_{f1}}\,dt \quad + \overline{V_{f1}} \qquad (2.7)$$

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.

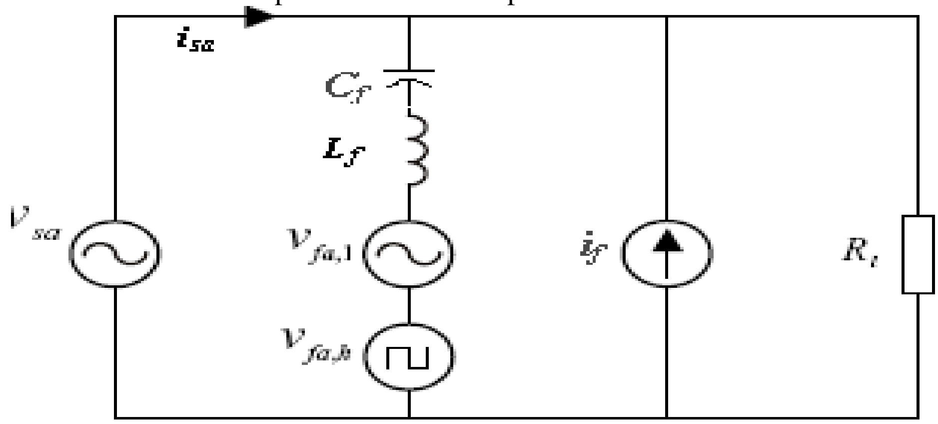


Figure 2.3. Equivalent circuit of a simple power system together with the APF

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 (2.7).

$$\overline{V_s} = \overline{V_{f1}} \tag{2.8}$$

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:

$$\overline{V_s} = R_s\,.I_s \tag{2.9}$$

Where $\overline{I_s} = \frac{2}{3}(i_{sa}a^0 + i_{sb}a^1 + i_{sc}a^2 = I_{sd} + JI_{sq} = I_s\angle\theta_i$

Then the relationship between I_s and the supply voltage amplitude Vs is

$$V_s = R_s\,.I_s \tag{2.10}$$

Substituting (2.9), (2.10) into (2.8) results in

$$\overline{V_{f1}} = \frac{V_s}{I_s}\overline{I_s} \tag{2.11}$$

Equation (2.11) describes the relationship between the output fundamental voltage of APF, the supply voltage and the supply current, which ensure that the APF operate normally[11-12]. 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. Hence, the average voltage of DC capacitor can be maintained at a constant value. If a power imbalance, such as the transient caused by load change, occurs, the DC capacitor must supply the power difference between the supply and the load, the average voltage of the DC capacitor is reduced. At this moment, the magnitude of the supply current must be enlarged to increase the real power delivered by the supply. 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 is fed to a PI controller, and amplitude control of the supply current I_s can be obtained by output of PI controller.

The Figure 2.4 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 with the equation of$-(i_{sa} + i_{sc})$, as the summation of three supply current is equal to zero. These three-phase supply currents are measured and transformed into synchronous reference frame (d-q axis) [13-14]. The fundamental component of the supply current is transformed into DC quantities in the (d-q) axis and the supply current amplitude I_s generated by the PI controller with V_{dc} and V_{ref}, the reference value of the DC bus voltage. 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 compared with the repeating sequence. Then the time durations T_1, T_2 and T_0, the on-time of V_1, V_2 and V_0 are calculated. The generated switching actions are applied to the APF and power balancing of the filter takes place.

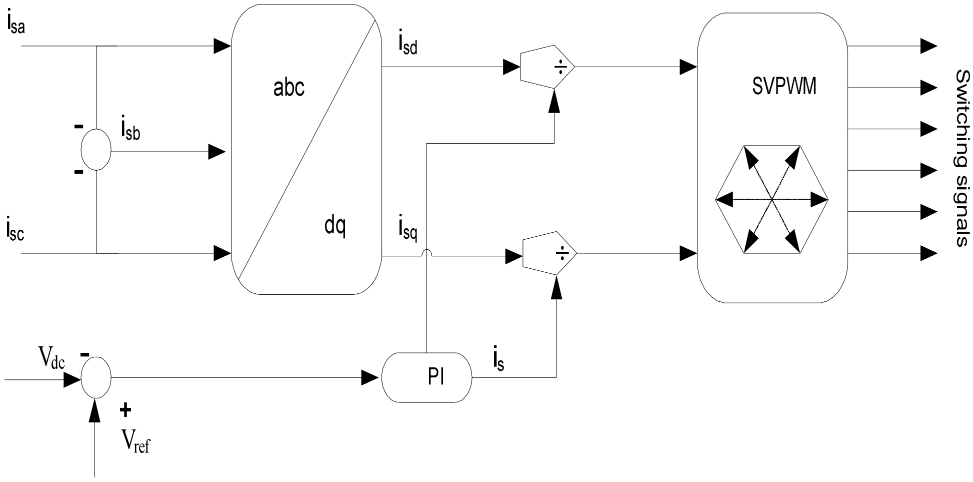


Figure 2.4. Control block diagram of proposed algorithm

III. RESULTS AND DISCUSSIONS

3.1.Discrete PWM Technique Based Hybrid Shunt Active Power Filter

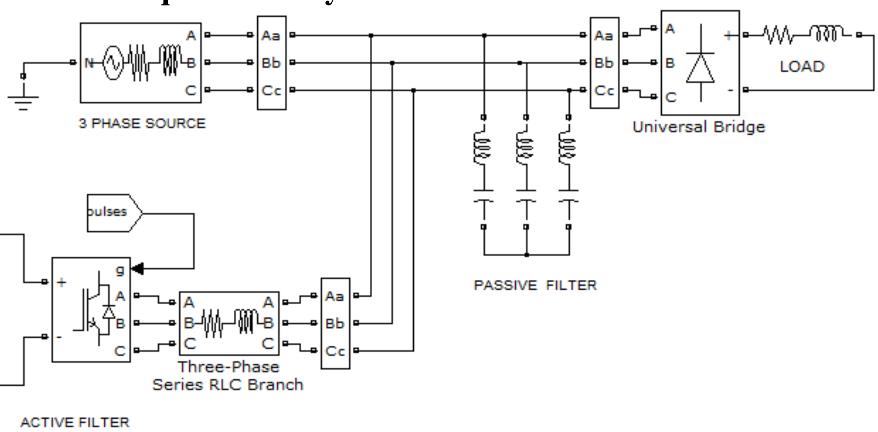


Figure 3.1. Simulation circuit of hybrid shunt active power filter

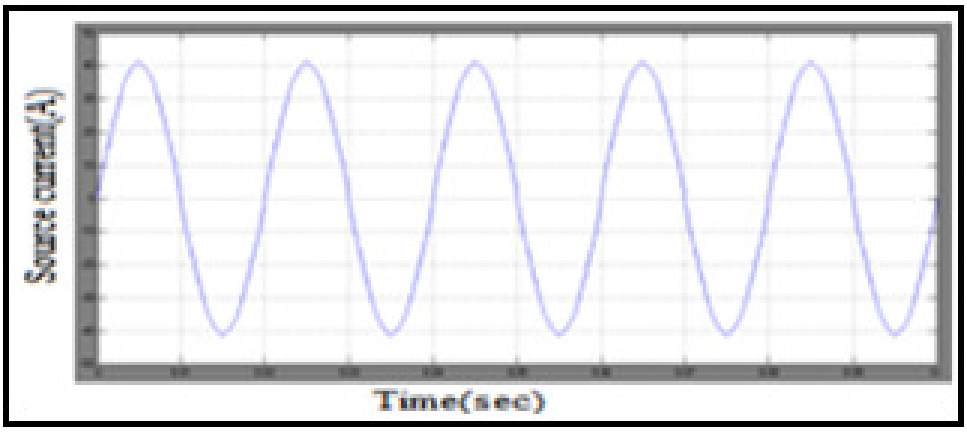


Figure 3.2. Source current waveform with hybrid filter

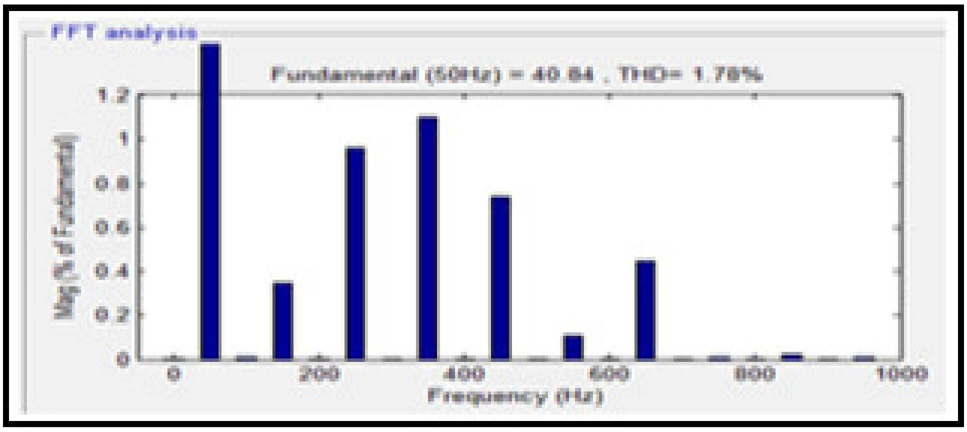


Figure 3.3. FFT analysis of source current with hybrid filter

The circuit shown in Figure 3.1 consists of both active and passive filters, the main purpose of this hybrid filter is that it reduces the harmonic content to a larger extent compared with the above methods. The lower and higher order harmonics are reduced by the passive filter and the other order harmonics are reduced by the active filter. In the case of hybrid filters, the wave form appears in a sinusoidal shape and the distortions are less as shown in the Figure 3.2 compared with the previous techniques. So, the hybrid filter is preferred due to its better performance characteristics. From the FFT analysis of source current with hybrid filter, It is observed that the %THD is 1.78.

3.2. SVPWM Technique Based Hybrid Shunt Active Power Filter

The developed control method for three-phase shunt APF is simulated in MATLAB/ Simulink. Firstly, the three-phase supply currents are sensed and transformed into synchronous reference frame (d-q) axis. The fundamental component of the supply current is transformed into DC quantities in the (d-q) axis and the supply current amplitude I_s generated by the PI controller. 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 APF. Thus, power balancing of the filter takes place. Further, the performance with different type of loads is presented. The complete simulation model of APF with different type of loads is shown in Figure 3.5 and Figure 3.8. For an input supply voltage of 230V (rms) and switching frequency of 5kHz, the simulation results before and after power balancing are shown.

3.2.1. For Balanced Linear Load

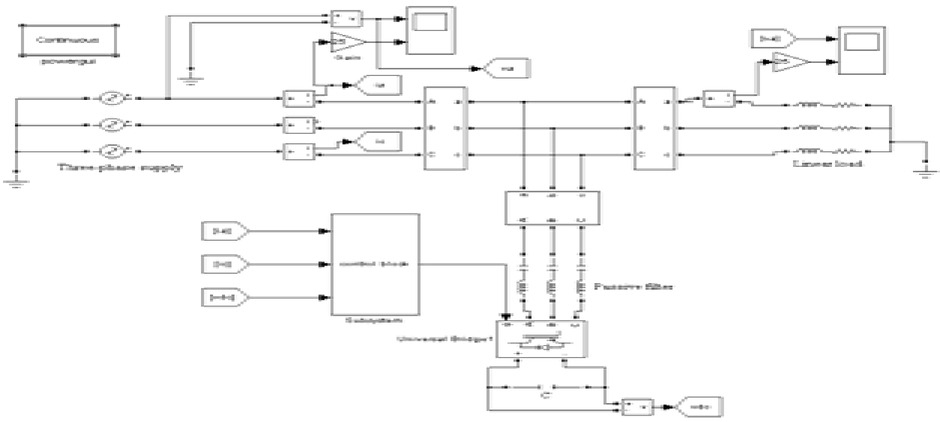
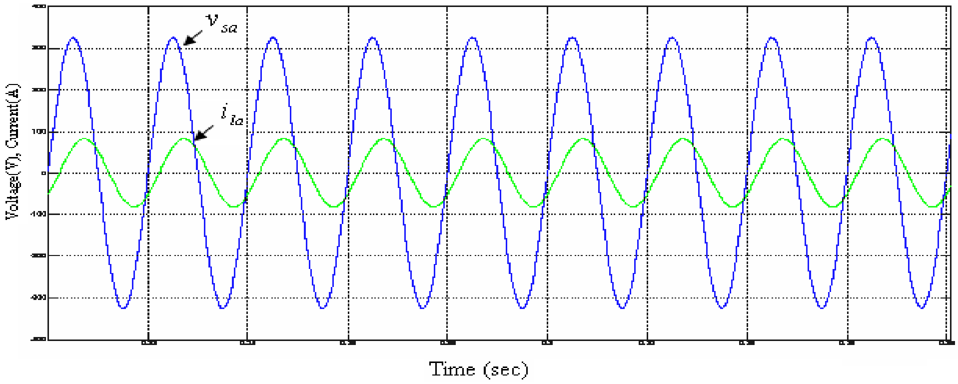
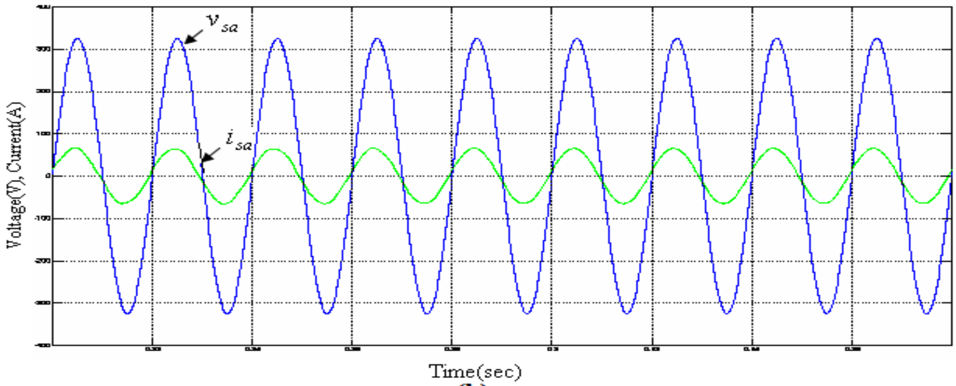


Figure 3.5. Simulation model of APF with linear load

The Figure 3.6 shows the simulation results of the APF when load is three-phase balanced RL load. Figure 3.6 (a) is the waveforms of the phase-A supply voltage and the load current before compensation. Figure 3.6 (b) is the waveforms of the phase-A supply voltage and the supply current after compensation.



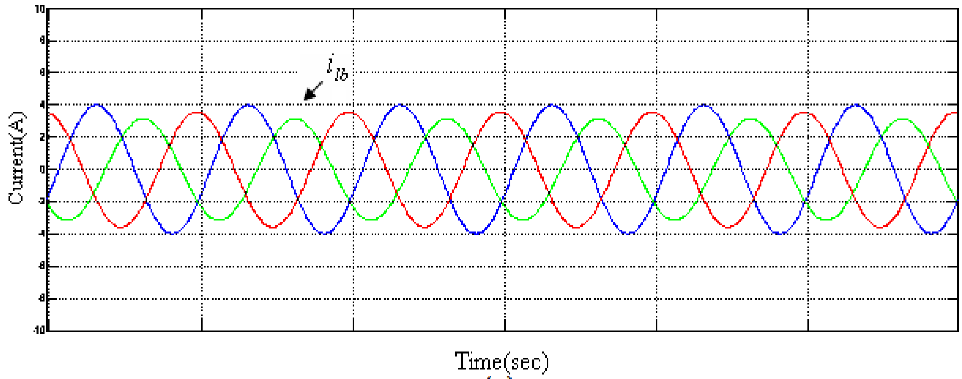
(a)



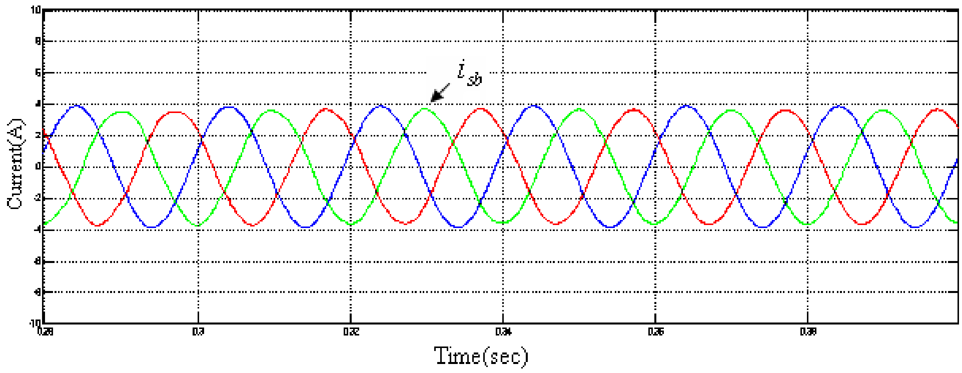
(b)

Figure 3.6. Simulation results of balanced linear load
(a) The phase-A supply voltage and load current waveforms
(b) The phase-A supply voltage and supply current waveforms

3.2.2. For Unbalanced Linear Load



(a)



(b)

Figure 3.7. Simulation results of unbalanced linear load
(a) Three-phase load current waveforms
(b) Three-phase supply current waveforms

The Figure 3.7 shows the simulation results of APF when three-phase unbalanced RL load is considered. Figure 3.7 (a) is the waveforms of the three-phase load current before compensation. Figure 3.7 (b) is the waveforms of the three-phase mains current after compensation. From the figures, it can be seen that APF controller can remedy the system unbalance.

3.2.3. For Non-Linear Load with Resistance

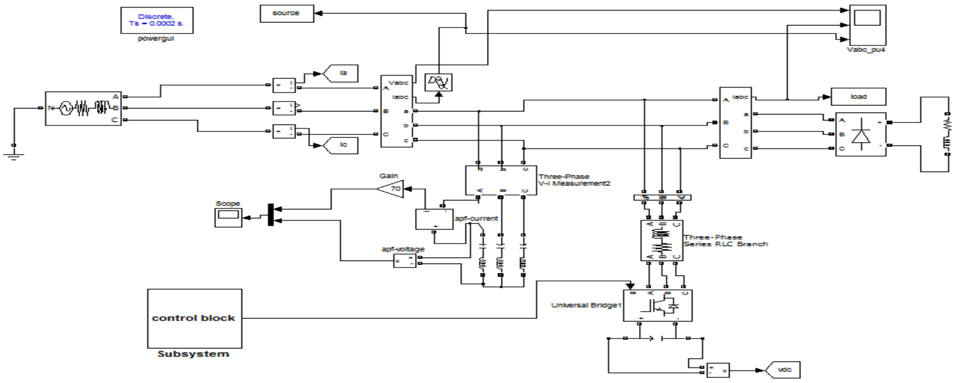


Figure 3.8. Simulation model of APF with non-linear load

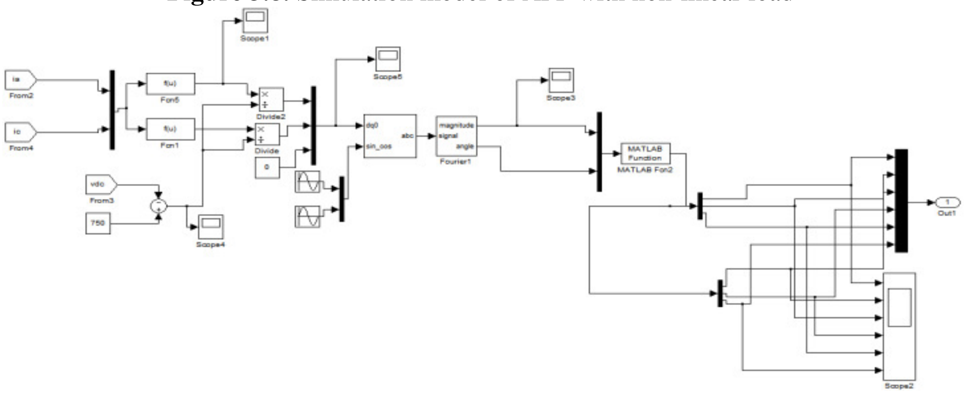
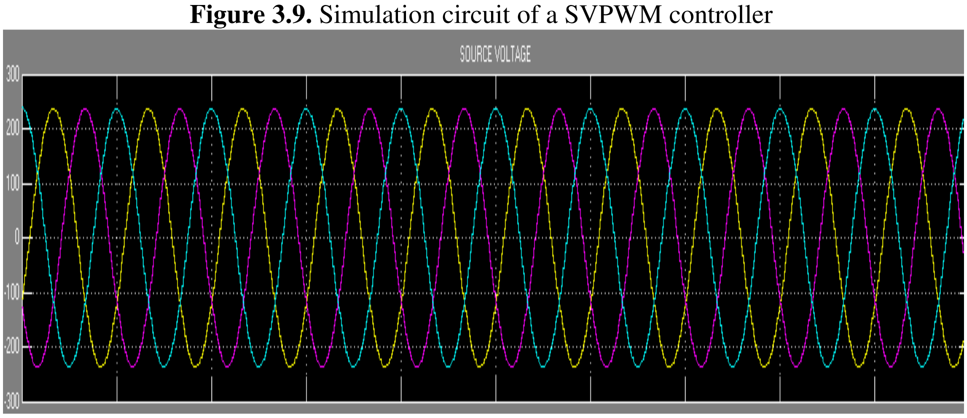
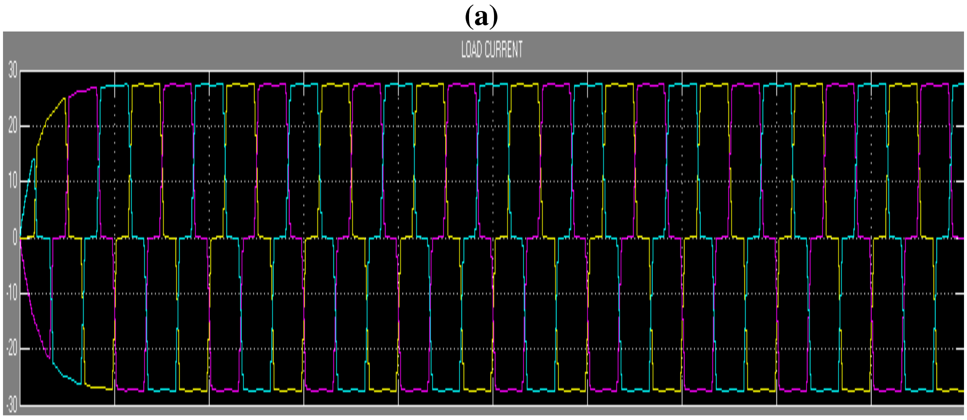


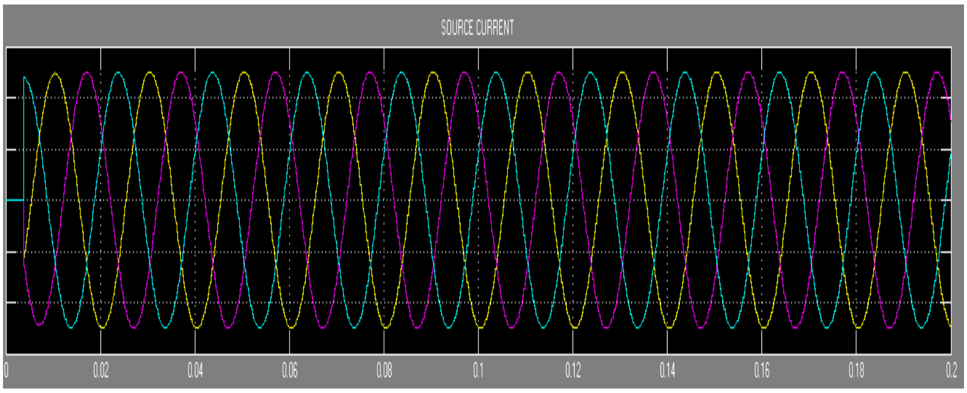
Figure 3.9. Simulation circuit of a SVPWM controller



(a)



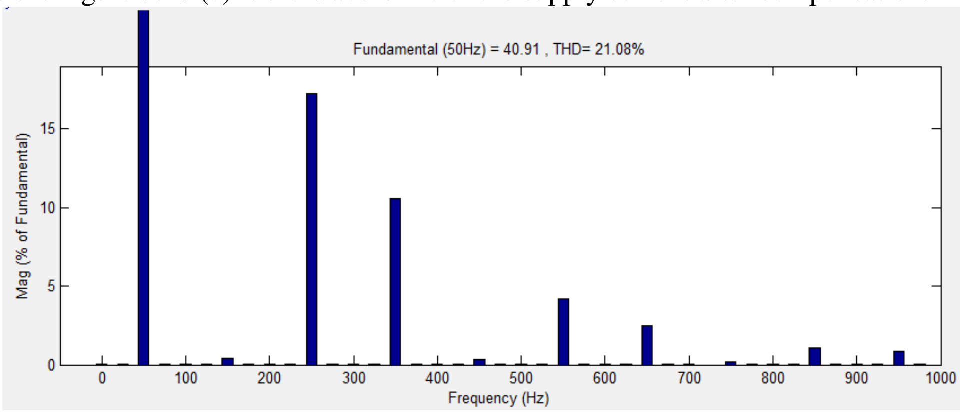
(b)



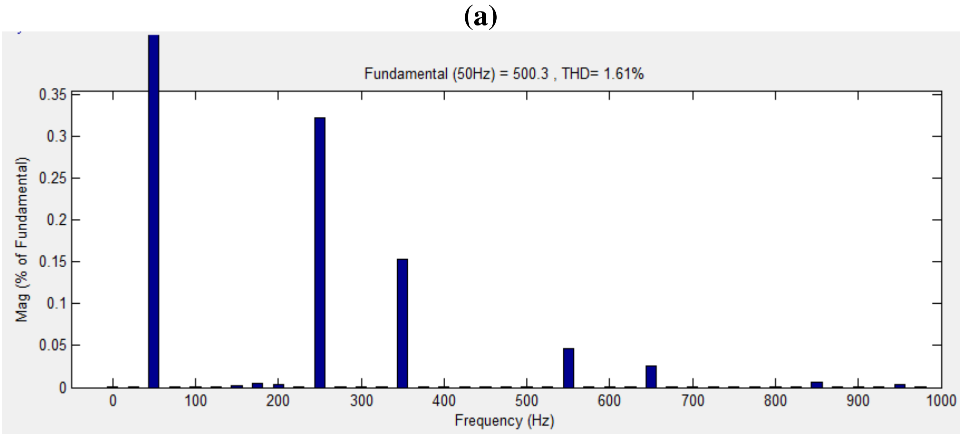
(c)

Figure 3.10. Simulation results of non-linear load
(a) The three-phase source voltage waveforms
(b) The three-phase load current waveforms
(c) The three-phase source current waveforms

The Figure3.8 and Figure 3.9 shows the simulation model of APF with non-linear load and its SVPWM controller respectively. The Figure 3.10 shows the behaviour of the APF when the non-linear load is a three-phase diode bridge rectifier with resistance load. Figure 3.10 (a) is the waveforms of the source phase voltage. Figure 3.10 (b) is the wave forms of the load current before compensation. Figure 3.10 (c) is the waveforms of the supply current after compensation.



(a)



(b)

Figure 3.11. Harmonic spectrum of non-linear load
(a) The phase-A load current harmonic spectrum
(b) The phase-A source current harmonic spectrum

The Figure 3.11 shows the simulation of harmonic spectrum of APF when the non-linear is a three-phase diode bridge rectifier with resistance load. Figure 3.11 (a) is the harmonic spectrum of the current before compensation on the load side. Figure 3.11 (b) is the harmonic spectrum of the current after compensation on the source side. The harmonic spectrum of the load current shows that magnitude of the 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonics is very large. The harmonic spectrum of the source current shows that magnitude of the 5th, 7th, 11th and 13th harmonics are evidently reduced after compensation. The load current Total Harmonic Distortion (THD) is 21.08%, while the supply current THD is 1.61%. It should be noted that the higher frequency harmonics caused by APF in mains current can be canceled easily by a small passive filter, and there are pulses in main current at the points, where di/dt of load current is large, because fixed switching frequency restrict the tracking capability of APF.

IV. CONCLUSIONS

In this paper, a control methodology for the APF using Discrete PWM and SVPWM is proposed. These methods require a few sensors, simple in algorithm and are able to compensate harmonics and unbalanced loads. The performance of APF with these methods is done in MATLAB/Simulink. The algorithm will be able to reduce the complexity of the control circuitry. The harmonic spectrum under non-linear load conditions shows that reduction of harmonics is better. Under unbalanced linear load, the magnitude of three-phase source currents are made equal and also with balanced linear load the voltage and current are made in phase with each other. The simulation study of two level inverter is carried out using SVPWM because of its better utilization of DC bus voltage more efficiently and generates less harmonic distortion in three-phase voltage source inverter. This SVPWM control methodology can be used with series APF to compensate power quality distortions.

From the simulated results of the filtering techniques, it is observed that Total Harmonic Distortion is reduced to an extent by the SVPWM Hybrid filter when compared to the Discrete PWM filtering technique i.e. from 1.78% to 1.61%.

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