Harmonic Compensation and Reactive Power control of Distribution System by using Shunt Active Power Filter

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Abstract—**This paper presents a control method for hybrid active power filter using 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. A MATLAB code is developed to generate the SVPWM switching pulses fed to the two-level inverter topology. The entire power system block set model of the proposed scheme has been developed in MATLAB environment. The developed control algorithm is simple. The APF based on the proposed method can eliminate harmonics, compensate reactive power and balance load asymmetry. Simulation results show the feasibility of the APF with the proposed control method.**

Keywords—Hybrid active power filter; Space vector pulse width modulation; Active power filter; Matlab software.

I. 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, and harmonic resonances in the utility, significant interference with communication circuits, flicker and audible noise, incorrect operation of sensitive loads [1, 2].

Traditionally, LC tuned passive filters have been used to absorb harmonic currents generated by nonlinear loads. Their main advantage is high reliability and low cost. However, passive filters have several drawbacks, which may cause harmonic interaction with the utility problems with the utility system, in the presence of stiff utility sharp tuning of the LC filter is required and may not meet the specified harmonic current limits [3, 4]. This provides the motivation for investigation of an active filter topology, which is practically viable, cost effective and can meet the recommended standard for high power nonlinear loads. For high-power applications, the active filters are not cost effective due to their large rating and high switching-frequency requirement of the Pulse Width Modulation (PWM) inverter.

II. INTRODUCTION TO HARMONICS

A. General

Electrical utilities generate what is called a "fundamental" frequency in a perfect sinusoidal wave shape. Harmonics is the name given to distorting signals which are also sinusoidal in shape but in multiple of the fundamental. They are generated by non linear "loads" or equipment. Industry has no alternative to non-linear equipment because it is a part of the western world's prescription for energy saving, this is why harmonic, one of several forms of electrical pollution, are exciting some alarm. Always present in electrical networks, they are now proliferating with new plant and replace must equipment to the proportion of epidemic.

The use of modern electronic equipment has changed our live (most would argue for the better) but has also changed the load characteristics of modern facilities. Electronic loads have earned the name "non-linear load "to describe the way they draw power, the injected harmonics, reactive power burden, unbalance and excessive neutral currents cause low system efficiency and poor power factor. Harmonic contamination has become a major concern for power system specialists due to its effects on sensitive loads and on the power distribution system harmonic current components.

B. Prominent world standard

Power electronic equipment can be designed to provide harmonic free performance. But in most applications, the economic incentives have not been sufficient to bring about design improper. Power system &power electronic engineers have turned to regulation to force the use of lower harmonic power system design. Their common objective is to preserve the sinusoidal nature of the power system while protecting components from added harmonic loading. The electrical utilities are quickly

adopting the philosophy and constraint proposed in IEEE 519-1992. A recommended practice (one level short of a mandatory standard), limiting both utility voltage and end user current distribution.

In order to maintain good power quality, various international agencies recommended limits of harmonic current injecting into the utility according to IEEE-519 standards the limits on the magnitude of harmonic currents and harmonic voltage distortion at various frequency are specified given in Tables 1 and 2

The amount of distortion in the voltage or current waveform is quantified by means of an index called THD, the THD in current is defined as

$$\%_{\text{THD}} = 100 \times \left(\sqrt{\sum_{n \neq 1} \left(Isn/Is1 \right) 2} \right)$$

TABLE 1

TOTAL HARMINIC DISTORTION IN CURRENT

I_{sc}/I_1	h<11	11≤h≤17	17<h<23	23≤h<35	THD
<20	4	2	1.5	0.6	5
20-50	7	3.5	2.5	1	8
50-100	10	4.5	4	1.5	12
100-1000	12	5.5	5	2	15

Where Isc is the main short circuit current at the point of common coupling. I_1 is the maximum fundamental frequency load current.

TABLE 2
HARMONIC VOLTAGE LIMITS FOR POWER PRODUCERS:

	2.3-69 kv	69-138 kv
Maximum for induced harmonics	3.0	1.5
THD	5.0	2.5

The table 2 lists the quality of the voltage that power producer is required to furnish a user. It is based on the voltage level at which the user is supplied.

III. ILL EFFECTS OF HARMONICS

A. Poor quality supply

As all power electronic converters generate harmonic currents, which will be injected into the utility, causing distortion of the supply waveform. The output effects in addition to the voltage distortion (where source has source impedance) are listed as below.

B. Additional heating

As the current because of the additional harmonics in the line is the rms value of the fundamental and the total harmonic that is the rms current increases which results in an increase in the copper losses and thus heating.

C. Over voltage due to conditions

Due to the harmonics creeping up the voltage can shoot up at a particular frequency under the resonant condition, can cause severe problem to the loads connected.

D. Errors in metering

Due to the harmonics the motors experience Torque pulsation if connected to the supply. Most of the measuring equipment like the induction disc device or designed for works for the fundamental frequency. The pulsating Torque experienced by the disc, the meter show improper reading.

E. Malfunction of utility relays

Due to the harmonics there will be shift in the zero crossing point. If a relay were to operate at the zero crossing at a particular condition, due to the shift of the zero crossing point or the relays using the phase comparators etc., the relay now responds at a new point which is undesirable.

F. Interference with communication lines

Human hearing sensitivity and telephone response peak near 1KHZ. Due to loop induction voltage is induced in the telephone lines forming the loop(conductor and earth).Higher the frequency of the smoke converters greater will be the EMI(electromagnetic interference)resulting in interference with the communication signals, which again is not desirable.

G. Low power factor

With the large harmonic content the reactive power for the system increases thus the power factor deteriorates badly.

IV. HORMONICS MITIGATION TECHNIQUES

A. Passive filter

One of the most popular methods of harmonic reduction involves the use of passive harmonic filters. These filters use inductors and capacitors, which are tuned to block or absorb particular harmonic content. These passive filters tend to be relatively large and expensive and they cannot provide optimal harmonic reduction without unwanted side effects such as ringing transient response, unwanted resonance.

B. Active harmonic filter

Active harmonic filters are commercially available. In principle, with sophisticated power electronic devices, it is possible to produce a device that either provides variable harmonic impedance to absorb some or all of the harmonic currents generated by the non-linear loads or else provides harmonic currents of opposite polarity to cancel the non-linear

load's harmonic currents. These active filters are very expensive and are not widely available.

Other harmonic reduction techniques applied involves the use of transformer to cancel certain harmonic currents. The triplen harmonics (via 3rd, 9th, 15th) circulate in the delta of the transformer with the unbalanced portion present in the transformer input line currents, cancels the 3rd, 9th, 15th harmonics.

Other way to cancel some harmonics is to connect the zig-zag grounding transformer that employs a 3-phase auto transformer to cancel third and triplen harmonics.

V.   ACTIVE POWER FILTER

In a modern power system, the growing use of non-linear loads and time-varying loads are increasing. These nonlinear loads may cause poor power factor, high degree of harmonics and distortion of current and voltage waveforms. These problems are solved by using APF's. By implementing these for power conditioning, it provides functions such as reactive power compensations, harmonic compensations, negative-sequence current or voltage compensation and voltage regulation. The main purpose of the APF installation by individual consumers is to compensate current harmonics or current imbalance of their own harmonic-producing loads. Besides that, the purpose of the APF installation by the utilities is to compensate for voltage imbalance or provide harmonic damping factor to the power distribution systems. Fig.1 shows the basic APF block diagram including non-linear load on three-phase supply conditions.
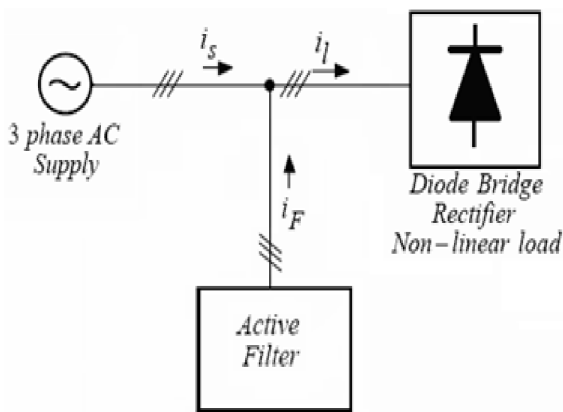

Fig. 1 Block diagram of APF

APF consisting of VSI and a dc capacitor have been researched and developed for improving the power factor and stability of transmission systems. APF have the ability to adjust the amplitude of the synthesized ac voltage or current of the inverter by means of pulse width modulation or by control of dc-link voltage, thus by drawing either leading or lagging reactive power from the supply. APF is an up-to-date solution to power quality problems. Normally, APF can be classified into shunt and series. Both are designed to compensate for reactive power or harmonics. APF consists of an inverter with switching control circuit. The inverter of the APF will generate the desired compensating harmonics based on the switching gates provided by the controller. The APF injects an equal-but-opposite distortion harmonics back into the power line and cancel with the original distorted harmonics on the line. Fig 2 shows the basic idea of operation of APF for a diode rectifier.
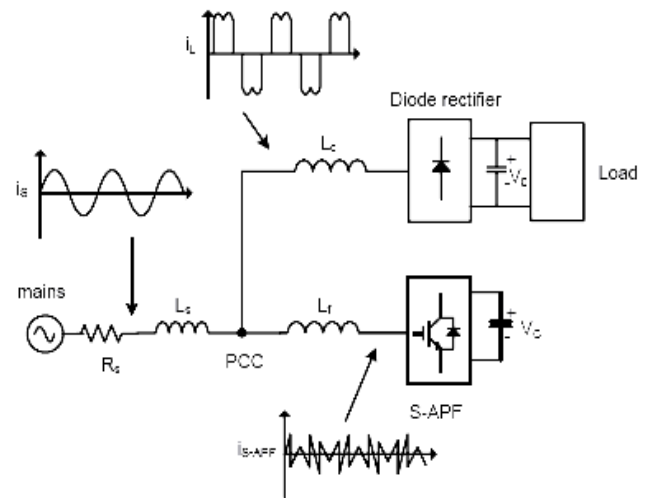

Fig 2 Principle of operation of a APF compensating a diode rectifier

The harmonic current compensation by the APF is controlled in a closed loop manner. The APF will draw and inject the compensating current, i_f to the line based on the changes of the load in the power supply system. The supply line current, i_s described by the following equation (1).

$$i_s = i_f + i_l$$

(1)

The line current, i_s shaped to be sinusoidal by adding the compensating current, i_f into the distorted load current, i_l. The problem of this APF is the suitable design for the controller and the filter configuration. Traditionally, its control techniques were mostly using Pulse Width Modulation (PWM) technique. However, before developing the controller, the configuration of the APF used in the design has to be defined.

The principal parts of an inverter based shunt APF are discussed below, the first part is a smoothing coupling low pass filter which can be a first order (inductor) or a third order filter in case of a voltage source inverter (VSI) otherwise a second order filter (an inductor and a capacitor) in case of a current source inverter (CSI). This filter allows the connection between the converter and the network. The second part is the converter, the third part represent the DC energy storage element, which can be either a capacitor for the VSI or an inductor for the CSI. Finally, the last part represents the control system of the APF, the role of which is to extract and control compensating current and regulate the current or voltage of the DC energy storage element.

In fact the VSI and CSI are similar in behavior, the choice between the two configurations depends on several criterion namely the semiconductors used, the DC energy storage element, power ratings, control complexity, etc...The comparison between the two configurations is presented in table 3; show a significant advantageous aspect of the VSI's compared to the CSI's as shunt APFs this can explain the dominance of the VSI based APFs.

The performances of a VSI based shunt APF to cancel harmonic distortion depend on several parameters namely the dimension of the smoothing and coupling element (Lf), the energy storage element dimension (C_{dc}), the methods adopted to extract compensation references and the control techniques used to regulate the filter currents and the DC bus voltage (V_{dc}).

TABLE 3
COMPARISION OF CSI AND VSI AS APF'S

	Active power filter type	
System	Current source inverter (CSI)	Voltage source inverter (VSI)
Action	Injects currents at PCC to cancel current harmonics	Acts with current control loop to generate the compensating waveform
Power rating	Medium power applications	Low/medium power applications, high power for multilevel version
Dc energy storage elements	Large DC inductor	Large DC capacitor
Switching frequency(KHZ)	2-5	20-30
Response speed	Medium (-1)	Fast
Control complexity	Complex (keep inductor current constant)	Simple (keep capacitor voltage constant)
Expandable	No	Yes (Multilevel versions)
Losses	High	Low
Cost	Heavy / Expensive	Lighter / Cheaper

VI. 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. It is a more sophisticated, advanced, computation intensive technique for generating sine wave that provides a higher voltage with lower total harmonic distortion and is possibly the best among all the pulse width modulation techniques. It confines space vectors to be applied according to the region where the output voltage vector is located. Because of its superior performance characteristics, it is been finding wide spread applications in recent years. The main aim of any modulation technique is to obtain variable output voltage having a maximum fundamental component with minimum harmonics. Many PWM techniques have been developed for letting the inverters to posses various desired output characteristics to achieve the wide linear modulation range, less switching losses, lower harmonic distortion. 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
- Prevent un-necessary switching hence less commutation losses.

A. 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 S1to S6 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 S1, S3, S5 can be used to determine the output voltage.
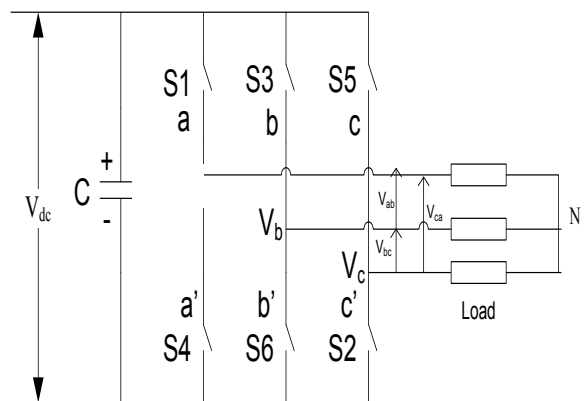

Fig 3 Power circuit of a three-phase VSI

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 (2) in the following:

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (2)$$

Also, the relationship between the switching variable vector $[a, b, c]^t$ and the phase voltage vector $[V_a \ V_b \ V_c]^t$ can be expressed below.

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

As illustrated in Fig.3, 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. According to equations (2) and (3), the eight switching vectors, output line to neutral voltage (phase voltage), and output line-to-line voltages in terms of DC-link V_{dc}.

VII. RESULTS AND DISSCUSIONS

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 Is 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.

TABLE 4
MODEL SPECIFICATIONS AND PARAMETERS

System parameters	Values of parameters
Supply system	230 V (rms), 50 Hz, three-phase supply
Balanced linear load	$Z_l = 75 + j\ 62.83\ \Omega$
Unbalanced linear load	$Z_{la} = 75 + j\ 31.42\ \Omega$, $Z_{lb} = 100 + j\ 23.56\ \Omega$, $Z_{lc} = 85 + j\ 31.42\ \Omega$
Non-linear load with resistance	R=1000 Ω
APF	C_{dc}=1000µf, Vref = 750V, C_f = 24µf, L_f = 30 mH

The complete simulation model of APF with different type of loads is shown in Fig.4, Fig5 and Fig.6. For an input supply

voltage of 230V (rms) and switching frequency of 5 kHz, the simulation results for balanced linear load is shown.
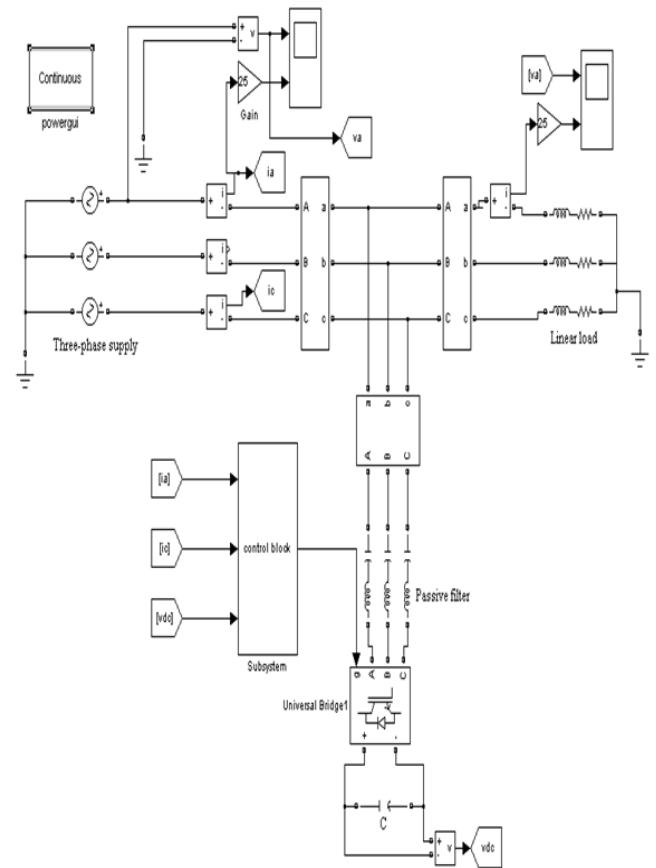

Fig.4 Simulation model of APF with linear load

A. For balanced linear load

Source current and load current are scaled by factor 25 for comparison purpose.
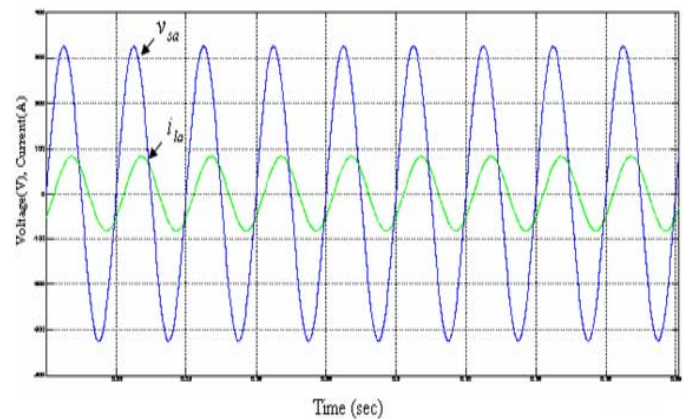

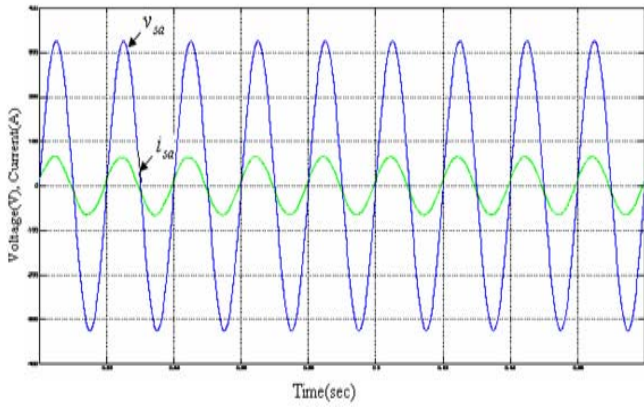Fig.5 The phase-A supply voltage and load current waveforms

Fig.6 The phase-A supply voltage and supply current waveforms

The above figures show the simulation results of the APF when load is three-phase balanced RL load. Fig.5 is the waveforms of the phase-A supply voltage and the load current before compensation. Fig.6 is the waveforms of the phase-A supply voltage and the supply current after compensation.
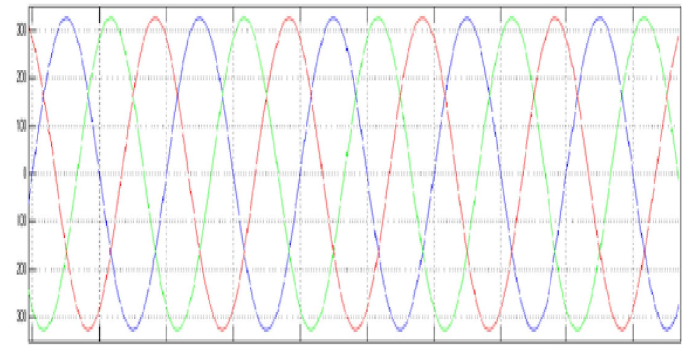

Fig.7 Simulation model of APF with non-linear load

B.   For non-linear load with resistance

Fig.8 The three-phase source voltage waveforms
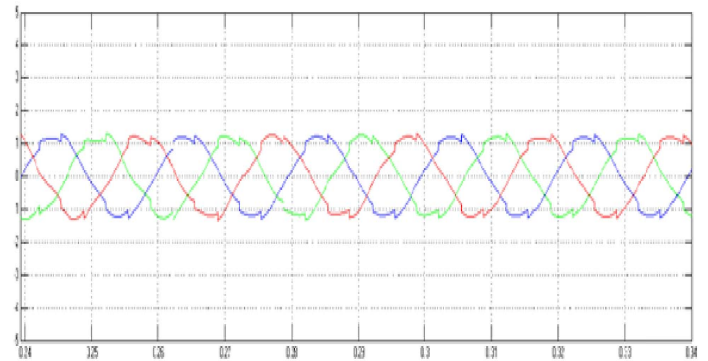

Fig.9 The three-phase load current waveforms

Fig.10 The three-phase source current waveforms

The above figures show the behavior of the APF when the non-linear load is a three-phase diode bridge rectifier with resistance load. Fig.8 is the waveforms of the source phase voltage. Fig.9 is the wave forms of the load current before compensation. Fig.10 is the waveforms of the supply current after compensation.
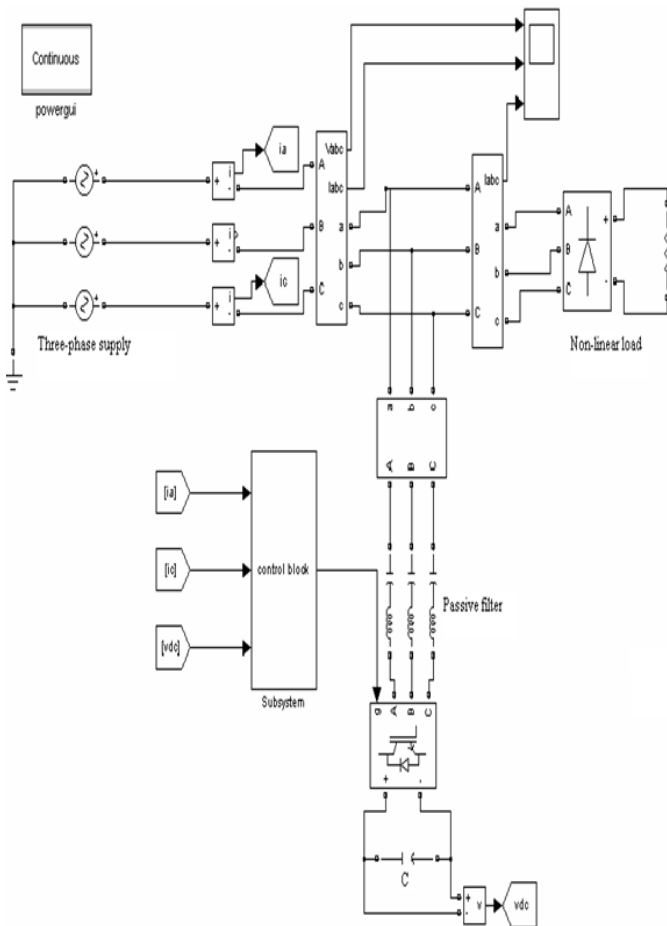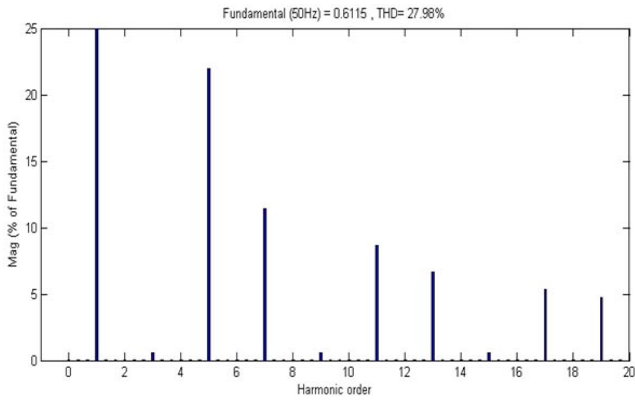
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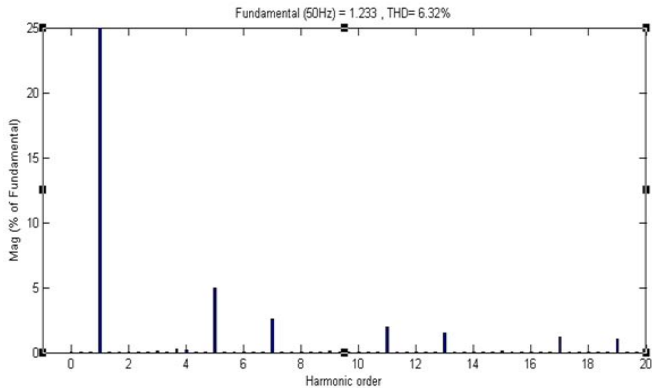Fig.11 The phase-A load current harmonic spectrum

Fig.12 The phase-A source current harmonic spectrum

The above figures show the simulation of harmonic spectrum of APF when the non-linear is a three-phase diode bridge rectifier with resistance load. Fig.11 is the harmonic spectrum of the current before compensation on the load side. Fig.12 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 5th, 7th, 11th and 13th 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 27.98%, while the supply current THD is 6.32%. 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.

VIII.   CONCLUSION

In this paper, a control methodology for the APF using SVPWM is proposed. This method requires few sensors, simple in algorithm and able to compensate harmonics and unbalanced loads. The performance of APF with this method 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.

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