Performance Analysis of Shunt Active Power Filter with Hysteresis and Space Vector Pulse Width Modulation Techniques

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ABSTRACT
In this paper, the performance of switching signal generation techniques for three phases shunt active power filter (SAPF) are compared for steady state load condition. The techniques which are considered for comparative study are (i) Hysteresis Current Control (HCC), & (ii) Space Vector Pulse Width Modulation (SVPWM) technique. Performance analyze of above two switching signal generation techniques based on %THD, Complexity, Speed of response, Switching frequency and Delay time in MATLAB/SIMULINK environment. After simulation, we can analyze the different results on above two methods based on given parameters of SAPF. The %THD of supply current reduces as per IEEE Standard. HCC is simple in implementation over the SVPWM technique. The speed of response of Hysteresis controllers is fast. The switching frequency of HCC is variable but the SVPWM technique operates fixed switching frequency. The delay time is required for SVPWM technique.

Keywords
Shunt Active Power Filter (SAPF), Hysteresis Current Controller (HCC), Space Vector Pulse Width Modulation (SVPWM), %THD, Switching Frequency.

1. INTRODUCTION
In previous decades electricity has predominantly been used to power electric motors, resistive heating, and incandescent lighting. Nowadays, with the wide application of the nonlinear loads and electronic equipment in distribution systems such as switch-mode power supplies, light controllers, interruptible power supplies, electric furnaces, AC voltage regulators, Domestic loads, Adjustable Speed Drives (ASD), etc… the problem of power quality has become increasing seriously[4]. These modern devices are becoming widely adopted due to their energy efficient operation. Modern electronic equipment generally draws non-sinusoidal currents from the AC supply. The generalization of static converters in industrial activities and by consumers leads to an increase in harmonic injection in the network and a lower power factor. The injection of these harmonics causes many problems to the distribution system, such as transformer overheating, resonance problems in the utility, increased losses, malfunction of protection devices such as relays, circuit breakers…etc. and interference to thethe communication network and electronic systems. Several methods of compensation are proposed to improve the power quality and reduce the harmonics indistribution system. In previous decades, thefilterwas used to eliminate harmonics. There are diverse types of filters used to inject the harmonic current.

Traditionally, passive LC filters have been used to eliminate lower order harmonics (5th, 7th, 11th . . .) of the line current and then limit the flow of harmonic currents in the distribution system. However, these passive filters present many disadvantages such as series and parallel resonances, tuning problems complexity in the power system, Large size, depend on system impedance& affected by capacitor aging particularly in thecase of an increase in the number of harmonic components that have to be canceled[3].Active filters have overcome the problem occurring in the passive filter. There are different configurations 1) Shunt APF 2) Series APF & 3) Hybrid APF.

For harmonic compensation and reactive power compensation, the most common solution is the shunt active power filter (SAPF). This active filter, based on a three-phase voltage source inverter, is connected in parallel with nonlinear loads to eliminate current harmonics and compensate reactive power.According to Akagi (1994), the first shunt active filter was put into practical use for harmonic compensation in 1982. Since the 1980's, improvements in power semiconductor devices, microprocessor, and digital signal processors have more and more also research and development in active power filters.This paper aims to investigate the various Switching Signal Generation techniques and performance analyze based on %THD, Complexity, Speed of response, Switching frequency and Delay time of SAPF under steady state load condition[2], [4].

2. THEORY OF SAPF
The recently used Active filter for harmonic current compensation is SAPF shown in Fig. 1 with nonlinear loads. It consists of a voltage source inverter with active filter controller. The inverter employed for the SAPF is an IGBT based inverter; it is a current controlled voltage source inverter which is connected in parallel with the load.This inverter injects an appropriate current into the system to compensate the harmonics. The dc side of the inverter is connected to a dc storage capacitor, whose voltage can be increased or decreased by controlling the switching loss of inverter.For controlling theinverter output; firing pulses are generated by the current control circuit shown in Fig. 1 [9]. In active filter controller, there are three main controllers a) Reference Current Generation b) Current Controller or Switching signal generation c) DC Capacitor Voltage Controller.The shunt active filter works in a closed loop manner continuously sensing the load current i_L and calculates the compensating reference current i_c^* for PWM controller.For Reference Current Generation the Synchronous Reference Frame (SRF) Theory can be implemented in this paper.

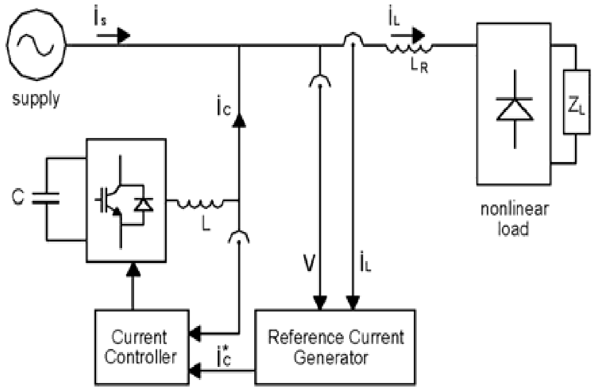

Fig.1 Basic configuration of a shunt active powerfilter

3. SWITCHING SIGNAL GENERATION TECHNIQUES

There is different switching signal generation technique will be implemented in shunt active power filters based on thecurrent controller or voltage controller. Current controllers can be classified as hysteresis, ramp comparison, Delta Modulation, Predictive controllers and Digital Deadbeat Control [4], [6]. Voltage controllers can be classified as sinusoidal pulse width modulation (SPWM) & space vector pulse width modulation (SVPWM). Hysteresis controllers utilize some type of hysteresis in the comparison of the line currents to the current references. The ramp comparison controller compares the current errors to a triangle waveform to generate the inverter firing signals. Predictive controllers calculate the inverter voltages required to force the currents to follow the current references.The digital current control technique can be achieved by adopting an improved version of the deadbeat control technique.In sinusoidal PWM, the modulating or the reference wave is the sine wave and the carrier is the triangular wave.Space vector modulation utilizes dc bus voltage more efficiently and generates less harmonic distortion in a three-phase voltage source inverter. In SVPWM methods, the voltage reference is provided using a revolving reference vector [1],[4].

a. Hysteresis current controller

The basic principle of hysteresis current controller is that the switching signals are generated from the comparison of the current error signal with a fixed width hysteresis band.It is closed loop system which detects the current error and generates the switching pulses of IGBTwhen the error exceeds an assigned band.The advantages of this technique are high simplicity, good accuracy, outstanding robustness and fast dynamic and automatic current limited characteristics response. This control technique exhibits several disadvantages. The main one is that variable switching frequency of the inverter. This is responsible for designing the ripple filter due to the resonance [5].

The hysteresis controller is used to control the load current and determine the switching signals for inverters gates. The hysteresis current control technique is based on nonlinear control as shown in fig.2.The compensating currents (i_{ca}, i_{cb}, i_{cc}) in fig.2 are compared with the reference currents $(i^*_{ca}, i^*_{cb}, i^*_{cc})$ by using hysteresis comparators to generate the six switching pulses. These pulses are used to control the IGBTs to turn ON and turn OFF. The basic concept of the hysteresis current control is shown in Fig.3.

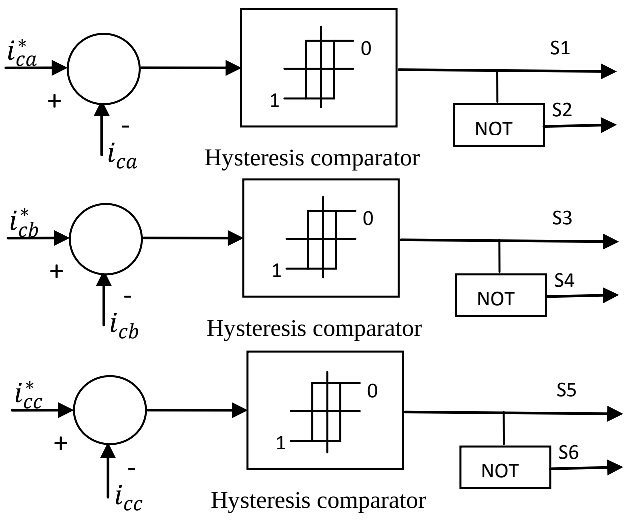

Fig 2. Block diagram of Hysteresis current controller

For the reference of fig.3 hysteresis band (HB) is the possible boundary of the compensating current. This current swing between upper and lower hysteresis limits. In hysteresis controller, instantaneous current or error in tolerance band except for system with theload. The current error reaches adouble value of the hysteresis band [1].For example, in phase a, if $i_{ca}$is equal or less than the lower hysteresis limit (i^*_{ca}- HB/2)then the comparator output is 1 (S1=1, S2=0).On the other hand, if $i_{ca}$is equal or over than the upper hysteresis limit (i^*_{ca}+ HB/2)then the comparator output is 0 (S1=0, S2=1). From this operating, the i_{ca}can swing inside the hysteresis band following the reference current (i^*_{ca}). This reference current can be calculated by the synchronous reference frame technique (SRF).

The switching frequency of hysteresis current controller depends on how fast the current changes from the upper limit of the hysteresis band to the lower limit of hysteresis band, or vice versa. The rate of change of the actual active filter linecurrents vary the switching frequency, therefore the switching frequency does not remain constant throughout the switching operation, but varies along with the current waveform [1],[2], [7].

The maximum switching frequency (fs, max) of IGBTs can be calculated by equation (1). The line inductance value of the active power filter and the dc link capacitor voltage are the main parameters determining the rate of change of active power filter line currents.

$$f_{s,max} = 2V_{dc}/9HBL_f \text{ .... (1)}$$

The switching frequency of the active power filter system also depends on the capacitor voltage and the line inductances of the active power filter configuration [5],[7].

b. Space Vector Pulse Width Modulation (SVPWM) technique

The SVPWM method is frequently used in vector controlled applications. In this method, the voltage reference is provided using a revolving reference vector. In this case magnitude and frequency of the fundamental component on the lineis controlled by the magnitude and frequency of the reference voltage vector, respectively. Space vector modulation utilizes dc bus voltage more efficiently and generates less harmonic distortion in a three-phase voltage source inverter of shunt active filter.

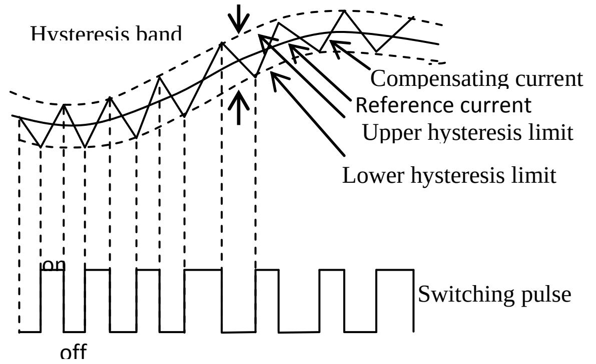

Fig 3. Principle of the Hysteresis current controller

The Space Vector PWM technique provides the wide range of the linearity and the improved harmonic performance although the high computational effort and the complexity of the implementation. Utilization of the dc bus is better in SVPWM [10].

The main section of shunt active filter shown in Fig. 1 is DC capacitor is connected across the voltage source inverter (VSI). The distortion of the source voltage is very low in actual distribution system, therefore considering the source voltage is sinusoidal and unbalance as shown below.

$$V_{sa} = V_s \sin(wt)$$

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

$$V_{sc} = V_s \sin(wt + 2\pi/3) \quad (2)$$

Where Vs is amplitude of supply voltage

The three-phase supply voltages $V_{sa} V_{sb} V_{sc}$ in a-b-c can be expressed as two axis representations in d-q frame by using Clark's transformation and it is given by

$$V_s = \begin{bmatrix} Vd \\ Vq \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \quad (3)$$

A balanced set of voltages is represented in the stationary referenceframe by a space vector of constant magnitude, equal to the amplitude of the voltages, and rotating with angular speed $\omega = 2\pi f$.

WhenShunt APF operates normally, 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 SAPF system. Hence, the average voltage ofDC capacitor can be maintained at a constant value.In order to maintain the 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.

Fig.4. shows the voltage space vectors in thed-q frame. Balancing 3-phase voltages are converted into 2-phase d-q quantities. By using angle α, calculate the reference voltage $V_{ref}$of d-q component.

The Fig.5shows the block diagram of active filter controller using SVPWM technique implemented for reducing the harmonics with shunt active filter system. Three-phase supply currents are measured and transferred in thesynchronous reference frame.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} andV_{ref} , the reference value of the DC bus voltage.

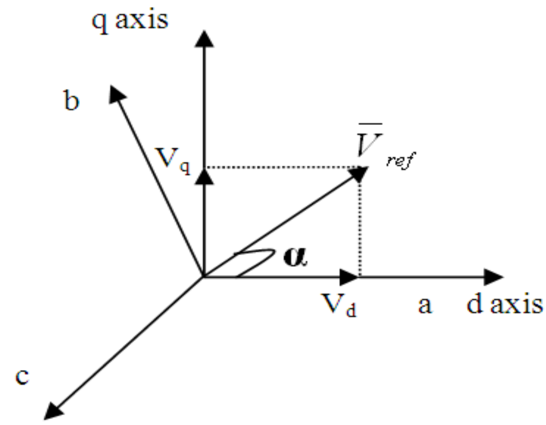

Fig 4.Voltage space vector in d-q frame

The Fig.5shows the block diagram of active filter controller using SVPWM technique implemented for reducing the harmonics with shunt active filter system. Three-phase supply currents are measured and transferred in the synchronous reference frame. 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} andV_{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 the 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 T1, T2 and T0, the on-time of V1, V2 and V0 are calculated. The generated switching actions are applied to the APF and power balancing of the filter takes place.

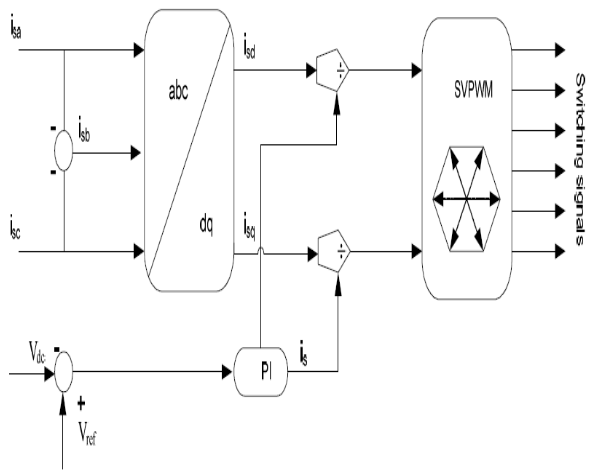

Fig 5. Block diagram of SVPWM controller

4. SIMULATION AND RESULTS

The developed control method for three-phase shunt APF is simulated in MATLAB/ Simulink as shown in Fig.6 Firstly,the three-phase supply currents are sensed and transformed into synchronous reference frame and calculating the reference current of shunt active power filter. Comparing this reference current and load current of the active filter and generate the switching signal of SAPF. Three different switching signals generation techniques are used to generatethe switching pulses of IGBT's under steady state load condition.

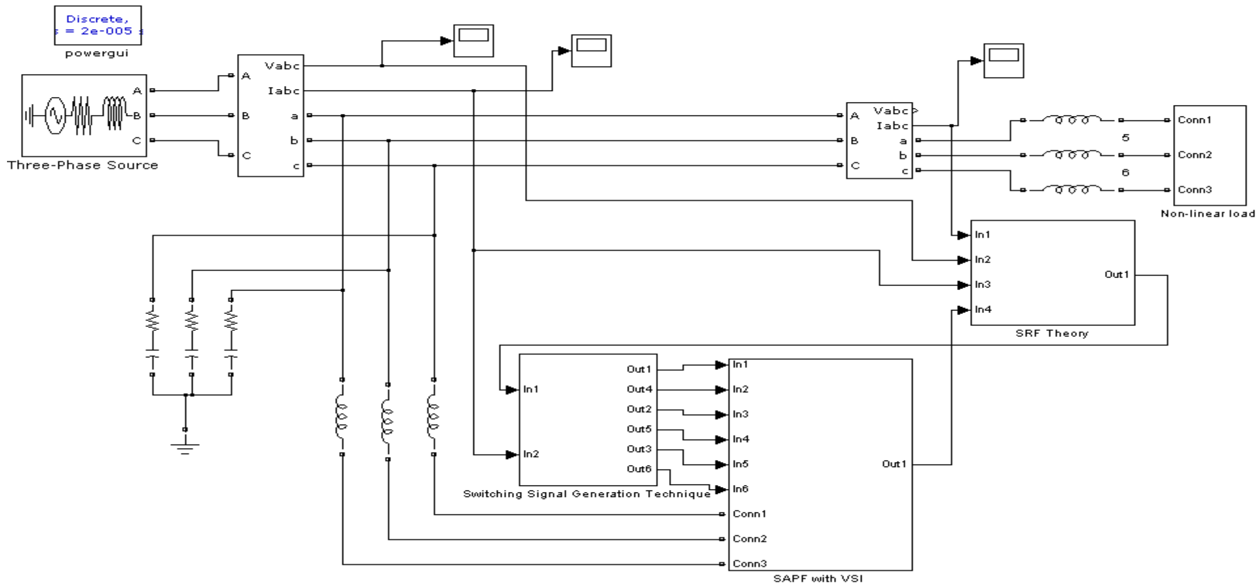

Fig6.Simulink diagram of Shunt Active Power Filter (SAPF)

Also, performance analyze based on the %THD,Complexity, Speed of response, switching frequency and Delay time.Fig. 7 shows the supply side current when the nonlinear load connected to the system without compensation of filtercurrent. The fundamental peak value of current is 25.31 A and %THD of this current is 25.02.

4.1 SAPF with Hysteresis current controller

This control technique is simple in implementation as shown in Fig. 8. The reference current ofthe active filter and load current are compared witha comparator and this error signal is given to the hysteresis comparator. Three hysteresis comparators are used each phase separately. Hysteresis comparator gives required pulses to drive the inverter of SAPF.

Distortion of supply current reduces by using the hysteresis controller as shown in Fig.9 (a), and also balancing the dc voltage across thecapacitor as shown in Fig.9 (b). The FFT analysis of source current shown in Fig. 10,thefundamental peak value of source current is 24.8 A, and %THD reduces from 25% to the 3.29%.

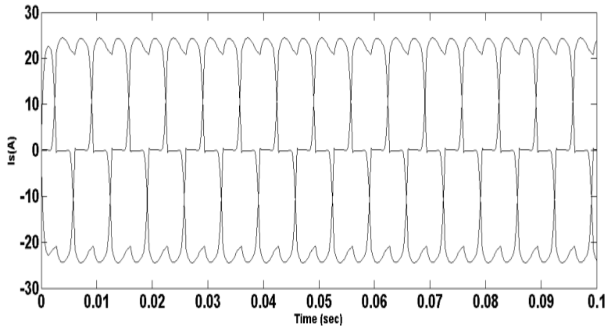

Fig 7.Source current of nonlinear load

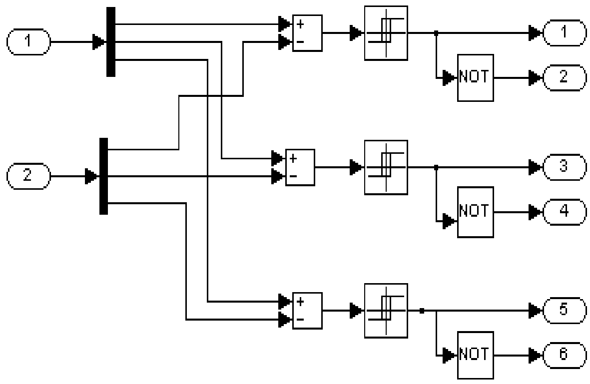

Fig8.Simulink diagram of Hysteresis controller

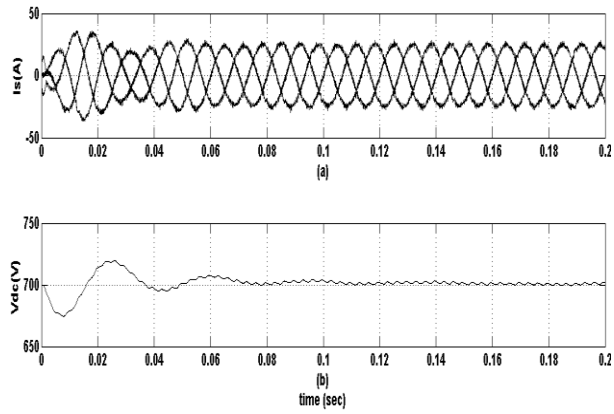

Fig 9.: (a) Source current (b) DC voltage across capacitor

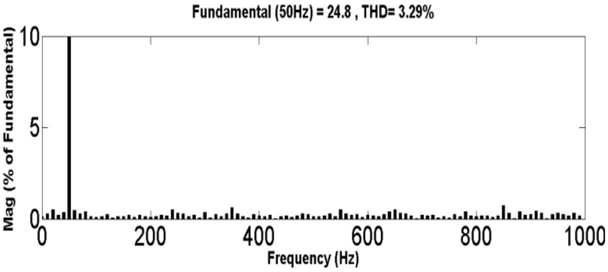

Fig10.: Source currentFFT with Hysteresis controller

4.2 SAPF with Space Vector Pulse Width Modulation technique

This switching signal generation technique is shown in Fig.11. Comparing the filter reference current & actual load current we can generate anerror signal which is given to the PI controller for each phase separately. The output of PI controller is given to the MATLAB function block, using this block 3-phase voltage signals are converted into the αβ plane.ThisVα & Vβ signals given to the generating algorithm of Space Vector Pulse Width Modulation controller and it generates the gate pulses of Voltage source inverter. Switching frequency of theinverter is fixed which has been taken as 5 kHz.

The distortion of supply current reduces by using the SVPWM technique as shown in Fig.12 (a), and also balancing the dc voltage across thecapacitor as shown in Fig.12 (b). The FFT analysis of source current shown in Fig. 13, %THD reduces from 25% to the 2.01%.Switching frequency of SVPWM technique has fixed. This technique is complex in implementation over the Hysteresis current control technique.The speed of response of HCC techniques is fast also it not required some delay time compare to the SVPWM controller.

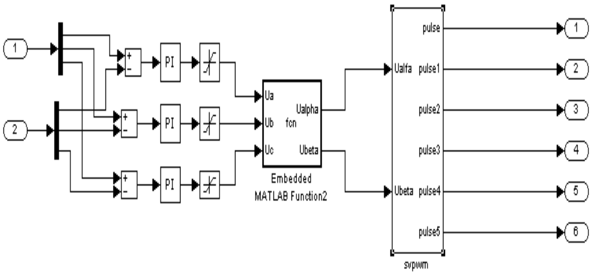

Fig 11.: Simulink diagram of SVPWM controller

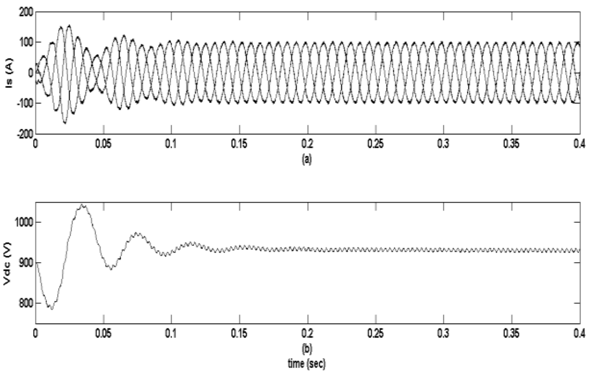

Fig12.:(a) Source current (b) DC voltage across capacitor

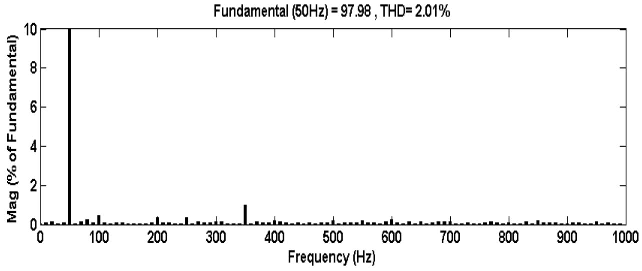

Fig 13.: Source currentFFT with SVPWM controller

5. CONCLUSION

After simulating the Shunt active power filter with hysteresis and space vector pulse width modulation technique we observe performance analysis based on %THD,Complexity,Switching frequency, Speed of response& Delay time. The %THD of HCC & SVPWM technique of SAPF reduces as per IEEE Standard. The complexity of HCC technique is less than the SVPWM technique. The switching frequency of SVPWM technique is fixed while the HCC has variable switching frequency. The speed of response of HCC is faster than the SVPWM controller.Also,SVPWM control techniques will require delay time.The performance of SVPWM technique is better than the Hysteresis current controller.

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