An Improved Current Control Technique for the Multilevel Inverter Used As A Shunt Active Power Filter

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***Abstract* - *The* ever increasing use of non linear loads especially the power electronic equipment leads to deterioration of the quality of power at the point of common coupling (PCC) of various consumers. To improve the power quality traditional compensation methods such as passive filters, synchronous capacitors, phase advancers, etc. were employed, however traditional controllers include many disadvantages. To overcome these disadvantages a dynamic and adjustable solution was developed by using custom power devices. Custom power devices are electronic converters like Active Power Filters (APF). The conventional multi carrier PWM techniques introduce additional harmonics of the fundamental component in over modulation region on load side. To overcome these drawbacks an improved level unipolar – multi carrier technique is produced which gives the benefits of gain in fundamental voltage in over modulation region without loss of control unlike in conventional multi carrier PWM technique for active power filters is simulated by using MATLAB / SIMULINK power system toolbox software. And the result compared with the conventional multi carrier PWM techniques.**

***Index terms*—Active Power Filter, multilevel inverter, modulation techniques, non linear load, power quality, total harmonic distortion, voltage source inverter.**

I.INTRODUCTION

Power quality (PQ) is certainly a major concern in the present era. Power quality become an important issue since many loads at various distribution ends like adjustable speed drives, process industries, printers, domestic utilities; computers, microprocessor based equipments etc. have become intolerant to voltage fluctuations, harmonic content and interruptions. To compensate harmonics conventional Passive Filters are used for specific number of harmonics. To compress total harmonic content Active Power Filters are used. For all types of power quality solutions at the distribution system voltage level DFACTS also called as Custom Power Devices are introduced to improve Power Quality [1].

To improve the power quality traditional compensation methods such as passive filters used have many disadvantages such as fixed compensation, bulkiness, electromagnetic interference and possible resonance etc. Active Power Filters (APF) have proved to be an attractive alternative to compensate for current and voltage disturbances in power distribution systems [2]. Two fundamental configurations of stand-alone APFs, either active or passive, have evolved: the series and the shunt filter.

The shunt active power filter shown in Fig.1 is recognized as a cost effective solution for harmonic compensation in low and medium power systems [3]. It has simple structure and construction, similar to a PWM voltage source inverter (VSI), with a large dc link capacitor, and connected to the line by means of an inductor. At low voltage levels, conventional two level inverters are used. At medium voltage levels, the conventional two level inverters either require interface transformers between the inverter terminals and the supply terminals or need active devices to be connected in series to achieve the required voltage levels. The multilevel inverters [4] are able to achieve the required voltage levels using devices of low voltage rating. Hence in this proposed work, the active power filter (APF) is realized using the cascaded H-bridge multi-level inverter.

Besides, steps are taken to operate the inverter in the over modulation region which is not intended to be a normal operating condition for a multilevel inverter, but in the case of active power filters there may be brief periods where the demanded output is sufficiently large [5], [6]. When over modulation occurs, the reference signal exceeds the Carrier (triangle) wave hence the actual resultant fundamental component does not linearly follow M_a, and the control is saturated. The modulation index M_a value increases more than unity i.e. $M_a>1$. Consequently the shape of the output voltage waveform is only partially under control.

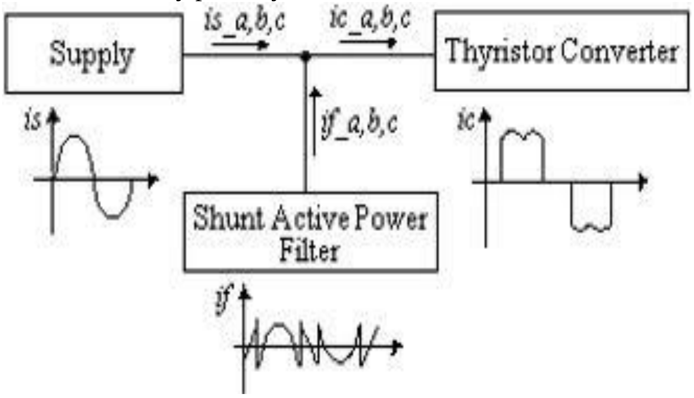

Fig. 1 Block diagram of shunt active power filter

Since the modulator effectively losses control of the output waveform during the saturation intervals the output introduces additional harmonics of the fundamental component. To overcome these drawbacks a unipolar-multi carrier technique is produced which gives the benefits of gain in fundamental voltage in over modulation region without loss of control unlike in conventional multi carrier PWM techniques.

The paper is organized as follows: Section II discusses the working of the APF with its schematic diagram. Section III presents a brief description of the various pulse width modulation techniques and also compares their performance. A closed loop control scheme using synchronous reference frame (SRF) for selectively eliminating the most harmful harmonics in the line current has been developed in Section IV. Suitable simulation exercises are carried out in Section V to evaluate the performance of shunt active power filters with a variety of non-linear loads.

II. DESIGN OF ACTIVE POWER FILTER

A. Active Power Filter

The increased severity of harmonic pollution in power networks has attracted the attention of power electronics and power system engineers to develop dynamic and adjustable solutions to the power quality problems. Such equipments, generally known as active filters [7], are also called active power line conditioners. To effectively compensate the line current harmonics, the active filter controller should be designed to meet the following three goals:

1. Extract harmonic currents and inject compensating current;
2. Maintain a constant dc capacitor voltage;
3. Avoid generating or absorbing reactive power with fundamental frequency components.

The shunt APF shown in Fig.1 has the structure of a multilevel voltage source inverter connected to the line by an inductance L_f rated at about 5% of the filter power. The dc link storage component is a capacitor, usually of larger value than in a standard power inverter [8].

B. Cascaded Multilevel Inverter

The cascaded multilevel inverter (CMLI) shown in Fig. 2 is one of the most important topology in the family of multilevel inverters. It requires least number of components when compared to diode-clamped and flying capacitors type multilevel inverters [9]. In addition it has several advantages that have made it attractive in power systems and drive applications [10].

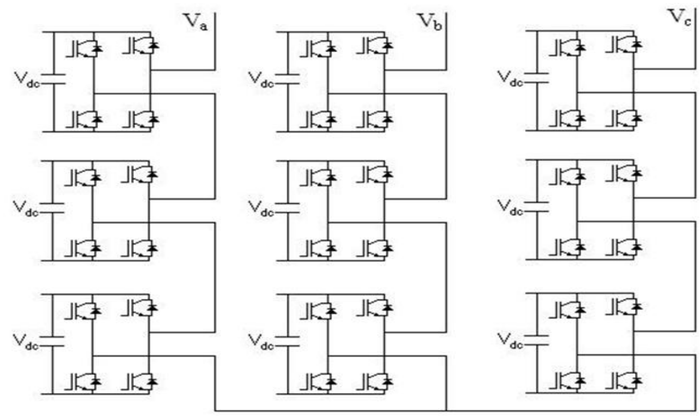

Fig. 2 Three Phase H-Bridge Inverter

A seven level cascaded multi level inverter output is shown in Fig. 3. With the increase of number of levels the response of inverter increases.

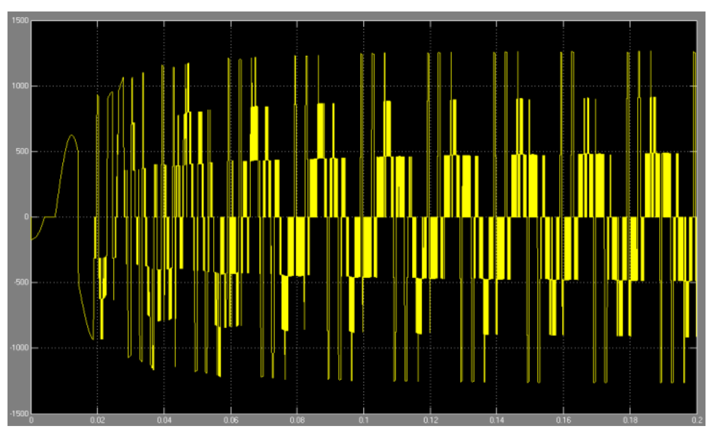

Fig. 3 Cascaded multi level inverter output for seven level

III. TYPES OF CARRIER BASED SPWM TECHNIQUES

Sinusoidal PWM can be classified according to carrier and modulating signals. This work used the intersection of a sine wave with a triangular wave to generate firing pulses. There are many alternative strategies to implement this. They are as given below.

A. Phase Shifted PWM

The essential principle of PSPWM is phase shifting the carriers of each bridge to achieve additional harmonic sideband cancellation, which occur around the even carrier multiple groups [11], [12]. Fig.4 shows the carrier arrangements and reference signal comparison for the phase shift PWM technique. Optimum harmonic cancellation is achieved by phase shifting each carrier by (k-1) /n, where k is the k^{th} converter, n is the number of series-connected single-phase inverters per phase leg. For three cascaded H-bridges with the carrier phase shift of 60°, harmonic cancellation up to side bands around multiples of $6f_c$ will be achieved. The cancellation is not dependent on the carrier/fundamental frequency ratio.

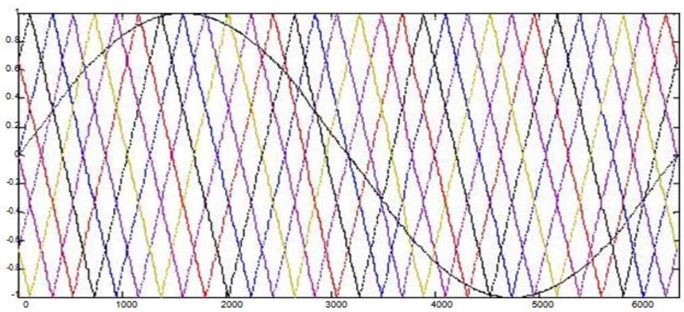

Fig. 4 PSPWM technique for 3-cell bridge

B. Phase Opposition Disposition PWM

The rules for phase opposition disposition method for a multilevel inverter are

1) 6 carrier waveforms are arranged as in Fig.4 in phase opposition disposition.
2) The converter is switched to Supply voltage when the sine wave is greater than upper carriers.
3) The converter is switched to zero when sine wave is lower than upper carrier but higher than the lower carrier.
4) The converter is switched to Supply voltage in reverse when the sine wave is less than lower carrier.

The above same rule is applicable to all PWM strategy i.e. PD, POD, APOD PWM techniques.

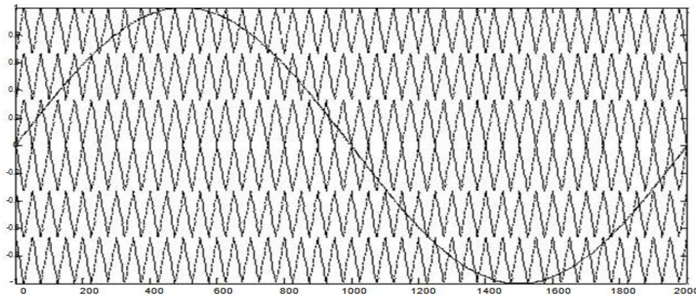

Fig. 5 Carrier arrangement for PODPWM strategy

C. Phase Disposition PWM

In Phase Disposition (PD) PWM all the carriers are in phase. By the comparison of all carriers with reference signal the pulses are produced which are given to Cascaded multi level inverter.

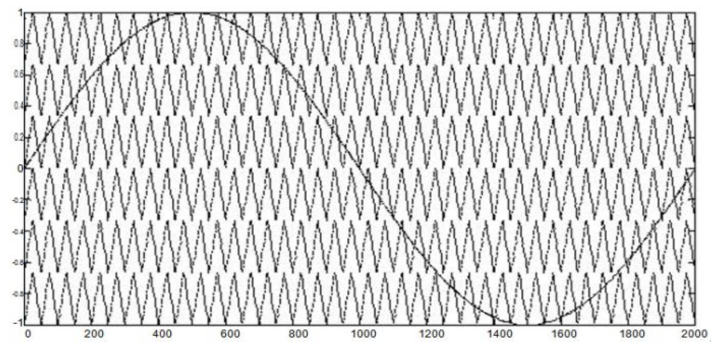

Fig. 6 PDPWM technique for 3-cell bridge

D. Alternative Phase Opposition Disposition PWM

This technique requires each of the (m-1) carrier waveforms for an m-level output to be phase displaced from another by 180 degree alternatively as shown in Fig.7.

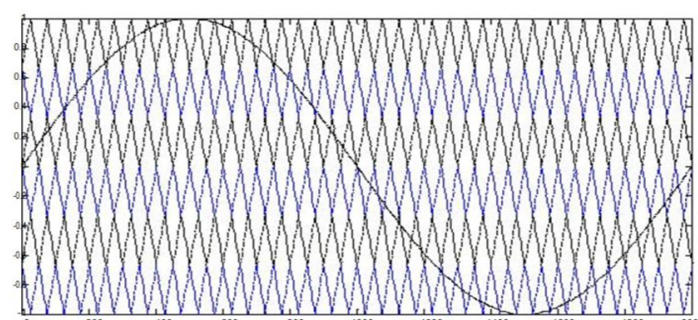

Fig. 7 APODPWM technique for 3 cell bridge

E. Unipolar Multi-carrier PWM schemes

The unipolar multi carrier pulse width modulation scheme is obtained by comparing the rectified sinusoidal reference with multi carriers positioned above the zero level as shown in Fig. 8. Similar to the multi-carrier PWM techniques with sinusoidal reference explained above, multi-carrier PWM techniques with unipolar reference are discussed. In the case of unipolar carrier disposition PWM scheme the carriers are positioned above the zero reference as shown in Fig. 8. In this scheme, only n carriers are required for an n-cell H-bridge inverter, unlike the above methods where 2n+1 carriers are required. In this method to obtain seven levels in the output voltage only three carriers are required but in CDPWM with sinusoidal reference six carriers are needed to attain the same number of levels. The degree of freedom for this method is given as:

$$Ma = \frac{Ar}{n * Ac}$$

Where, **Ar** is the amplitude of the reference

Ac is the amplitude of the carrier

n is the number of H-bridge cells.

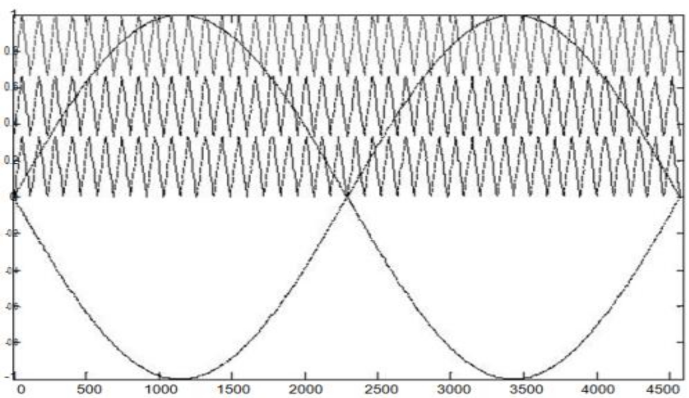

Fig. 8 Unipolar –PDPWM Technique

The unipolar-phase shifted PWM is similar to the sinusoidal reference PSPWM, the carriers are phase shifted but all the carriers are arranged above the zero level as depicted in Fig. 9. For the three cell H-bridge inverter the carriers are phase shifted by 60° to obtain seven levels. The unipolar-phase shifted PWM for seven level inverter is shown in the Fig. 9. The normal PWM technique has 2.94% of THD value. But by using Unipolar PWM technique the THD value is reduced to 2.49% i.e. it is an advanced PWM technique. The nine level Cascaded Inverter is a better harmonic control which reduces the THD value to 2.39%. So with the increase of number of levels there is betterment in harmonics.

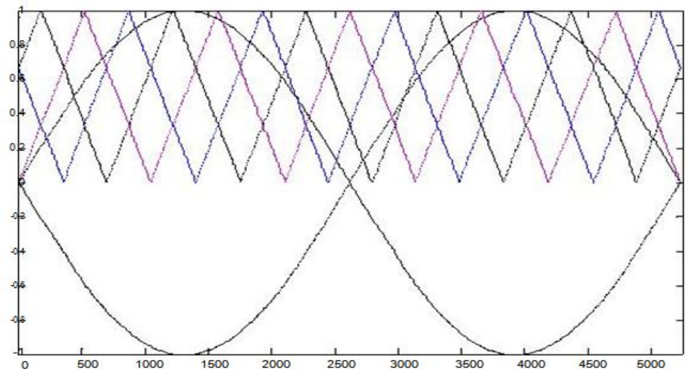

Fig. 9 Unipolar-PSPWM technique

F. Comparison of PWM schemes

A model of seven-level and nine-level cascaded multilevel inverter topology (using IGBTs) comprising of three modules in each phase leg is developed using MATLAB/SIMULINK. Each module has a separate DC source of 1000V. In order to verify the control effect of the proposed method, the CDPWM and PSPWM methods, which already exist in the literature, and the proposed carrier/reference method are simulated using MATLAB/SIMULINK software. The THD and fundamental voltage in all the cases are investigated at switching frequency equal to carrier frequency i.e.2000Hz. From the plots it is observed that for the proposed scheme the THD decreases in the over modulation region and hence an improved voltage is obtained. But in the conventional technique the THD plot varies in a non-linear manner in the over modulation region. When M_a = 1 the unipolar-inverted sine carrier PWM technique is found to improve the fundamental voltage from 5185V (conventional APOD) to 5414V i.e. the fundamental voltage is increased by 4.4%.

Utility interface is the major problem in considering the inverter, in applications like active filters where sometimes it is required to vary the modulation index Ma>1 to meet the grid voltage. As seen from the modulation index Vs THD and modulation index Vs fundamental plots the unipolar-multi carrier PWM method offers remarkable decrease in THD over a wide modulation range with an increase in fundamental voltage. Thus it enables the cascaded inverter to meet the required grid voltage and thereby the interface problem can be reduced by this proposed unipolar multi-carrier technique.

Another advantage of the unipolar-multi carrier technique is that the complexity of pulse generation for high voltage applications is reduced as the number of carriers is reduced to half the number of carriers compared to conventional CDPWM techniques. If the number of levels of cascaded multi level inverter increases this improves the line current. In table.1 a comparison is given between Unipolar and all other PWM techniques with different levels of cascaded multi level inverter. Therefore unipolar multi carrier modulation technique is an advanced technique to mitigate harmonics in a system.

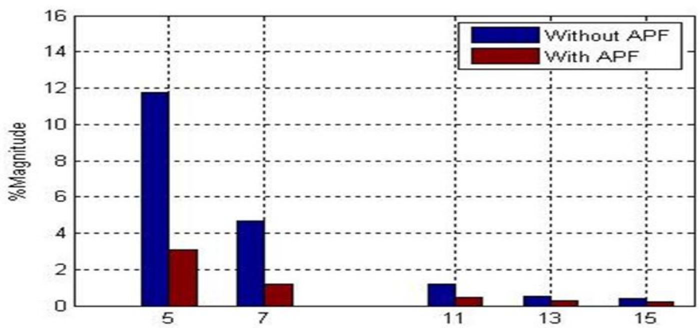

Fig. 10 THD comparison with and without APF

IV. CLOSED LOOP CONTROL SCHEME

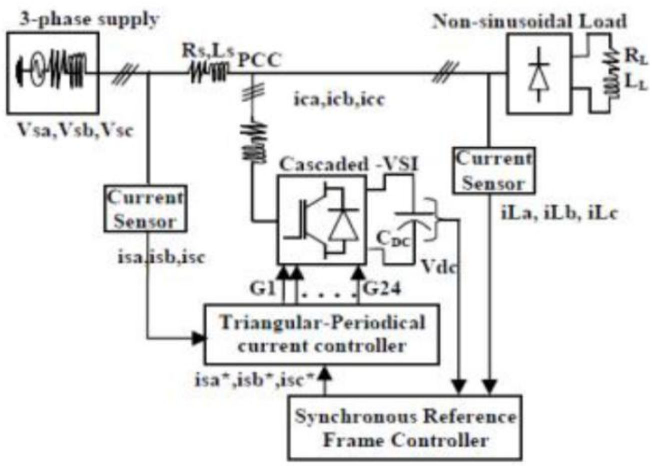

Fig. 11 Closed loop circuit of shunt active power filter

The closed loop control scheme for extracting the reference current using synchronous reference frame method is depicted in Fig.11. The harmonic currents are extracted and are used as reference currents for the cascaded multilevel inverter and compare with the triangle carrier signals which generate pulses to the power electronic switches. The function of the harmonic detection block is separately highlighted in Fig.12. The SRF method [14] is based on Park's transformation whereby the 3-phase line currents are transformed into 2-phase quantities using Park's transformation.

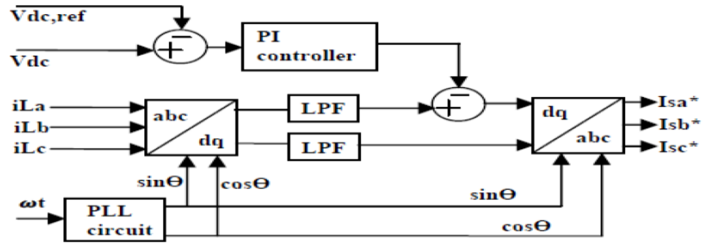

Fig. 12 Synchronous Reference Frame Controller

The synchronous reference frame theory is developed in time-domain based reference current generation techniques. The conventional SRF method can be used to extract the harmonics contained in the supply voltages or currents. For current harmonic compensation, the distorted currents are first transferred into two-phase stationary coordinates using $\alpha-\beta$ transformation (same as in $p-q$ theory).After that, the stationary frame quantities are transferred into synchronous rotating frames using cosine and sinus functions from the phase-locked loop (PLL). The sine and cosine functions help to maintain the synchronization with supply voltage and current. The conventional SRF algorithm is also known as $d-q$ method, and it is based on $a-b-c$ to $d-q-0$ transformation (park transformation), which is proposed for active filter compensation. This proposed algorithm derivate from a three-phase stationary coordinate load current iLa, iLb, iLc are convert to id-iq rotating coordinate current, as follows.

$$id = \frac{2}{3}[iLa\sin(\omega t) + iLb\sin(\omega t - \frac{2\pi}{3}) + iLc\sin(\omega t + \frac{2\pi}{3})$$

$$iq = \frac{2}{3}[iLa\sin(\omega t) + iLb\sin(\omega t - \frac{2\pi}{3}) + iLc\sin(\omega t + \frac{2\pi}{3})$$

Here the Proportional Integral (PI) controller is used to eliminate the steady state error of the DC-component of the cascaded multilevel inverter and maintains the dc-side capacitor voltage constant. The dc capacitor voltage is sensed and compared with reference voltage to calculate the error voltage. These error voltage involved the P-I gain (KP=0.1 and KI=1) for regulate the capacitance voltage in the dynamic conditions. In accordance to the PI controller output is subtracted from the direct axis (d axis) of harmonic component for eliminate the steady state error. Similar to the $p-q$ theory, using filters, the harmonics and fundamental components are separated easily and transferred back to the $a-b-c$ frame as reference signals for the filter.

$$Isa^* = id\sin(\omega t) + iq\cos(\omega t)$$

$$Isb^* = id\sin\left(\omega t - \frac{2\pi}{3}\right) + iq\cos(\omega t - \frac{2\pi}{3})$$

$$Isb^* = id\sin\left(\omega t + \frac{2\pi}{3}\right) + iq\cos(\omega t + \frac{2\pi}{3})$$

V. SIMULATION RESULTS

The presented simulation results have been obtained by using Matlab Simulink power system toolbox software. For the purpose of simulation a three phases 415V, 50Hz ac supply has been considered. The proposed APF with closed loop control has been simulated under certain non linear load namely three phase uncontrolled bridge rectifier which generates non-sinusoidal currents with typical THD factors. The basic simulink block diagram is shown in Fig.13.

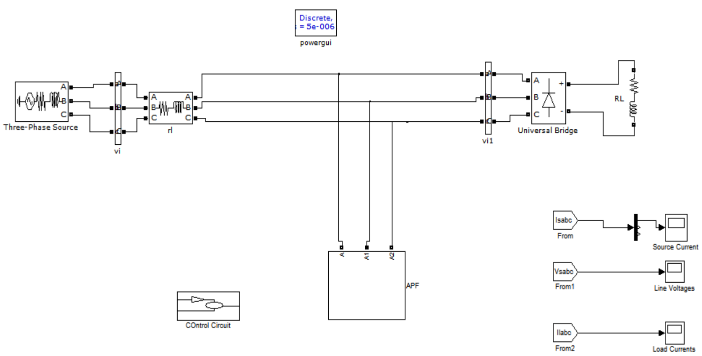

Fig. 13 Simulink model of APF

The simulated results of the test system for uncontrolled bridge rectifier load by using SRF current generation method. Without filter the line current waveform will not be sinusoidal as shown in Fig.14 and its THD is 19.46% and the 5th harmonic is found to be the dominant harmonic as displayed.

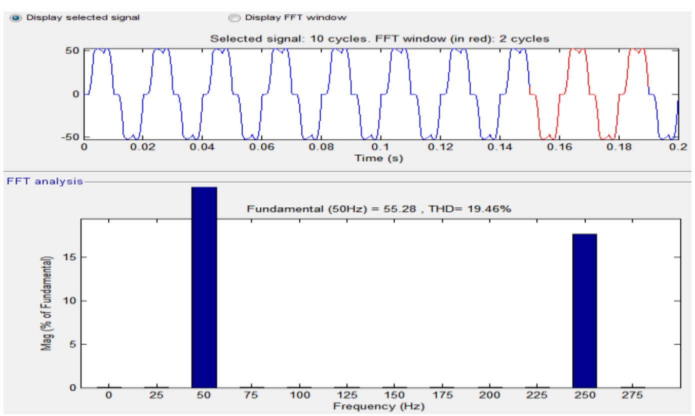

Fig. 14 Line currents and it's THD without filer

The harmonic currents are extracted and are used as reference currents for the cascaded multilevel inverter and compare with the triangle carrier signal which generates pulses to the power electronic switches. And the compensated currents are injected into line from Active Power Filter in phase opposition to the line current which cancels the harmonic currents. An improved line current with THD after placing filter is shown in Fig.15.

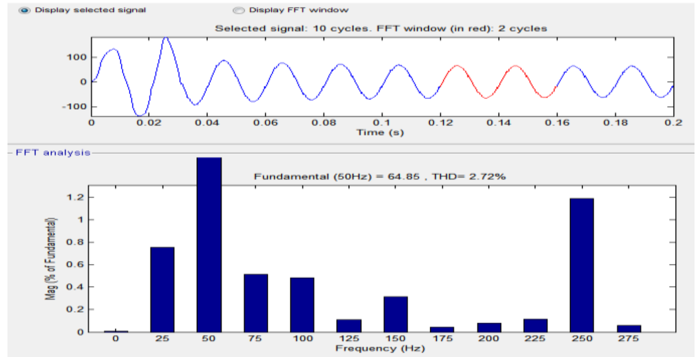

Fig. 15 Line current and it's THD with filter

VI. CONCLUSION

A new modulation strategy is proposed for a three phase cascaded H-bridge multilevel inverter which achieves improvement in line to line harmonics in the over modulation region compared to conventional modulation techniques. Besides, in the proposed PWM technique complexity of the pulse generation is reduced as the number of carriers is reduced to half compared to the already existing CDPWM and PSPWM techniques. The modulation index can be varied over a wide modulation range. As the lower base band harmonics are cancelled due to doubling effect THD decreases with increase in modulation index even greater than one. The cascaded H-bridge seven level multilevel inverter with the proposed unipolar multicarrier PWM technique has been used as the shunt active power filter. The deterioration of power quality and increase of harmonic pollution due to the increase in the usage of non-linear loads especially the power electronic equipments has been highlighted. Then the role of APF in compensating the line current harmonics has been demonstrated by considering certain non-linear loads.

With out Active Power Filter THD = 19.27%			
THD'S With Active Power Filter			
Normal PWM Techniques	THD	Unipolar PWM Techniques	THD
7Level PD PWM	3.34	7 Level PD PWM	2.76
7 Level POD PWM	3.17	7 Level PS PWM	2.49
7 Level APOD PWM	2.8	9 Level PD PWM	2.39
7 Level PS PWM	2.94	9 Level PS PWM	2.36

Table. 1 Comparison of PWM Techniques

A simulation result shows that the dominant harmonics in the line current and total harmonic distortion have been reduced significantly. Hence there is an improvement in the power quality. The unipolar PWM technique is a new approach which improves the line current. And also with increase of no. of levels the THD value reduces to minimum as possible. The comparison for all PWM techniques is as shown in Table.1.

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