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A Comparative Study on Multilevel Inverters for Shunt Active Power Filter

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ABSTRACT

In recent decade, extensive applications of high power switching devices affecting the power quality significantly. In order to maintain a quality power mainly for sensitive loads, shunt Active Power Filter (APF) are often used, which improves the power factor and decreases the percentage of Total Harmonics Distortion (THD). The APF, when connected with the load generates an reference compensating current which is in phase opposition to the harmonics present in the system, thus the resultant supply current becomes sinusoid and in phase. The compensating reference current waveform is of complex in nature, and therefore a suitable inverter operated through high frequency switching is necessary for generation of such complex waveform. A multistage inverter could be more capable of generating such complex waveform as required for the compensating current. This work explores a three-Level and five-level Cascaded H-bridge (CHB) inverter for shunt Active Power Filter in Power System (PS) to compensate the reactive power and harmonics. The performance comparisons between three-level and five-level cascaded H-bridge (CHB) inverter for a shunt active power filter (APF) are presented.

Keywords-- Active power filters (APF), cascaded H-bridge (CHB) inverter, sinusoidal pulse width modulation (SPWM), IGBT, Total harmonic distortion (THD), and P-Q theory

I. INTRODUCTION

Due to the increasing use of high power switching device, the electrical power quality has become a major concern.

The quality of electric power is affected by the nonlinear loads such as power electronic converters used at typical power distribution systems, adjustable speed drives, computer power supplies and induction furnaces [1]. The presence of harmonics in the system is responsible for overheating of equipments, reducing equipment life, EMI and renders many other harmful effects. These non linear loads result in degraded power factor and increase harmonics. The normal operation of user equipment and power system is threatened by harmonics. To eliminate many drawbacks of passive filters, now a day's active power filters are used [2]. Active power filter (APF) uses a converter which produces a compensating current in phase opposition to the harmonic current prevalent in the system. When the harmonic current is combined with the compensating current, the resultant output becomes sinusoidal in nature. The main aim of shunt APF is to track the reference current and compensating current preciously [3]. The total reactive and harmonic power, provided by the active power filter, will be in phase with the utility voltage and will be sinusoidal. The compensation current must be provided by the active power filter to estimate the fundamental components in order to compensate the harmonic current and reactive power [4]. The inverter which has more than two levels is called a multilevel inverter. The multilevel inverters generate desired output with increasing number of states. Since, conventional two-level inverter has just two steps at its output i.e. positive half cycle, negative half cycle whereas a multi-level inverter has more than one level in each half cycle. The goal of this work is to investigate suitable inverter levels of shunt-APF as per precise requirement of some typical application. In the work Cascaded H-bridge (CHB) inverter has been considered as it is less sensitive to capacitor voltage balancing problem, having less harmonic distortion, and provide less switching losses. On the other hand, switching losses and voltage stress on power electronic devices can be reduced by using multi-level inverters [5]. The semiconductor devices can be operated at low voltages compared to the conventional two level inverters. In multi-level inverters [6-10], as more number of stages is summed up to obtain the output, it is possible to obtain high voltage without the application of a transformer. Thus high rating transformer is needed with APF in a high voltage system, which is costly and bulky in size [10]. But a multilevel inverter can be used in active power filters to reduce harmonics in high voltage system without using a transformer. In the work, the Instantaneous Reactive Power Theory (P-Q Theory) is used to generate the reference compensating current [1] [8]. In this paper simulated results of a Cascaded-H Bridge multilevel inverter based Shunt APF, are presented. Level shifted Sinusoidal Pulse Width Modulation (SPWM) [9] method is applied to generate the pulse for the multilevel inverter implemented through Matlab Simulink [7].

II. BACKGROUND

A. CASCADED H-BRIDGE INVERTER

There are different topologies for multilevel structure such as the flying capacitor, diode clamped, cascaded H-bridge, but out of these three cascaded multilevel inverter has many advantages. This topology gives same voltage level using less number of switches thus reducing the complexity and the voltage unbalancing problem. The configuration of a three-level inverter is similar to that of a single H-bridge inverter. The cascaded H-bridge inverter has H-bridges connected in a series. Fig-1 shows a single phase full bridge inverter. The three discrete outputs VAB with levels of –Vdc, 0, +Vdc are generated by controlling the four switches S1, S2, S3, and S4. The output –Vdc is obtain when S2 and S3 are turned ON. The output is 0 when either pair S1 and S2 or S3 and S4 is turned ON. When S1and S4 are turned ON the output is +Vdc. In cascaded multilevel inverter, the phase output voltage is obtained by the sum of series of H-bridge outputs. The number of levels (m) is equal to twice the number (H) of independent H-bridge plus one (2H+1).

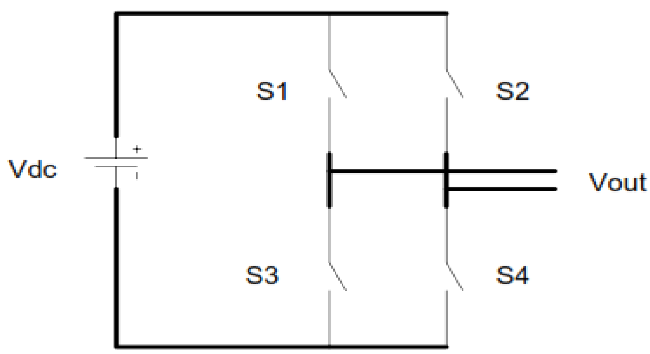

Fig-1: H-bridge configuration

III. SYSTEM DESCRIPTION

Fig-2 shows the system under consideration; the electrical system consists of a 415V, 50Hz source resistance Rs=0.02Ω, source inductance Ls=0.05mH supply. The non-linear load is given by two three- phase rectifiers. One rectifier is a resistive load R=250Ω other, capacitive-resistive load across it, c=800µf, R=80Ω. At the point of common coupling, the shunt APF is connected in parallel to the system (in between supply and non-linear load). The circuit consists of voltage and current measurements. Fig-2 represents a five-level cascaded H-bridge inverter for shunt APF. A three-level cascaded H-bridge inverter for shunt APF has the same configuration but with a different switching pattern.

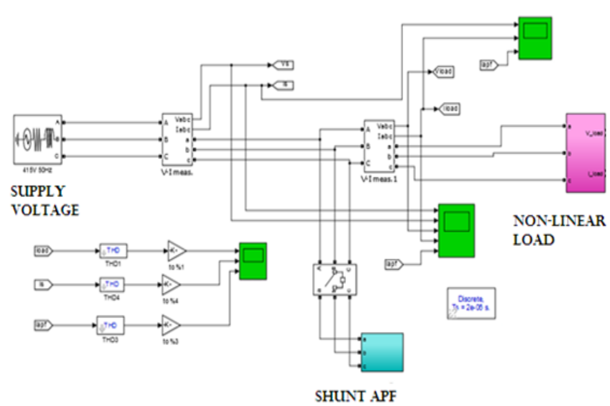

Fig-2 a simple system with non-linear load and shunt APF

IV. CONTROL STRATEGY

DESIGN OF SHUNT APF:

Figure-3 represents the block diagram of SHUNT ACTIVE POWER FILTER. The APF block has two main parts 1) power converter circuit. 2) Circuit to generate reference current. The control strategy proposed by us is aimed to generate reference signal for shunt APF. The instantaneous P-Q based theory is one of the most conventional methods for reference current generation. The shunt APF [11] explained in this paper compensates the current harmonics generated in the non-linear load and the reactive power. The shunt active filter system consists of a cascaded H-bridge inverter**,** instantaneous P-Q theory block, switching signal generator and a coupling inductor of 9mH. The active filter controller operates in a closed-loop manner continuously where the output current from the power converter is fed to the system through a three phase inductor connected in the line between the APF and the system. The inverter output current is compared with the current reference generated and the output is generated accordingly. Thus the generated compensating current which is in phase opposition to the harmonics is fed to the main system. The inductor minimizes the high current flow and smoothes out the current waveform.

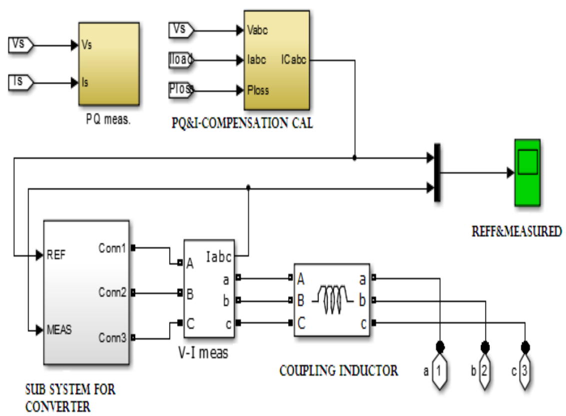

Fig-3 block diagram of shunt APF

REFERENCE CURRENT GENERATION:

The output waveform of the power converter tracks the reference waveform in order to mitigate the harmonics. Reference current block is used for generating the reference current for the converter as shown fig-4. Then the converter produces the current similar to the reference waveform and feeds the system. The system is calculated using the instantaneous p-q theory. It is defined by using Clarke transformation, in which the three phase voltage and current, is transformed into stationary α-β-0 orthogonal co-ordinates by a real matrix.

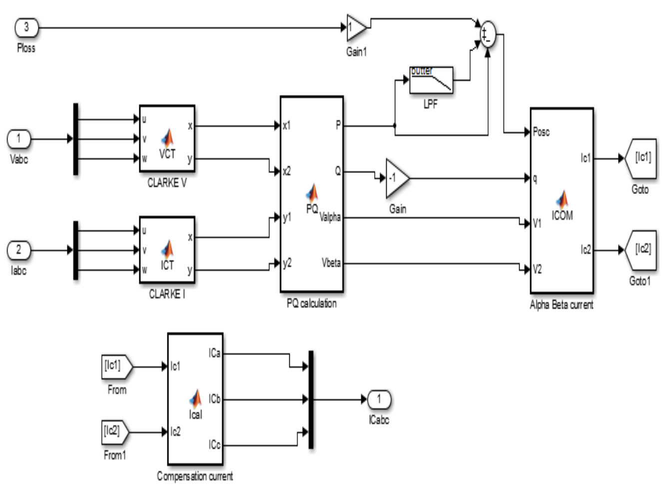

Fig-4 Reference current generation circuit

CLARKE TRANSFORMATION:

Clarke transformation transforms the three phase voltage or current from a-b-c axis to stationary α-β-0 axis. These currents and voltages are taken as inputs to the filter and then to the load. The a-b-c axis is stationary axis which are displaced 2π/3 rad. whereas the a-β-0 axis are orthogonal in nature. The Clarke transformation matrix of three phase generic voltages is given as.

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2)$$

And the inverse Clarke transformation matrix is

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (4)$$

No zero sequence components in a three phase three wire system. Now when the zero sequence component is eliminated only the α and β of current and voltage exist. [12] The Clarke transformation and its inverse have the characteristic of being invariant in power. Here the source voltage and the load current are sensed properly as the Clarke transformation is applied over them. After Clarke transformation, the voltage and current can be written as.

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (6)$$

The above instantaneous vectors are represented in a complex plane having α as a real axis and β as imaginary axis. Now α, β components are used to calculate the instantaneous complex power.

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (8)$$

These two powers (active and reactive) consist of two parts - the main part called the DC part and oscillating part also known as the AC part. The active power and reactive power of the load can be given as:

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$p_0 = v_0 i_0$ (9)

$p = v_\alpha i_\alpha + v_\beta i_\beta$ (10)
$q = v_\alpha i_\alpha - v_\beta i_\beta$ (11)

The $v_\alpha i_\alpha$ *and* $v_\beta i_\beta$ are instantaneous real and imaginary powers.
Where
p_0 = instantaneous zero-sequence power.
p= instantaneous active power (unit is watt).
q=instantaneous imaginary power.
The p and q can be expressed in terms of the dc plus ac components.
P=p1+p2 (12)
Q=q1+q2 (13)

The DC part can be calculated by using low-pass filter, which eliminates the high frequency and gives the fundamental component. The DC part of active and reactive power, a-ß reference current can be represented below. Low pass butter worth filter is used with cut off frequency 50Hz. The dc voltage control block determines the extra real power (p_{loss}) that causes an additional flow of energy to (from) the dc capacitor to keep the bus voltage constant around a reference value. This power (p_{loss}) is summed up with the compensating real power [13].

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} p_c \\ q_c \end{bmatrix} \quad (14)$$

The obtained reference current is converted to a-b-c axis by inverse Clarke transformation.

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (15)$$

These three phase reference current are fed to the gate pulse generating circuit where it is compared with the instantaneous output current of each phase and the switching is done accordingly. The resultant source current is equal to the sum of the load current and the compensating current.

POWER CONVERTER:

The multi-level inverters are used for a shunt APF to compensate the current harmonics. As an alternative a multi level inverter can be used without a coupling transformer to generate AC waveform from small voltage steps by using a separate DC sources or series capacitor bank. There are different source wise topologies in the inverter- a separate dc source and a common dc source. The cascaded inverter is the separate DC source and the flying capacitor and diode clamped inverter are the common DC sources. So the cascade h-bridge configuration has many advantages than the others. Fig-5 shows a three phase fine level inverter which has two modules in each phase. A three phase reference current is generated by the reference current generation block to the inverter. This reference current is fed into three different phase having two modules in each. The DC capacitor acts as an energy storage device across each module. No separate external DC sources are used. IGBT has many advantages over other electronic switches so it is used as a switching element. To obtain the gating signal the obtained APF current output is compared with the reference current in the gate control block. If the reference current is greater than the APF output of that phase the upper IGBT of leg one and the lower IGBT of leg two in both of the modules conduct and others are off and for lesser value vice-versa. The same comparison is done for the three phases and compensating current in each phase is obtained.

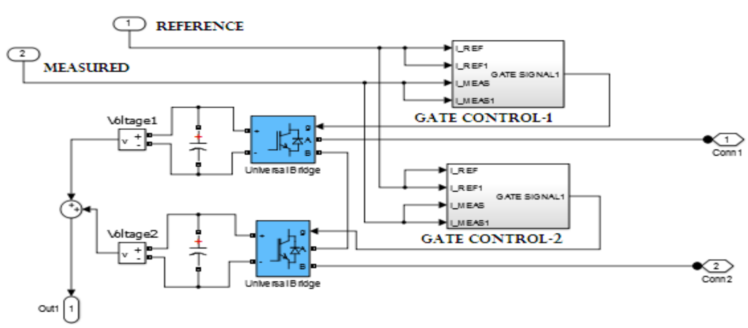

Fig-5 five-level inverter connected in shunt APF for one phase

The power loss component are to be considered it is also require to regulate the DC link voltage. As the DC link capacitor works as an energy storage element. The voltage across DC link is regulated by using the PI controller. Fig-6 shows the DC voltage regulation for converter.

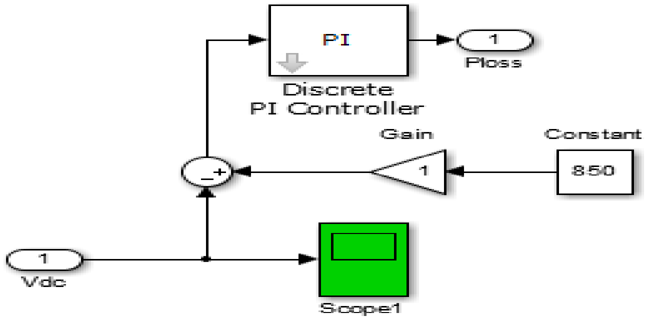

Fig-6 DC voltage regulation for converter

To maintain a constant voltage across DC link, the controller sets a reference DC current [9]. In case of cascaded H-bridge multilevel inverter, a constant voltage across each capacitor of individual bridge has to be maintained. For this the capacitor voltages are measured and the average leg voltage is calculated. Then it is compared with reference and the voltage across each capacitor is maintained constant according to the error. The full converter circuit for a shunt APF shown fig-7.

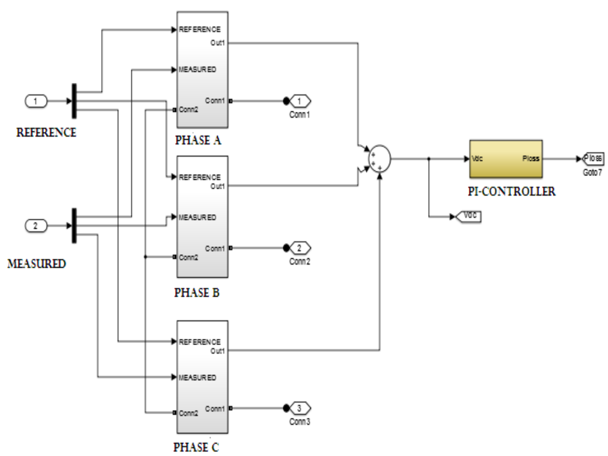

Fig-7 full converter circuit for the shunt APF

V. SIMULATION RESULT

The proposed simulation model for five-level and three-level cascaded H-bridge inverter for shunt active filter are carried out using MATLAB/SIMULINK. The results show a five-level CHB inverter for shunt APF. The three-phase breaker transition time is 0.02 Sec. Fig-8&9 show a three-phase supply voltage and load-voltage before shunt APF respectively.

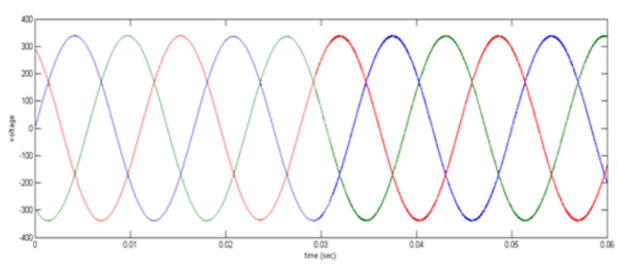

Fig-8 Three-phase supply voltage before shunt APF

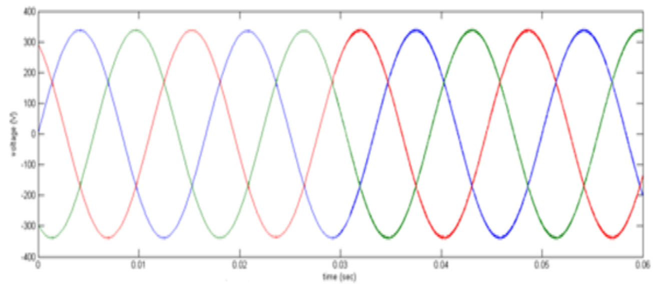

Fig-9: Three-phase load voltage before shunt APF

Fig-10 shows the load current waveform which is same as the source current when the APF is not connected. It can be easily seen that the load current waveform is much different from the ideal sine wave. Now, APF is connected to the circuit after 0.2 sec. The Fig-11 represents the source current Up to 0.2 sec the source current is same as the load current as APF is not connected. After switching on the shunt APF, source current changes and almost a sine wave is obtained from 0.03sec.

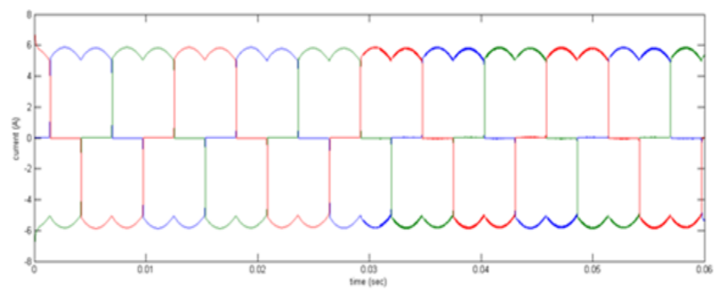

Fig-10: load current before connect the shunt APF

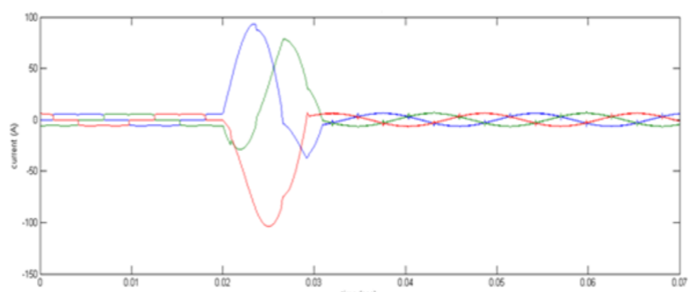

Fig-11: source current before and after shunt APF

The proper tracking of reference and measured current before and after connecting the shunt APF. The APF is connected to the circuit after 0.02 sec. The fig-12 shows proper tracking of reference and measured current before and after shunt APF.

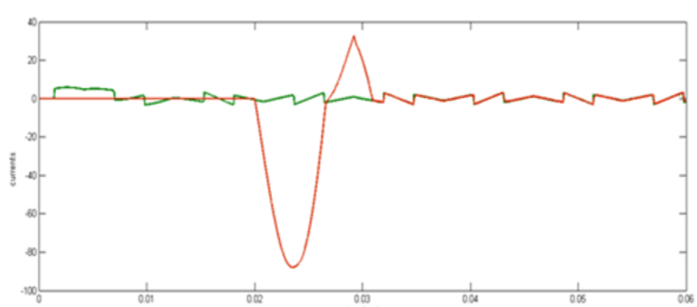

Fig-12 tracking of reference and measured current before and after shunt APF

COMPARISION OF 5-LEVEL AND 3-LEVEL FOR SHUNT APF:

The results 5-level and 3-level cascaded inverter for shunt APF at different frequencies and different load. The simulation results for a 3&5-level cascaded inverter before and after shunt APF 50 Hz, load Rc=80Ω, C=800μf, R=250Ω as shown fig-13 to16.

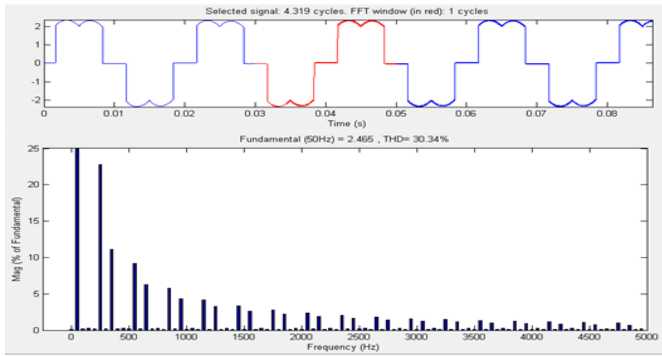

Fig-13: 50 Hz THD for 3-level CHB inverter before shunt APF

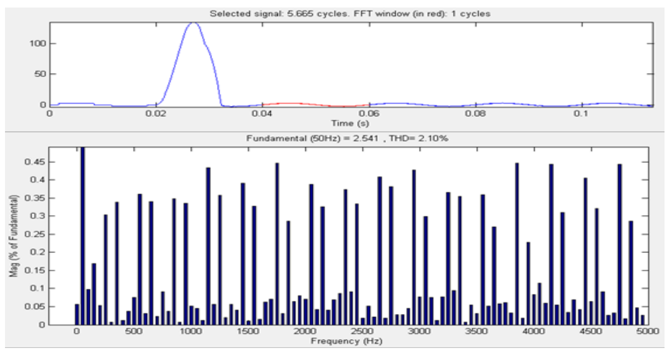

Fig-14: 50 Hz THD for 3-level CHB inverter after shunt APF

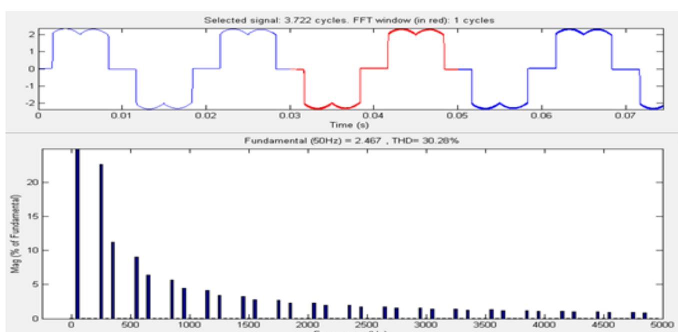

Fig-15:50 Hz THD for 5-level CHB inverter before shunt APF

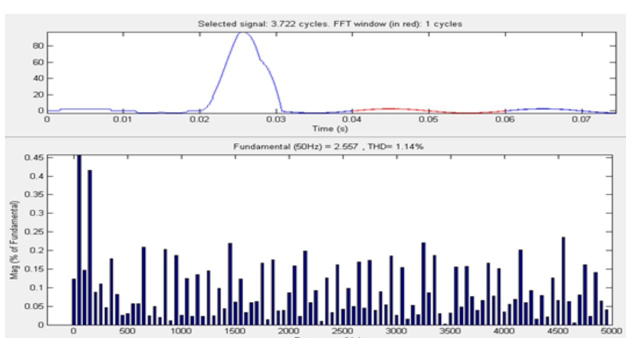

Fig-16:50 Hz THD for 5-level CHB inverter after shunt APF

COMPARISION OF THD 5-LEVEL AND 3-LEVEL FOR SHUNT APF

The comparison of the for 50 Hz 3&5-level using R=80Ω, C=800µf, RC=250Ω. As shown fig-17

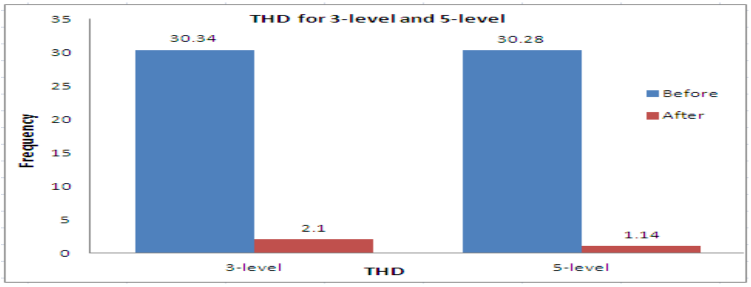

Fig-17 COMPARISON OF THD FOR 50HZ, 3-LEVEL AND 5-LEVEL INVERTER

The comparison for the 50 Hz 3&5-level using R=100Ω, C=1100µf, RC=1000Ω, as shown fig-18.

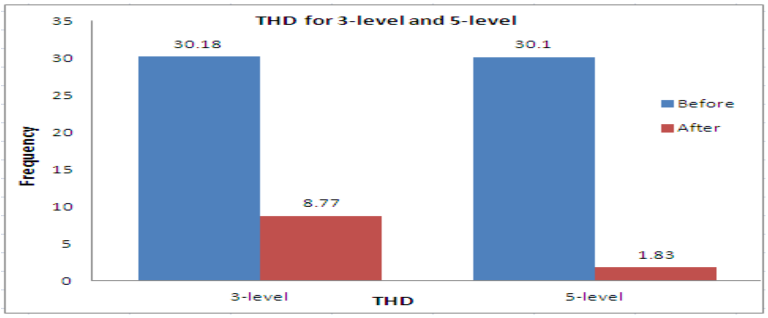

Fig-18 COMPARISON OF THD FOR 50HZ, 3-LEVEL AND 5-LEVEL INVERTER

The comparison for the 60 Hz 3&5-level using R=80Ω, C=800µf, RC=250Ω as shown fig-19.

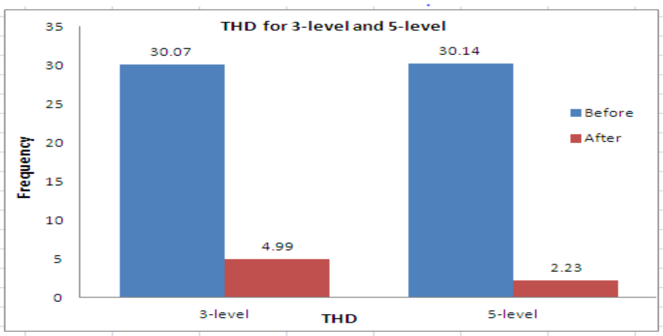

Fig-19 COMPARISON OF THD FOR 60HZ, 3-LEVEL AND 5-LEVEL INVERTER

The comparison for the 60 Hz 3&5-level using R=100Ω, C=1100µf, RC=1000Ω as shown fig-20.

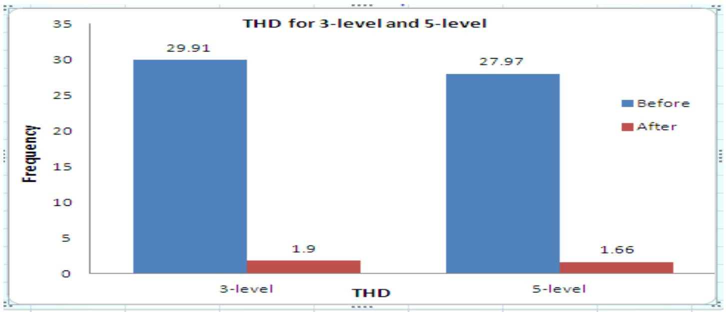

Fig-20 COMPARISON OF THD FOR 60HZ, 3-LEVEL AND 5-LEVEL INVERTER.

VI. CONCLUSION

In this paper 3-level cascaded H-bridge inverter with a 5-level cascaded H-bridge inverter for shunt APF have been studied, for different frequency and different loads using MATLAB simulation. A shunt active power filter reduces the load harmonic current from the System. A three level inverter has more total harmonic distortion as compared to a five level inverter. It was observed that when the number of level increases, THD decreases and active power increases. This study will be helpful to a design engineer in selecting the appropriate multilevel inverter for specific application.

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