A HYBRID ACTIVE FILTER FOR A DIODE RECTIFIER USED AS THE FRONT END OF AN INDUCTION MOTOR DRIVE

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Abstract – *Power quality issues created in power system are due to the nonlinear characteristics and fast switching of power electronic equipment. The major power quality issues such as harmonics, voltage unbalance, and notching, poor power factor etc… are studied. Among them harmonics is considered as one of the major issue. The line side harmonic current in the front end of a three phase diode rectifier of a 400 V, 15 KW induction motor drive is analyzed. To mitigate the source side harmonic current, a transformer-less hybrid active filter is realized. The hybrid active filter is based on direct connection of a passive filter tuned to seventh harmonic frequency in series with an active filter using a three level Neutral point clamped PWM converter. Simulations have been carried out on the Matlab/Simulink platform and results are presented. The experimental results verify the viability and effectiveness of the proposed hybrid filter.*

Key Words: Active filter, Passive filter, Neutral point clamped PWM inverter, SRF Theory etc…

1. INTRODUCTION

Now a day's power electronics based equipments are used in industrial and domestic purposes. These equipments have significant impact on the quality of supply voltage and have increased harmonic current pollutions. The drawbacks include additional losses in overhead and underground cables, transformers and rotating electric machines, error of measuring instruments, and low efficiency of customer sensitive loads.

A medium-voltage motor drive for energy savings neither require fast speed control nor regenerative braking when it is applied to fans, blowers, pumps, and compressors. Therefore manufacture uses a three-phase six-pulse diode rectifier as the front end of the medium voltage motor drive. The diode rectifier produces a large amount of harmonic current at the line side. Pulse width modulated (PWM) rectifier is capable of drawing three-phase sinusoidal currents from the ac mains, so that it may be preferable to the diode rectifier in specific low-voltage applications. However, the diode rectifier is much more efficient, reliable and less expensive than the PWM rectifier in medium-voltage motor drives without regenerative braking. Nevertheless, the diode rectifier brings a large amount of harmonic current to the ac mains, and therefore it does not comply with harmonic guidelines or regulations.

Passive filters have been used earlier to mitigate problems due to harmonics. But they have many drawbacks such as resonance problem, dependency of their performance on the system impedance, absorption of harmonic current of non-linear load. To overcome these drawbacks active filters are introduced. They inject harmonic voltage or current with appropriate magnitude and phase angle into the system and cancel harmonics of nonlinear load. But it has also some drawbacks like high initial cost and high power losses. This limits their wide application, especially with high power rating system.

To minimize these limitations hybrid active filters has been introduced and implemented in practical system applications. Hybrid filter consist of an active filter which is connected in series or parallel with a passive filer. It provides cost effective harmonic compensation for high power nonlinear load. Different control techniques are present for extracting harmonic components of the source current. Some of them are synchronous reference frame (SRF) theory, instantaneous power theory (p-q), where high pass filters extract harmonic components of the source current from the fundamental components.[5][6]

1.1 Hybrid Active Filter

Active power filters can be used with passive filters for improving the compensation characteristics of the passive filter. This avoids the possibility of the generation of series or parallel resonance. If active filters are used alone it will compensate only voltage regulation and voltage unbalance. Hybrid combination eliminates harmonics in the system and reduces reactive power flow. Depending on the application, series or parallel configuration or combination of active or passive filters are used. In this way the compensating characteristics of passive filter is improved since the voltage harmonic components generated by active scheme across the terminal of the primary windings of the series transformer, forcing current harmonics generated by the load to circulate through the passive filter instead of the distribution system. The amplitude of the fundamental voltage component across the coupling transformer can be controlled and thus the power factor of the distribution system can be adjusted.[1]

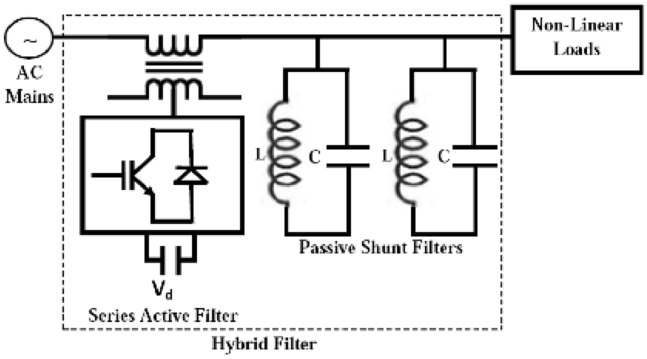

Fig -1: Hybrid filter

This type of system configuration is very convenient for compensation of high power medium voltage non-linear loads, such as large power ac drives or high power medium voltage rectifiers for application in arc furnaces.[2]

2. SYSTEM CONFIGURATION

Fig. 2 shows a feasible system configuration of the 400V motor drive equipped with a hybrid active filter at the line side. The 400V motor can be driven by a three-level-NPC (neutral point clamped) PWM inverter with a dc-link voltage of 200V. Each of the 12 insulated gate bipolar transistors (IGBTs) or three IGBTs connected in series. The hybrid active filter consists of a simple passive filter tuned to the seventh harmonic frequency and an active filter using a three-level NPC PWM converter. The passive and active filters are directly connected in series without transformer. Thus, the hybrid filter is well suited to the 400V motor drive for energy conservation because the motor drive does not require any line frequency transformer. This passive filter has an additional power factor correction for the other inductive load connected on the same 400V industrial power distribution system. The combination with the passive filter allows the active filter (three level NPC-PWM converters) to have a lower dc-link voltage. This allows active filter to use IGBTs that are currently available from market at reasonable cost.[9][10]

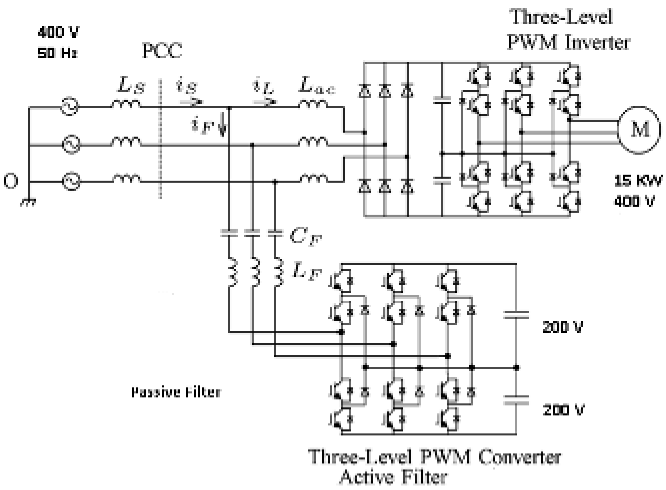

Fig -2: Circuit diagram

2.1 Neutral Point Clamped Voltage Source Converter

The 400V motor is driven by a three-level NPC-PWM inverter with a dc-link voltage of 200V. Also the active filter is based on NPC-PWM inverter. This new breed of AC/DC converters gives excellent power quality indices like nearly unity power factor, negligible THD in source current, reduced ripple factor of load voltage and fast regulated load voltage. Among the various topologies of power quality converters, multi-level converters provide viable solution for medium to high power industrial applications at high voltages. Diode clamped topology is the most popularly used topology among multi-level converters.

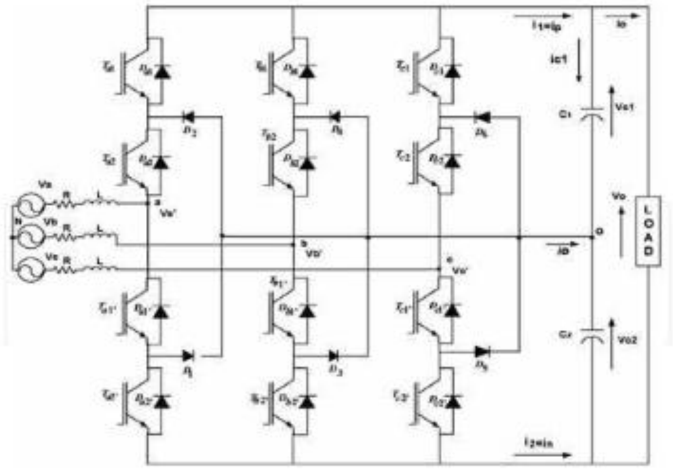

Fig -3: Three-level Neutral Point Clamped PWM inverter

The independent power switches (T_{X1} and T_{X2}, x = a, b, c) are controlled in each leg of the converter. The constraints for four power switches in an arm of the converter are defined so as to avoid the power switches conducting at the same time.

$T_{Xi} + T_{xi'} = 1$ (1)

Where T_{Xi} = 1(or 0) if the power switch T_{Xi} is turned on or off and x = a, b, c and i = 1,2.

Four switching states are possible for each rectifier leg. But only three valid switching states can be generated. This is to achieve three voltage levels on the Ac terminals of rectifier leg. The equivalent switching functions in leg A of converter are defined below.

Operation mode 1 (S_a = 1): In this mode the power switches T_{a1} and T_{a2} are turned on. The Ac terminal voltage $V_{a'} = V_0 / 2$. The boost inductor voltage $V_L = V_a - V_o/2 < 0$ if the voltage drop across equivalent series resistance is neglected. The line current decreases and the current slope is $(V_a - V_0/2)/L$. The line current i_a will charge or discharge the DC-bus capacitor C_1 if AC system voltage is positive or negative respectively.

Operation mode 2 (S_a = 0) : In this mode, the power switches $T_{a1'}$ and T_{a2} are turned on and AC terminal voltage V_{a0} = 0. The boost inductor voltage $V_L = V_a$. The line current increase or decrease during the positive or negative half cycle of mains voltage V_a. The input current i_a will not charge or discharge any of DC-bus capacitors. The input power is stored in the boost inductor in this mode of operation.

Operation mode 3 (S_a = -1): In this mode, the power switches $T_{a1'}$ and $T_{a2'}$ are turned on and AC terminal voltage $V_{a0} = -V_0/2$. The boost inductor voltage $V_L = V_a + V_0/2 > 0$ and line current increases. The current slope is $(V_a + V_0/2)/L$. The line current i_a will charge or discharge the DC bus capacitor C_2 during the positive or negative half of mains voltage respectively.

The operation modes are similar in converter legs B and C for controlling line currents i_b and i_c.

The valid switching states of the power switches of three legs and corresponding voltages on the ac side of rectifier is shown by table 1.[11]

Table -1: Valid switching states and corresponding voltages

S	T_{X1}	T_{X2}	$T_{X1'}$	$T_{X2'}$	V_{Xn}
1	1	1	0	0	$V_1 = V_0/2$
0	0	0	1	1	0
-1	0	0	1	1	$V_2 = -V_0/2$

2.2 Control system of Active filter

Fig.4 shows a control circuit of the active filter. The active filter detects the three phase supply currents and three phase load currents for feedback control. The active filter can also regulate its dc bus voltage without any external supply by a feedback dc-voltage controller.

First of all the currents in a-b-c co-ordinates are transformed into α-β co-ordinates using Clark's transformation.

$$\begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3/2} & \sqrt{3/2} \end{bmatrix} * \begin{bmatrix} iLa \\ iLb \\ iLc \end{bmatrix} \quad (2)$$

Where α and β axes are the orthogonal coordinates. The instantaneous power for three phase circuits are defined as

$$p = v\alpha\, i_\alpha + v_\beta i_\beta \quad (3)$$

where p is also defined as

$$p = v_a i_a + v_b i_b + v_c i_c \quad (4)$$

$$q = - v_\beta i_\alpha + v_\alpha i_\beta \quad (5)$$

In matrix instantaneous real and reactive powers are given as

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V\alpha & V\beta \\ -V\beta & V\alpha \end{bmatrix} \begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} \quad (6)$$

Then α-β current can be obtained as

$$\begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} V\alpha & -V\beta \\ V\beta & V\alpha \end{bmatrix}\begin{bmatrix} P \\ Q \end{bmatrix} \quad (7)$$

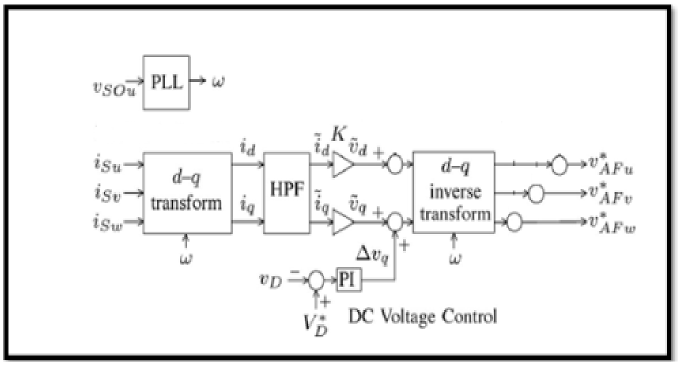

Fig -4: Control block diagram of Active Filter

Using Θ as transformation angle, these currents are transformed from α-β frame to d-q frame. This is defined as Park's transformation.

$$\begin{bmatrix} id \\ iq \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix}\begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} \quad (8)$$

DC components are extracted by using low-pass filters (LPFs). The dc components are then transformed back to a-b-c co-ordinate using reverse Park's transformation and reverse Clark's transformation.[3][4]

2.3 Sinusoidal Pulse Width Modulation (SPWM)

The switches in the voltage source inverter can be turned on and o as required. In the simplest approach, the top switch is turned on If turned on and o only once in each cycle, a square wave waveform results. However, if turned on several times in a cycle an improved harmonic pro le may be achieved.

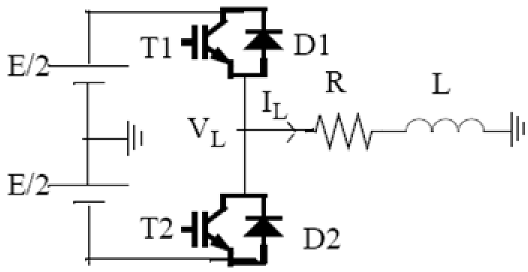

Fig -5: Simple voltage source inverter

In the most straightforward implementation, generation of the desired output voltage is achieved by comparing the desired reference waveform (modulating signal) with a high-frequency triangular carrier wave as depicted schematically in Fig.5. Depending on whether the signal voltage is larger or smaller than the carrier waveform, either the positive or negative dc bus voltage is applied at the output. Note that over the period of one triangle wave, the average voltage applied to the load is proportional to the amplitude of the signal (assumed constant) during this period. The resulting chopped square waveform contains a replica of the desired waveform in its low frequency components, with the higher frequency components being at frequencies of a close to the carrier frequency. Notice that the root mean square value of the ac voltage waveform is still equal to the dc bus voltage, and hence the total harmonic distortion is not affected by the PWM process. The harmonic components are merely shifted into the higher frequency range and are automatically filtered due to inductances in the ac system.

When the modulating signal is a sinusoid of amplitude Am, and the amplitude of the triangular carrier is Ac, the ratio m=Am/Ac is known as the modulation index. Note that controlling the modulation index there for controls the amplitude of the applied output voltage. With a sufficiently high carrier frequency the high frequency components do not propagate significantly in the ac network (or load) due the presence of the inductive elements. However, a higher carrier frequency does result in a larger number of switching per cycle and hence in an increased power loss. Typically switching frequencies in the 2-15 kHz range are considered adequate for power systems applications. Also in three-phase systems it is advisable to use FC/Fm = 3K (K < N) so that all three waveforms are symmetric.

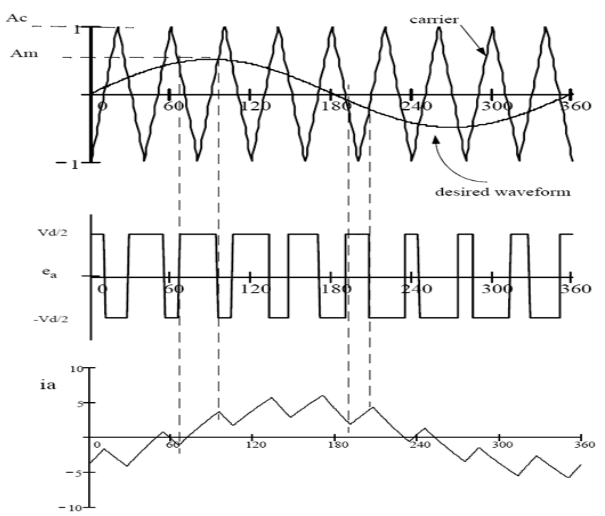

Fig -6: SPWM with fc/fm = 48, L/R = T/3

2.4 Design of passive filter

The passive filter used here has the function of mainly absorbing harmonic current produced by the diode rectifier. Therefore the passive filter should have impedance as low as possible at the fifth, seventh, 11th, and 13th harmonic frequencies to achieve good filtering characteristics. For this reason most hybrid filters consist of fifth and seventh tuned LC passive filter and a high pass filter. However, many passive elements are required thus making conventional hybrid filter costly and bulky. Moreover, the high pass filter allows a no negligible amount of switching ripple current to flow from active filter into supply, so it is mandatory to install an additional switching-ripple filter. The 11th and 13th harmonic tuned LC filters can be used instead of high pass filter. This passive filter configuration would still be bulky, although no switching-ripple filter may be required.

The hybrid filter proposed in this paper uses a single LC filter per phase as passive filter. It is characterized by being tuned to seventh harmonic frequency which is the second most dominant. The reasons for selecting seventh harmonic frequency are summarized below. The LC filter tuned at seventh harmonic frequency is less bulky and less expensive than that tuned at fifth harmonic frequency. The seventh harmonic tuned filters presents lower impedances at the 11th and 13th harmonic frequencies than the fifth harmonic frequency tuned filter does. The filtering characteristic for the fifth harmonic frequency can be significantly improved by the control strategy used in this paper.

Design of inductance and capacitance has many criteria that should be considered. The impedance of LC filter must be as low as possible, thus contributing to good filtering characteristics and making active filter voltage rating low. The required dc voltage of the active filter should be around 200V for this system, so that general purpose IGBTs can be used for active filters. These imply that the capacitance values should be as large as possible, whereas the inductance value should be as low as possible. However, a large capacitance value is accompanied by a large amount of capacitive reactive current owing into the LC filter. Moreover a low inductance value would make the LC filter have no capability of suppressing the switching ripples caused by the active filter.[7]

3. SIMULATION RESULTS

The simulation is carried out using MATLAB/SIMULINK software. Fig.5 shows the basic simulation model of hybrid filter that correlates to the system configuration shown in Fig.2 in terms of source, load, hybrid filter and control blocks. T he considered load is an induction motor drive with rating 400V, 15 KW. The hybrid active filter consist of a passive filter tuned to seventh harmonic frequency and an active filter using a three-level NPC PWM inverter. The passive and active filters are directly connected without transformer. The performance of active filter is based on SRF theory and sine PWM method.

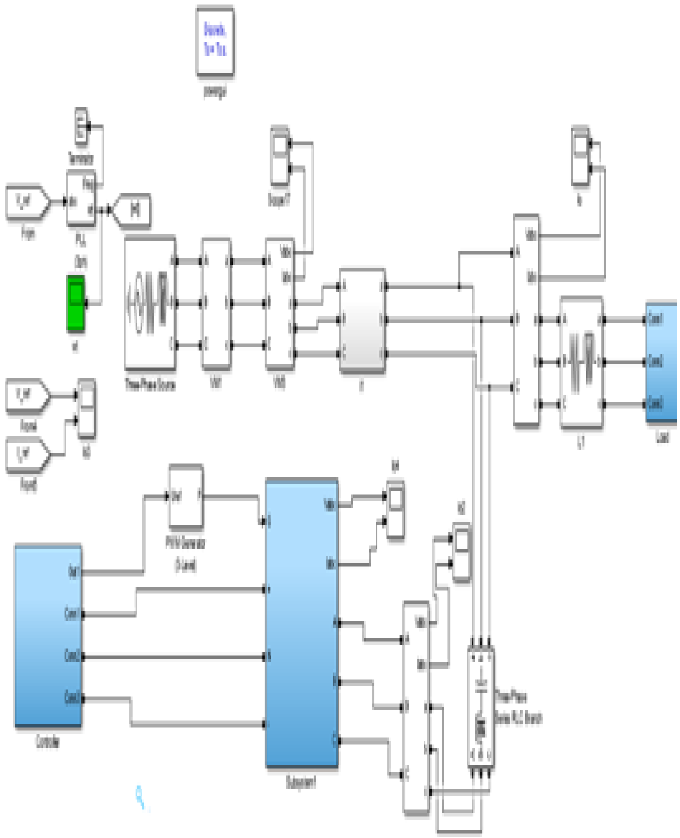

Fig -7: MATLAB/SIMULINK model

The generation of voltage templates (sine and cosine) plays an important role in the calculation of reference source currents. These templates are generated using PLL, and therefore the tuning of PLL is crucial. The operation of PLL is slow, and is also imposes some amount of delay in computation. THD is observed with and without connecting hybrid active filter.

3.1 Uncompensated System- source voltage and current waveform

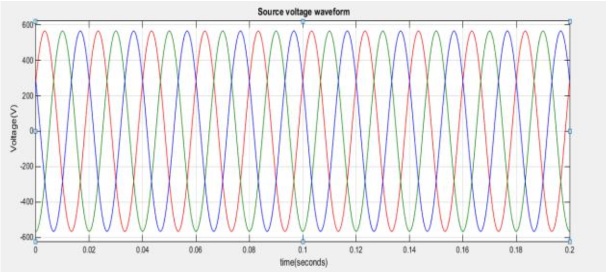

Fig -8: Source Voltage

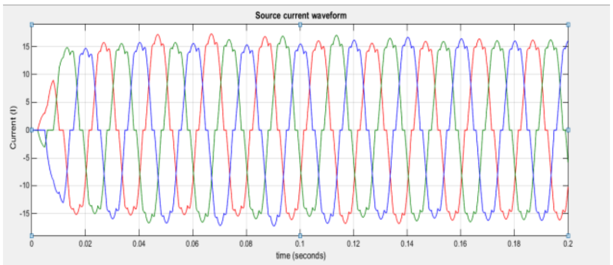

Fig -9: Source Current

3.2 Uncompensated System- Load voltage and current waveform

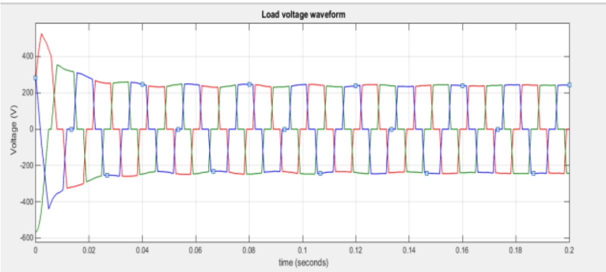

Fig -10: Load Voltage

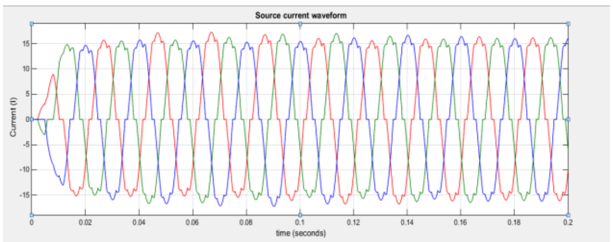

Fig -11: Load Current

The voltage and current waveform of uncompensated model is shown above. It is clear from the figure that the current and voltage waveform is distorted.

3.3 Compensated System- Source voltage and current waveform

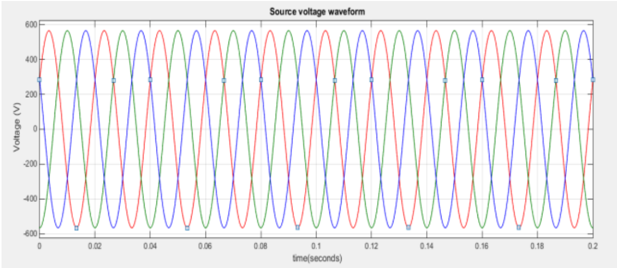

Fig -12: Source Voltage

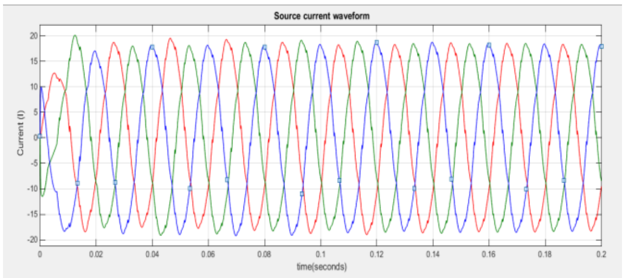

Fig -13: Source Current

3.4 Compensated System- Load voltage and current waveform

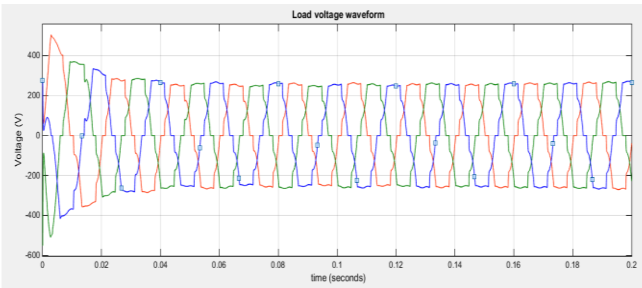

Fig -14: Load Voltage

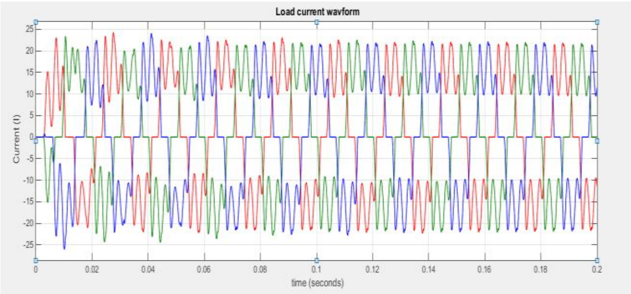

Fig -15: Load Current

Table -2: Measured Harmonic Spectra And THD values of source current

	1	3	5	7	11	13	THD
Uncompensated System	100	3.3	7.5	3.5	1.2	1.6	23.9
Compensated System	100	0.4	2.6	0.4	1.4	0.9	4.86

4. CONCLUSIONS

A hybrid active filter for harmonic current mitigation of a diode rectifier has been studied. The hybrid filter is characterized by series connection of a simple LC filter tuned to the seventh harmonic frequency and a small-rated active filter. The Active filter used is based on three-level-Neutral point clamped PWM inverter. The hybrid active filter has the following advantages over a pure active filter and a traditional passive filter consisting of multiple-tuned LC filters and a high pass filter: The active filter taking part in the hybrid filter is much smaller in converter capacity than the pure active filter, The simple single-tuned LC filter used in the hybrid filter is much smaller in size, lower in cost and weight, than the traditional passive filter.

The control strategy for reference current generation for active filter is based on SRF theory. Sinusoidal pulse width modulation has been used for gating signal generation.

Both experimental and theoretical analysis has verified that hybrid filter has provided satisfactory harmonic filtering of the diode rectifier. The THD obtained here are within the limit of 5 percentages prescribed by IEEE.

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