Received Date: 5th November, 2022
Accepted Date: 12 April, 2023

Active Power Filter Integrated with Transformer

Thakur Paudel[1*], Sunil Kumar Yadav[2], Rabin Devkota[3], Yogendra Jha[4], Prof. Dr. Indraman Tamrakar[5]

[1] *Department of Electrical Engineering, Pulchowk Campus, IOE, TU. E-mail: 072bel347thakur@pcampus.edu.np,*
[2] *Department of Electrical Engineering, Pulchowk Campus, IOE, TU. E-mail: star77sunil@gmail.com*
[3] *Department of Electrical Engineering, Pulchowk Campus, IOE, TU. E-mail: rabindevkota9847@gmail.com*
[4] *Department of Electrical Engineering, Pulchowk Campus, IOE, TU. E-mail: yogendrajha348@gmail.com*
[5] *Department of Electrical Engineering, Pulchowk Campus, IOE, TU. E-mail: imtamrakar@ioe.edu.np*

***Abstract*— In recent years, the use of non-linear load is increasing day by day. Non-linear loads such as traditional diode/ thyristor rectifiers with inductive load generate harmonic and reactive current, which leads to poor power factor, low energy efficiency, and harmful disturbance to other appliances. Also, in recent years, the large-scale use of the power electronic equipment has led to an increase of harmonics in the powersystem. Harmonics also affects on the performance of distribution transformer. It increases power loss due to skin effect and proximity effect. Current harmonics are one of the most common causes of these problems and are usually resolved by using shunt active filter (SHAF). By the implementation of a shunt active power filter on the secondary side of the transformer, the harmonics can be compensated which is produced by non-linear load. Finally, by the implementation of this concept the efficiency of the transformer, losses of the transformer, overheating of the conductor due to skin effect, power quality, etc. can be improved. Results of simulation and hardware fabrication are presented in this paper.**

***Keywords* — Shunt active filter (SHAF), Power Quality, Skin effects, Proximity effect, Harmonic Component, Non-linear Load.**

I. INTRODUCTION

The growing number of power electronics- based equipment has produced deterioration in the power quality by introduction of harmonics in the distribution network. At the same time, much equipment is quite sensitive to the deviations from the ideal sinusoidal line voltage when exposed to such disturbances. The presence of harmonics in the power lines results in greater power losses in distribution, interference problems in communication systems and, sometimes, in operation failures of electronic equipment, which are more sensitive since they include micro-electronic control systems, which work with very low energy levels. Because of these problems, the issue of the power quality delivered to the end consumers is of great concern.

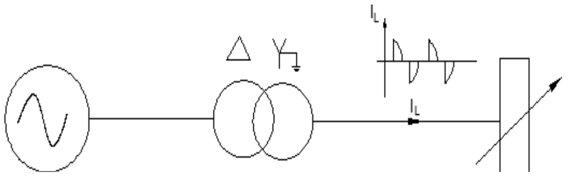

Fig.1 Transformer supplying power to non-linear load

Fig.1 shows a step-down distribution transformer supplying power to non-linear load. The load draws non-sinusoidal current (I_L). That means the load current contains fundamental frequency (50 Hz) components as well higher frequencies harmonic components. This load current has to be supplied by the transformer through its secondary winding. The higher frequency current tends to flow through outer surface of the conductor thus by reducing effective cross-sectional area of the conductor, which exhibits high resistance to the high frequency current producing increased heat loss. The higher frequency current in secondary winding will have effect on thevoltage waveform as well to some extent. Once the voltage wave form has higher frequency components the reactance of the winding will be higher and which in turn produces higher voltage drop ultimately it will result poor power factor. In such a case the VA rating of the transformer cannot be fully utilized. At the expense of active power, the transformer will bound to supply more reactive power drawn by the nonlinear load.

Harmonic distortion is conventionally suppressed by using passive LC filters. However, the application of passive filters for harmonic reduction may result in parallel resonances with the network impedance, over compensation of reactive power at fundamental frequency, and poor flexibility for dynamic compensation of different frequency harmonic components.

This paper presents a scheme with active shunt filter, which supplies harmonic current drawn by the load so that transformer need not supply harmonic current drawn by the load resulting in sinusoidal current in the secondary winding of the transformer. It does not produce parallel resonance problem like in passive filter.

II. PROPOSED SCHEME

The shunt active power filter is used for compensation of harmonic of currents drawn by the non-linear load. Shunt active power filter operates as a current source injecting the harmonic currents drawn by the load so that the transformer need not supply harmonic currents. Fig.2 shows the overall control logic of the proposed scheme. Here AC mains represent the secondary side of the distribution transformer. The load current is sensed by using Hall effect current

---

[*] *Corresponding Author*

transformer which is converted in to digital signal by ADC

and the digital signal carrying the information of load currentis passed to the micro-controller.

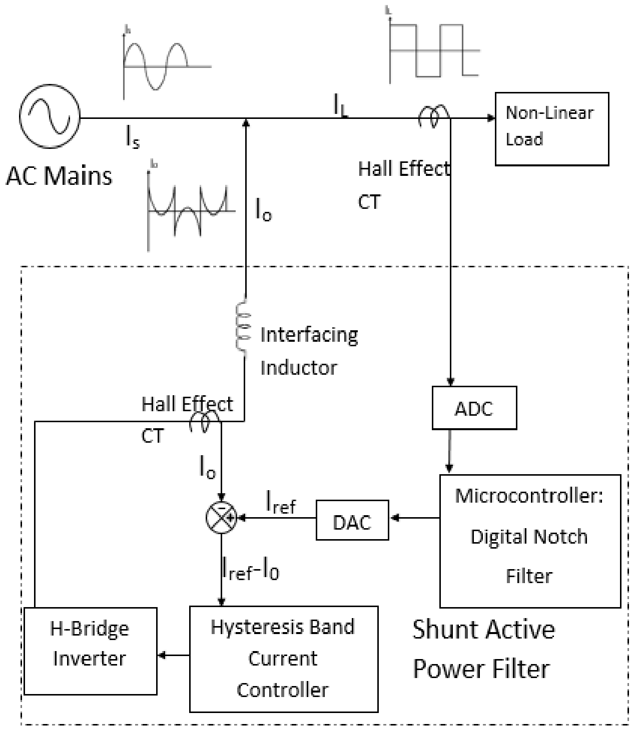

Fig.2 Overall diagram of the proposed scheme

The harmonic current to be injected to the load is set as reference current (Iref). The current injected by the H-bridge inverter is sensed and compared with the Iref. The error signal so obtained is passed through the hysteresis band current controller which generates required gate signals for H-bridge inverter so that the switches in the inverter turns On and Off is such a way that the current injected by the inverter (IO) tracks

the reference current (Iref) through the interfacing inductor within a specified bands. Since all the harmonics components of the current I_0 is supplied by the inverter, the current drawn from the secondary side of the distribution transformer I_s is only fundamental component of that drawn by the load.

Here,

$$I_s = I_L - I_0$$

Where I_S = Source current

I_L = Load Current

I_0= Current injected by inverter

III. MODELING OF PROPOSED SCHEME

A.Digital Notch Filter

Filters can be analog or digital. Analog filters use electronic circuits made from components, such as resistors, capacitors, inductors and so forth, to produce the required filtering effect. At all stages, the signal being filtered is an electrical voltage or current, which is the direct analogue of the physical quantity (e.g. a sound or video signal or transducer output) involved. A digital filter uses a digital processor to perform numerical calculations on sampled values of the signal. The processor may be a general-purpose computing machine, such as a PIC18 microcontroller, AVR microcontrollers, FPGAs or a specialized Digital Signal Processor (DSP) chip. The approach for the design of the digital notch filter is explained as below:

A band stop filter (or band rejection filter) is a filter that passes most frequencies unaltered but attenuates those in a specific range to a very low level. Notch filter is a band stop filter with a narrow stop band (high Q-factor). Notch filter can be realized by simple passive components (R, L, and C) by the arrangement as shown in the fig.3. In the figure the parametersL and C are tuned with a cutoff frequency so that the path impedance along L-C becomes zero and for all otherfrequencies beyond are attenuated highly.

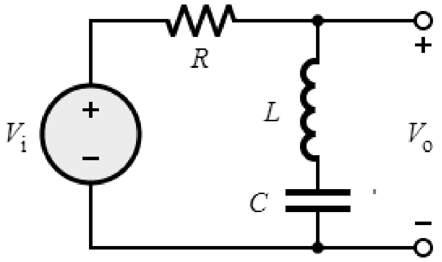

Fig. 3 Realization of Notch Filter using Passive Components

Mathematically, $V_0 = 0\,V\ for\ f = 50\ Hz$

$$\therefore X_L - X_C = 0$$

$X_L = \omega L$ Where, And, $Xc = \frac{1}{\omega C}$ Thus,$\omega = \frac{1}{\sqrt{LC}} = \omega_C$

Using KVL in s-domain,

$$\frac{V_o}{V_i} = \frac{Ls + \frac{1}{Cs}}{R + Ls + \frac{1}{Cs}}$$

$$or, \frac{V_o}{V_i} = \frac{LCs^2 + 1}{LCs^2 + RCs + 1}$$

$$or, \frac{V_0}{V_i} = \frac{s^2 + \frac{1}{LC}}{s^2 + \frac{Rs}{L} + \frac{1}{LC}}$$

$$\therefore G(S) = \frac{V_0}{V_i} = \frac{s^2 + \omega_C^2}{s^2 + \beta s + \omega_C^2}$$

Where, ω_c = the cutoff or notch frequency (rad/s), β= width ofthe notch (rad/s).

$$\omega_c f_c = 50Hz,$$

$$\omega_c = 2\pi f_c = 2 * 3.14 * 50 = 314\ rad/sec$$

the transfer function becomes,

$$G(s) = \frac{s^2 + 314^2}{s^2 + 25s + 314^2}$$

If quality factor (Q-factor) is Q, here we have a relation,

$$\frac{\omega_c}{Q} = \beta$$

Here, $\beta = 25,\ \omega_c = 314$

$$\therefore\ Q = 12.56$$

Thus, the Q-factor of the implemented Notch filter is 12.56. Fig. 4 shows the Bode Plot of G(s) with the cutoff frequency 50Hz.

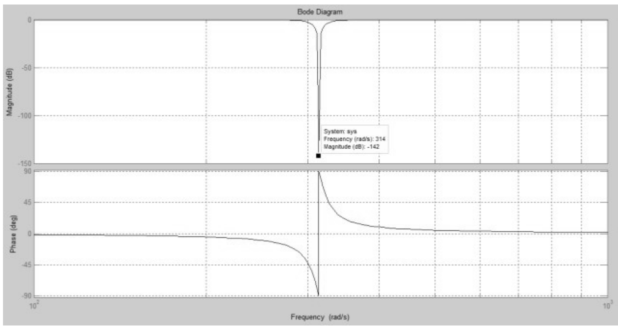

Fig.4 Bode plot of transfer function G(s)

B.Digital Filter Implementation

Sampling is the process of sensing the analog values at discrete time intervals. Quantization is the process of converting the sensed analog voltage to discrete values. Note that with quantization, the signal values are approximated to a finite set of values. The value obtained after sampling and quantization is referred to as Sampled Value. According to Nyquist theorem, if the signal has frequency components only up to a frequency of f Hz, then the signal must be sampled at $2f$ times/sec or more to prevent loss of signal information. After sampling and quantization, the signal is in the form of a sequence of numbers.

The common method of designing a filter is as follows. The transfer function G(S) of an analog filter is derived for the required specifications. This transfer function is then converted to Z domain G(Z), which represents the Z transformof the transfer function of the desired digital filter.

The bilinear transformation (also known as Tustin's method) isused in digital signal processing and discrete-time control theory to transform continuous-time system representations to discrete-time and vice versa. Bilinear transformation technique is used in the conversion in which 's' in the continuous transfer function is substituted with the 'z' expression as shown below, to create the transfer function of the digital filter.

$$s = \frac{2(z-1)}{T(z+1)}$$

Where, T= sampling period satisfying the Nyquist Criteria[3]

Now, continuous transfer function is:

$$G(s) = \frac{s^2 + 314^2}{s^2 + 25s + 314^2}$$

Now for bilinear transformation, let's take sampling frequencyof 5000 Hz and then substituting $s = \frac{2(z-1)}{T(z+1)}$ at T=1/5000 sec,

$$G(z) = \frac{0.9975 \quad - 1.9911z^{-1} + 0.9975z^{-2}}{1.0000 \quad - 1.9911z^{-1} + 0.9950z^{-2}} = \frac{Y(z)}{X(z)}$$

Writing this transfer function into difference equation,

$$Y(z) = 0.9975X(z) \ - 1.9911z^{-1}X(z) + 0.9975z^{-2}X(z) + 1.9911z^{-1}Y(z) - 0.9950z^{-2}Y(z)$$

Taking Inverse Z-transform,

$$\therefore y(k) = 0.9975x(k) \ - 1.9911x(k-1) + 0.9975x(k-2) + 1.9911y(k-1) - 0.9950y(k-2)$$

Where, k=n*T, n=0, 1, 2, 3 …

C.Hysteresis Band Current Control Scheme

It is an instantaneous feedback current control method in which a band is created around a reference current. The reference current is the required current that is expected to be injected ideally. The hysteresis band provides boundary around reference within which the injected current is made to fluctuate. This is achieved by controlling the gate signal of the inverter.

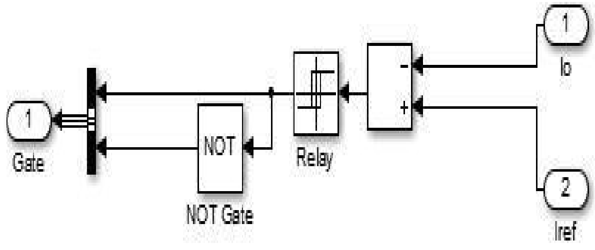

Fig.5 Hysteresis Band Current Controller in Simulink Model

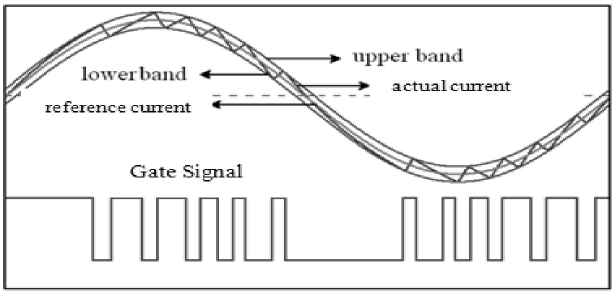

Fig.6 Hysteresis band current control

Fig.5 shows the Simulink model of hysteresis current controllerto generate required gate signals for the switches in the inverterto inject required current for proper compensation.

As shown in Fig.2, the current injected by the H-bridge inverter is sensed and compared with the I_{ref}. The error signal so obtained is passed through the hysteresis band current controller which generates required gate signals for H-bridge inverter so that the switches in the inverter turns On and Off is such a way that the current injected by the inverter (I_O) tracks the reference current (I_{ref}) through the interfacing inductor within a specified band. Fig.6 shows the waveforms of reference and actual current tracking the reference current within upper band and lower band and corresponding gate signal.

IV. SIMULATION MODEL AND RESULTS

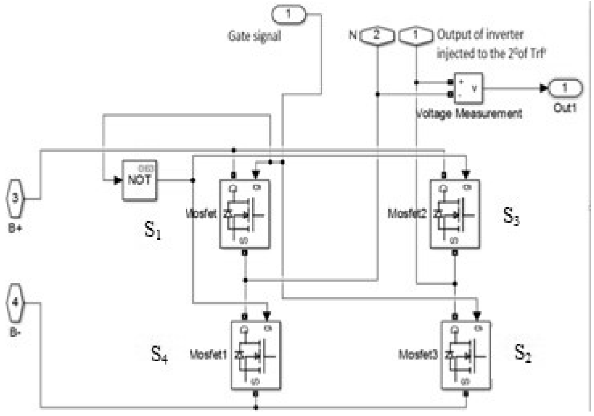

Fig.7 Simulink model of H-bridge inverter.

Fig.7 shows Simulink model of H-bridge inverter. Four MOSFET switches are used in two legs of the bridge inverter. S_1 and S_2 forms one pair and S_3 and S_4 forms another pair switches. The configuration is maintained in such a way that one pair is OFF when another pair is ON using NOT gate. When the first pair is ON, the voltage at output is positive resulting rise in the inverter current. Alternately, when the second pair is ON, the voltage at the output of inverter is negative causing fall in the inverter current. A constant dc supply V_C from a battery is fed to the inverter.

The relay is configured with the switch on point as 0.1 and switch off point as -0.1. Hence, the relay creates a hysteresis band and checks if the injected current is within the band. Thus, the relay generates gate signals in following pattern:

When $I_{ref} - I_0 \leq -0.1$, output of relay=1

When $I_{ref} - I_0 \geq 0.1$, output of relay =0

The complete simulation model of proposed scheme is shown in the Fig.8. The scheme consist of generator modeled as an AC voltage source of 220V, 50Hz with the resistance of 0.002 ohm and inductance as 20mH which is supplying a non-linear load which is a thyristor bridge fired at an angle of 30^0. The dcoutput of the bridge is fed to a RL load with resistance of 10 ohm and 100mH. The sensed load current is fed to shunt activepower filter portion and output of the APF is fed through an interfacing inductor with inductance=1mH and resistance =0.5Ohm into the grid. Then the simulation results with the parameters are as follows:

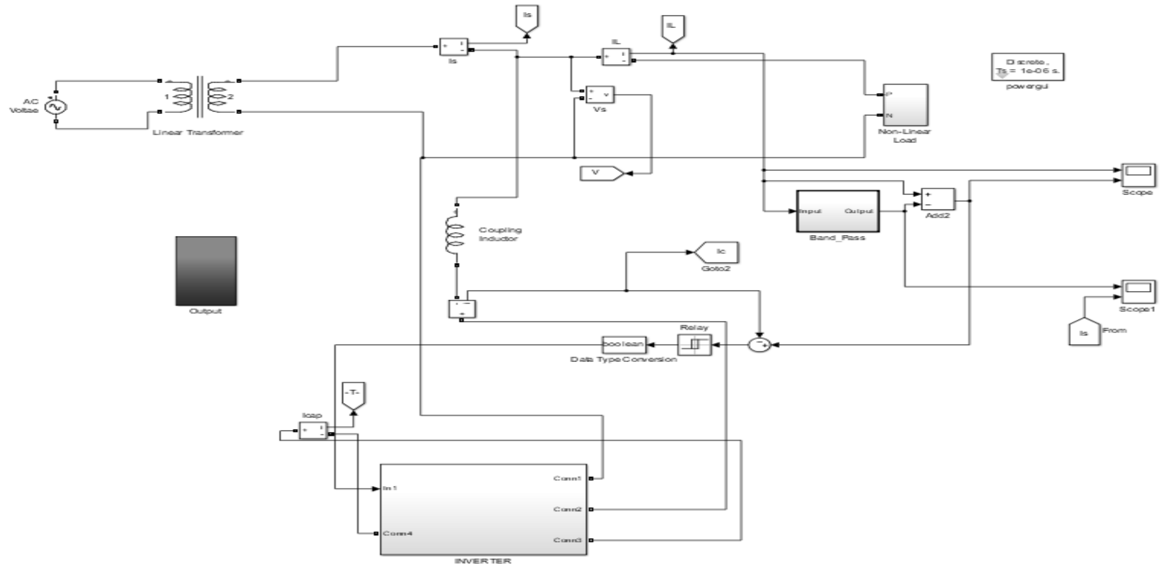

Fig.8 Overall Simulink Model of Proposed Scheme.

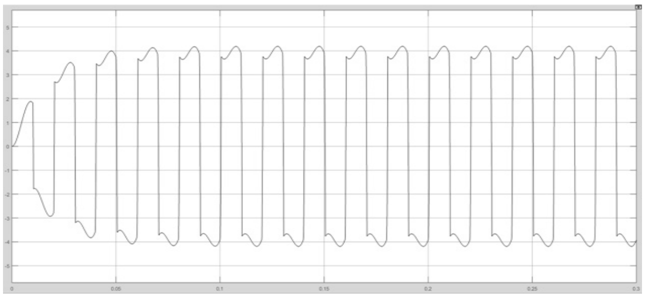

Fig.9 Waveform of current drawn by non-linear load

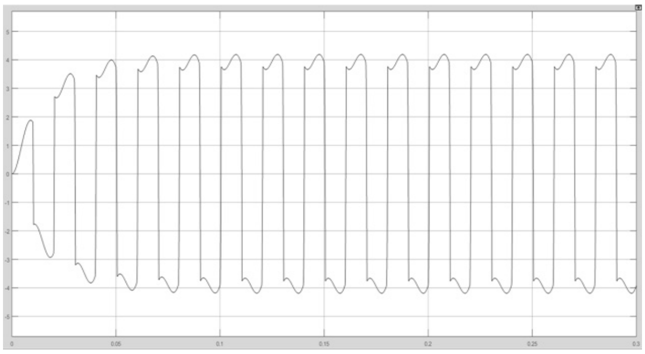

Fig.10 Waveform of source current before compensation

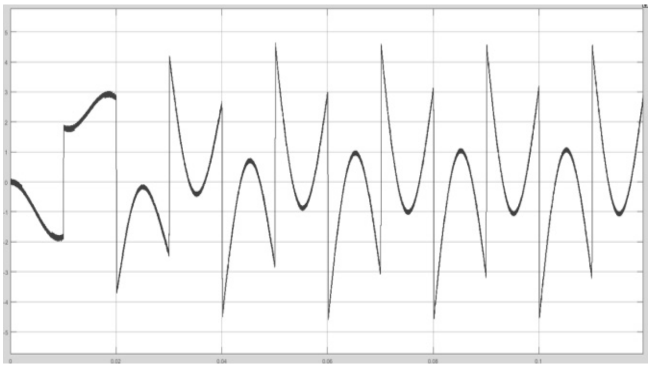

Fig. 11 Waveform current injected by inverter

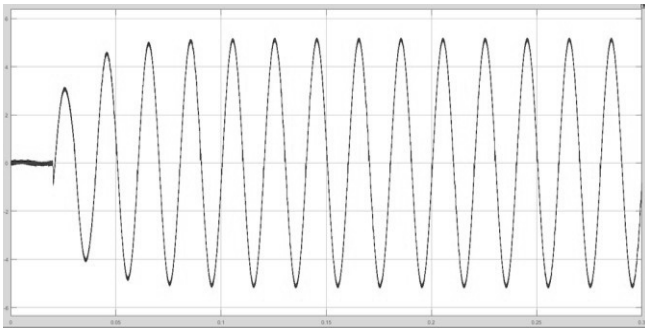

Fig.12 Waveform of source current after compensation

Simulation results shows that the inverter injects the harmonic current drawn by the non-linear load and the source supplies only the fundamental component of the load current.

V. HARDWARE RESULTS

The complete model of proposed scheme is implemented on the hardware with H-Bridge Inverter using MOSFETs and Schmitt Trigger circuit as Hysteresis band current controller. Fig.13 shows the photograph of fabricated hardware.

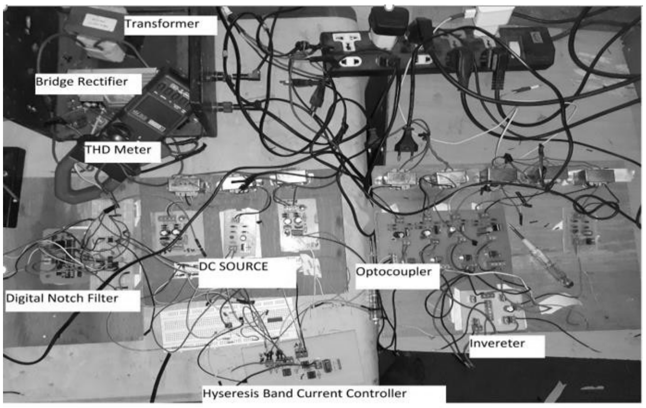

Fig.13 Photograph of fabricated hardware.

The complete model of proposed scheme was implemented on the hardware with H-Bridge Inverter using MOSFETs and Schmitt Trigger circuit as Hysteresis band current controller. A 230/8.5V, 5A transformer is used as the distribution transformer. A RL load with inductance (L) = 6 H and resistance (R) =30 ohm, fed through full-wave bridge rectifier was used as nonlinear load and 8.5V ac from transformer was supplied to the rectifier. The digital notch filter implemented on Arduino Uno kit, gave total current harmonics as output which was then fed to the hysteresis band current controller consisting of Schmitt trigger with the band of 5%, as referencecurrent. Hysteresis band current controller produced a switching signal to the inverter with constant dc supply of +12V which finally injected the reference current to the grid through interfacing inductor of inductance 75mH and resistance 3.8 ohm. The implementation of this hardware scheme improved the source current THD from 48.5% to 5%. Source current captured on the oscilloscope is shown in Fig.14.

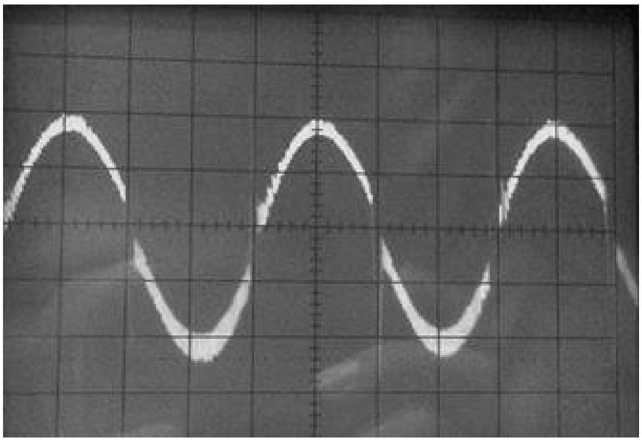

Fig.14 Waveform of source on oscilloscope

The waveform of current injected by the inverter is shown in Fig.15

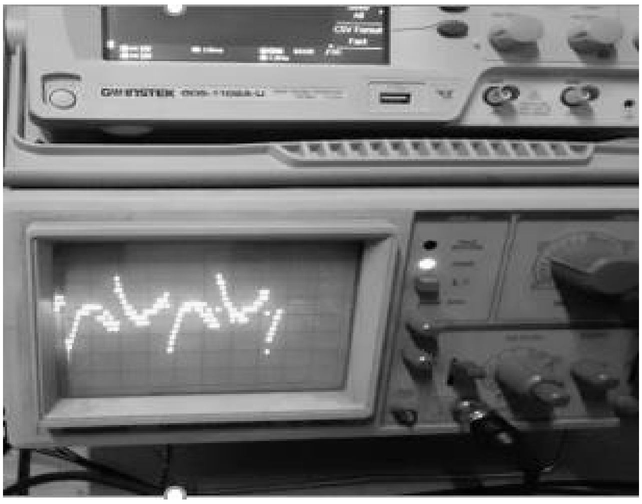

Fig.15 Waveform of current injected by inverter

VI. CONCLUSION

Simulation results and hardware results are very close. The simulation results shows that the THD in the source current decreases from 36% to 5.07%. The hardware results shows thatthe THD in the source current decreases from 46.8 % to 5%.

References

[1] J. G. Pinto, Pedro Neves, Ricardo Pregitzer, Luis F.C. Monteiro, Jao L.Afonso, “Single Phase Shunt Active Filter with Digital Control,” International Conference on Renewable Energies and Power Quality(ICREPQ’07)

[2] Rashid, M. H. (Ed). Power Electronics Handbook: Devices, Circuits, and Applications, 3rd Ed, Butterworth-Heinemann Publishers, 2011, pp.1193-1228

[3] B. K. Anantha Ramu, “Implementing FIR and IIR Digital FiltersUsing PIC18 Microcontrollers-AN852”, Microchip Technology Designs, India, Pvt. Ltd., pp.24-29