Harmonic Analysis and Selective Elimination in PWM Technique Controlled Three Phase Inverter

Prajkta Pawar
Department of Electrical Engineering.
Fr. C. Rodrigues Institute Technology
Vashi, Navi Mumbai

Sushil Thale
Department of Electrical Engineering.
Fr. C. Rodrigues Institute Technology
Vashi, Navi Mumbai

***Abstract*— Nowadays, power electronic devices are widely used and caused an increase of the harmonic disturbances in the power systems. Power electronic devices generate harmonic. The harmonics causes problems in power systems and in consumer products such as equipment overheating, capacitor blowing, motor vibration, and low power factor. In three phase inverter, power electronic devices used and harmonics are the one of the problem in three phase inverter. There are various PWM methods to eliminate lower order harmonics. The advantages of the PWM techniques are easy to implement and control. This paper considers the problem of eliminating harmonics in inverter-output waveforms. In this paper, sine PWM, space vector modulation & selective harmonic elimination PWM techniques are used to eliminate lower order harmonics and compared. Sine PWM, SVM has many disadvantages as compared to selective harmonic elimination. All the PWM techniques mentioned above are first simulated using MATLAB Simulink software using existing control schemes and the observed simulation results are then validated on hardware using 200 watt inverter with digital signal processor TMS320F28069 from Texas Instruments.**

Keywords: Three Phase Inverter, Sine PWM, Space Vector PWM, Selective Harmonic Elimination, Digital signal processor.

I. INTRODUCTION

Voltage source inverters (VSIs) are important for power electronics applications. In recent development, industry has demand higher power equipment, which now reaches the megawatt level. In medium voltage- medium and high power inverters which are most likely to connect distributed generation systems to grids, it is of great importance to reach high quality waveforms [1]. The power quality is also important to be kept as high as possible. The objective of a dc-ac inverter is to produce a sinusoidal ac voltage with adjustable amplitude and frequency. There are two types of harmonics.

1. Voltage and Current harmonics. The reasons for current harmonics are non-linear loads; Non-linear voltage (presence of voltage harmonics) depends on impedance of the network between source & load. The reasons for voltage harmonics are various kinds of PWM techniques, Non-linear currents which produce non- sinusoidal voltage drops.

2. Lower and Higher order harmonics. Lower order harmonics (up to 40th) harmonics of 50Hz are important in practice. Higher order harmonics are introduced by switching frequency components & depend upon the kind of PWM technique used.

A. Three Phase Voltage Source Inverter

Three-phase inverters are normally used for high-power applications. A three phase power electronic DC-AC converter, so called "Inverter", is required for converting DC output voltage to AC voltage for distribution purpose. Voltage Source Inverters are generally classified into two types viz, square-wave and pulse width modulated. In early 1960s these inverters were introduced when force commutation technique was developed [6]. The major disadvantage of this inverter is that, for low or medium power applications the output voltage contains lower order harmonics. In many industrial applications, it is often required to vary the output voltage of inverter [4] due to following reasons:

- To compensate for the variations in the input voltage.
- To compensate for the regulation of inverters.
- To supply some special loads which need variations of voltage with frequency, such as an induction motor.

Pulse Width Modulated (PWM) voltage inverter is the most applied in the industry. Today pulse Width Modulation based variable speed drives are increasingly applied in many new industrial applications that require superior performance [5]. Pulse width modulation (PWM) is one of the most commonly used techniques in static inverters. The most efficient method of controlling output voltage is to incorporate PWM control within inverters. In PWM method, a fixed d. c. voltage is supplied to inverter and a controlled a.c. output voltage is obtained by adjusting on-off period of inverter devices. To reduce the harmonics further, different sinusoidal PWM and space-vector PWM schemes are suggested in this paper. However, these PWM techniques increase the control complexity and the switching frequency. Thus, to overcome switching losses, electromagnetic interferences caused by high dv/dt and to reduce the harmonics is to calculate the switching angles in order to eliminate certain order harmonics. This technique is known as Selective Harmonic Elimination

II . DIFFERENT PWM TECHNIQUES FOR THREE PHASE VOLTAGE SOURCE INVERTER

Voltage source inverters have become standard in most dc-to-ac applications. It is possible to control the output voltage as well as optimize the harmonics by performing multiple switching within the inverter with constant dc input voltage. The principle of PWM is to control output voltage and eliminate lower order harmonics. There are various PWM methods are as follows:

A. Sinusoidal PWM

B. Space Vector PWM

C. Selective Harmonic Elimination(SHE)

D. Harmonic compensation

A. Sinusoidal PWM

The sinusoidal PWM technique is very popular for industrial converter. To produce a sinusoidal output voltage waveform at a desired frequency, a sinusoidal control signal at the desired frequency is compared with a triangular waveform and point of intersection determine the switching points of the power device. In sine PWM technique, triangle carrier wave of frequency f_c is compared with fundamental frequency f sinusoidal modulating wave. The triangular wave frequency is same as switching frequency of inverter f_s. Modulation index should be in between 0 to 1. If modulation index $m_a \le 1$, the fundamental frequency component in the output voltage varies linearly with m_a [10]. When the peak magnitude of modulating signal exceeds the peak magnitude of carrier signal, the PWM inverter operates under over-modulation. In overmodulation ie, $m_a > 1$ more sideband harmonics appear centered around the frequencies of harmonics. The modulation index and frequency modulation ratio [9] are given by

$$m_a = V_p / V_t \qquad (1)$$

V_p= peak value of sine wave and V_t = peak value of carrier wave

$$m_f = f_s / f_1 \qquad (2)$$

f_s = switching frequency and

f_1 = fundamental frequency

m_f should be an odd integer. Therefore only odd harmonics are present and even harmonics are disappear. The harmonic spectrum of the load voltage is shown in Fig. 1.

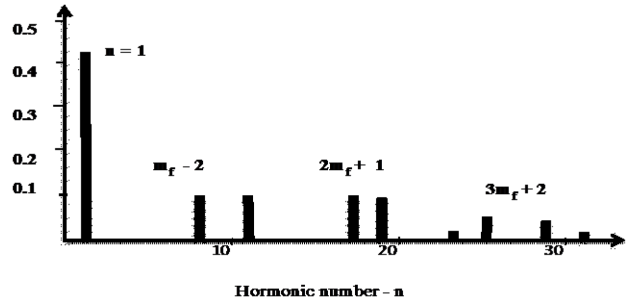

Fig. 1: Harmonic spectrum

Advantages of Sine PWM

- ❖ The output voltage control is easier with PWM than other schemes.
- ❖ The filtering requirements are minimized as lower order harmonics are eliminated and higher order harmonics are filtered easily.

Disadvantages of Sine PWM

- ❖ Switching losses are more in sine PWM because of high switching frequency.
- ❖ EMI problem is there due to high dv/dt.

B. Space Vector PWM

The space vector PWM (SVM) is advanced and complex PWM method. In SVM method the three-phase sinusoidal and balanced voltages are applied it can be shown that space vector with magnitude V_m rotates in a circular orbit at an angular velocity ω and direction of rotation depend on phase sequences of voltages[2]. With the sinusoidal three-phase command voltages, the composite PWM fabrication at the inverter o/p should be such that the average voltage follows these command voltages with minimum amount of harmonic distortion [9].

$$V_a = V_m \cos\omega t \qquad (3)$$

$$V_b = V_m \cos(\omega t - 2\pi/3) \qquad (4)$$

$$V_c = V_m \cos(\omega t + 2\pi/3) \qquad (5)$$

- ❖ This PWM technique approximates the reference voltage V_{ref} by a combination of the eight switching patterns ($V_0$to V_7)
- ❖ The vectors ($V_1$to V_6) divide the plane into six sectors (each sector: 60 degrees)
- ❖ V_{ref} is generated by two adjacent non-zero vectors and two zero vectors.

Advantages

- ❖ Less harmonic distortion in output.
- ❖ More efficient use of supply voltage.
- ❖ Offers superior performance in variable speed drives.

Disadvantages

- ❖ The SVM technique is complex and computation-intensive; therefore the switching frequency is somewhat limited.

C. Selective Harmonic Elimination

In selective harmonic elimination notches are created on the square wave at predetermined angle. Therefore a large number of harmonic components can be eliminated if the waveform can accommodate additional notch angle. As the fundamental frequency decreases, number of notch angle increases therefore higher number of harmonics can be eliminated. Low switching frequency can be used to eliminate the harmonics. The implementation of the solutions is an involved problem. Complex logic circuits are needed to generate the desired waveforms accurately. The general Fourier series [8] is given by

$$bn=4/n\pi[1+2(-\cos n\alpha 1+\cos n\alpha 2-\cos n\alpha 3\ldots\ldots\ldots\ldots\ldots\pm\cos n\alpha k)] \quad (6)$$

Where

n – order of harmonics and k – number of switching angle

With k number of α angles, the fundamental voltage can be controlled and k-1 harmonics can be eliminated. For example, 5^{th} and 7^{th} harmonics are to be eliminated and fundamental voltage is to be controlled.

Fundamental - $b_1 = 4/\pi\ (1- 2\cos\alpha_1 + 2\cos\alpha_2 – 2\cos\alpha_3)$ (7)

5^{th} harmonic - $b_5 = 4/5\pi\ (1- 2\cos 5\alpha_1 + 2\cos 5\alpha_2 – 2\cos 5\alpha_3) = 0$ (8)

7th harmonic - $b7= 4/7\pi\ (1- 2\cos 7\alpha 1 + 2\cos 7\alpha 2 – 2\cos 7\alpha 3) = 0$ (9)

The switching frequency of the inverter switches can be equated to

$$f_{sw} =2* k*f \quad (10)$$

f_1 is fundamental frequency.
k is number of switching angle
The harmonic spectra of SHE for phase to phase is shown in Fig. 2. as follows.

Advantages

- Low switching frequency therefore low switching losses.
- More no. of notch angles, more no of harmonics can be eliminated.

Disadvantage

- Elimination of lower order harmonics considerably boosts the next higher level of harmonics.

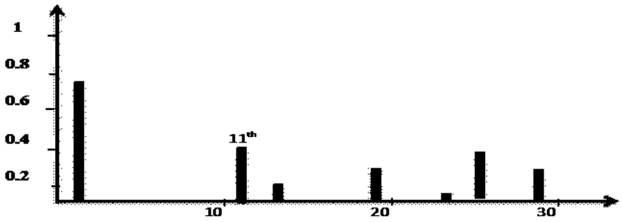

Fig. 2: The harmonic spectra of SHE for phase to phase voltage

D .Closed Loop System For Harmonic Compensation

In this, non- linear load is connected to the supply. The PWM inverter is used to supply the compensation currents [7] in such a way that the utility supplies only the balanced fundamental frequency current, even if the load draws harmonic currents.

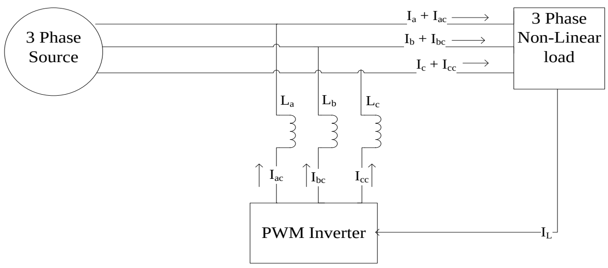

Fig. 3: Closed Loop Harmonic Compensation

III. Simulation Analysis and Experimental Result

The above mentioned PWM techniques are simulated in MATLAB and the observed simulation results are then validated on hardware using 200 watt inverter with digital signal processor TMS320F28069 from Texas Instruments. The output voltage waveform and FFT analysis for sine PWM are shown in Fig. 4. From the FFT analysis, it can be seen that the THD for sine PWM is 97.85%. Lower order harmonics are not completely eliminated.

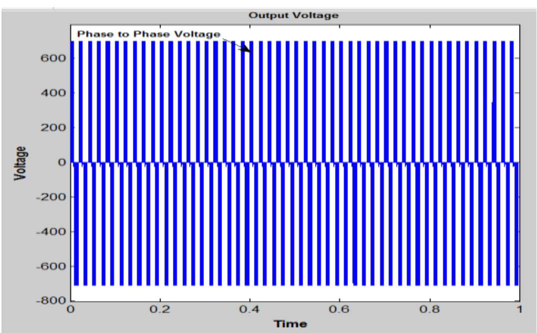

Fig. 4: a) output voltage waveform

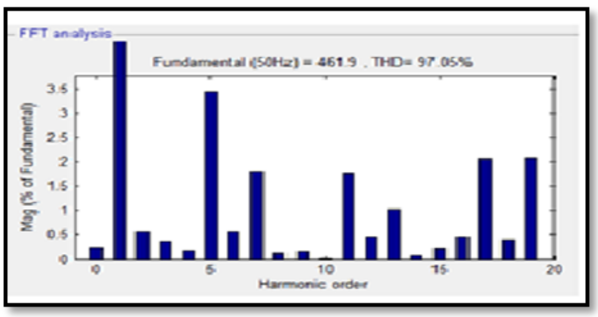

Fig. 4: b) output voltage FFT analysis

Sine PWM is tested on hardware setup for linear load as well as non linear load using 200 watt inverter with dsp TMS320F28069. Figure 5 shows the waveform and FFT analysis for linear and non linear load.

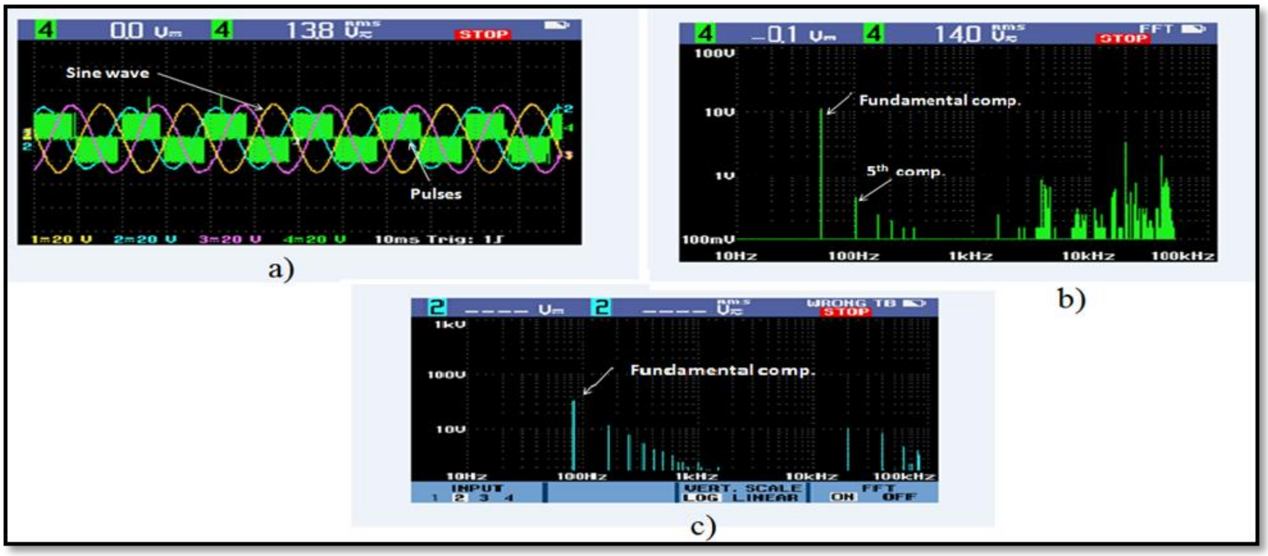

Fig. 5: a) Waveform of sine triangular b) FFT analysis for linear load c) FFT analysis for non linear load

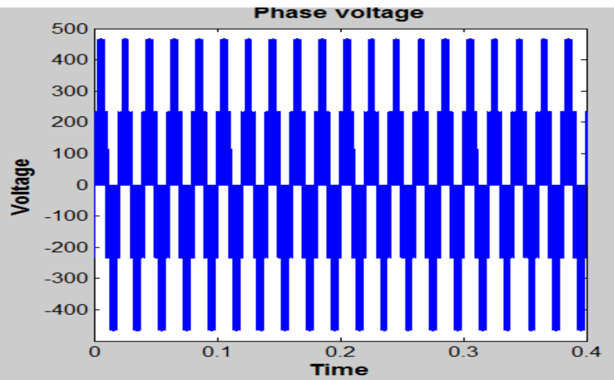

Fig. 6: a) Waveform of SVM Line to Line

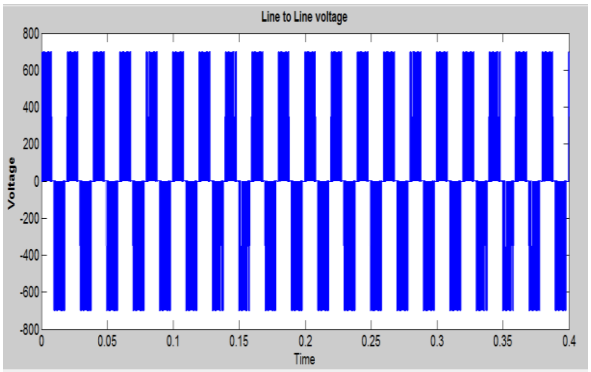

Fig.6: b) Waveform of SVM Line to neutral

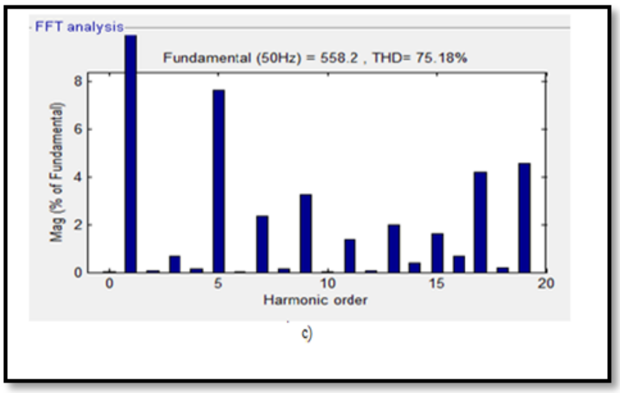

Fig.6: c) FFT Analysis of SVM output voltage

Fig. 7:a) FFT analysis non linear load

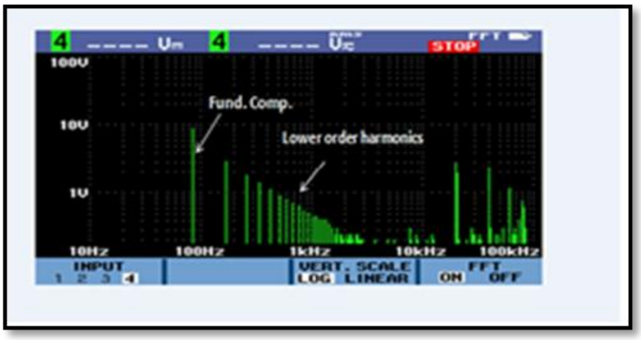

Fig. 7:b) FFT analysis linear load

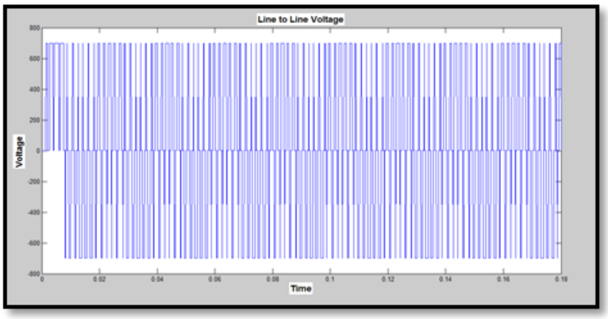

Fig. 8: a) Phase to Phase output voltage with SHE

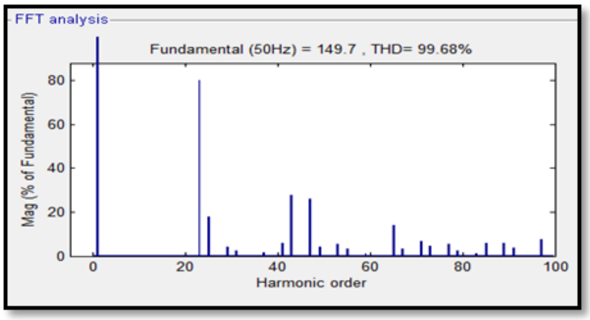

Fig.8: b) FFT analysis of SHE based VSI output

The SVM output voltage waveform of line to line and line to neutral are shown in Fig. 6. Also FFT analysis is shown in the above Figures.Analysis of SVM generated from hardware setup by using inverter with dsp for linear and non linear load are shown in Fig. 7. From the above hardware results, it is found that lower order harmonics are not eliminated completely by using space vector modulation technique. The FFT analysis of output voltage is shown and it can be seen that total harmonic distortion is 75.18%. On the other hand, by using selective harmonic elimination lower order harmonics upto 20th are completely eliminated and fundamental component is very high. In Fig. 8 the waveform of phase to phase voltage and FFT analysis are shown respectively. For current harmonic compensation ,different cases are Shown. Case 1. For simulation purpose, three phase source is used.Three phase diode rectifier is used as non-linear load. PWM inverter supplied compensation current to non linear load and source current and output current as shown in Figure9.

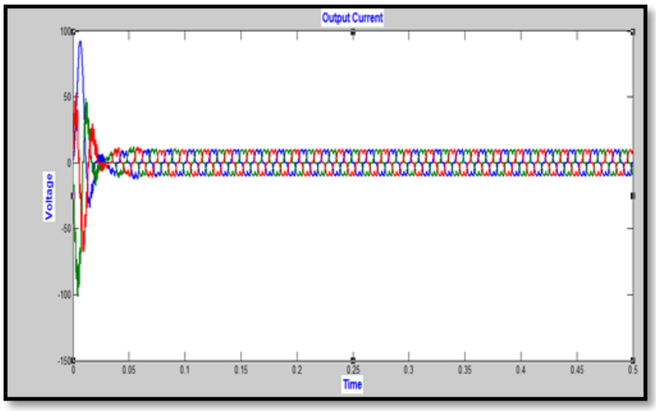

Fig. 9: a) Source current

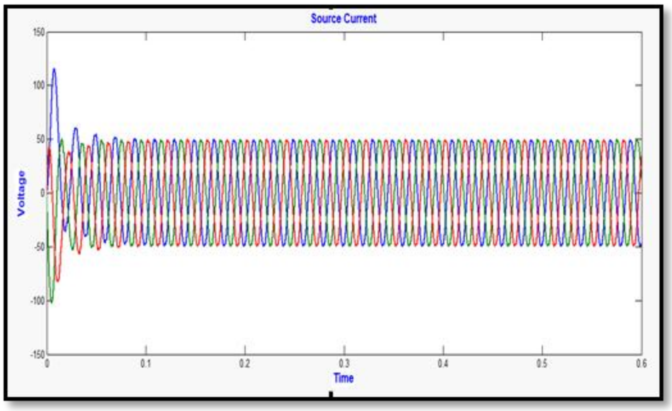

Fig.9: b) output current

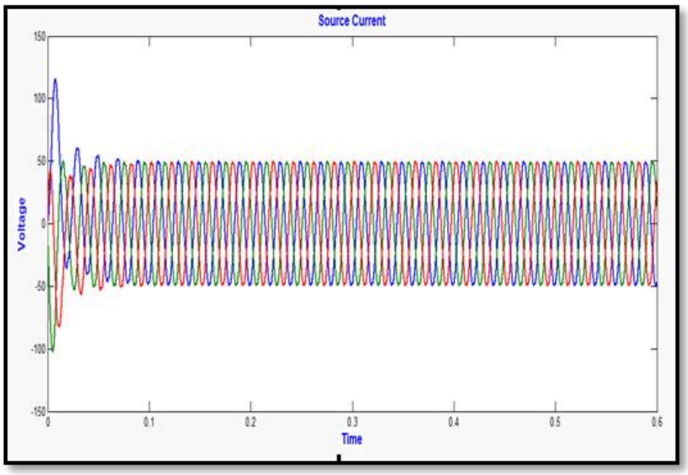

Fig. 9:c) source current

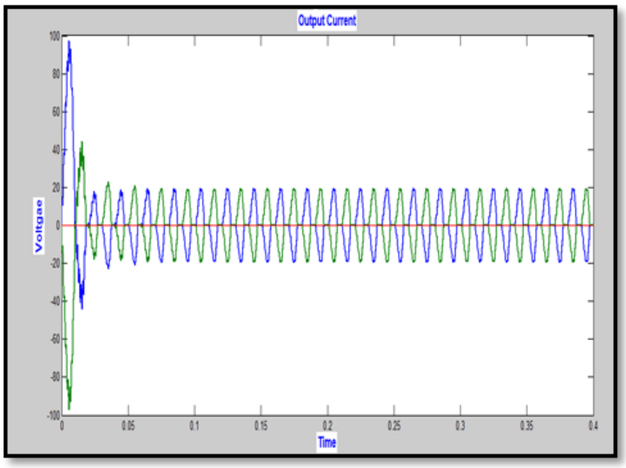

Fig. 9:d) output current

Case 2 Half bridge rectifier load is connected. The source and output voltage in figure 9 c) and 9 d).
It can be seen that in both case1 & case2 source current is pure sine wave. harmonic current.After compensation ouput current is Full bridge & half bridge rectifier draws the peaky current.

IV. Conclusion

PWM techniques are very useful in improving the power quality. The different PWM technique here is considered and the output is given in the form of waveforms. It is concluded that switching losses are more in sine PWM because of high switching frequency. Also EMI problem is there due to high dv/dt. SVM is complex and computation- intensive. As per the MATLAB simulation, it is concluded that, lower order harmonics are not completely eliminated in sine and space vector PWM. In selective harmonic elimination switching losses are less and lower order harmonics are eliminated. Also a control structure for the compensation of selected stationary harmonics has been presented.

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