# CHAPTER 5

# MODIFIED SINUSOIDAL PULSE WIDTH MODULATION (SPWM) TECHNIQUE BASED CONTROLLER

## 5.1 INTRODUCTION

Pulse Width Modulation method is a fixed dc input voltage is given to the inverters and a controlled ac output voltage is obtained by adjusting the on and off periods of the inverter components. This is the most popular method of controlling the output voltage and in this method is known as pulse width modulation (PWM CONTROL)

## 5.2 TYPES OF PWM TECHNIQUE

Different types of PWM control technique is given as follows

- Single pulse width modulation (Single PWM)
- Multiple pulse width modulation (MPWM)
- Sinusoidal pulse width modulation (SPWM)
- Modified Sinusoidal pulse width modulation (MSPWM)

### 5.2.1 Single Pulse Width Modulation (Single PWM)

In single pulse width modulation control technique only one pulse will be there for every half cycle. The width of the single pulse can be adjusted in order to control the output voltage of the inverter. By comparing rectangular reference signal of amplitude ($A_r$) and a triangular carrier wave ($A_c$), the gating signals can be generated as shown in Figure 5.1. This generated gating signal is used to control the output of single phase full bridge inverter. The fundamental frequency of the output voltage is determined by the frequency of the reference signal. For this technique the amplitude modulation index (M) can be defined as

$M = \frac{A_c}{A_r}$, whereas the instantaneous output voltage of the inverter

can be given as $V_O = V_s(S_1 - S_4)$

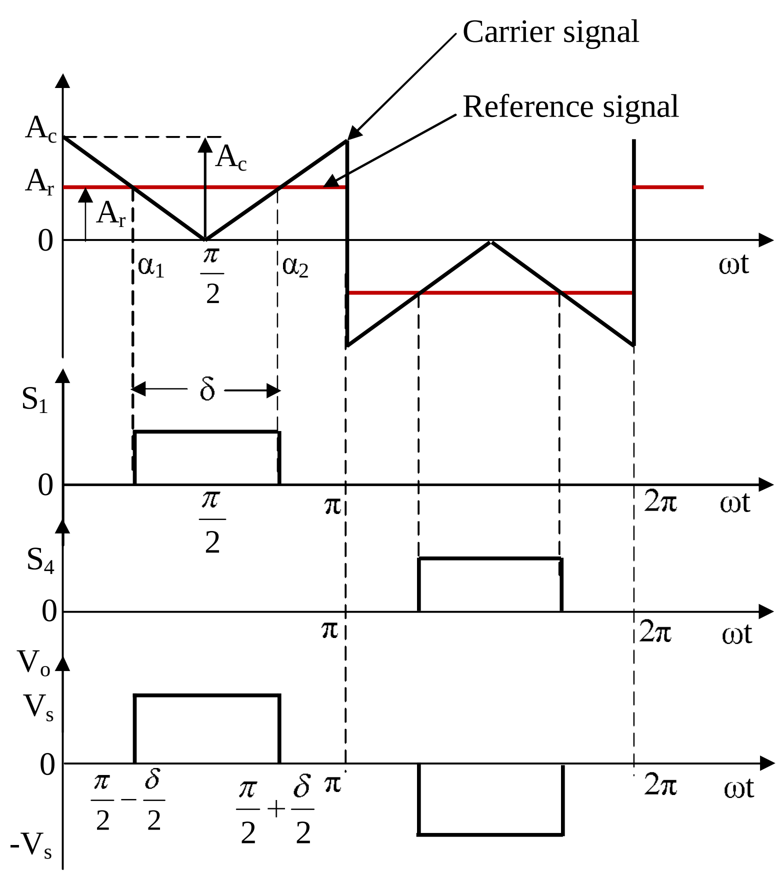


**Figure 5.1 Generation of Single pulse width modulation**

### 5.2.2 Multiple Pulse Width Modulation (MPWM)

The main drawback of single PWM technique is high harmonic content. In order to reduce the harmonic content, the multiple PWM technique is used, in which several pulses are given in each half cycle of output voltage. The generation of gating signal is achieved by comparing the reference signal of the amplitude ($A_r$) with a triangular carrier wave ($A_c$) as shown Figure 5.2.

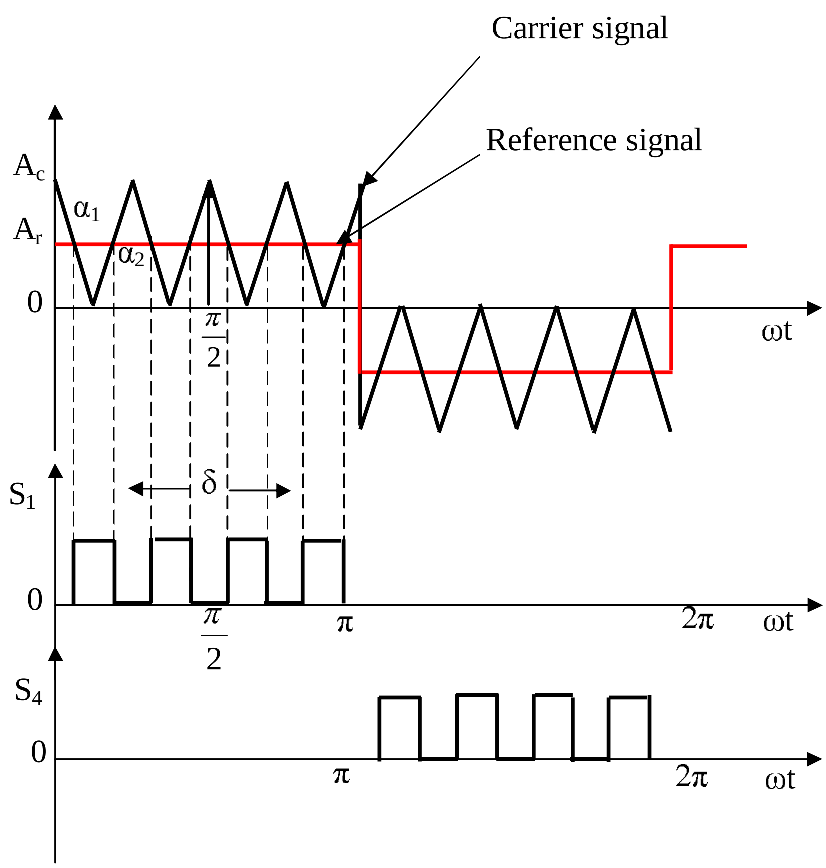


**Figure 5.2 Generation of Multiple pulse width modulation**

The output frequency ($f_o$) is determined by the frequency of the reference signal. The output voltage can be controlled by modulation index.

The number of pulses (p) per half cycle is calculated by the carrier frequency ($f_c$). Number of pulses per half cycle is found by

$$p = \frac{f_c}{2 f_o}$$

$$= = \frac{m_f}{2}$$

Where

$m_f = \frac{f_c}{f_o}$, called as frequency modulation ratio.

The instantaneous output voltage of the inverter can be given as $V_O = V_s(S_1 - S_4)$

### 5.2.3 Sinusoidal Pulse Width Modulation (SPWM)

Figure 5.3 explains the generation of a sinusoidal PWM signal, which finds more applications in industries. the gating signal can be generated by comparing a sinusoidal reference signal with a triangular carrier wave and the width of each pulse varied proportionally to the amplitude of a sine wave evaluated at the center of the same pulse.

The output frequency ($f_o$) of the inverter can be found by using the frequency of the reference signal ($f_r$). The rms output voltage ($v_o$) can be controlled by modulation index M and in turn modulation index is controlled by peak amplitude ($A_r$). The voltage can be calculated by $V_O = V_s(S_1 - S_4)$. The number of pulses per half cycle depends on the carrier frequency.

The gating signal can be produced by using the unidirectional triangular carrier wave.

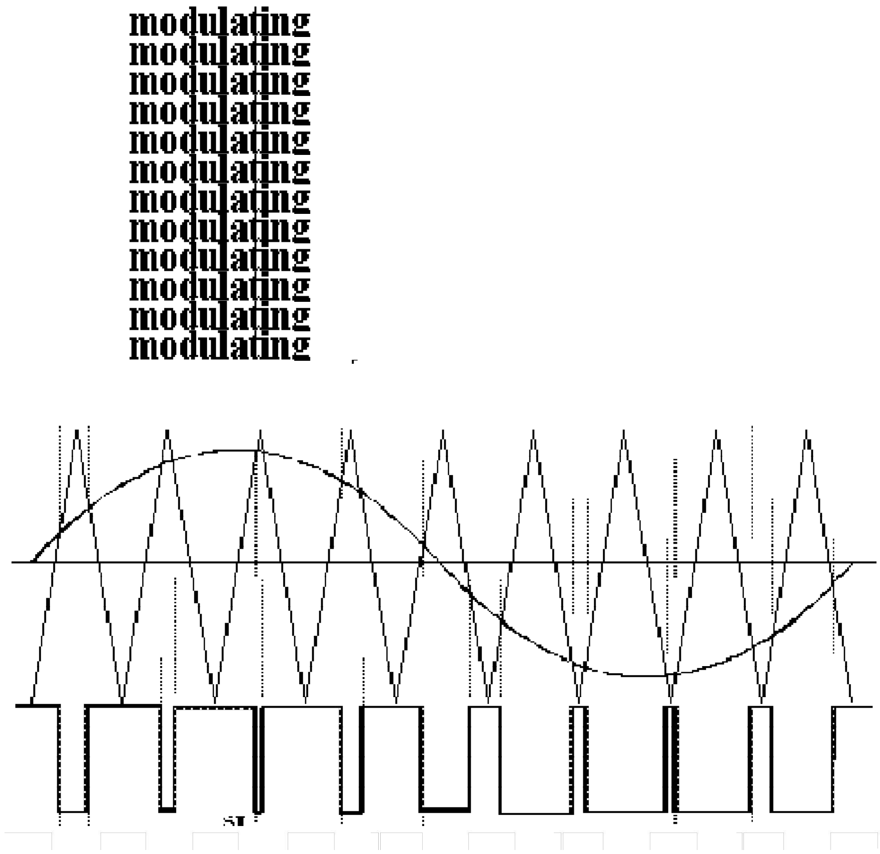


**Figure 5.3 Generation of Sinusoidal pulse width modulation**

### 5.2.4 Modified Sinusoidal Pulse Width Modulation

When considering sinusoidal PWM waveform, the pulse width does not change significantly with the variation of modulation index. The reason is due to the characteristics of the sine wave. Hence this sinusoidal PWM technique is modified so that the carrier signal is applied during the first and last $60^0$ intervals per half cycle as shown in Figure 5.4. The fundamental component is increased and its harmonic characteristics are improved. The main advantages of this technique is increased fundamental component, improved harmonic characteristics, reduced number of switching power devices and decreased switching losses.

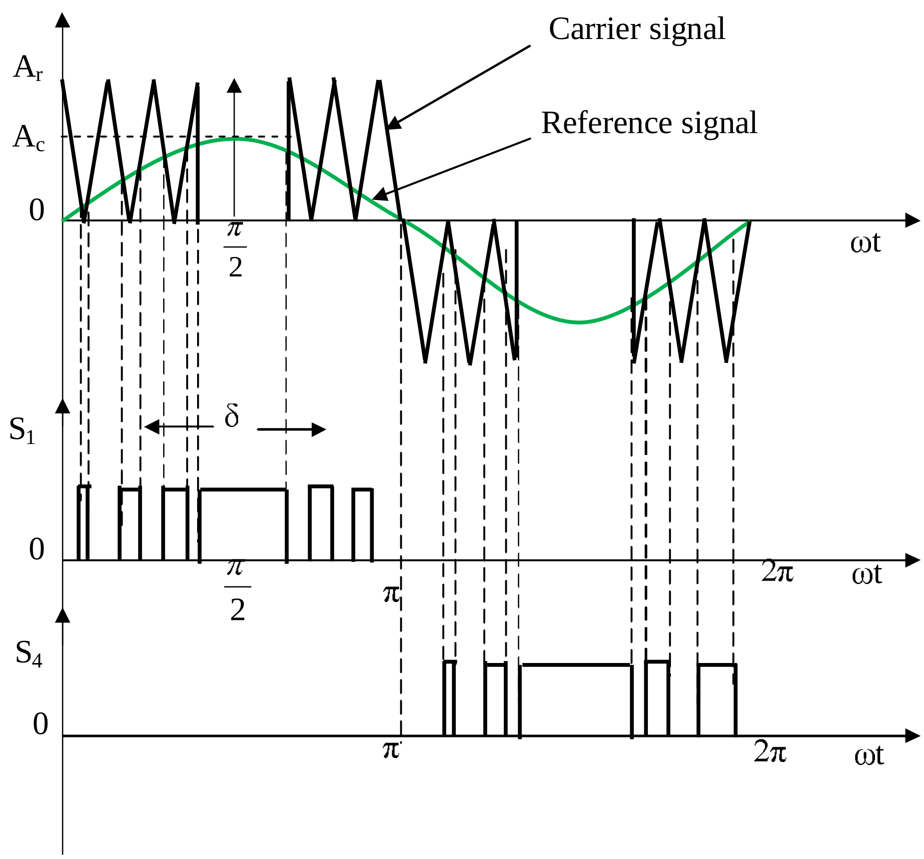


**Figure 5.4 Generation of Modified sinusoidal pulse width modulation**

### 5.2.5 Advantages of PWM

- The output voltage control with method can be obtained without any additional components
- With this method, lower order harmonic can be eliminated or minimized along with it's output voltage control.
- It reduces the filtering requirements

## 5.3 PROPOSED SINUSOIDAL PULSE WIDTH MODULATION TECHNIQUE BASED MODIFIED CONTROLLER.

A Sinusoidal Pulse Width Modulation (SPWM) technique (Yaosuo Xue & Liuchen Chang 2004) based controller with modifications for controlling the output of the boost dc-ac inverter as shown in Figure 5.5 is presented in this chapter.

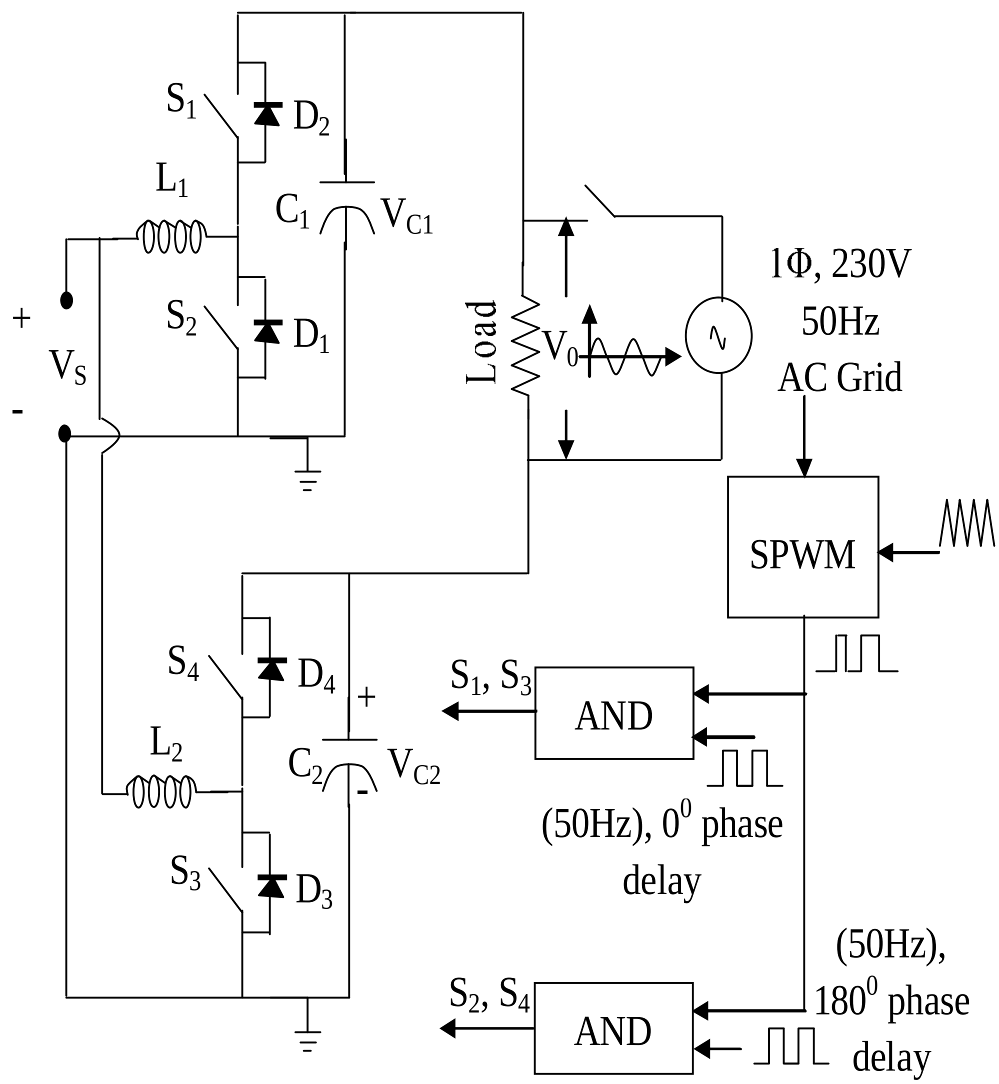


**Figure 5.5 Circuit description of boost inverter with sinusoidal pulse width modulation technique based modified controller**

In this control technique the error values of the grid voltage ($V_{Grid}$) is compared with the high frequency triangular signal with proper gain. As a result an unequal width continuous pulsated signal can be obtained for each period.

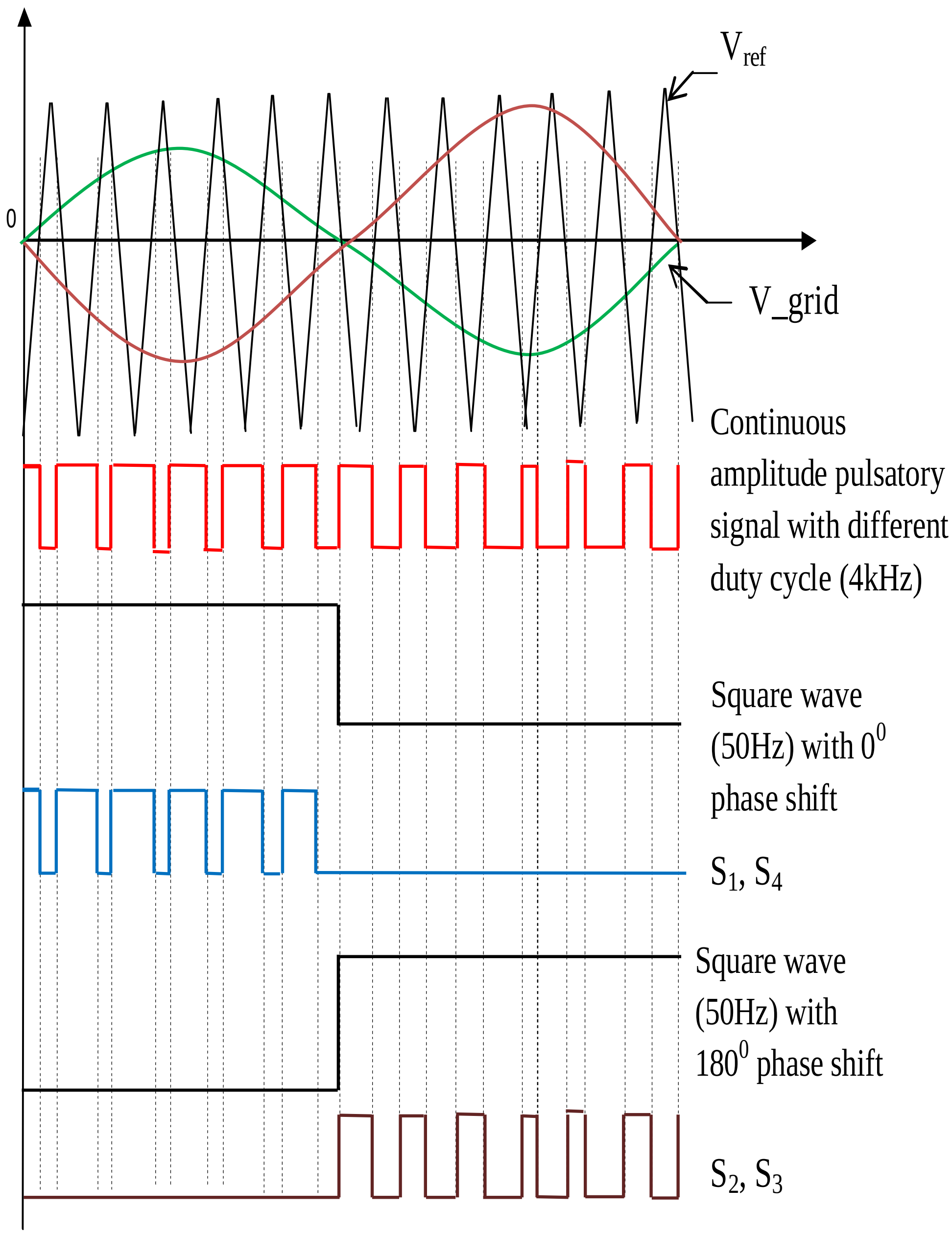


**Figure 5.6 Generation of control signal for the boost inverter by proposed sinusoidal pulse width modulation (SPWM) technique based modified controller**

Again this pulsated signal is subjected to logically AND with $0^0$ phase shifted square wave of fundamental frequency with 50Hz. As a result a pulsated continuous signal can be obtained for every alternative 10ms as shown in Figure 5.6 and it controls the switches ($S_1$ & $S_4$) of the boost inverter, the capacitor voltage ($V_{C1}$) and inductor current ($I_{L1}$) of the current bi-directional boost dc-dc converter 1.

The same technique is used to control the capacitor voltage ($V_{C2}$), inductor current ($I_{L2}$) and switches ($S_2$ & $S_3$) of the boost inverter to get the fundamental frequency of the square wave with the $180^0$ phase shift.

Therefore the output of the boost dc-ac inverter can be regulated by controlling the switches of the both current bi-directional boost dc-dc converters to match with the grid parameters like voltage, phase angle and frequency.

## 5.4 SIMULATION MODEL OF PROPOSED SYSTEM

The proposed Sinusoidal Pulse Width Modulation Control Technique Based Single Phase Grid Connected Boost Inverter was developed by MATLAB SIMULINK Figure 5.7 assuming the power switches, capacitor voltage and inductors current with internal resistance Ra are ideal. The parameters are $V_s$ = 100V, $V_o$ = 325sinωt (230$V_{RMS}$), $L_1$ & $L_2$ = 850μH each, $C_1$ & $C_2$ = 5μF each, $f_{sw}$ = 4000Hz.

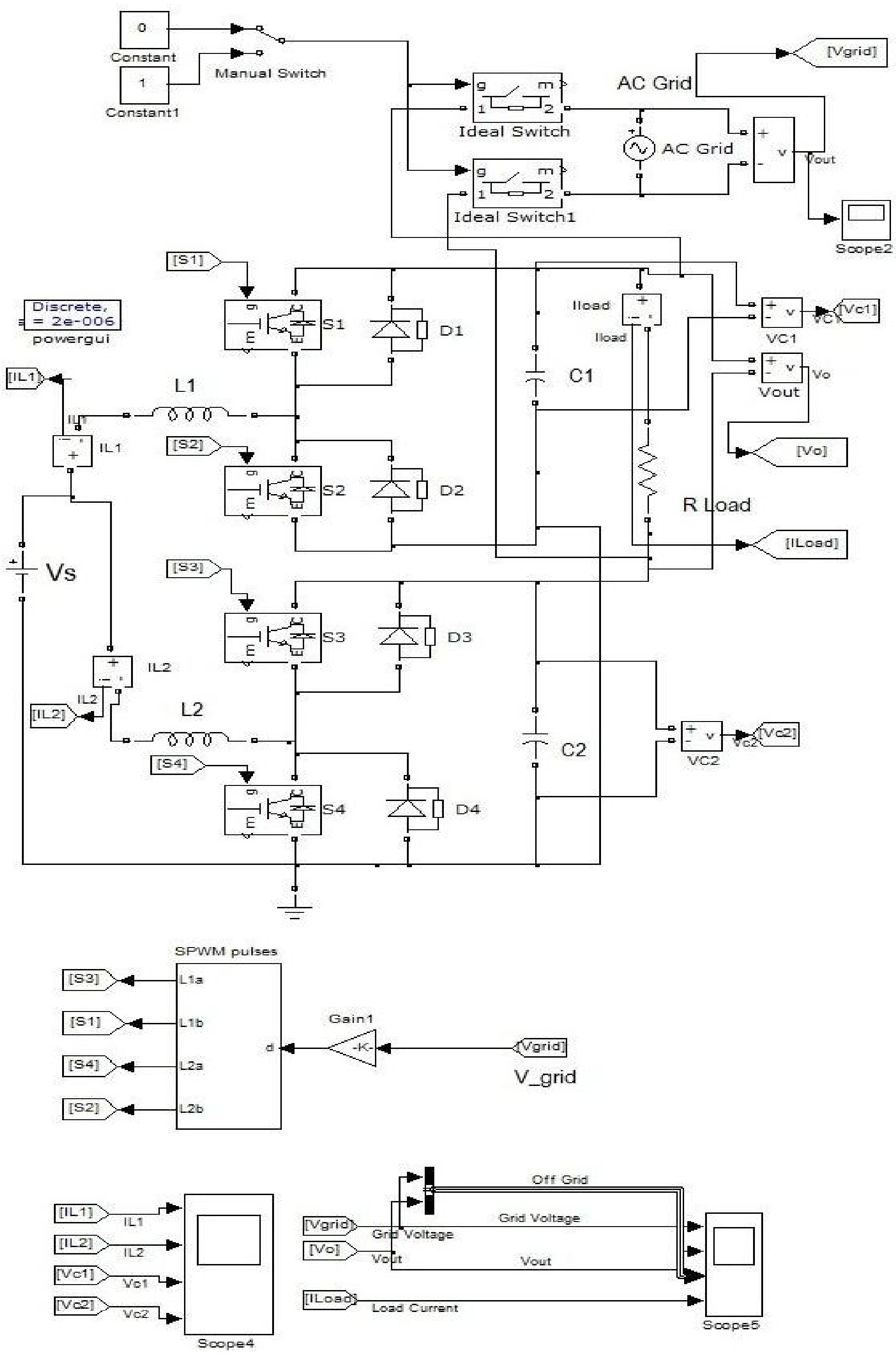


**Figure 5.7 Simulation model of proposed SPWM control technique based single phase grid connected boost inverter**

## 5.5 SIMULATION RESULTS

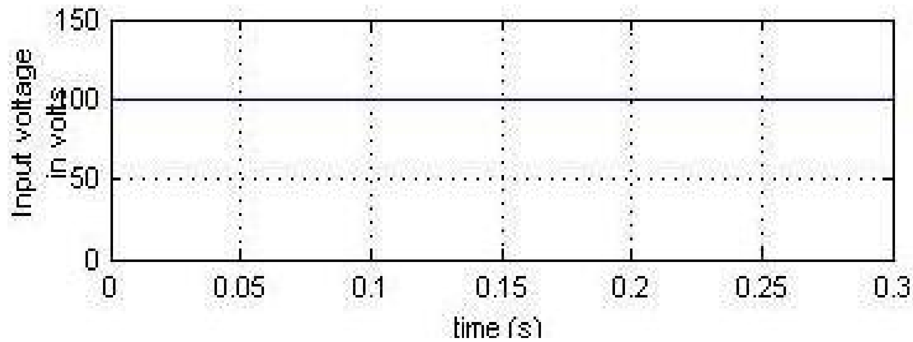


**Figure 5.8(a) Input voltage ($V_S$) of the boost inverter**

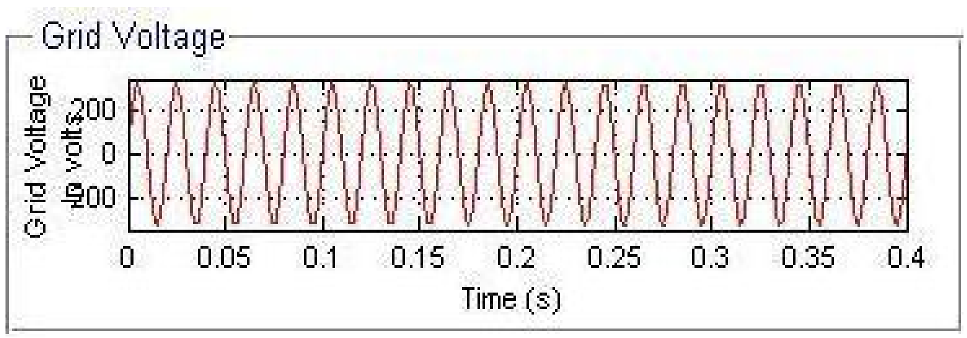


**Figure 5.8(b) Grid voltage $V_{\_grid}$=230$V_{rms.}$**

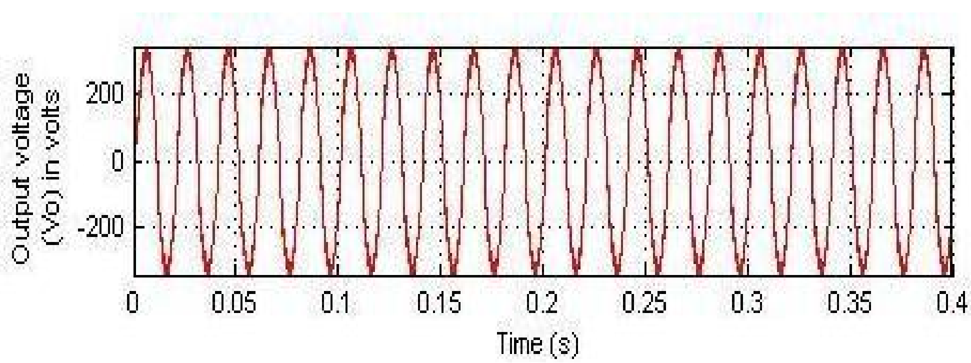


**Figure 5.8(c) Output voltage of the boost inverter for 60W**

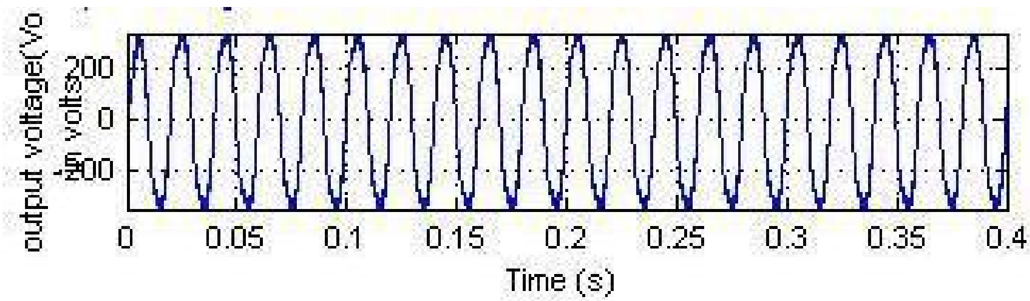


**Figure 5.8(d) Output voltage of the boost inverter for 100W**

An input voltage 100V dc as shown in Figure 5.8 (a) is applied through battery, which is charged from the solar panel. The Figure 5.8 (c) shows the simulated results of output voltage of the proposed modified SPWM technique based control strategy for single stage boost inverter. It has the RMS value of the output voltage of the boost inverter is 220V and the maximum ac voltage is 325V with a fundamental frequency of 50Hz for the load of 60W. By operating the set of switches alternatively for every 10ms at, a fundamental frequency of 50Hz can be obtained. Figure 5.8(d) shows the output voltage of boost inverter is $220V_{rms}$ with 50Hz for a load of 100W resistive load when input was $100V_{dc}$.

Therefore the proposed controller generates a output voltage of $220V_{rms}$ for 60W and 100W which satisfies the grid parameters such as magnitude of voltage, frequency and phase angle as shown in Figure 5.8 (b).

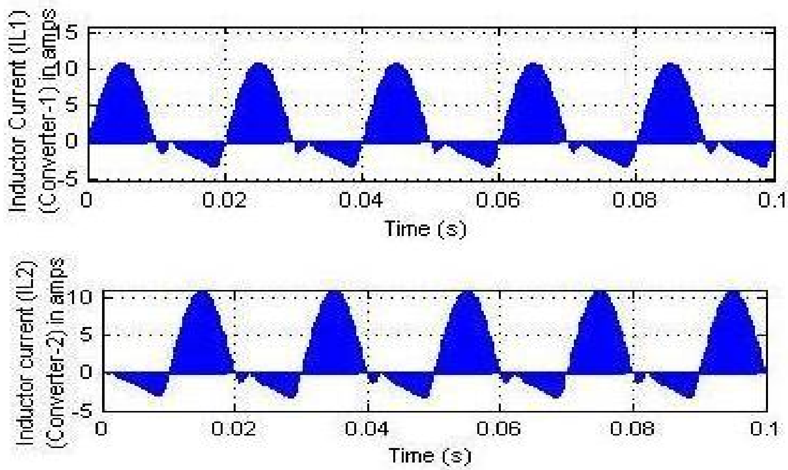


**Figure 5.9(a)Inductor current ($I_{L1}$ & $I_{L2}$) of the boost dc-dc converter -1 & 2 for 60W**

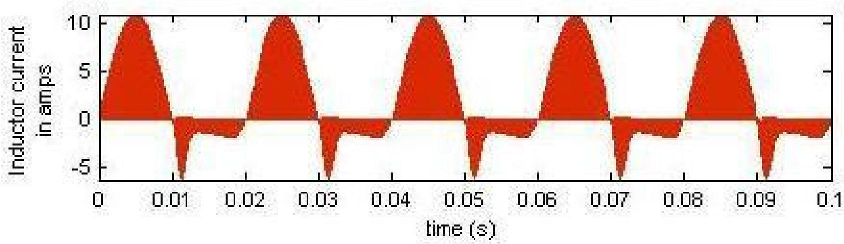


**Figure 5.9(b) Inductor current ($I_{L1}$ & $I_{L2}$) of the boost dc-dc converter -1 & 2 for 100W**

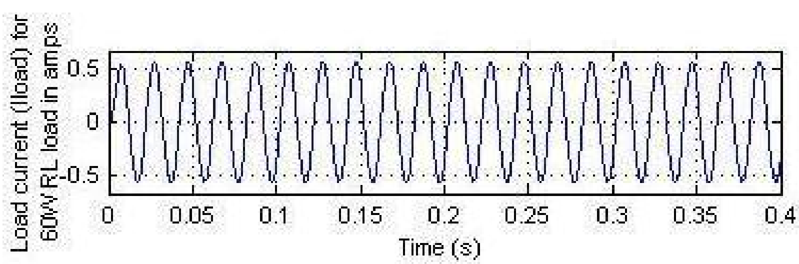


**Figure 5.9(c) Load Current for 60watts load**

Figure 5.9 (a) shows that the inductor current $I_{L1}$ is 10A for 60W resistive load. The proposed modified SPWM controller based single stage boost inverter takes the same inductor current of 10A with for 100W resistive load as shown Figure 5.9(b). Therefore the proposed modified SPWM controller controls the inductor averaged current for any variations in load to a maximum of 100W.

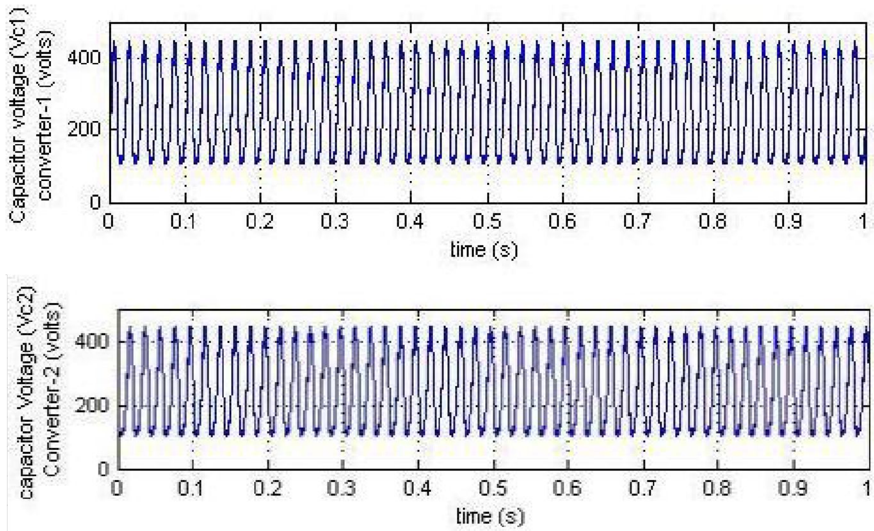


**Figure 5.10(a) Capacitor maximum voltage ($V_{C1}$ & $V_{C2}$) of the boost inverter for 60W**

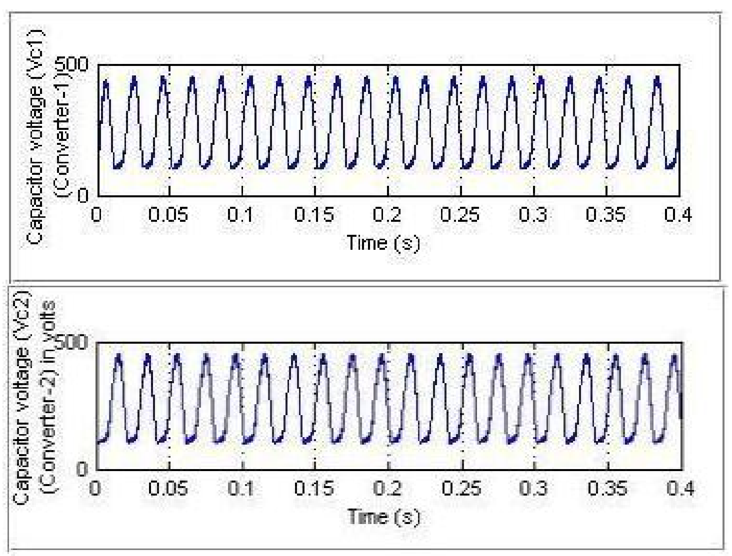


**Figure 5.10(b) Capacitor maximum voltage ($V_{C1}$ & $V_{C2}$) of the boost inverter for 100W load**

The capacitor voltages ($V_{C1}$ & $V_{C2}$) of the boost inverter are maintained at constant magnitude for both loads of 60W and 100W with voltage ripple is 10V as shown in Figures 5.10(a) and Figure 5.10(b) respectively. Also the phase shift is maintained at $180^0$ between two capacitor voltages ($V_{C1}$ & $V_{C2}$) of the two bi-directional boost dc-dc converters. Hence the proposed controller regulates the capacitor voltages of boost inverter for any variations in load to a maximum of 100W.

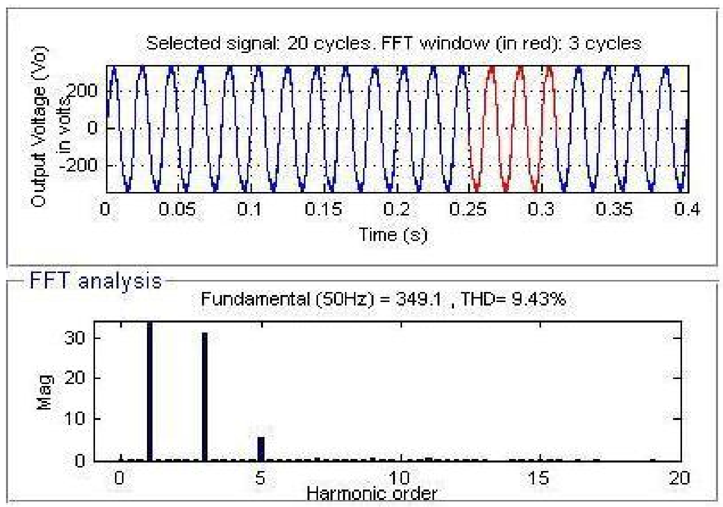


**Figure 5.11(a) Total Harmonic Distortion of boost inverter output voltage (R load)**

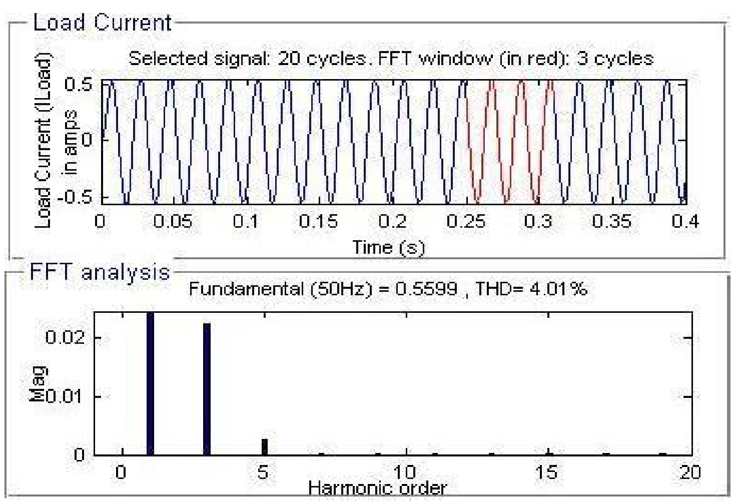


**Figure 5.11(b) Total Harmonic Distortion of the load current (R load)**

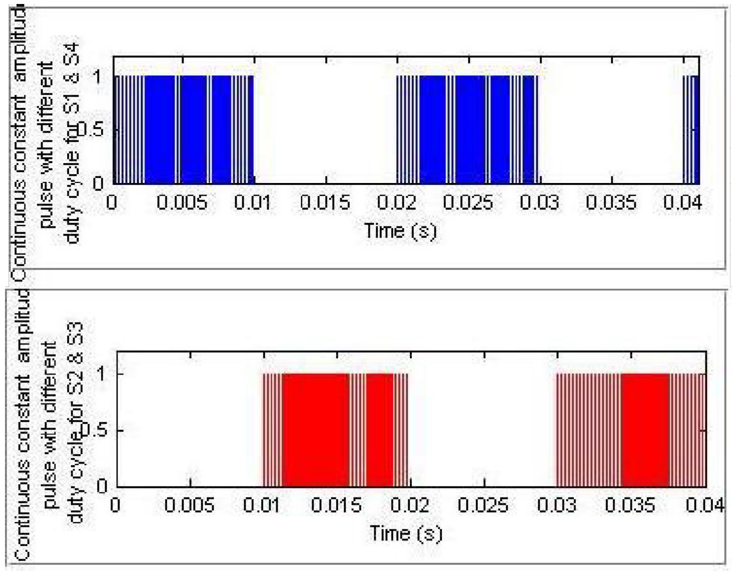


**Figure 5.12 Continuous constant amplitude pulse signal with different duty for $S_1$, $S_2$, $S_3$ & $S_4$ of the boost inverter**

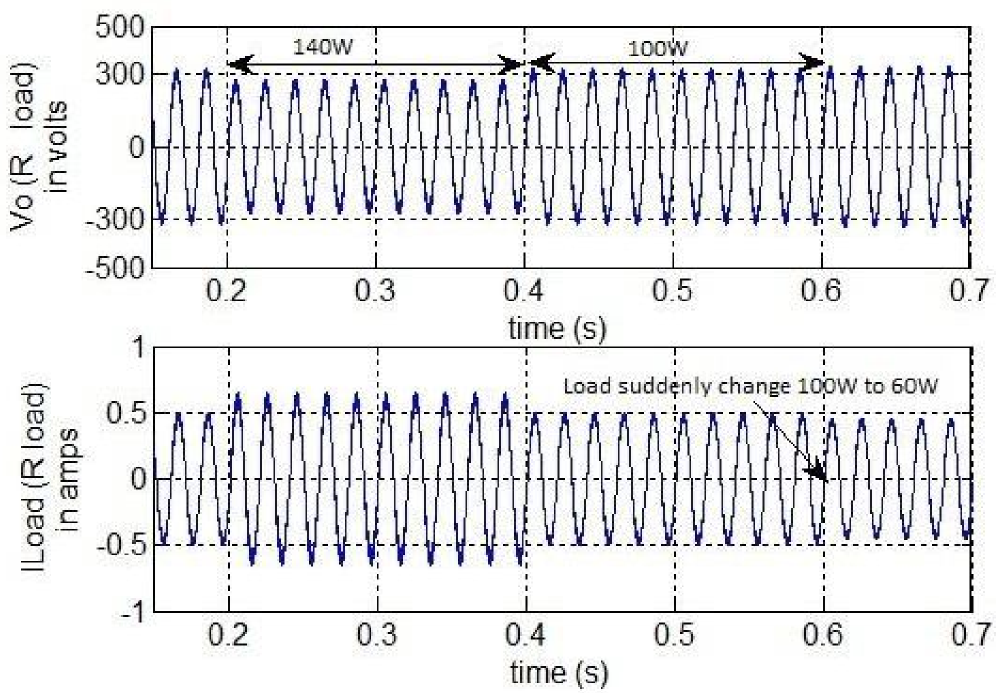


**Figure 5.13(a) Output voltage and load current for variable (dynamic) Resistive load**

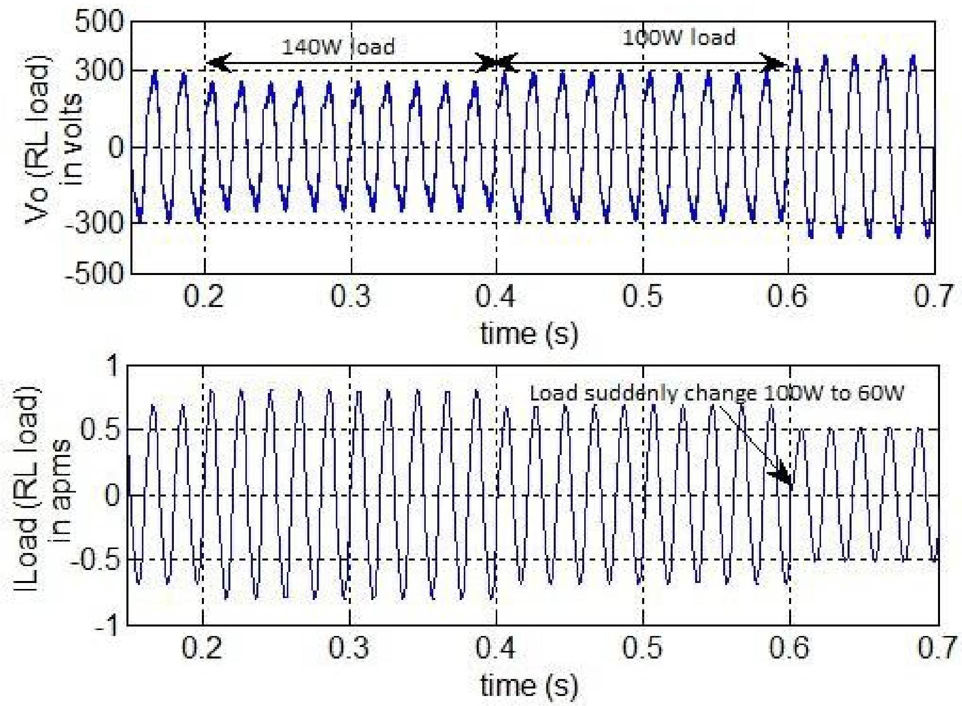


**Figure 5.13(b) Output voltage and load current for variable (dynamic) RL load**

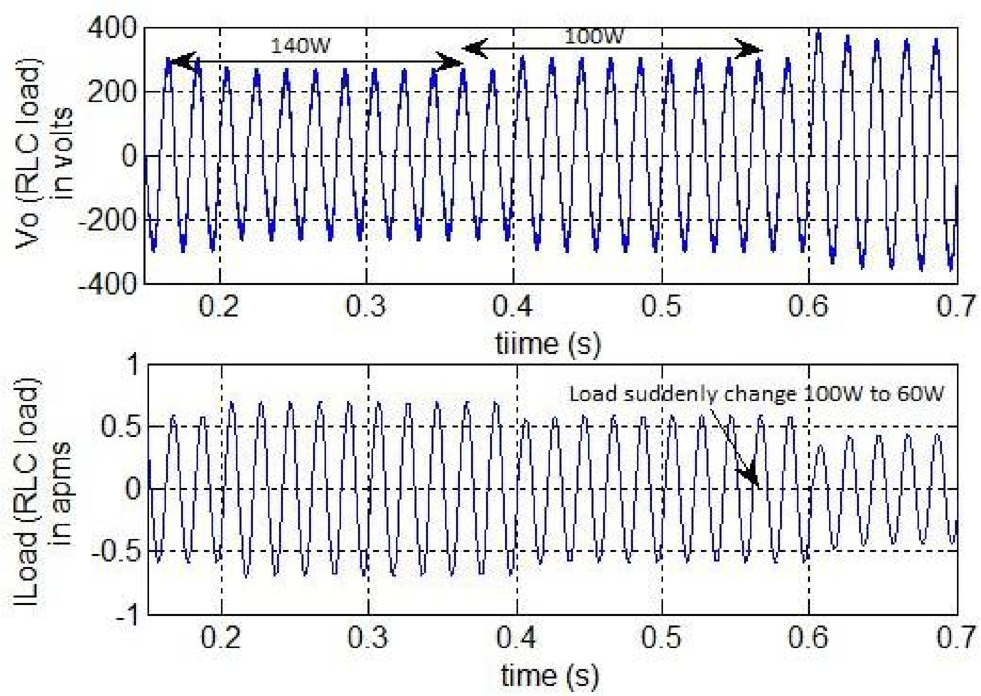


**Figure 5.13(c) Output voltage and load current for variable (dynamic) RLC load**

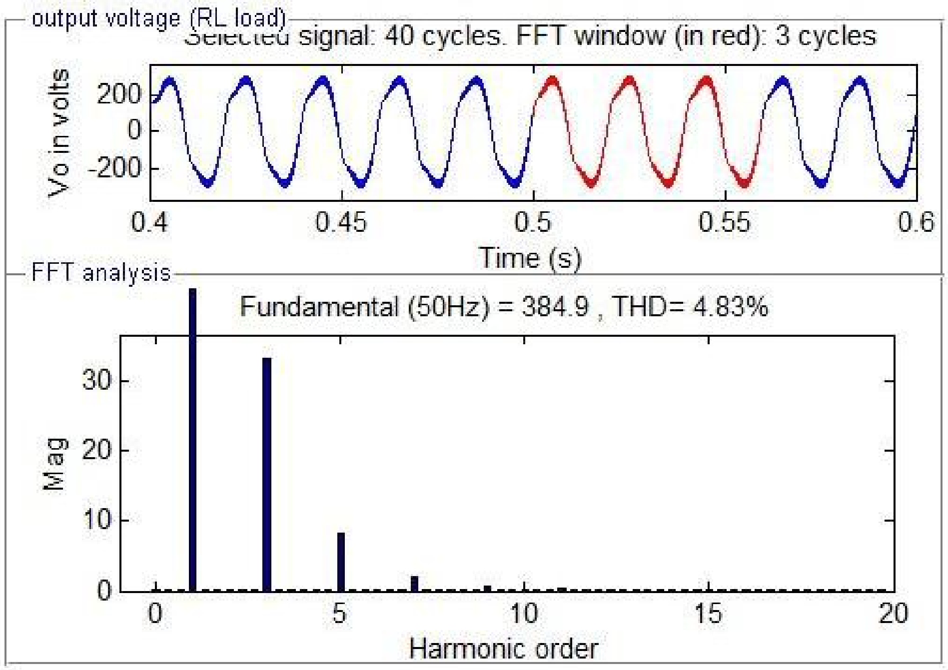


**Figure 5.14 (a) Output voltage THD for RL load**

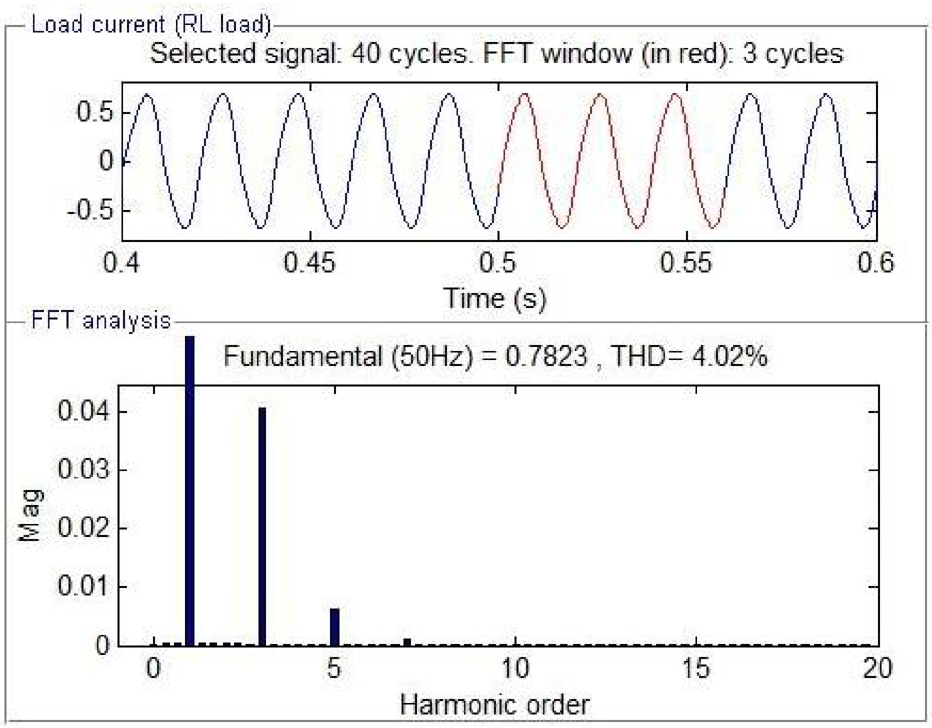


**Figure 5.14 (b) Load current THD for RL load**

Figure 5.13(a) shows the simulated results of output voltage of the SPWM based control strategy for boost inverter under dynamic resistive loads of 40% greater than rated load and 40% less than rated load. It has shows that, the output voltage slightly varies in magnitude. Figure 5.13(a) and Figure 5.13(b) shows that the output voltage under variable load RL and RLC.

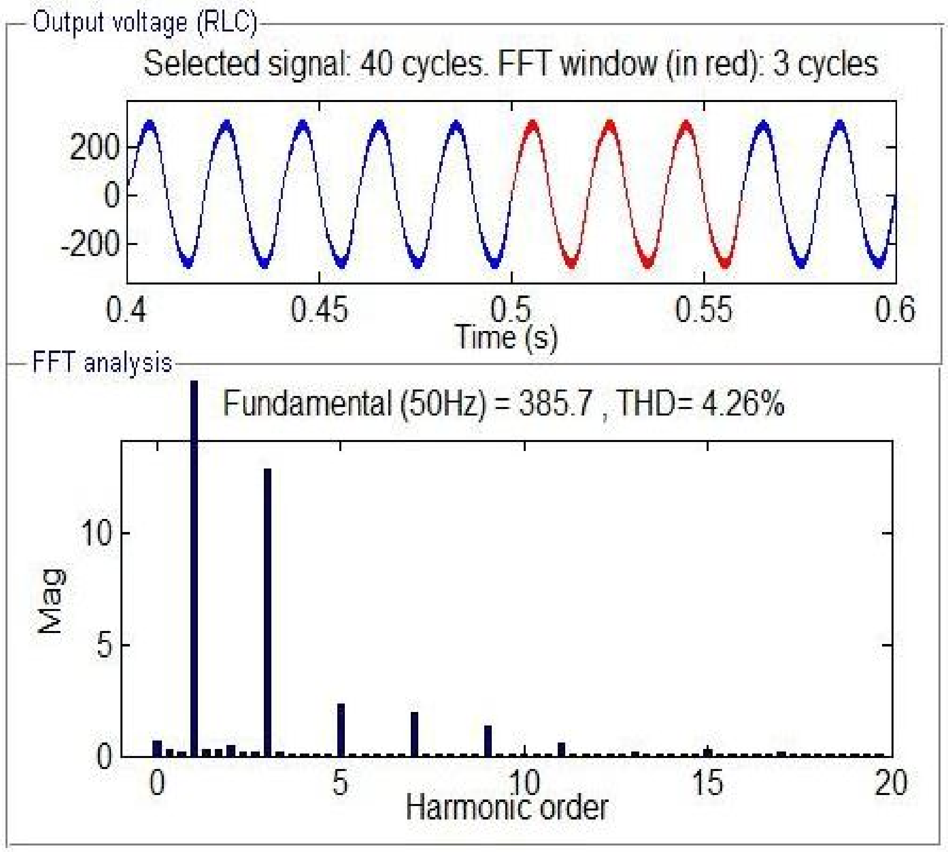


**Figure 5.15 (a) Output voltage THD for RLC load**

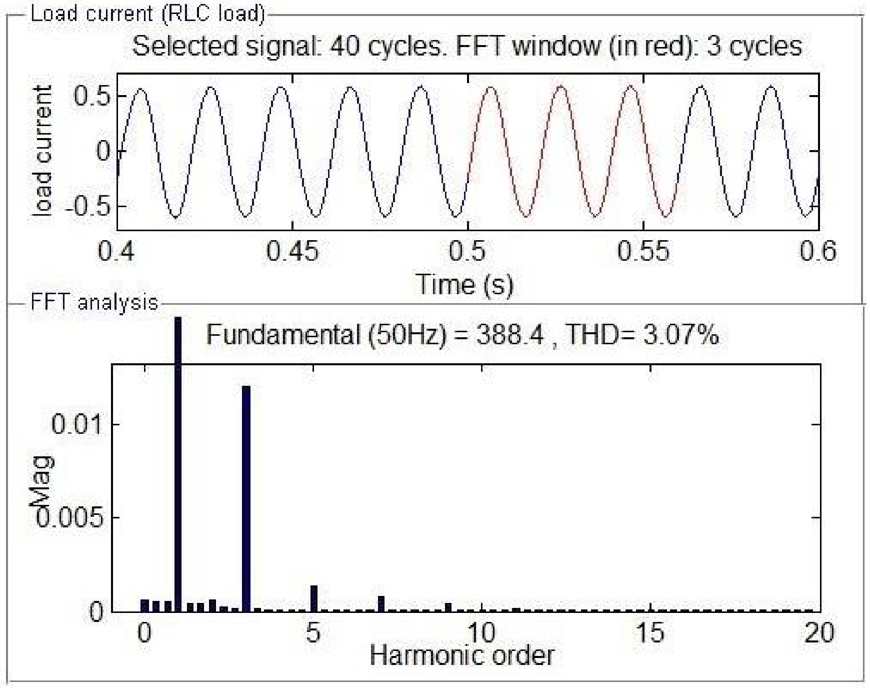


**Figure 5.15 (b) Load current THD for RLC load**

The Total Harmonic Distortion of the output voltage and load current are obtained for RL load of 100W, which shows the THD level of 4.83% and 4.02% respectively as shown in the Figure 5.14(a) and Figure 5.14(b). Figure 5.15(a) and Figure 5.15(b) shows the output voltage and load current THD for RLC load of 100W. The simulation result shows that output voltage THD of 4.26% and load current THD 3.07% are obtained.

Simulated results of output voltage THD, load current THD, output voltage for various loads are noted and given in the table 5.1 and table 5.2.

**Table 5.1 Output voltage, output voltage THD and load current THD for various loads**

| Type | Load (W) | $V_{O(rms)}$ Volts | % THD for $V_O$ | % THD for $I_{load}$ |
|---|---|---|---|---|
| R | 60 | 230 | 4.54 | 4.53 |
| | 100 | 230 | 9.43 | 4.01 |
| | 140 | 205 | 4.78 | 3.78 |
| RL | 60 | 255 | 4.65 | 3.07 |
| | 100 | 209 | 4.83 | 4.02 |
| | 140 | 184 | 4.52 | 4.61 |
| RLC | 60 | 255 | 4.84 | 2.10 |
| | 100 | 213 | 4.26 | 3.07 |
| | 140 | 184 | 4.71 | 4.02 |

**Table 5.2 Output voltage and Grid voltages under static resistive loads**

| **Sl. No.** | **Load in Watts** | **Grid Voltage in volts** | **Output voltage ($V_0$) in volts** | **Phase angle difference between V_grid & Vo in deg** | **Frequency (Hz)** |
|---|---|---|---|---|---|
| 1. | 60 | 230 | 230 | ($0^0$) In-phase | 50 |
| 2. | 100 | 230 | 230 | ($0^0$) In-phase | 50 |
| 3. | 140 | 205 | 230 | ($0^0$) In-phase | 50 |

## 5.6 RESULTS AND DISCUSSION

The simulated results of the proposed sinusoidal pulse width modulation (SPWM) technique based control strategy for single stage boost dc-ac inverter for a variable load has been shown in the waveforms as shown in the figures. The rms value of the output voltage of the model is equal to 230V and the instantaneous ac voltage is 315$V_m$ volts with a fundamental frequency of 50Hz for an input voltage of $V_S$ =100volts. The phase of output voltage of the boost inverter is synchronized with the phase the single phase ac grid voltage as shown in Figure 5.8 (c) & (d). The Total Harmonic Distortion (THD) of $V_O$ for R load is 9.43%, RL load is 4.83% and RLC load is 4.26% which are greater than the THD obtained by using sliding mode controller (Arunkumar Verma et al 2010), modified non linear state variable structure controller and Comparator based non linear variable structure controller as shown in the Figure 5.11 (a), Figure 5.14(a) and Figure 5.15(a).

Figure 5.9 (a) and 5.9 (b) shows that the inductor current $I_{L1}$ is 12A with no initial surge current for the load of 60W and 100W and hence the inductor averaged current is controlled when compared to double loop control scheme and sliding mode control method (Pablo Sanchis at al 2005). The maximum instantaneous voltages of capacitors $V_{C1}$ and $V_{C2}$ is 450V and are phase shifted by $180^0$ and the structure of these waveforms are dc biased sinusoidal voltage as shown in the Figure 5.10 (a) & Figure 5.10 (b).

The SPWM based controller with single stage boost inverter produces a load current THD of 4.01%, 4.02% and 3.07% for R, RL and RLC load respectively. The load current THD waveforms for R, RL and RLC loads are shown in the Figure 5.11(b), Figure 5.14(b) and Figure 5.15(b) respectively. Table 5.1 and table 5.2 shows the THDs and the output voltages of various load conditions were noted.