

# Analysis and simulation of three phase sinusoidal PWM Inverter fed by PV array

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**Abstract**—Mathematical analysis and simulation of a three phase sinusoidal PWM (SPWM) inverter fed by PV array is presented. Modeling of SPWM using MATLAB-Simulink is introduced based on MATLAB function and m-files. The inverter is supplied from a PV array through voltage controlled boost chopper to maintain the inverter input voltage within a specified range. Simulation results using MATLAB-Simulink introduce high performance of the system when a step change is carried out representing variation of PV array voltage.

**Index Terms**—Sinusoidal PWM Inverter, PV array, voltage controlled boost chopper

## 1 INTRODUCTION

THE main objective of DC/AC inverters is to convert the DC input voltage to a symmetrical AC output voltage having a suitable voltage magnitude and frequency. The input of the inverter may be a constant or a variable DC voltage. Most applications of DC/AC inverters utilize constant DC voltage [1-3]. The DC voltage may come through controlled or uncontrolled rectifier and smoothing capacitors, PV arrays, Fuel cells, or batteries.

DC/AC inverters based on their output waveform can be classified into two types: voltage source inverters (VSI) and current source inverters (CSI). VSIs are the most widely used and they are applied in many industrial applications, such as adjustable speed drives ASDs, uninterruptible power supply (UPS) and induction heating [2, 4]. The output voltages of the inverters are desired to be very close to sinusoidal waveform especially in variable speed drives. Deviations from the sinusoidal shape may result in speed fluctuations, torque ripples and motor heating [2]. According to the switching technique and the requirements needed by the load, three phase VSIs can be classified into several categories [1-3]. Pulse width modulation (PWM) inverters are considered as the most common inverters. In these inverters, the dc input voltage is chopped by six switches to achieve ac output voltage in a form of pulses [2, 3]. The duty cycle of these pulses are adjusted according to the type of the PWM technique. The frequency and the amplitude of the output voltage are controlled to meet the requirements of the load. SPWM inverters are still found in many industrial applications although space vector PWM (SVPWM) scheme became more attractive in the recent years. The main problem of SPWM is the variation of switching frequency and the existence of very narrow pulses on the output waveform of the inverter. The dc input voltage of the inverter is required to be constant in most applications. However when the inverter is fed from PV array, this dc voltage may vary. Therefore a voltage controlled chopper is utilized to maintain the output voltage of the inverter within a

specified value. This voltage controlled chopper can be applied with a mathematical algorithm to achieve maximum power tracking of the PV array where the maximum power point of PV array occurs at a certain point on the V-I characteristic of the PV array [5-7]. This paper presents analysis and simulation of SPWM based on MATLAB function and m-files. The method of simulation overcomes the problem of variation of switching frequency. The inverter is fed from a PV array and voltage controlled chopper. Since the output voltage of the PV array may vary, it is represented by a step change having two levels of output voltage. This paper is organized as follows. Section 2 concentrates on analysis of SPWM. Section 3 presents modeling of SPWM in MATLAB. Simulation results are introduced and discussed in section 4. Section 5 concludes the paper

## 2 ANALYSIS OF SPWM

The basic principle of operation of three phase SPWM inverter is shown in Fig. (1). In this method a triangular (carrier) wave having a frequency " $f_c$ " is compared with three phase sinusoidal waveforms which have the required fundamental frequency " $f_s$ ". The outputs of the three comparators are utilized to generate the control signals of the six switches. The relative levels of the carrier wave and sinusoidal waves determine the pulse widths and control the switching of devices in each phase leg of the inverter [2, 3]. The modulation index ( $m_i$ ) is defined as the ratio of the amplitude of the sinusoidal waveform  $A_s$  (reference signal) to the amplitude of the carrier wave  $A_c$ . The modulation index is sometimes called amplitude modulation. The modulation index can be controlled by varying  $A_s$ . As a result the widths of pulses that control the inverter switches can be controlled and consequently the rms of output voltage.

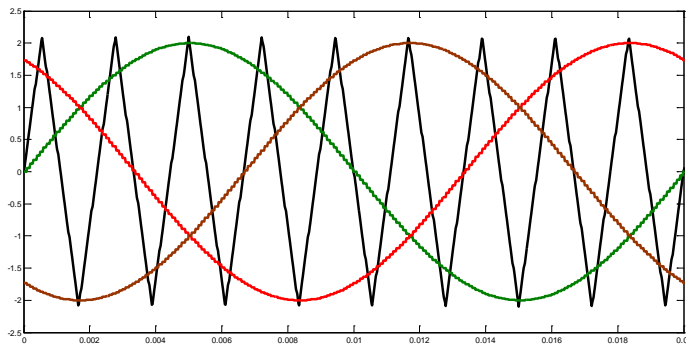


Fig. 1 Principle of operation of SPWM

$$m_i = \frac{A_s}{A_c} \quad (1)$$

The frequency modulation ( $m_f$ ) is defined as the ratio of the frequency of the carrier wave  $f_c$  to the frequency of the sinusoidal waveform (reference signal)  $f_s$ . The frequency index is sometimes called frequency modulation

$$m_f = \frac{f_c}{f_s} \quad (2)$$

The frequency of the reference sinusoidal wave determines the fundamental frequency of the output waveform. The frequency of the carrier wave determines the number of pulses in one cycle "n"

$$n = m_f \quad (3)$$

In SPWM, the harmonics of low order can be reduced significantly as the frequency modulation increases. With  $m_f = 9$  the third and fifth harmonics are nearly eliminated. The third, fifth, seventh and ninth harmonics are nearly eliminated with  $m_f = 15$ . On the other hand increasing the frequency modulation will increase the carrier frequency which is limited because this will result in higher switching losses and very narrow pulses.

### 3 MODELING OF SPWM IN MATLAB

Conventional modeling of SPWM in MATLAB includes Simulink blocks for modeling carrier and reference signals then comparison between them is carried out to generate the control signals. In this paper, another approach is presented using MATLAB function and m-files. This approach has many advantages over conventional modeling. Variation of switching frequency is overcome and the switching frequency became constant. The model is written in m-file using commands similar to C-language. This later advantage makes the implementation of SPWM using microcontrollers easier. Moreover the model is simpler than conventional modeling since several blocks are excluded

In the proposed model, three phase sine waves with  $120^\circ$  out of phase are generated. Each cycle of sine wave is divided

into fixed number of samples ( $N_{sin}$ ). If the frequency of the reference signal is denoted as  $f_s$ , each sample period " $T_s$ " can be determined as:

$$T_s = 1 / N_{sin} f_s \quad (4)$$

The number of samples in one cycle of carrier wave "M" is determined as:

$$M = N_{sin} / m_f \quad (5)$$

And the period of one cycle of the carrier wave " $T_c$ " is calculated as:

$$T_c = 1 / f_c \quad (6)$$

The period of the carrier cycle can be divided into three portions as seen in Fig. (2). The first portion is from beginning of the cycle to  $0.25 T_c$ . The second is from  $0.25 T_c$  to  $0.75 T_c$  and the third portion is from  $0.75 T_c$  to  $T_c$ . The three portions can be represented by lines 1, 2 and 3 whose equations are:

$$\text{Line 1} \quad V_c(t) = \frac{4 A_c}{T_c} t \quad (7)$$

$$\text{Line 2} \quad V_c(t) = 2 A_c - \frac{4 A_c}{T_c} t \quad (8)$$

$$\text{Line 3} \quad V_c(t) = \frac{4 A_c}{T_c} t - 4 A_c \quad (9)$$

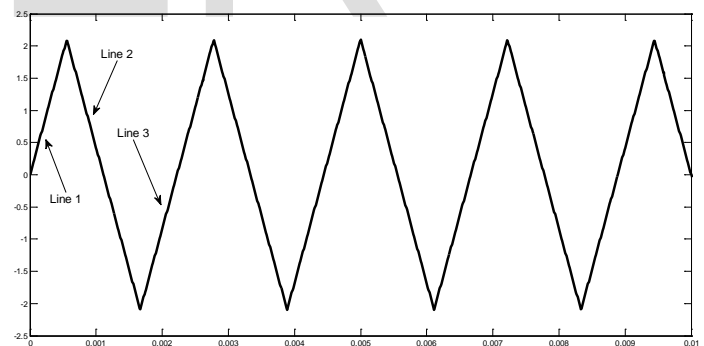


Fig. 2 portions of carrier wave

If the period of the carrier wave is divided into samples and the number of these samples is denoted as "M", then Equations 7-9 can be rewritten as:

$$\text{Line 1} \quad V_c(k) = \frac{4 k A_c}{M} \quad (10)$$

$$\text{Line 2} \quad V_c(k) = 2 A_c - \frac{4 k A_c}{M} \quad (11)$$

$$\text{Line 3} \quad V_c(k) = \frac{4 k A_c}{M} - 4 A_c \quad (12)$$

Where "k" is a counter starts from "one" to "M"

The three phase reference sinusoidal voltages are

$$V_A = A_S \sin(\omega t) \quad (13)$$

$$V_B = A_S \sin(\omega t - 2\pi/3) \quad (14)$$

$$V_C = A_S \sin(\omega t + 2\pi/3) \quad (15)$$

If the sine wave is sampled into " $N_{\sin}$ " samples ( $N_{\sin} = m_f * M$ ), Equations 13-15 can be rewritten as:

$$V_A = A_S \sin(2\pi I / N_S) \quad (16)$$

$$V_B = A_S \sin(2\pi I / N_S - 2\pi/3) \quad (17)$$

$$V_C = A_S \sin(2\pi I / N_S + 2\pi/3) \quad (18)$$

Where "I" is a counter starts from "one" to " $N_S$ "

The algorithm of the m-file is described in the following steps:

- **Generating carrier wave form**

Based on the current instant, the counter "k" is determined. Then equations 10-12 are utilized to calculate the value of carrier wave at the current instant

- **Generating three phase sine-waves**

Based on the current instant, the counter "I" is determined. Then equations 16-18 are utilized to calculate the value of the three phase sine-waves at the current instant

- **Generating logic control signals**

The three phase sine waves are compared with the carrier waves. The following relations summarize the results of the comparisons which are the states of the inverter six switches. "1" means the switch is to be turned on and "0" means the switch is to be turned off

if ( $V_A(I) > V_C(k)$ ),  $S_1 = 1$ ;  $S_4 = 0$ ; else  $S_1 = 0$ ;  $S_4 = 1$ ;

if ( $V_B(I) > V_C(k)$ ),  $S_3 = 1$ ;  $S_6 = 0$ ; else  $S_3 = 0$ ;  $S_6 = 1$ ;

if ( $V_C(I) > V_C(k)$ ),  $S_5 = 1$ ;  $S_2 = 0$ ; else  $S_5 = 0$ ;  $S_2 = 1$ ;

The m-file is included in a matlab block named matlab function. The block receive the current instant as an input via a sampled block whose sampling period is defined by equation (4). If the sampling period is kept constant, the switching frequency becomes constant.

For practical implementation, if the required fundamental frequency is 50 Hz and the number of sampling in one sine-wave cycle  $N_{\sin}$  is 180 samples, the sampling period is 111  $\mu s$  and the switching frequency is constant of about 9 kHz which is suitable in practical implementation.

The output phase voltages of the inverter are calculated based on the states of the upper switches of the inverters ( $S_1, S_3$  and  $S_5$ ) as follows:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_1 \\ S_3 \\ S_5 \end{bmatrix} \times V_{dc} / 3 \quad (19)$$

The inverter is supplied from a PV array through a voltage controlled boost chopper to maintain the inverter input voltage within a specified range. The V-I characteristic of the PV is shown in Fig. (3). The characteristic is based on the model of the PV array as in the following equation [5]:

$$V_{PV} = \frac{AkT_r}{e} \ln \left( \frac{I_{PV} + I_o - I_L}{I_o} \right) - R_S I_L \quad (20)$$

Where "k": Boltzmann constant, " $T_r$ ": reference cell temperature, "e": electron charge, "A": curve fitting factor, " $I_{PV}$ ": cell photocurrent, " $I_o$ ": diode reverse saturation current, " $I_L$ ": cell output current and " $R_S$ ": cell series resistance

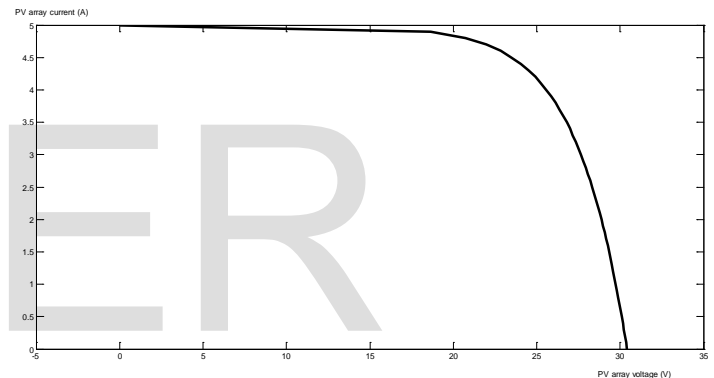


Fig. 3 V-I characteristic of the PV array

Investigating fig. (3), it is noticed that the output voltage of the PV array varies with the array current. Several researches aim to operate the PV array at maximum power point [5-7]. In this paper, a step function representing two voltage levels of the PV array is introduced. A voltage controlled boost chopper is utilized to control the dc voltage within a specified level.

## 4 SIMULATION RESULTS

The block diagram including model of SPWM inverter, voltage controlled boost chopper and step function is shown in Fig. (4). The step function represents a step change of the output of the PV array from 15V to 20V. The boost chopper is controlled to keep the output voltage of the chopper around 24 V which supply the inverter. The fundamental frequency is 50 Hz and the frequency modulation is 9 which eliminates the third and fifth harmonics. Figures 5-7 illustrate the output phase voltages of the inverter, output line-line voltages and spectrum analysis of the output phase voltage. As discussed, the third and fifth harmonics are reduced significantly. The load is 80 W, with power factor 0.8 lagging.

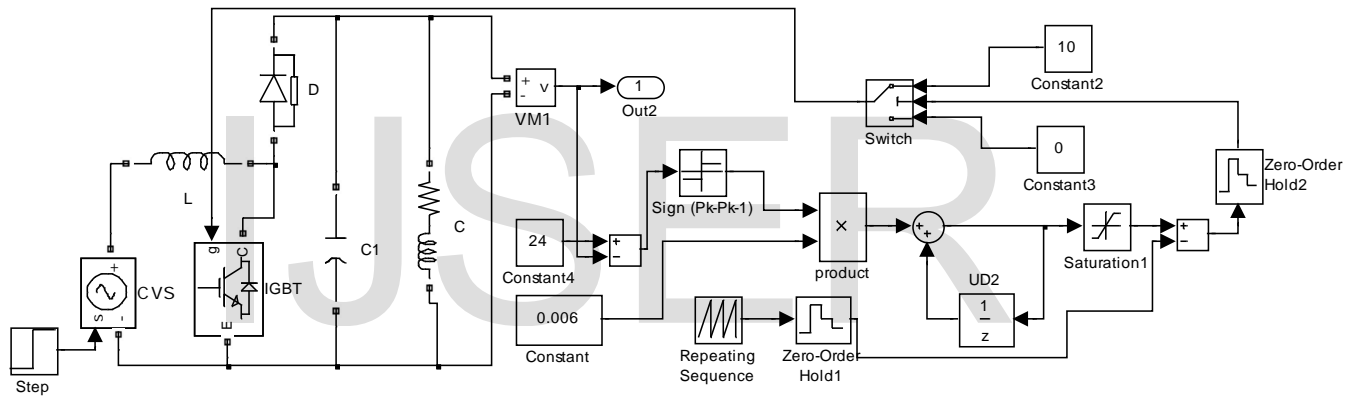
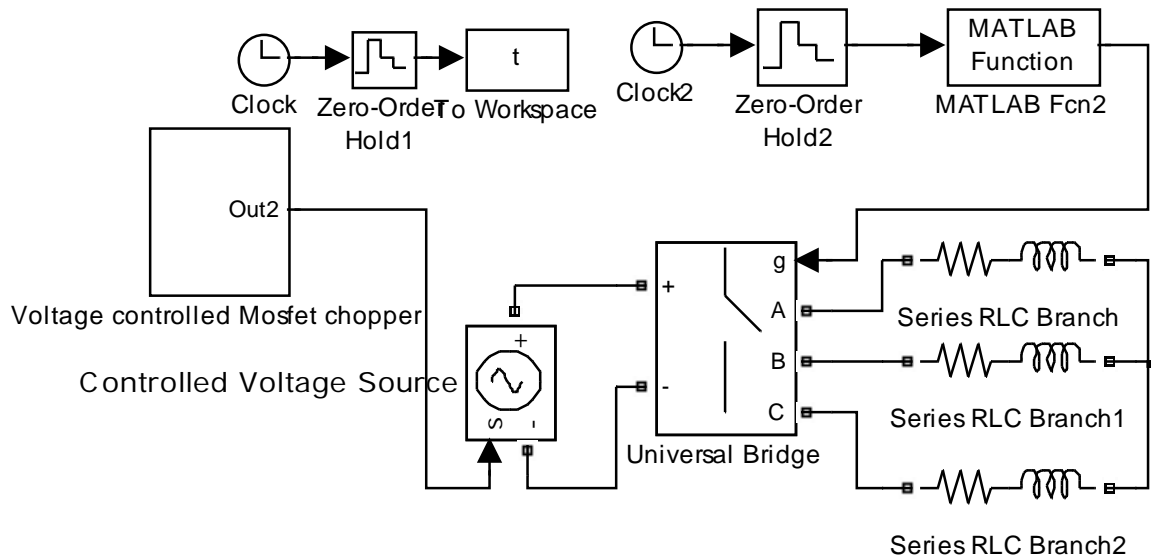


Fig. 4 Block diagram including SPWM model, boost chopper and step function

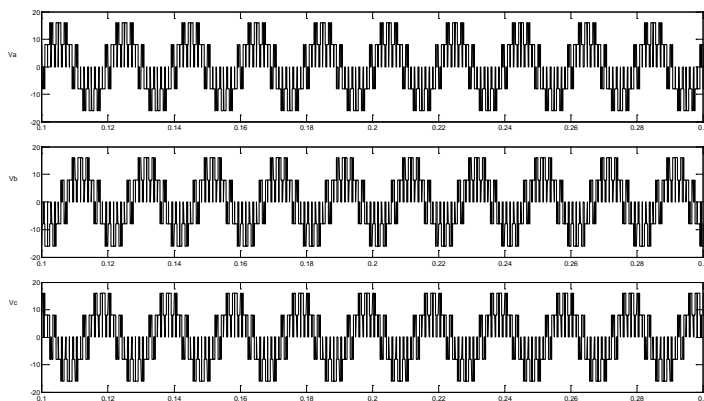


Fig. 5 Output phase voltages of the inverter

( $V_{dc} = 24 \text{ V}$ ,  $n = 9$ ) time (sec)

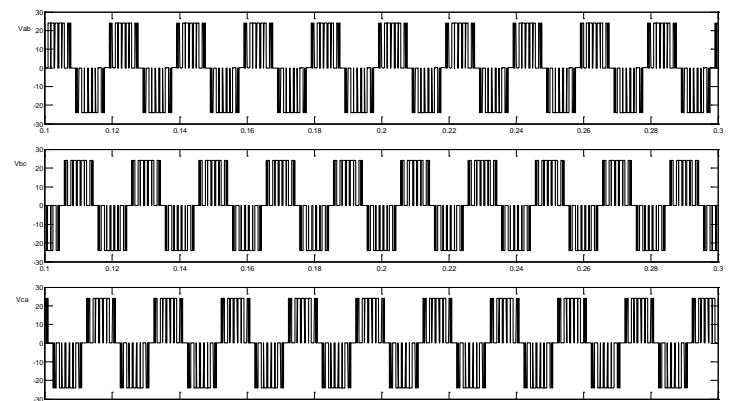


Fig. 6 output line-line voltage of the inverter

( $V_{dc} = 24 \text{ V}$ ,  $n = 9$ ) time (sec)

The load currents are given in Fig. 8 during steady state operation. Figure 9 illustrates the output voltage of the voltage controlled boost chopper when the PV array voltage is increased from 15 V to 20 V at time = 7 sec

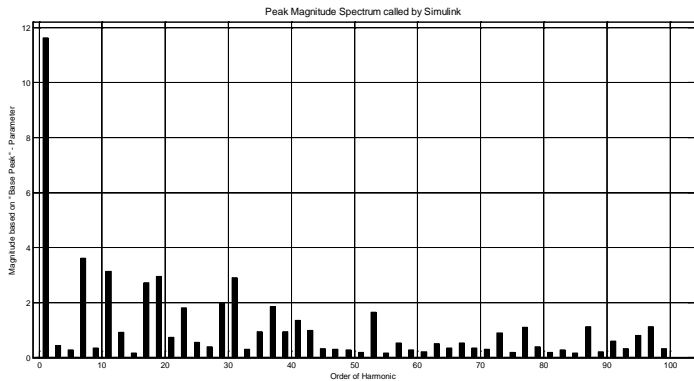


Fig. 7 Spectrum analysis of line-line voltage ( $V_{an}$ ) for PWM inverter

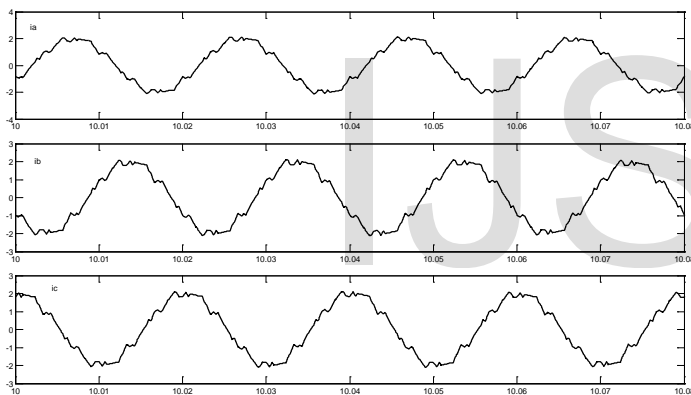


Fig. 8 Load currents (A) during steady state operation

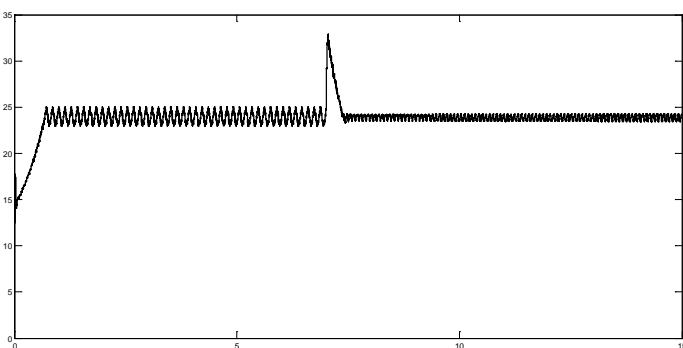


Fig. 9 Output voltage of the voltage controlled boost chopper

model can be transformed into program code if microcontrollers are applied to achieve SPWM experimentally. The inverter is supplied from PV array through voltage controlled chopper. Simulation results illustrate great reduction in the third and fifth harmonics of the inverter output voltage. Simulation results show high performance when a step function is applied representing voltage variation in the PV array voltage.

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## 5 CONCLUSION

Modeling of SPWM using MATLAB-function and m-files is proposed in which has many advantages over conventional models. The switching frequency becomes constant and the