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Design of Three Phase Inverter Using Space Vector Pulse Width Modulation Technique (SVPWM)

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Abstract: A voltage source inverter is commonly used to supply a three-phase induction motor with variable frequency and variable voltage for variable speed applications. A suitable pulse width modulation (PWM) technique is employed to obtain the required output voltage in the line side of the inverter. The different methods for PWM generation can be broadly classified into Triangle comparison based PWM (TCPWM) and Space Vector based PWM (SVPWM). In SVPWM methods, a revolving reference voltage vector is provided as voltage reference instead of three phase modulating waves. The magnitude and frequency of the fundamental component in the line side are controlled by the magnitude and frequency respectively, of the reference vector. Space Vector Modulation (SVM) Technique has become the important PWM technique for three phase Voltage Source Inverters for the control of AC Induction, Switched Reluctance and Permanent Magnet Synchronous Motors. The study of space vector modulation technique reveals that space vector modulation technique utilizes DC bus voltage more efficiently. In this paper a model for Space vector PWM is made and simulated using MATLAB/SIMULINK software and its performance is verified.

Keywords: Pulse width modulation (PWM), Space Vector Modulation (SVM), Sinusoidal PWM (SPWM), Triangle comparison based PWM (TCPWM).

1. INTRODUCTION

1.1 Objective of PWM techniques

AC drives are more predominant than dc drives. Ac drives requires high power variable voltage variable frequency supply. The research in Pulse width modulation schemes has been intensive in the last couple of decades. PWM techniques have been used to achieve variable voltage and variable frequency in ac-dc and dc-ac converters. PWM techniques are widely used in different applications such as variable speed drives (VSD), static frequency changers (SFC), and un-interruptible power supplies (UPS) etc. The classical square wave inverter used in low or medium power applications suffers from a serious disadvantage such as lower order harmonics in the output voltage. One of the solutions to enhance the harmonic free environment in high power converters is to use PWM control techniques. The objective of PWM techniques was to fabricate a sinusoidal AC output whose magnitude and frequency could both be restricted.

1.2 PWM strategy

Real-time method of PWM generation can be broadly classified into Triangle comparison based PWM (TCPWM) and Space Vector based PWM (SVPWM).

In TCPWM methods such as sine-triangle PWM, three phase reference modulating signals are compared against a common triangular carrier to generate PWM pulses for the three phases. In SVPWM methods, the voltage reference is provided using a revolving reference vector. In this case magnitude and frequency of the fundamental component in the line side are controlled by the magnitude and frequency, respectively, of the reference voltage vector. Space vector modulation utilizes dc bus voltage more efficiently and generates less harmonic distortion in a three phase voltage source inverter.

2. SPACE VECTOR PULSE WIDTH MODULATION

2.1 A Space vector PWM

The circuit model of a typical three-phase voltage source PWM inverter is shown in Figure1:

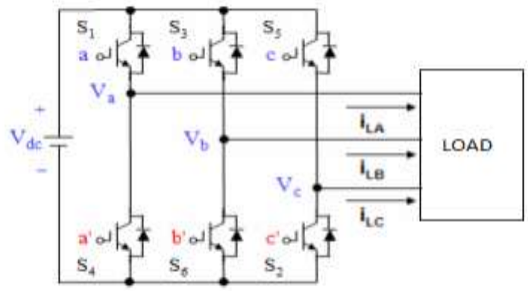


Figure 1: Typical three-phase voltage source PWM Inverter

S1 to S6 are the six power switches that shape the output, which are controlled by the switching variables a, a', b, b', c and c'. When an upper switch is switched on, i.e., when a, b or c is 1, the corresponding lower transistor is switched off, i.e., the corresponding a', b' or c' is 0. Therefore, the on and off states of the upper switch S1, S3 and S5 can be used to determine the output voltage. SVPWM is a different approach from PWM modulation, based on space vector representation of the voltages in the α-β plane. The α-β components are found by Clark's transformation. Space Vector PWM (SVPWM) refers to a special switching sequence of the upper three power transistors of a three-phase power inverter. Because of its superior performance characteristics, it has been finding widespread application in recent years.

2.2 Space Vector Concept

The space vector concept, which is derived from the rotating field of induction motor, is used for modulating the inverter output voltage. In this modulation technique the three phase quantities can be transformed to their equivalent two-phase quantity either in synchronously rotating frame (or) stationary frame. From these two-phase components, the reference vector magnitude can be found and used for modulating the inverter output. The process of obtaining the rotating space vector is explained in the following section, considering the stationary reference frame. Considering the stationary reference frame let the three-phase sinusoidal voltage component be,

$$Va = Vm \sin(\omega t) \quad (1)$$

$$Vb = Vm \sin(\omega t - 2\pi/3) \quad (2)$$

$$Vc = Vm \sin(\omega t - 4\pi/3) \quad (3)$$

When this three-phase voltage is applied to the AC machine it produces a rotating flux in the air gap of the AC machine. This rotating resultant flux can be represented as single rotating voltage vector. The magnitude and angle of the rotating vector can be found by means of Clark's Transformation as explained below in the stationary reference frame. To implement the space vector PWM, the voltage the stationary dq reference frame that consists of the horizontal (d) and vertical (q) axes as depicted in Figure 2 from Figure2: the relation between these two reference frames is below

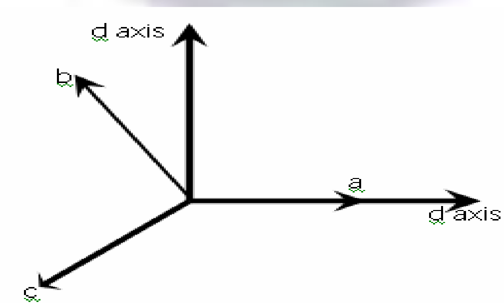


Figure 2: The relationship of abc reference frame and stationary dq reference

$$f_{dq0} = K_s f_{abc} \quad (4)$$

$$K_s = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & -\sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix},$$

$$f_{dq0} = [f_d f_q f_0]^T$$

$$f_{abc} = [f_a f_b f_c]^T$$

And f denotes either a voltage or a current variable. As described in Figure2: This transformation is equivalent to an orthogonal projection of [a b c] t onto the two-dimensional perpendicular to the vector [1 1 1] t (the equivalent d-q plane) in a three-dimensional coordinate system. As a result, six non-zero vectors and two zero vectors are possible. Six non-zero vectors (V1-V6) shape the axes of a hexagonal as depicted in Figure-3, and supplies power to the load. The angle between any adjacent two non-zero vectors is 60 degrees. Meanwhile, two zero vectors (V0 and V7) and are at the origin and apply zero voltage to the load. The eight vectors are called the basic space vectors and are denoted by (V0, V1, V2, V3, V4, V5, V6, V7). The same transformation can be applied to the desired output voltage to get the desired reference voltage vector, V_{ref} in the d-q plane. The objective of SVPWM technique is to approximate the reference voltage vector Vref using the eight switching patterns. One simple method of approximation is to generate the average output of the inverter in a small period T to be the same as that of Vref in the same period.

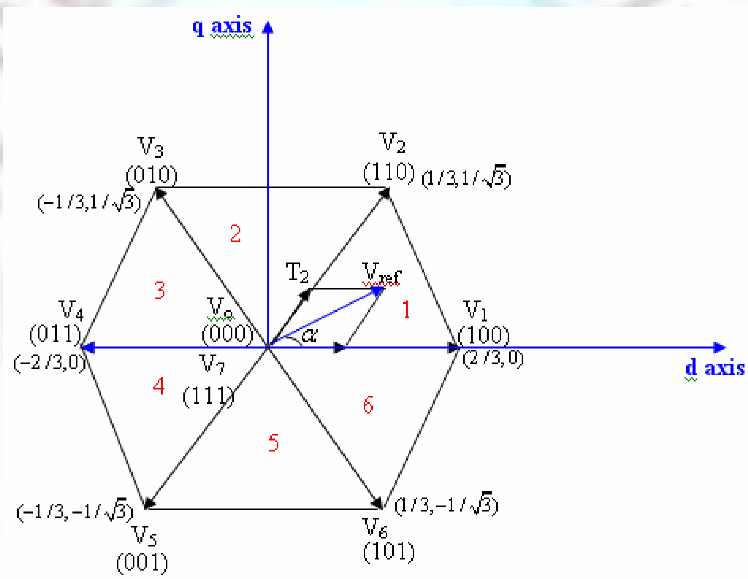


Figure 3: Basic switching, vectors and sectors.

2.3 Switching Gates

Table 1: Switching patterns and output vectors.

Voltage Vectors	Switching Vectors			Line to neutral voltage			Line to line voltage		
	a	b	c	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
V_0	0	0	0	0	0	0	0	0	0
V_1	1	0	0	2/3	-1/3	-1/3	1	0	-1
V_2	1	1	0	1/3	1/3	-2/3	0	1	-1

V_3	0	1	0	-1/3	2/3	-1/3	-1	1	0
V_4	0	1	1	-2/3	1/3	1/3	-1	0	1
V_5	0	0	1	-1/3	-1/3	2/3	0	-1	1
V_6	1	0	1	1/3	-2/3	1/3	1	-1	0
V_7	1	1	1	0	0	0	0	0	0

(Note that the respective voltage should be multiplied by V_{dc})

For 180° mode of operation, there exist six switching states and additionally two more states, which make all three switches of either upper arms or lower arms ON. To code these eight states in binary (one-zero representation), it is required to have three bits (23 = 8). And also, as always upper and lower switches are commutated in complementary fashion, it is enough to represent the status of either upper or lower arm switches. In the following discussion, status of the upper bridge switches will be represented and the lower switches will it's complementary. Let "1" denote the switch is ON and "0" denote the switch in OFF. Table1: gives the details of different phase and line voltages for the eight states.

3. IMPLEMENTATION OF SVPWM

3.1 Calculation of timing values V_d, V_q, V_{ref}

3.1.1 Determine V_d, V_q, V_{ref} and angle (α)

$$V_d = V_{an} - V_{bn}\cos 60 - V_{cn} \cos 60^0 \quad (5)$$

$$= V_{an} - \frac{1}{2}V_{bn} - \frac{1}{2}V_{cn}$$

$$V_q = 0 + V_{bn} \cos 30^0 - V_{cn} \cos 30^0 \quad (6)$$

$$= V_{an} + \frac{\sqrt{3}}{2}V_{bn} - \frac{\sqrt{3}}{2}V_{cn}$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \quad (7)$$

$$|V_{ref}| = \sqrt{{V_d}^2 + {V_q}^2} \quad (8)$$

$\alpha = \tan^{-1}\frac{V_d}{V_q} = \omega t = 2\pi ft$,where f is fundamental frequency.

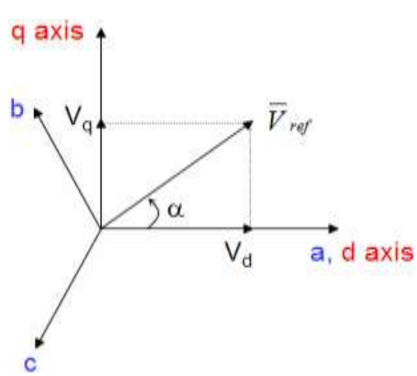


Figure 4: Voltage space vector and its components in (d,q)

3.1.2- Determine the time duration T1, T2 and T0

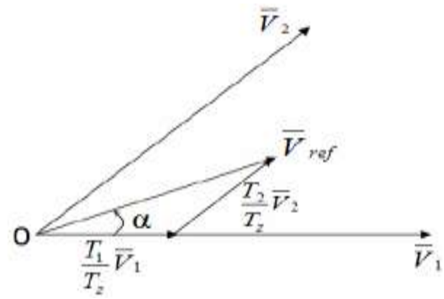


Figure 5: Reference vector as a combination of adjacent vectors at sector-1.

From figure 5: Switching times can be calculated as follows,

$$\int_0^{T_z} V_{ref} = \int_0^{T_1} V_1 dt + \int_{T_1}^{T_1+T_2} V_2 dt + \int_{T_1+T_2}^{T_z} V_0 dt \quad (9)$$

$$T_z V_{ref} = T_1 V_1 + T_2 V_2 \quad (10)$$

$$T_z V_{ref} \begin{bmatrix} \cos\alpha \\ \sin\alpha \end{bmatrix} = T_1 \frac{2}{3} V_{dc} \begin{bmatrix} 1 \\ 0 \end{bmatrix} + T_2 \frac{2}{3} V_{dc} \begin{bmatrix} \cos{}^{\pi}/_{3} \\ \sin{}^{\pi}/_{3} \end{bmatrix} \quad (11)$$

$$T_1 = T_z * a * \frac{\sin({}^{\pi}/_{3} - \alpha)}{\sin{}^{\pi}/_{3}} \quad (12)$$

$$T_2 = T_z * a * \frac{\sin(\alpha)}{\sin{}^{\pi}/_{3}} \quad (13)$$

Switching time during any sector,

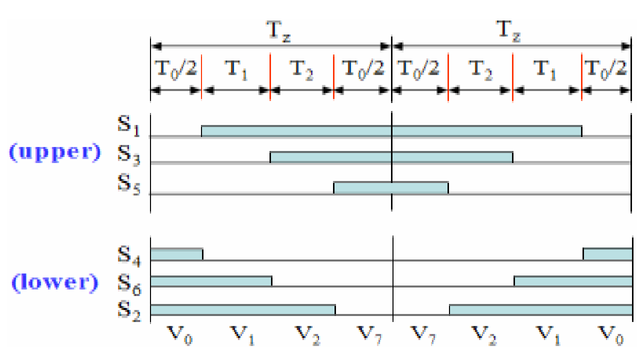
$$T_1 = \frac{\sqrt{3} T_z V_{ref}}{V_{dc}} \sin\left(\frac{n}{3}\pi - \alpha\right) \quad (14)$$

$$T_2 = \frac{\sqrt{3} T_z V_{ref}}{V_{dc}} \sin\left(\alpha - \frac{(n-1)}{3}\pi\right) \quad (15)$$

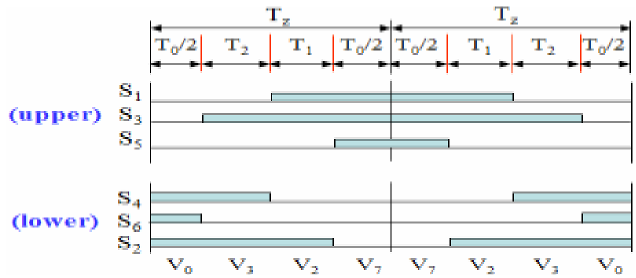
$$T_0 = T_z - T_1 - T_2 \quad (16)$$

(Where, n=1through 6(that is, Sector 1 to 6)

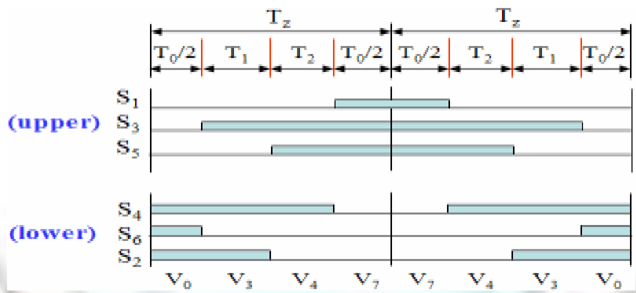
3.1.3 Determine the switching time of each transistor (S1 TO S6)



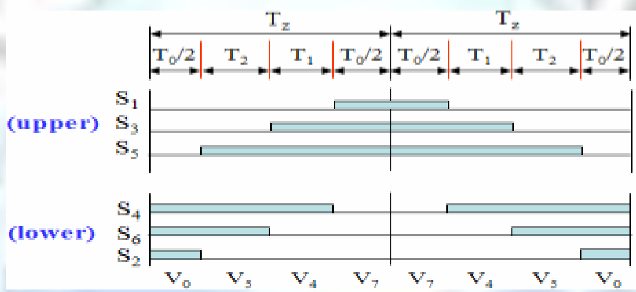
(a) Sector 1



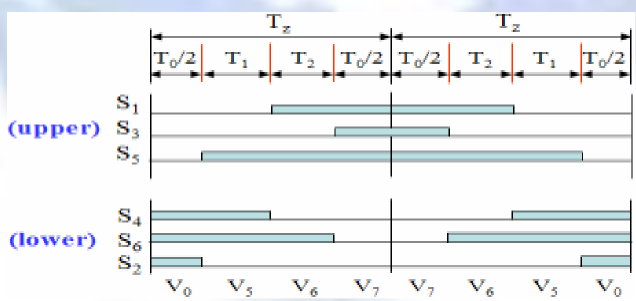
(b) Sector 2



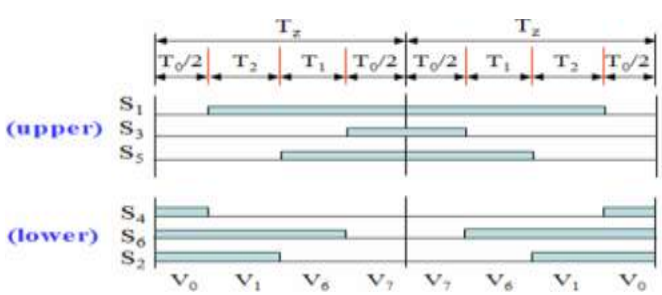
(c) Sector 3



(d) Sector 4



(e) Sector 5



(f) Sector 6

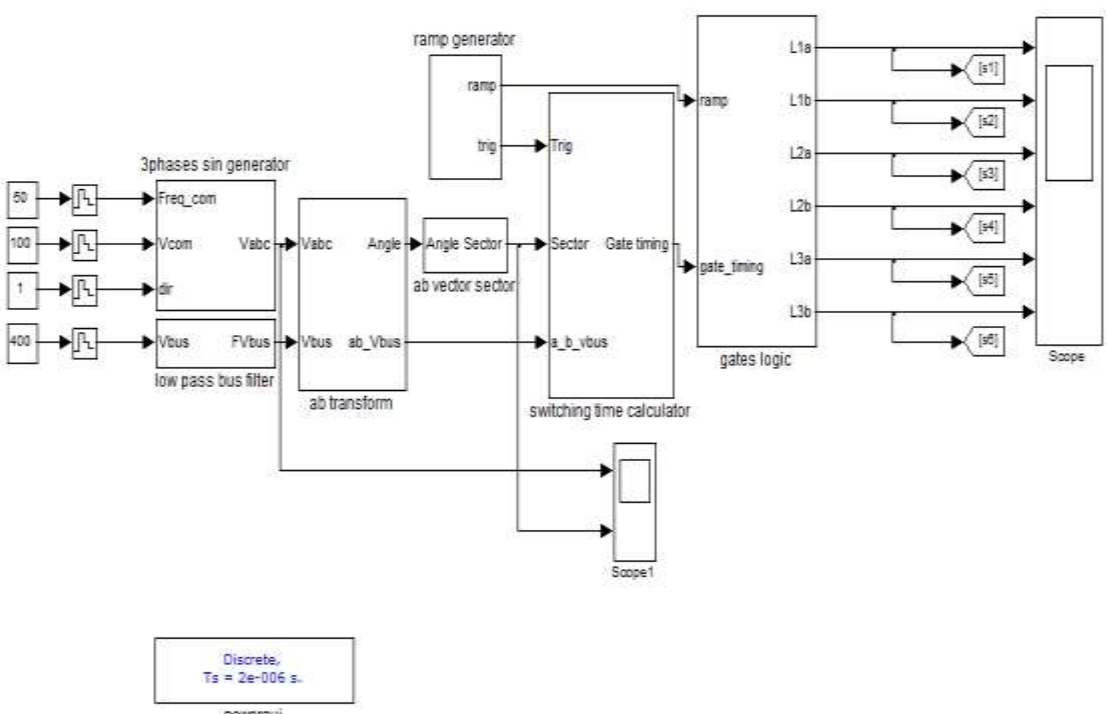
Figure 6: Space Vector PWM switching patterns at each sector.

Based on Figure 6, the switching time at each sector is summarized in Table 2: and it will be built in Simulink model to implement SVPWM

Table 2: Switching Time Calculation at Each Sector

Sector	Upper Switch (S_1,S_3,S_5)	Lower Switches (S_4,S_6,S_2)
1	S_1=T_1+T_2+T_0/2 S_3=T_2+T_0/2 S_5=T_0/2	S_4=T_0/2 S_6=T_1+T_0/2 S_2= T_1+T_2+T_0/2
2	S_1=T_1+T_0/2 S_3= T_1+T_2+T_0/2 S_5=T_0/2	S_4= T_2+T_0/2 S_6= T_0/2 S_2= T_1+T_2+T_0/2
3	S_1=T_0/2 S_3=T_1+T_2+T_0/2 S_5=T_0/2	S_4=T_1+T_2+T_0/2 S_6=T_0/2 S_2=T_1+T_0/2
4	S_1=T_0/2 S_3=T_1+T_0/2 S_5=T_1+T_2+T_0/2	S_4=T_1+T_2+T_0/2 S_6=T_2+T_0/2 S_2=T_0/2
5	S_1=T_2+T_0/2 S_3=T_0/2 S_5=T_1+T_2+T_0/2	S_4=T_1+T_0/2 S_6=T1+T2+T0/2 S_2=T_0/2
6	S_1=T_1+T_2+T_0/2 S_3=T_0/2 S_5=T_1+T_0/2	S_4= T_0/2 S_6= T_1+T_2+T_0/2 S_2= T_2+T_0/2

4. MATLAB SIMULATION



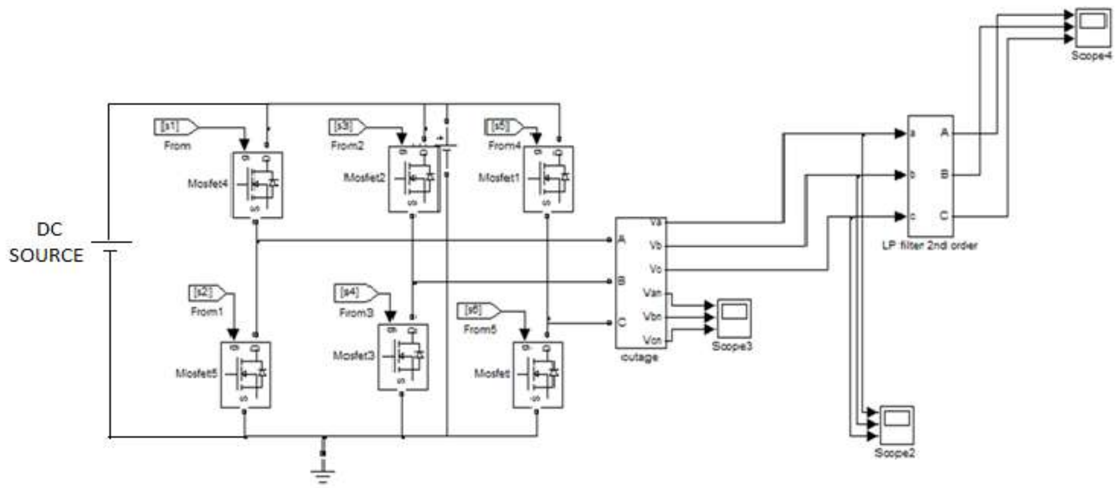


Figure 7: Simulation of SVPWM inverter

4.1. OUT PUT WAVEFORMS OF MATLAB SIMULATION

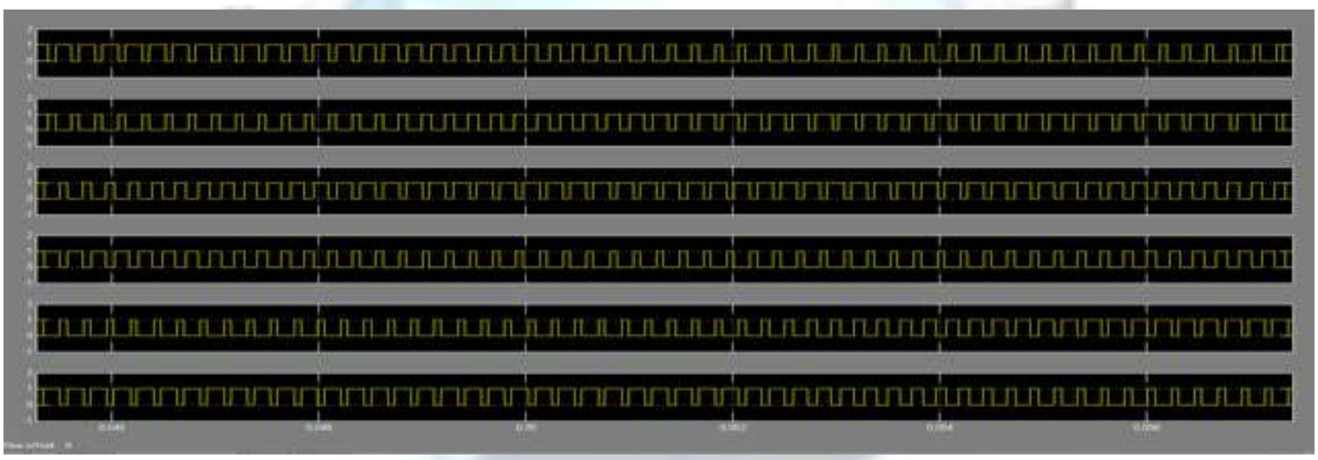


Figure 8: SVPWM pulse train

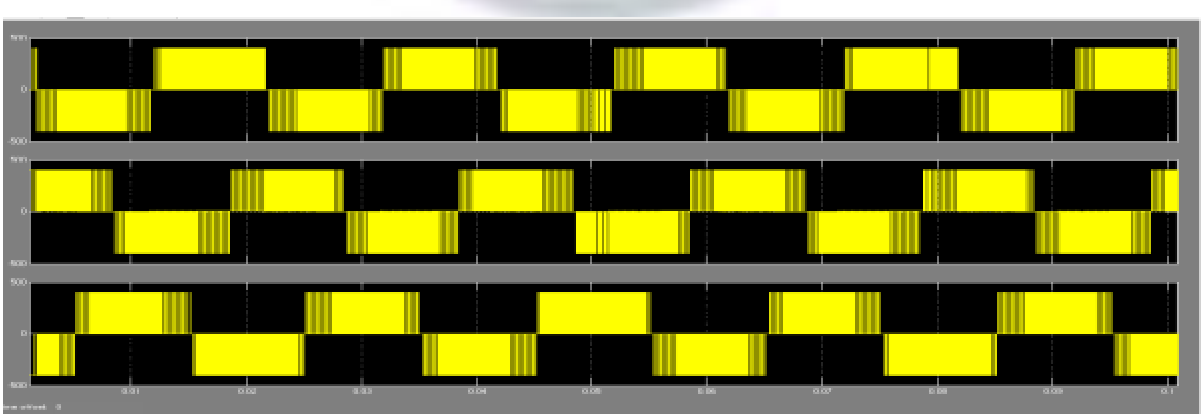


Figure 9: Waveform of Line voltage of inverter before filter

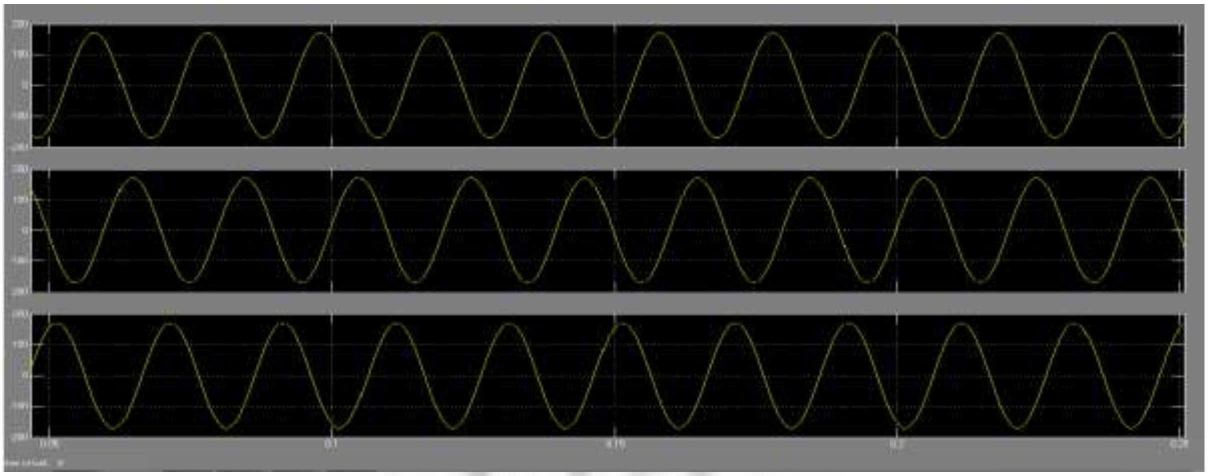


Figure 10: Waveform of Line voltage of inverter after filter

CONCLUSION

A simple Matlab/Simulink model is represented to implement SVPWM for three phase inverter. A brief review of the Voltage source inverter model is also reported based on space vector representation. Space vector modulation technique utilizes DC bus voltage more efficiently & used to generate sinusoidal voltage.

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