International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 2 Issue 5, May - 2013

Simulation And Comparison Of Space Vector Pulse Width Modulation For Three Phase Voltage Source Inverter

Associate Prof. S. Vasudevamurthy
Department of Electrical and Electronics
Dr. Ambedkar Institute of Technology
Bangalore, India

Swetha
Department of Electrical and Electronics
Dr. Ambedkar Institute of Technology
Bangalore, India

Abstract

This paper presents successful application of space vector pulse width modulation (SVPWM) for a three phase VSI and it is the standard PWM technique to utilize in DC to AC power conversion. 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 (SV) pulse width modulation (PWM) technique has become a popular PWM technique for three-phase voltage-source inverters (VSI) in applications such as control of AC induction and permanent-magnet synchronous motors SVPWM technique enjoy an assortment of advantages such as high output quality, less THD, low distortion. In addition, SVPWM technique offers flexible control of output voltage as well as frequency which is an indeed requirement in ac drives. Hence, to obtain good voltage transfer and reduced distortion space vector PWM is required. Space vector PWM can produce about 15% higher output voltage than sine PWM. The simulation study reveals that Space vector PWM utilizes dc bus voltage more effectively and generates less THD when compared with sine PWM.

1. Introduction

The project dealing with renewable energy is in need of renewable energy conversion in form of power electronics converter. PWM techniques have been used to achieve variable voltage and variable frequency in ac-dc and dc-ac converters. This paper covers the calculation and implementation of a pulse width modulation system using a modulation strategy that uses a space vector as a reference in order to achieve a desired three-level waveform (Space Vector Pulse Width Modulation).Due to the advancement in the field of power device technology and development in large scale integrated circuits in recent years have paved the way for the modern fast switching PWM technique for DC-AC conversion. Because of the advancement in solid state power device and microprocessor PWM converter are becoming more popular in today’s motor applications. PWM inverter, control both frequency and magnitude of the voltage and current applied to a motor. As a result, PWM inverter offers better efficiency and high performance compared to fixed frequency motor drives.

A number of PWM techniques have been presented to obtain variable voltage and frequency supply [1]. The most popular among those are carrier-based sinusoidal PWM and SVPWM. The major disadvantage of this scheme is lower dc bus utilisation. PWM techniques are widely used in different applications such as variable speed drives (VSD), un-interruptible power supplies (UPS) etc. Sinusoidal pulse width modulation (SPWM) is used to control the inverter output voltage and maintains good performance in the entire range of the operation between zero and 78% of the value that would be reached by square wave operation[1]-[3]. If the modulation index exceeds this value then output voltage is not maintained and over modulation methods are required. On the other hand space vector pulse width modulation (SVPWM) increased its applications from last decade, because they allow reducing commutation losses and the harmonic content output voltage. Space vector PWM (SVPWM) offers easy digital realisation and better dc bus utilisation.

Sinusoidal PWM compares a high frequency triangular carrier with three sinusoidal reference signals, known as the modulating signals, to generate the gating signals for the inverter switches but having a disadvantage that it contains third harmonic in output [3]. To the cancellation of the third-harmonic components and better utilization of the dc supply, the third harmonic injection PWM scheme is preferred in three-phase applications. Space vector modulation technique has advantage of an optimal output and also reduces harmonic content of the output voltage/current [4]. Space vector PWM (SVPWM) has the advantages of lower harmonics.

2. Sinusoidal pulse width modulation

The sinusoidal pulse-width modulation (SPWM) technique produces a sinusoidal waveform by filtering an output pulse waveform with varying width. The desired output voltage is achieved by varying the frequency and amplitude of a reference or modulating voltage. The variations in the amplitude and frequency of the reference voltage change the pulse-width patterns of the output voltage but keep the sinusoidal modulation.

The switches are controlled in pairs ((S1;S4), (S3;S6), and (S5;S2)) and the logic for the switch control signals is:

_ S1 is ON when Va>VT S4 is ON when Va<VT
_ S3 is ON when Vb>VT S6 is ON when Vb<VT
_ S5 is ON when Vc>VT S2 is ON when Vc<VT

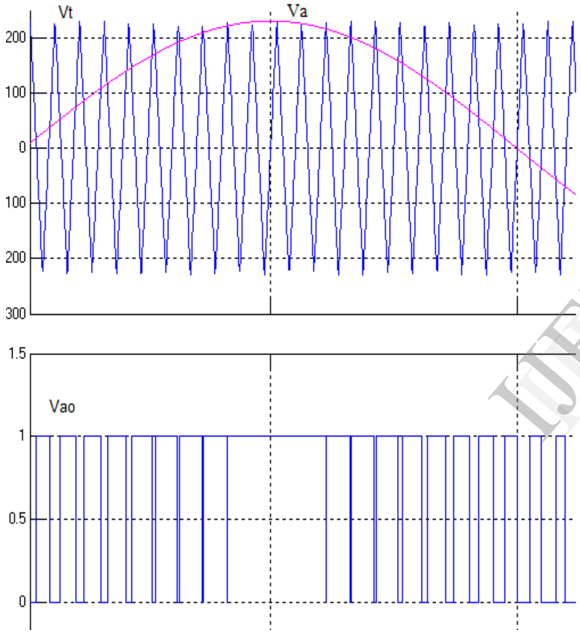


Figure 1. Pulse Width Modulation

Inverter output voltage has the following features by using SPWM technique

- PWM frequency is the same as the frequency of Vt.
- Amplitude is controlled by the peak of Va.
- Fundamental frequency is controlled by the Va.

Modulation index(m):

$$m = \frac{Vc}{Vt} = \frac{\text{peak of Vao}}{\text{peak of Vt}}$$

Where, Vao is the fundamental frequency component of Vao for phase A.

3. Simulation results

Simulation results are given below for the DC to AC converter with the Sinusoidal Pulse Width Modulation technique.

Simulation parameters taken for analysis are:

Input DC voltage V_{dc} = 400 volts
Modulation Index = (0.1- 1)
Switching Frequency = 2 kHz

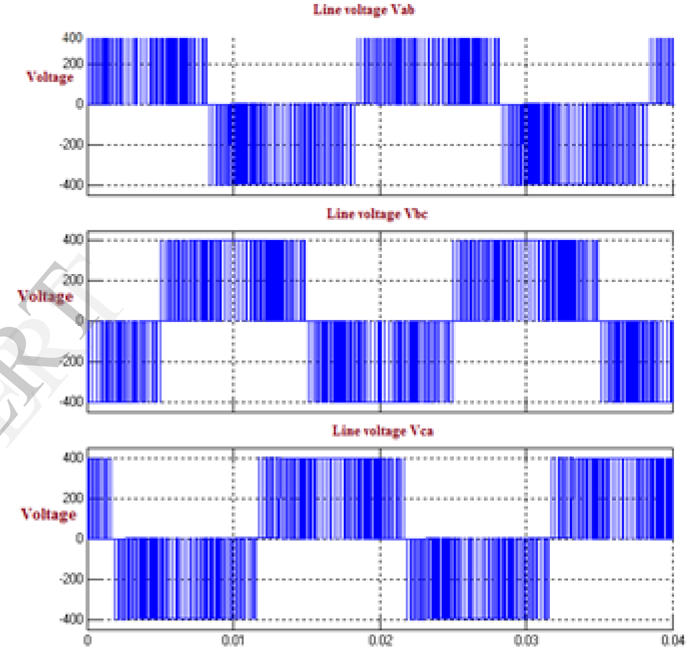


Figure 2. Output Line Voltages

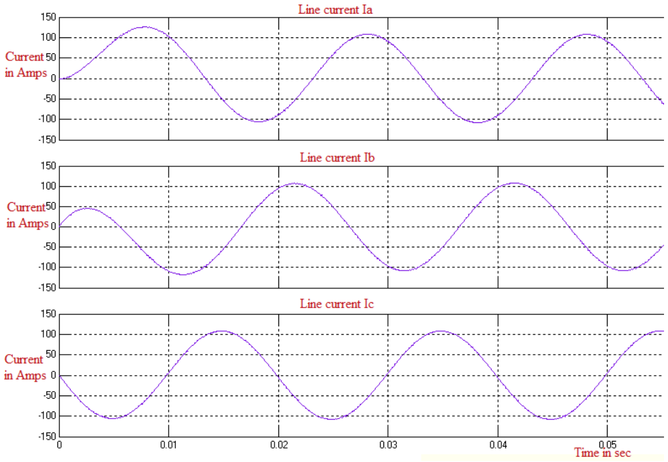


Figure 3: Output Line currents (Ia, Ib, Ic)

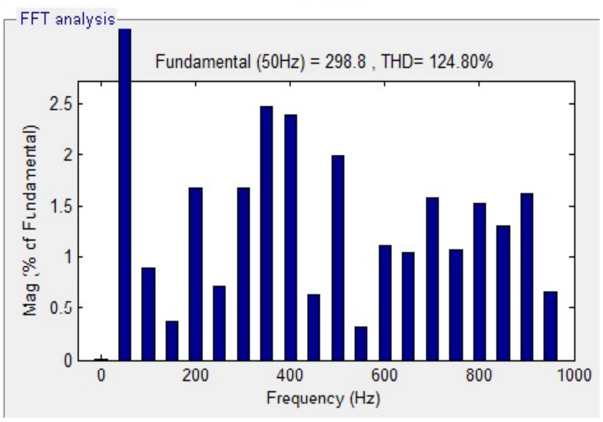


Figure 4: FFT analysis of output voltage (SPWM) for m=0.94

4. Space Vector Modulation

Space Vector Modulation (SVM) was originally developed as vector approach to Pulse Width Modulation (PWM) for three phase inverters. It is a more sophisticated technique for generating sine wave that provides a higher voltage to the motor with lower total harmonic distortion. The main aim of any modulation technique is to obtain variable output having a maximum fundamental component with minimum harmonics.

The structure of a typical three-phase VSI is shown in Figure 4. As shown below Va, Vb and Vc are the output voltages of the inverter. Q1 through Q6 are the six power transistors that shape the output, which are controlled by a, a', b, b', c and c'. When an upper transistor 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 on and off states of the upper transistors Q1,Q3 and Q5, or equivalently, the state of a, b and c, are sufficient to evaluate the output voltage for the purpose of this discussion. The six switching power devices can be constructed using power BJTs, GTOs, IGBTs etc. The choice of switching devices is based on the desired operating power level, required switching frequency, and acceptable inverter power losses. Two switches on the same leg cannot be closed or opened at the same time.

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. It has been shown to generate less harmonic distortion in the output voltages and/or currents applied to the phases of an AC motor and to provide more efficient use of dc input voltage. Because of its superior performance characteristics, it has been finding widespread application in recent years.

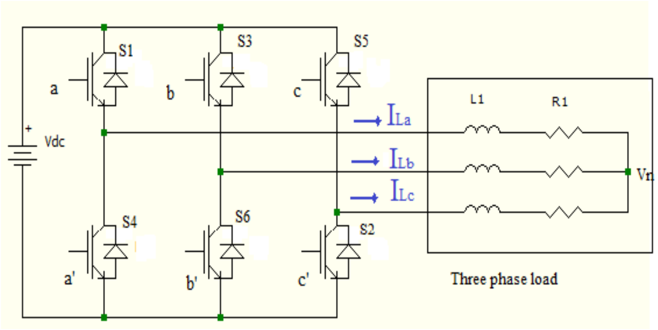


Figure 5: Three phase voltage source PWM inverter

4.1 Principle of space vector PWM

The basic principle of SVPWM is based on the eight switch combinations of a three phase inverter. The switch combinations can be represented as binary codes that correspond to the top switches Q1, Q3, and Q5 of the inverter as shown in Figure 1. 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,

$V_a = V_m Sin\omega t$ ………………… (1)
$V_b = V_m Sin(\omega t - 2\pi/3)$ ………………… (2)
$V_c = V_m Sin(\omega t - 4\pi/3)$ ………………… (3)

When this three-phase voltage is applied to the machine it produces a rotating flux and 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. To implement the space vector PWM, the voltage equations in the abc reference frame can be transformed into the dq reference frame that consists of the horizontal (d) and vertical (q) axes as depicted Figure 5.

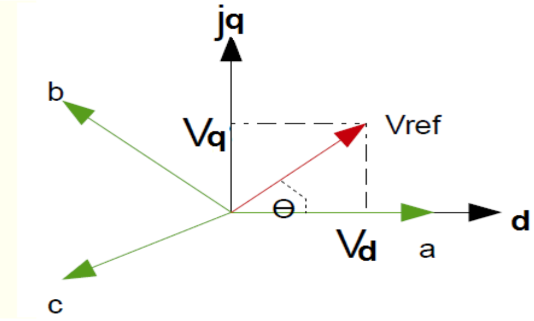


Figure 6: The reference vector in the two and three dimensional plane

The reference vector is represented in a dq-plane as in figure 5, a two dimensional plane transformed from a three dimensional plane containing the vectors of the three phases. The relation between these two reference frames is below

$$\begin{pmatrix} Vd \\ Vq \end{pmatrix} = 2/3 \begin{pmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{pmatrix} \begin{pmatrix} Va \\ Vb \\ Vc \end{pmatrix} \quad \text{……(4)}$$

The switches being ON or OFF, meaning 1 or 0 are determined by the location of the reference vector on this dq-plane. The switches 1, 3, 5 are the upper switches and if these are 1 (separately or together) it turns the upper inverter leg ON and the terminal voltage (Va, Vb, Vc) is positive (+VDC). If the upper switches are zero, then the terminal voltage is zero. The lower switches are complementary to the upper switches, so the only possible combinations are the switching states: 000, 001, 010, 011, 100, 110, 110, 111. This means that there are 8 possible switching states, for which two of them are zero switching states and six of them are active switching states. 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 (V_0 and V_7) 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 (V_0, V_1, V_2, V_3, V_4, V_5, V_6, V_7). 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 using the eight switching patterns.

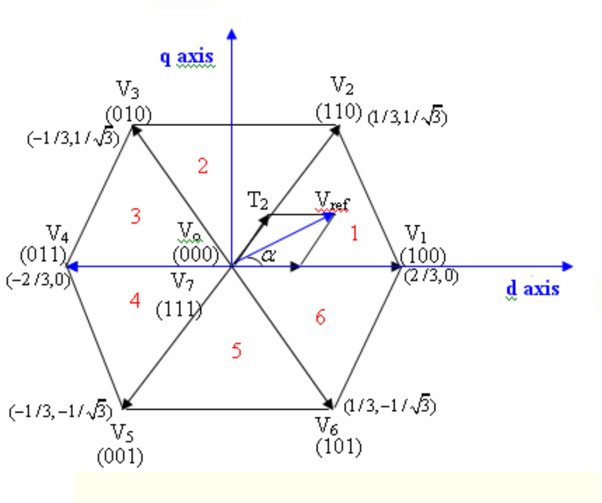


Figure 7: Basic switching, vectors and sectors.

The relationship between the switching variable vector $[a\ ,b,\ c]^t$ and the line-to-line output voltage vector $[V_{ab}\ V_{bc}\ V_{ca}]^t$ and the phase (line-to-neutral) output voltage vector $[V_a\ V_b\ V_c]^t$ is given by equation 1 and equation 2 below.

$$\text{(5)} \begin{pmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{pmatrix} = Vdc \begin{pmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{pmatrix} \begin{pmatrix} a \\ b \\ c \end{pmatrix} \quad \text{………}$$

$$\text{(6)} \begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} = \frac{1}{3} . V_{dc} \begin{pmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{pmatrix} \begin{pmatrix} a \\ b \\ c \end{pmatrix} \quad \text{………}$$

Where Vdc is the DC supply voltage, or bus voltage. The eight combinations and the derived output line-to-line and phase voltages in terms of DC supply voltage V_{dc}, according to equations 5 and 6 are shown in Table 1.

Table 1. Device on/off state and corresponding output of three phase VSI

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_0
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 voltages should be multiplied by V_{dc}

4.2 Space Vector Algorithm

Space vector PWM can be implemented by the following steps:

Step-1: Determine Vd, Vq, Vref and angle α.
Step-2: Determine the time duration T1, T2,T0.
Step-3: Determine the switching time of each transistor.

Step-1: Determine Vd, Vq, Vref and angle (α)
From Figure-4: Vd, Vq, Vref and angle (α) can be determined as follows:

$$V_d = V_{an} - V_{bn} * \cos 60^0 - V_{cn} * \cos 60^0$$

$$= Van - ½ * V_{bn} - ½ * V_{cn} \quad \ldots\ldots\ldots\ldots (3)$$

$$V_q = 0 + Vbn * \cos 30^0 - V_{cn} * \cos 30^0$$

$$= Van + \sqrt{3}/2 * V_{bn} - \sqrt{3}/2 \quad \ldots\ldots\ldots\ldots (4)$$

Therefore,

$$\begin{pmatrix} Vd \\ Vq \end{pmatrix} = 2/3 \begin{pmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{pmatrix} \ldots\ldots (5)$$

Therefore, $|Vref| = \sqrt{(Vd^2 + Vq^2)}$ …………… (6)

$$\alpha = \tan^{-1} \left(V_d / V_q\right) \quad \ldots\ldots\ldots\ldots (7)$$

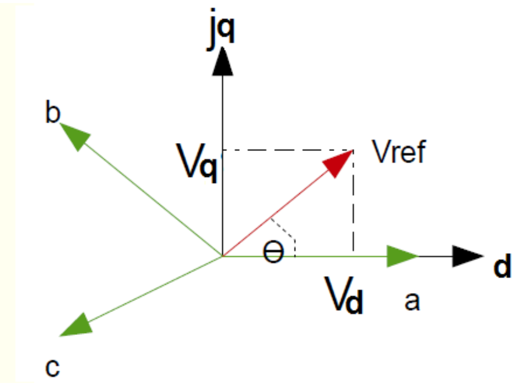


Figure 8. The reference vector in the two and three dimensional plane

Step-2: Determine the time duration T1, T2 and T0
From fig 5 the switching time duration can be calculated as follows

Switching time at sector-1

$$\int_0^{T_Z} V_{ref} = \int_0^{T_1} V_1 dt + \int_{T_1}^{T_{1+}T_2} V_2 dt + \int_{T_{1+}T_2}^{T_Z} V_0 \quad \ldots\ldots\ldots\ldots (8)$$

Therefore,

$$T_Z \, . \, V_{ref} = T_1 \, . \, V_1 + T_2 \, . \, V_2 \quad \ldots\ldots\ldots (9)$$

$$T_Z \, . \, |V_{ref}| . \begin{pmatrix} \cos\alpha \\ \sin\alpha \end{pmatrix} = T_1 \, . \, 2/3 . V_{dc} \, . \begin{bmatrix} 1 \\ \end{bmatrix} + T_2 \, . \, 2/3 \, . \begin{pmatrix} V_{dc} \, . \cos(\pi/3) \\ 0 \quad \sin(\pi/3) \end{pmatrix} \quad \ldots\ldots\ldots\ldots (10)$$

Therefore,

$$T_1 = \frac{T_Z \, . \, a \, . \, \sin(\pi/3 - \alpha)}{\sin(\pi/3)} \quad (\text{where } 0 \le \alpha \le 60^0) \ \ldots\ldots\ldots (11)$$

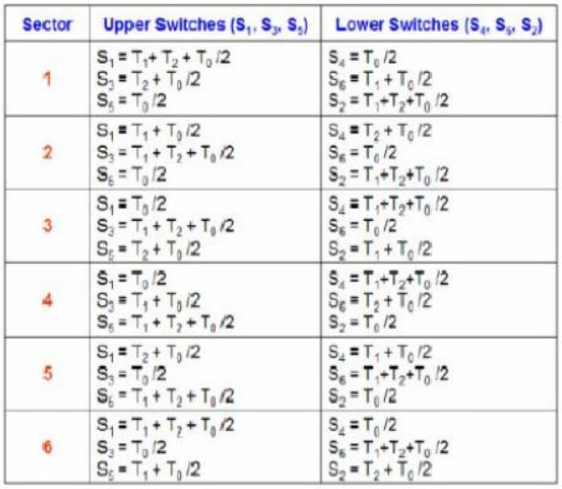
$$\therefore \quad T_2 = \frac{T_Z \, . \, a \, . \, \sin(\alpha)}{\sin(\pi/3)} \quad \ldots\ldots\ldots\ldots (12)$$

Therefore, $T_0 = T_Z - (T_1 + T_2)$ ………………..(13)

Where, $T_Z = \frac{1}{f_z}$ and $a = \frac{|V_{ref}|}{\frac{2}{3} . Vdc}$

Step-3: Determine the switching time of each transistor (S_1- S_6) is as illustrated in the table 2

Table2. Switching time calculation at each sector



Sector	Upper Switches (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	$S_1 = T_0/2$ $S_3 = T_1 + T_2 + T_0/2$ $S_5 = T_2 + T_0/2$	$S_4 = T_1 + T_2 + T_0/2$ $S_6 = T_0/2$ $S_2 = T_1 + T_0/2$
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	$S_1 = T_2 + T_0/2$ $S_3 = T_0/2$ $S_5 = T_1 + T_2 + T_0/2$	$S_4 = T_1 + T_0/2$ $S_6 = T_1 + T_2 + T_0/2$ $S_2 = T_0/2$
6	$S_1 = T_1 + T_2 + T_0/2$ $S_3 = T_0/2$ $S_5 = T_1 + T_0/2$	$S_4 = T_0/2$ $S_6 = T_1 + T_2 + T_0/2$ $S_2 = T_2 + T_0/2$

5. Simulation results

Simulation results are given below for the DC to AC converter with the Space Vector Pulse Width Modulation technique.

Simulation parameters taken for analysis are:
Input DC voltage Vdc = 400 volts
Modulation Index = (0.1- 1)
Switching Frequency = 2 kHZ
Load Resistance = 5 ohm
Load Inductance = 8 mH

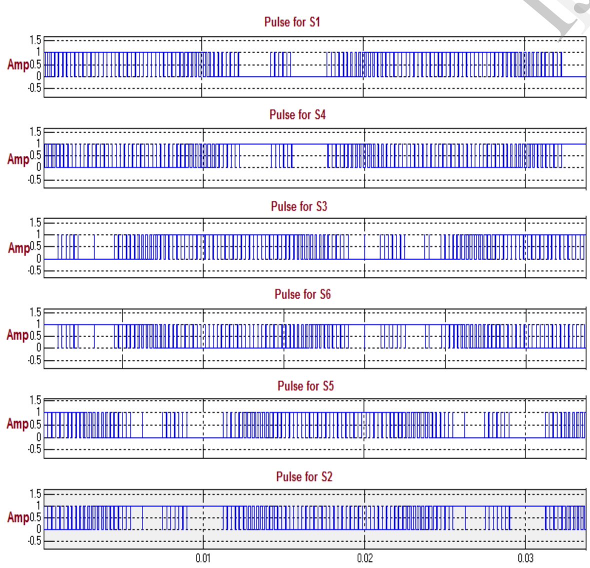


Figure 9: Pulses for Space Vector PWM

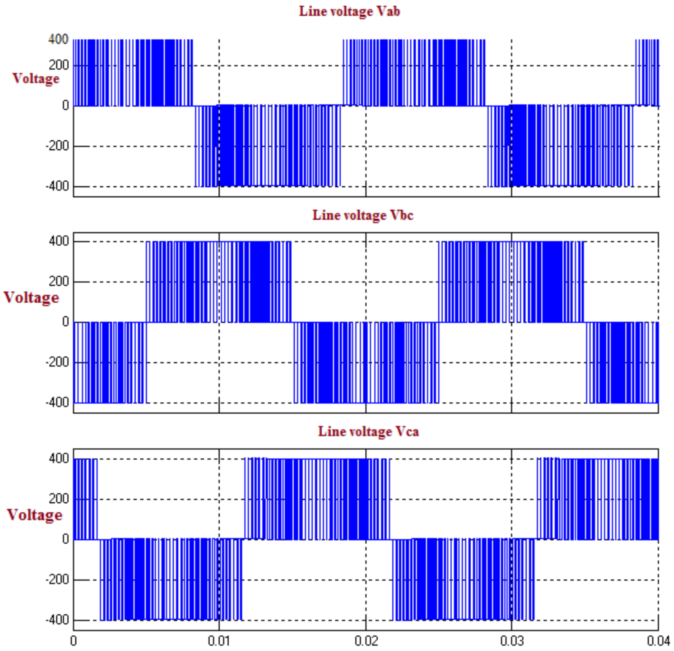


Figure 10: Output Line Voltages

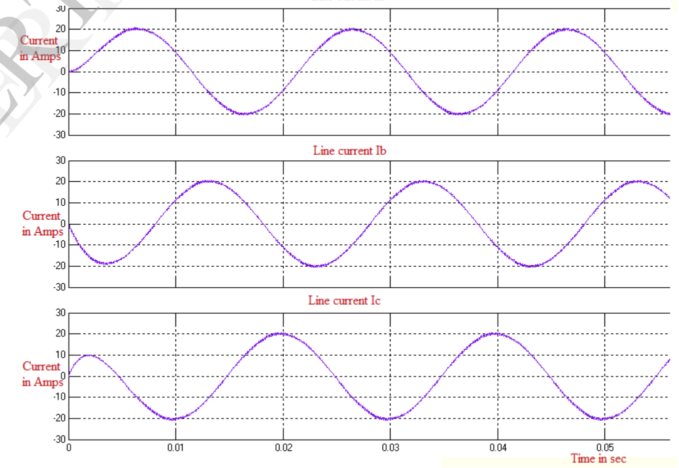


Figure 11: Output Line currents (Ia, Ib, Ic)

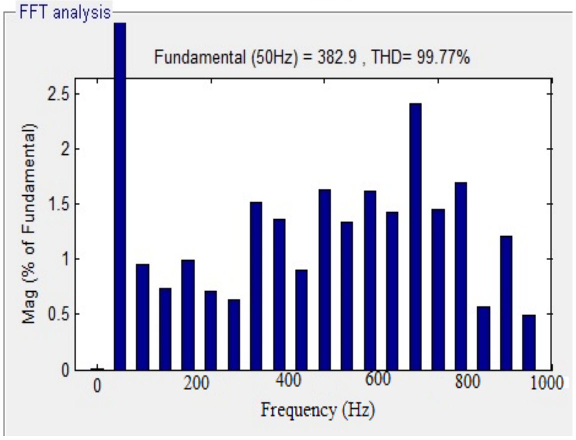


Figure 12: FFT analysis of output voltage(SVPWM) for m=0.94

6. Comparison of SPWM and SVPWM

In SPWM only 78% of square wave operation is obtained but in case SVPWM the amplitude of maximum possible voltage is 90%, the maximum phase voltage by sinusoidal PWM and space vector PWM are respectively,

$V_{max} = V_{dc}/2$: SPWM

$V_{max} = V_{dc}/\sqrt{3}$: SVPWM

Where V_{dc} is the dc link voltage.
This means the space vector PWM can produce about 15% higher output voltage than sinusoidal PWM.

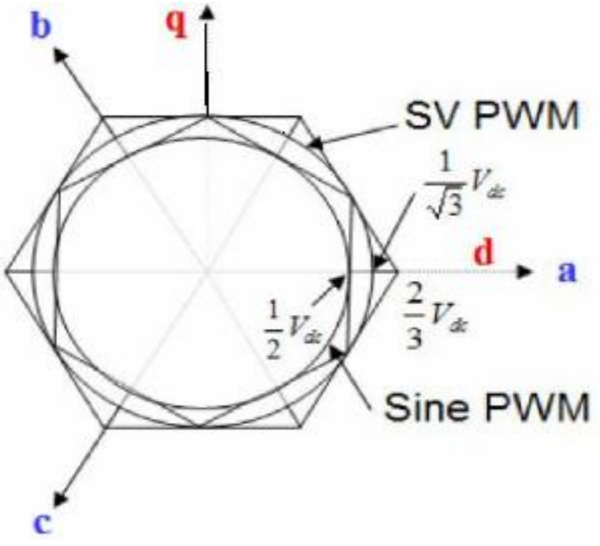


Figure 13: Locus comparison of maximum linear control voltage of SPWM and SVPWM.

SVPWM is an orthogonal projection on to the two dimensional (dq-plane), as a result six non-zero active vectors and two zero vectors are possible. The six non-zero vectors (V_1- V_6) shape the axes of hexagon as in figure 13 and feed electric power to the load. Flat shape in SVPWM is the phase to neutral voltage contains triple order harmonics generated by SVPWM and circular is the sinusoidal reference voltage. The triple order harmonics are not appeared in the phase to phase voltage, this leads to the higher modulation than SPWM.

7. Conclusion

This paper work provides successful attempt to analysis of space vector pulse width modulation (SVPWM) for the three phase voltage source inverter (VSI). A Matlab Simulink based model for the implementation of SVPWM is presented step by step. By varying the magnitude of the input reference different modulation index can be achieved. SVPWM utilizes DC bus voltage more efficiently. From the simulation results and fft analysis it is shown that SVPWM generates less harmonics and high output voltage for the modulation index given same for both SPWM and SVPWM techniques.

8. References

[1] H.w. Van der Broeck, H.C. Skudelny, and G.V. Stanke, “Analysis and realization of a pulsewidth modulator based on voltage space vectors,” IEEE Trans, Ind. Applicat., vol. 24, pp.142-150, Jan/Feb. 1988.

[2] Z. Yu, A. Mohammed, and I. Panahi, “A review of three PWM techniques,” in Proc. Amer. Control Conf., 1997, pp. 257-261.

[3] V. R. Stefanovic and S. N. Vukosavic, “Space vector PWM voltage control with optimized switching strategy,” in Proc. IEEE Industry Applications Soc, Annu. Meeting, 1992,pp.1025-1033.

[4]W. vander Broek, H. C. Skudelny, and G. V. Stanke, ―Analysis and realization of PWM based on voltage space vectors‖, IEEE Trans. Ind. Applicat., vol. 24, no. 1, pp. 142–150, 1988.

[5]Grahame Holmes and Thomas a. Lipo, ― pulse width modulation for power converters – principles and practices‖, IEE press Wiley publications 2000.

[6]Blasko, ―A hybrid PWM strategy combining modified space vector and triangle comparison methods‖, in IEEE PESC Conf. Rec., 1996, pp.1872–1878.