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VOLTAGE SOURCE INVERTER USING SPACE VECTOR MODULATION

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Abstract

Space Vector Modulation (SVM) Technique has become the most popular and important PWM technique for three phase Voltage Source Inverters for the control of AC Induction, Brushless DC, Switched Reluctance and Permanent Magnet Synchronous Motors. This paper proposes a new software implementation for Two Level Voltage Source Inverter using Space Vector Modulation technique. This software implementation is performed by Matlab. The switching pattern generation and sector identification for space vector modulation technique is generated using Matlab. The definite pattern for switching the voltage source inverter is provided using the software packages. The simulation study of space vector modulation technique of two level Voltage Source Inverter reveals that space vector modulation technique utilizes DC bus voltage more efficiently and generates less harmonic distortion when compared with SPWM technique. Simulation results are presented to demonstrate the validity of space vector modulation technique.

1. INTRODUCTION

Space Vector modulation (SVM) technique was originally developed as a 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. It confines space vectors to be applied according to the region where the output voltage vector is located.

A different approach to PWM modulation is based on the space vector representation of voltage in the α-β plane. The α-β components are found by transformations .The determination of switching instant may be achieved using space vector modulation technique based on the representation of switching vectors in α-β plane. The Space vector modulation technique is an advanced, computation intensive PWM technique and is possibly the best among all the PWM techniques for drives applications. Because of its superior performance characteristics, it is been finding wide spread application in recent years. The purpose of this paper is to present the space vector modulation technique and then to simplify the explanation of how it can be implemented using software packages.

2. FEATURES OF SPACE VECTOR PWM

The main aim of any modulation technique is to obtain variable output having a maximum fundamental component with minimum harmonics. During the past years many PWM techniques have been developed for letting the inverters to posses various desired output characteristics to achieve the following aim:

1. Wide linear modulation range
2. Less switching loss.
3. Lower total harmonic distortion.

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The space vector modulation (SVM) technique is more popular than conventional technique because of the following excellent features:

1. It achieves the wide linear modulation range associated with PWM third-harmonic injection automatically.
2. It has lower base band harmonics than regular PWM or other sine based modulation methods, or otherwise optimizes harmonics.
3. 15% more output voltage then conventional modulation, i.e. better DC-link utilization.
4. More efficient use of DC supply voltage.
5. SVM increases the output capability of SPWM without distorting line-line output voltage waveform.
6. Advanced and computation intensive PWM technique.
7. Higher efficiency.
8. Prevent un-necessary switching hence less Commutation losses.
9. A different approach to PWM modulation based on space vector representation of the voltages in the α-β plane.

2. SPACE VECTOR CONCEPT

The concept of space vector is derived from the rotating field of AC machine which is used for modulating the inverter output voltage. In this modulation technique the three phase quantities can be transformed to their equivalent 2-phase quantity either in synchronously rotating frame (or) stationary ωt frames. From this 2-phase component 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.
Let the three phase sinusoidal voltage component be,

$$V_a = V_m \sin \omega t$$
$$V_b = V_m \sin (\omega t - 2\Pi/3)$$
$$V_c = V_m \sin (\omega t - 4\Pi/3) \quad (1)$$

When this 3-phase voltage is applied to the AC machine it produces a rotating flux in the air gap of the AC machine. This rotating flux component can be represented as single rotating voltage vector. The magnitude and angle of the rotating vector can be found by mean of Clark's Transformation as explained below in the stationary reference frame. The representation of rotating vector in complex plane is shown in Figure 1.

Space Vector representation of the 3 phase quantity

$$\overline{V}^* = V_\alpha + jV_\beta = \frac{2}{3}(V_a + aV_b + a^2 V_c) \quad (2)$$

Where,

$$a = e^{j2\pi/3}$$

$$|\overline{V}| = \sqrt{V_\alpha^2 + V_\beta^2}, \alpha = \tan^{-1}\left(\frac{V_\beta}{V_\alpha}\right) \quad (3)$$

$$V_\alpha + jV_\beta = \frac{2}{3}\left(V_a + e^{j\frac{2\pi}{3}} V_b + e^{-j\frac{2\pi}{3}} V_c\right) \quad (4)$$

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$$V\alpha + jV\beta = \frac{2}{3}\left(V_a + \cos\frac{2\pi}{3}V_b + \cos\frac{2\pi}{3}V_c\right) + j\frac{2}{3}\left(\sin\frac{2\pi}{3}V_b - \sin\frac{2\pi}{3}V_c\right)$$

Equating real and imaginary parts:

$$V_\alpha = \frac{2}{3}\left(Va + \cos\frac{2\pi}{3}V_b + \cos\frac{2\pi}{3}V_c\right) \quad (5)$$

$$V\beta = \frac{2}{3}\left(0Va + \sin\frac{2\pi}{3}V_b - \sin\frac{2\pi}{3}V_c\right) \quad (6)$$

$$\begin{bmatrix} V\alpha \\ V\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & \cos\frac{2\pi}{3} & \cos\frac{2\pi}{3} \\ 0 & \sin\frac{2\pi}{3} & -\sin\frac{2\pi}{3} \end{bmatrix} \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} V\alpha \\ V\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (8)$$

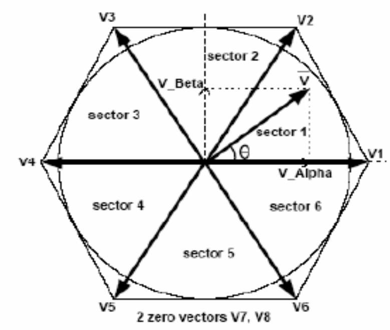

Figure 1.Representation of Rotating Vector in Complex Plane

4. PRINCIPLE OF SPACE VECTOR PWM

1. Treats the sinusoidal voltage as a constant Amplitude vector rotating at constant frequency.
2. This PWM technique approximates the reference voltage Vref by a combination of the eight switching patterns (V0 to V7).
3.Coordinate Transformation (abc reference frame to the stationary d-q frame): A three-phase voltage vector is transformed into a vector in the stationary d-q coordinate frame which represents the spatial vector sum of the three-phase voltage.

5. REALIZATION OF SPACE VECTOR PWM

The space vector PWM is realized based on the
Following steps:
Step1. Determine Vd, Vq, Vref, and angle (α).
Step2. Determine time duration T1, T2, T0.
Step3.Determine the switching time of each transistor (S1 to S6).

A. DETERMINE VD, VQ, VREF, AND ANGLE (α):

Coordinate transformation: abc to dq
The Voltage Space vector and its components in dq plane is shown in Figure 2.1

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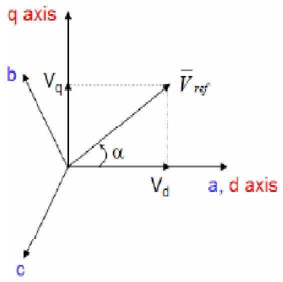

Figure 2.1.Voltage Space Vector and its components in (d, q)

$$V_d = V_{an} - V_{bn} \cdot \cos 60 - V_{cn} \cdot \cos 60$$
$$= V_{an} - \frac{1}{2} V_{bn} - \frac{1}{2} V_{cn}$$

$$V_q = 0 + V_{bn} \cdot \cos 30 - V_{cn} \cdot \cos 30$$
$$= V_{an} + \frac{\sqrt{3}}{2} V_{bn} - \frac{\sqrt{3}}{2} V_{cn} \qquad (9)$$

$$\therefore \begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \qquad (10)$$

$$\left| \bar{V}_{ref} \right| = \sqrt{V_d{}^2 + V_q{}^2}$$
$$\alpha = \tan^{-1}\left(\frac{V_q}{V_d}\right) = \omega_s t = 2\pi f_s t$$
$$(\text{where}, f_s = \text{fundamental frequency})$$

The voltage Vd, Vq, Vref, and angle (α) are calculated using the above equation.

B. DETERMINE TIME DURATION T1, T2, T0:

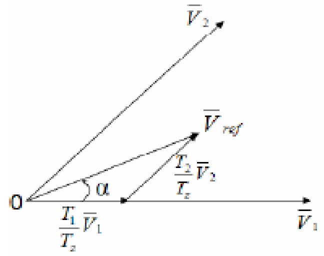

Figure 2.2. Reference vector as a combination of adjacent vectors at sector 1

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$$\int_0^{T_z} \overline{V}_{ref} = \int_0^{T_1} \overline{V}_1 dt + \int_{T_1}^{T_1+T_2} \overline{V}_2 dt + \int_{T_1+T_2}^{T_z} \overline{V}_0$$

$$\therefore T_z \cdot \overline{V}_{ref} = (T_1 \cdot \overline{V}_1 + T_2 \cdot \overline{V}_2)$$

$$\Rightarrow T_z \cdot \left|\overline{V}_{ref}\right| \cdot \begin{bmatrix} \cos(\alpha) \\ \sin(\alpha) \end{bmatrix} = T_1 \cdot \frac{2}{3} \cdot V_{dc} \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} + T_2 \cdot \frac{2}{3} \cdot V_{dc} \cdot \begin{bmatrix} \cos(\pi/3) \\ \sin(\pi/3) \end{bmatrix}$$

$$(\text{where, } 0 \le \alpha \le 60^\circ)$$

$$\therefore T_1 = T_z \cdot a \cdot \frac{\sin(\pi/3 - \alpha)}{\sin(\pi/3)}$$

$$\therefore T_2 = T_z \cdot a \cdot \frac{\sin(\alpha)}{\sin(\pi/3)}$$

$$\therefore T_0 = T_z - (T_1 + T_2), \quad \left(\text{where, } T_z = \frac{1}{f_s} \text{ and } a = \frac{\left|\overline{V}_{ref}\right|}{\frac{2}{3}V_{dc}}\right)$$

WhereT1,T2,T0 represent the time widths for vectors V1,V2,V0.T0 is the period in a sampling period for null vectors should be filled. As each switching period (half of sampling period) Tz starts and ends with zero vectors i.e. there will be two zero vectors per Tz or four null vectors per Ts, duration of each null vector is to/4. Figure 2.3 gives switching pattern for all sectors.

SWITCHING TIME DURATION AT ANY SECTOR:

$$\therefore T_1 = \frac{\sqrt{3} \cdot T_z \cdot \left|\overline{V}_{ref}\right|}{V_{dc}} \left(\sin\left(\frac{\pi}{3} - \alpha + \frac{n-1}{3}\pi \right) \right)$$

$$= \frac{\sqrt{3} \cdot T_z \cdot \left|\overline{V}_{ref}\right|}{V_{dc}} \left(\sin \frac{n}{3}\pi - \alpha \right)$$

$$= \frac{\sqrt{3} \cdot T_z \cdot \left|\overline{V}_{ref}\right|}{V_{dc}} \left(\sin \frac{n}{3}\pi \cos\alpha - \cos \frac{n}{3}\pi \sin\alpha \right)$$

$$\therefore T_2 = \frac{\sqrt{3} \cdot T_z \cdot \left|\overline{V}_{ref}\right|}{V_{dc}} \left(\sin\left(\alpha - \frac{n-1}{3}\pi \right) \right)$$

$$= \frac{\sqrt{3} \cdot T_z \left|\overline{V}_{ref}\right|}{V_{dc}} \left(-\cos\alpha \cdot \sin \frac{n-1}{3}\pi + \sin\alpha \cdot \cos \frac{n-1}{3}\pi \right)$$

$$\therefore T_0 = T_z - T_1 - T_2, \quad \left(\begin{matrix} \text{where, } n = 1 \text{ through } 6 \text{ (that is, Sector1 to 6)} \\ 0 \le \alpha \le 60^\circ \end{matrix} \right)$$

C.DETERMINE THE SWITCHING TIME FOR EACH THYRISTOR (S1 TO S6):

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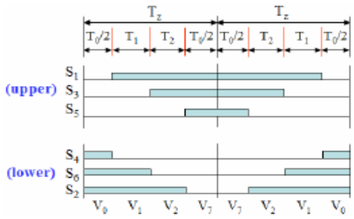
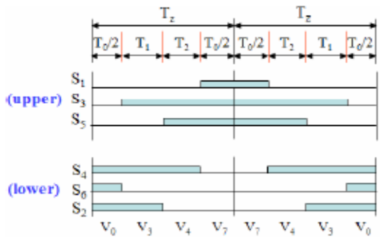
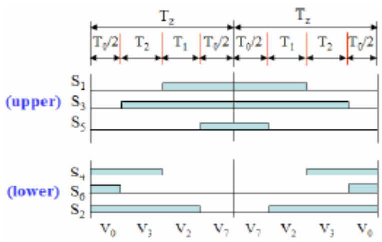
(a) Sector 1



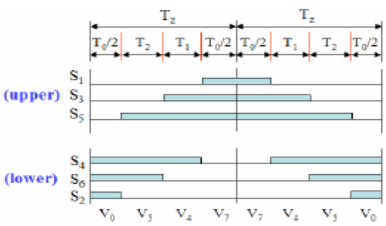
(b) Sector 2



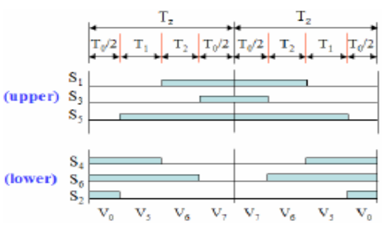
(c) Sector 3



(d) Sector 4



(e) Sector 5



(f) Sector 6

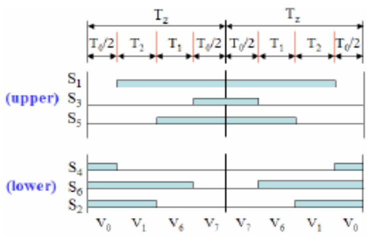


Figure 2.3. Switching pulse pattern for the three phase in the 6 different sectors

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D. SWITCHING TIME TABLE AT EACH SECTOR :

Table 1. Switching sequence table

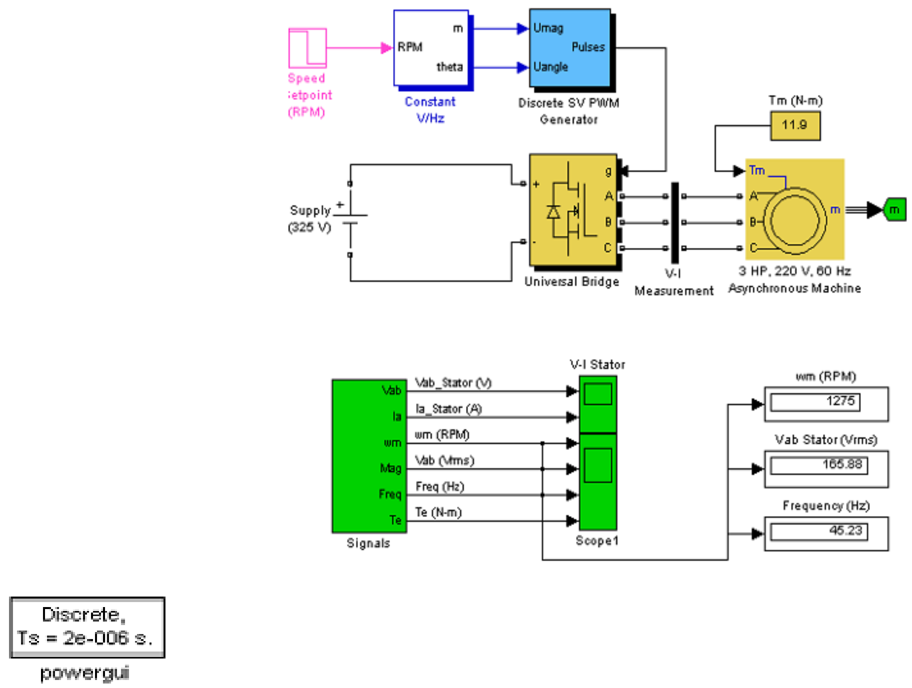
Sector	Upper Switches (S_1, S_3, S_5)	Lower Switches (S_4, S_6, S_2)
1	$S_1 = T_1 + T_2 + T_0/2$ $S_3 = T_2 + T_0/2$ $S_5 = T_0/2$	$S_4 = T_0/2$ $S_6 = T_1 + T_0/2$ $S_2 = T_1 + T_2 + T_0/2$
2	$S_1 = T_1 + T_0/2$ $S_3 = T_1 + T_2 + T_0/2$ $S_5 = T_0/2$	$S_4 = T_2 + T_0/2$ $S_6 = T_0/2$ $S_2 = T_1 + T_2 + T_0/2$
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	$S_1 = T_1 + T_2 + T_0/2$ $S_3 = T_0/2$ $S_5 = T_1 + T_0/2$	$S_4 = T_0/2$ $S_6 = T_1 + T_2 + T_0/2$ $S_2 = T_2 + T_0/2$

The Switching pulse pattern for the three phase in the 6 different sectors are shown in the Figure 2.3.The Switching sequence table for the lower and upper thyristors are shown in the table 1.
The above construction of the symmetrical pulse pattern for two consecutive Tz intervals are shown and Ts = 2Tz =1 / fs (fs = Switching frequency) is the sampling time. Note that the null time has been conveniently distributed between the V0 and V7 vectors to describe the symmetrical pulse width. Studies have shown that a symmetrical pulse pattern gives minimal output harmonics.The over modulation region where the reference voltage vector V exceeds the hexagon boundary is not discussed in this paper.

6. SOFTWARE PACKAGE

The Matlab/Simulink is used to implement and simulate power circuits in their original circuit form, thus greatly shortening the time to set up and simulate a system which includes electric circuits and motor drives. The power circuit is simulated and controlled in Matlab/Simulink.

7. CIRCUIT DIAGRAM



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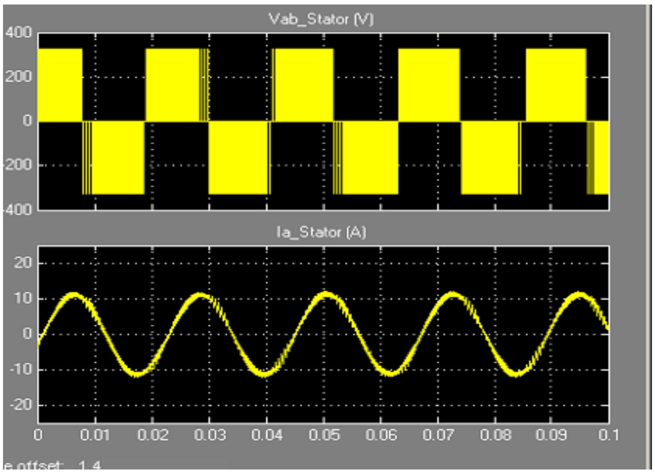
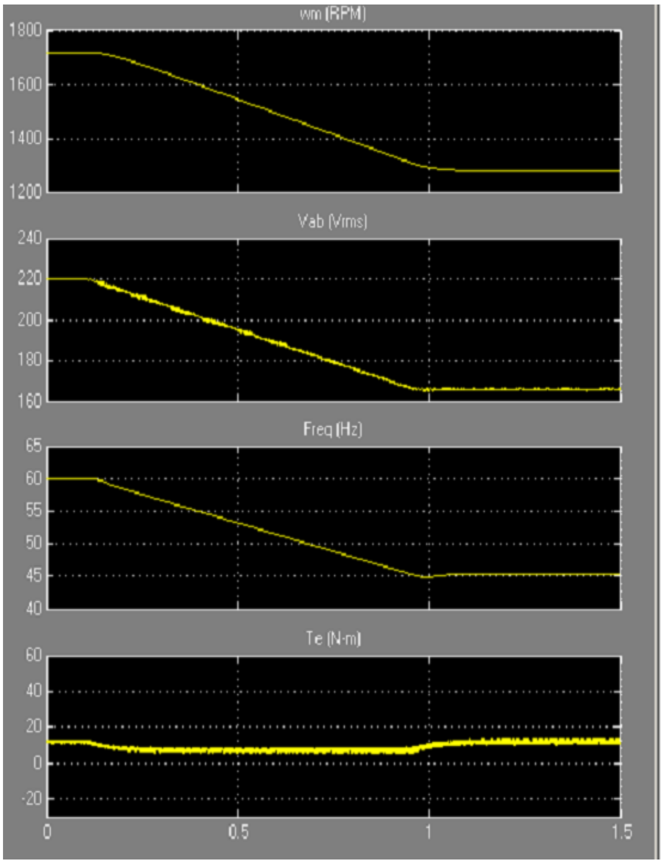
8. SIMULATION RESULTS





9. CONCLUSIONS

Using Matlab simulation, the simulation study of Two Level Inverter using space vector modulation technique is carried out in this paper. This paper gives out a new way of implementing the SVM technique using the software packages. From this paper, the space vector modulation technique concludes to the following:

1. Space Vector PWM can be used to generate an averaged-sinusoidal voltage.
2. SVM technique utilizes DC bus voltage more efficiently and generates less harmonic distortion in a three phase voltage source inverter.
3. The phase-to-center voltage of the Space Vector PWM is not sinusoidal.

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4. Compared with sinusoidal PWM, space vector PWM can work with a higher modulation index (m>1) and the harmonic content of the inverter voltage is less in the space vector PWM than in sinusoidal PWM.
5. The SVPWM technique can be further applied to three level, four leg and multilevel inverters. This software implementation used in this paper can be extended further to over modulation region i.e. modulation index m>1which will be a future enhancement.

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