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Simulation of Space Vector Modulation in PSIM

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***Abstract* — Space Vector modulation technique was originally developed as vector approach to PWM for Three Phase inverter. Space vector modulation has become one of the most popular and important technique for three phase VSI, Brushless DC motor, switched reluctance motor and permanent magnet motor. 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. In this paper various advantages of Space vector are verified and also a comparison between SVPWM and Sine PWM for three phase 2 level VSI is discussed.**

Index Terms **— Pulse width modulation, Direct current, and space vector PWM and Total harmonic distortion.**

I. Introduction

SVPWM modulates the command voltage vector as a whole using three phase to two phase transformation. Basically, this algorithm aims to have the average of the output voltage vector equal to the command reference vector [1] .SVPWM is one of the most popular PWM technique for DC to AC conversion for the following reasons:

- Wide linear range of operation.
- Better DC link utilization.
- 15%more output voltage than conventional modulations.
- Less harmonics content.

SVPWM requires very complex on-line computation, which usually limits its operation up to several kHz of switching frequency. The difficulty increases when operation in undermodulation and overmodulation regions is required. In this case, different algorithms are required for each region [1].In this paper method used in [1] to simplify the operation by extending the operation from undermodultion to overmoduation has been used.

A Three phase two level VSI with a balanced load has been shown in Fig. 1.Fig. 2 shows various PWM technique often used for 2 level three phase. In Section II operation of SVPWM (Space Vector PWM), Section III operation of Sine PWM, Section IV Simulation and results and in Section V Comparison between Sine and SVPWM has been done.

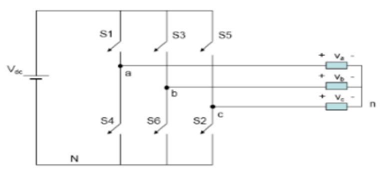

Fig. 1 A 3-phase Voltage Source Inverter (VSI)

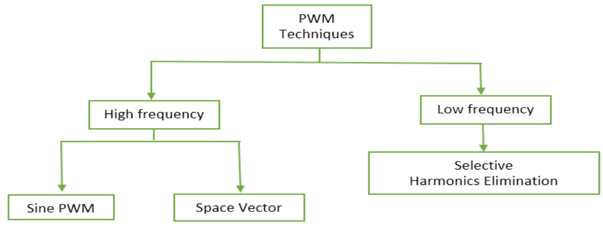

Fig. 2 Various PWM Techniques for 2 level Three phase VSI

II. Space Vector PWM(SVPWM)

The output of two level inverter depends upon the switching state of switches S1-S6 of inverter shown in Fig. 1.The notation used for representing switching state is [Sw_a,Sw_b,Sw_c],Ex. [100] from upper half switch S1 is ON and from lower half S6 and S2 is ON. Considering all the switching states, the total switching states are: 2^3 =8.These switching states or vectors can be classified into 6 unit vector of magnitude 2/3 V_{dc} and 2 zero vectors .These vectors are represented as V_0 [000]-V_7 [111].Fig. 3 shows all eight vectors in dq frame. This results into splitting of dq frame into 6 equal sector and the hexagon form the boundary of the Space Vector modulation.

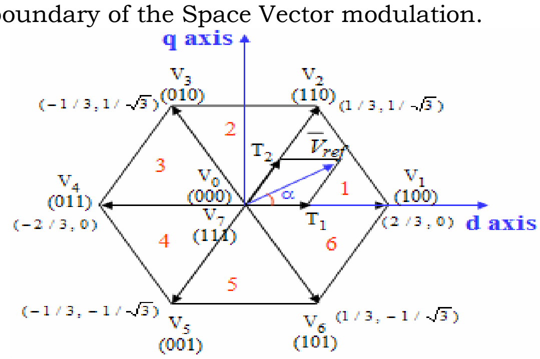

Fig. 3 Space Vector modulation

The modulation index m can be given as:

$$m = \frac{\bar{V}_{ref}}{V_{1sw}} \quad (1)$$

Where $\bar{V}_{ref}$ is the magnitude of command or reference voltage vector and V_{1sw} is the peak value (

$2V_{dc}/\pi$) of square (or six step) voltage wave. The modulation factor can vary between 0–1, depending upon the modulation index the operation of SVPWM can be classified into three regions;

- undermodulation (0<m<0.907),
- overmodulation mode 1(0.907<m<0.952)
- overmodulation mode 2 (0.952<m<1).

A. *Undermodulation (0<m<0.907)*

In the undermodulation or linear region, shown in Fig. 4,$\bar{V}_{ref}$ the rotating reference voltage remains within the hexagon. The objective of space vector PWM technique is to approximate the reference voltage vector $\bar{V}_{ref}$ 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 $\bar{V}_{ref}$ in the same period [2]. In one sampling interval, the output voltage vector reference $\bar{V}_{ref}$ can be given as:

$$\bar{V}_{ref} = \frac{t_0}{t_s}\overline{V_0} + \frac{t_1}{t_s}\overline{V_1} + \frac{t_2}{t_s}\overline{V_2} + \ldots\ldots\ldots \frac{t_7}{t_s}\overline{V_7} \qquad (2)$$

Where t_0-t_7 is turn on time for each vector.

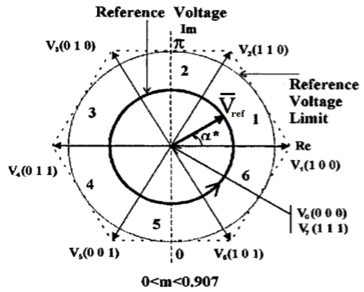

Fig. 4 Undermodulation

Hence $\bar{V}_{ref}$ can be defined in infinite number of ways depending upon the various switching time (t_0-t_7) of the vectors. However, in order to reduce the number of switching actions and make full use of active turn-on time for space vectors, the vector $\bar{V}_{ref}$ is commonly split into the two nearest adjacent voltage vectors and zero vectors and in an arbitrary sector. Consider $\bar{V}_{ref}$ lies between V_1 [100] and V_2 [110], hence the switching will occur between V_1 and V_2 depending on magnitude of $\bar{V}_{ref}$ and remaining switching time is split between V_0 and V_7. Hence $\bar{V}_{ref}$ now can be given as [3]:

$$\bar{V}_{ref} = \frac{t_0}{t_s}\overline{V_0} + \frac{t_1}{t_s}\overline{V_1} + \frac{t_2}{t_s}\overline{V_2} + \frac{t_7}{t_s}\overline{V_7} \qquad (3)$$

1) *Sector Identification*

In [1] has used sector identification logic with minimum computation. The sector identification is implemented using three bit variables as follows:

$$\begin{aligned} &A=\mathrm{Sign}(V_q)\\ &B=\mathrm{Sign}(-\sqrt{3}Vd-Vq)\\ &C=\mathrm{Sign}(\sqrt{3}Vd-Vq) \end{aligned} \qquad (4)$$

Hence the sector can be given by:

Sector = (A XOR C) +2*(A XOR B)

Fig. 5, shows the Sector identification calculations.

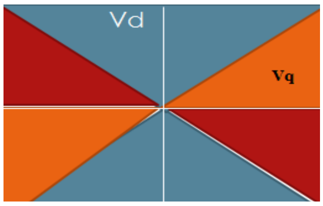

Fig. 5 Sector Identification

2) *Time Dwell Calculations*

The effective times for switching for sector 1 can be given as [3]:

$$\begin{aligned} T_1 &= T_s.a.\left(\sin\left(\frac{\pi}{3}-\alpha\right)/\sin\left(\frac{\pi}{3}\right)\right)\\ T_2 &= T_s.a.\left(\sin(\alpha)/\sin\left(\frac{\pi}{3}\right)\right) \\ T_0 &= T_s-(T_1+T_2) \end{aligned} \qquad (5)$$

Where a= $|\bar{V}_{ref}|/(2/3\,Vdc)$

Switching time duration at any Sector [3]:

$$\begin{aligned} T_1 &= \frac{\sqrt{3}T_s|V^*|}{V_{dc}}\left(\sin\frac{n}{3}\pi.\cos\alpha - \cos\frac{n}{3}\pi.\sin\alpha\right)\\ T_2 &= \frac{\sqrt{3}T_s|V^*|}{V_{dc}}\left(-\cos\alpha.\sin\frac{n-1}{3}\pi + \sin\alpha.\cos\frac{n-1}{3}\pi\right)\\ T_0 &= T_s-(T_1+T_2) \end{aligned} \qquad (6)$$

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

$$0 \le \alpha \le 60$$

The simplification of the SVPWM algorithm is given by using the dq components. The strategy can simplify the calculation of the sin(α) and sin(π /3- α) terms, avoiding the use of look-up table. The calculation of the turn-on switching times of the phases becomes simpler, and are given by the following equation [1]:

$$T_{A-on} = \begin{cases} \frac{T_s}{4}\left(1+\frac{3}{2V_{DC}}\left[-V_d-\frac{V_q}{\sqrt{3}}\right]\right) & S=1,4\\ \frac{T_s}{4}\left(1+\frac{3}{2V_{DC}}[-2V_d]\right) & S=2,5\\ \frac{T_s}{4}\left(1+\frac{3}{2V_{DC}}\left[-V_d-\sqrt{3}V_q\right]\right) & S=3,6 \end{cases}$$

$$T_{B-on} = \begin{cases} \frac{T_s}{4}\left(1+\frac{3}{2V_{DC}}\left[V_d-\sqrt{3}V_q\right]\right) & S=1,4\\ \frac{T_s}{4}\left(1+\frac{3}{2V_{DC}}\left[-\frac{2V_q}{\sqrt{3}}\right]\right) & S=2,5\\ \frac{T_s}{4}\left(1+\frac{3}{2V_{DC}}\left[V_d-\frac{V_q}{\sqrt{3}}\right]\right) & S=3,6 \end{cases} \qquad (7)$$

$$T_{C-on} = \begin{cases} \frac{T_s}{4}\left(1+\frac{3}{2V_{DC}}\left[V_d+\frac{V_q}{\sqrt{3}}\right]\right) & S=1,4\\ \frac{T_s}{4}\left(1+\frac{3}{2V_{DC}}\left[\frac{2V_q}{\sqrt{3}}\right]\right) & S=2,5\\ \frac{T_s}{4}\left(1+\frac{3}{2V_{DC}}\left[V_d+\sqrt{3}V_q\right]\right) & S=3,6 \end{cases} [1]$$

B. *Overmodulation mode 1(0.907<m<0.952)*

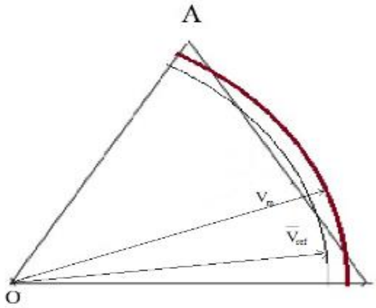

Fig. 6 Overmodulation mode 1(0.907<m0.952)

In overmodulation the reference vector $\bar{V}_{ref}$ exceeds the hexagon boundary. The reference vector $\bar{V}_{ref}$ cuts the hexagon at two different points in each sector as shown in Fig. 6. The operation of Space Vector is classified into circular region and a linear region along line AB as shown in Fig. 6. In the circular region the operation remain same as the undermodulation region. On the hexagon trajectory, time t_0 vanishes, giving t_1 and t_2 expressions as [4]:

$$t_1 = \frac{T_s}{2}\left(\frac{\sqrt{3}\cos\alpha - \sin\alpha}{\sqrt{3}\cos\alpha + \sin\alpha}\right)$$
$$t_2 = \frac{Ts}{2} - t_1 \tag{8}$$

To compensate for the loss a new reference vector Vm (Vm>$\bar{V}_{ref}$) is used. Pre calculation using computer program can be used to find the compensation required due to loss occurring in linear region. For the new extended reference V_m crossover angle as a function of modulation factor is plotted in Fig. 7[5] [1].

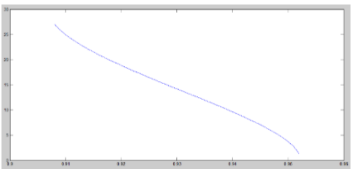

Fig. 7 Crossover angle (°) v/s modulation index

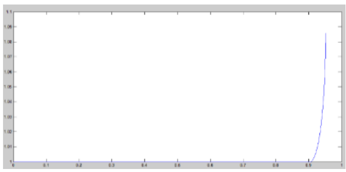

Fig. 8 fc v/s modulation index

For simplification, it can be shown that the undermodulation curve can be expanded to Mode-1 by using a nonlinear scale factor fc. In order to get linear transfer characteristics in the whole range. The nonlinear scale factor can be given as [1]:

$$f_c = \frac{V_m}{\bar{V}_{ref}} \tag{9}$$

Where V_m is new extended reference in case of overmodulation mode 1, $\bar{V}_{ref}$ is reference voltage. Fig. 8 shows the plot of fc v/s modulation index.

C. *Overmodulation mode 2(0.952<m<1)*

In overmodulation Mode-2, the reference vector V* increases further. Therefore, the actual trajectory is modified so that the output fundamental voltage matches that of the reference voltage. The operation in this region, as explained in Fig. 9. is characterized by partly holding the modified vector at the hexagon corner for holding angle α_h, and partly tracking the hexagon sides in every sector. During holding angle, the magnitude of V_{an} remains constant, whereas during hexagon tracking, the voltage changes almost linearly, as shown in the lower part of Fig. 9. At the end of Mode-2, the linear segments vanish, giving six-step or square-wave operation when the modified vector is held at hexagon corners for 60 i.e. α_h=30[1] [4] [5].

In [8] the equation for relationship between holding angle and modulation index is derived and is given by:

$$m = \frac{\sin(\pi/6 - \alpha_h)}{\pi/6 - \alpha_h} \tag{10}$$

Fig. 10 shows the graph of holding angle v/s modulation index .In [9] a comparative study for overmoduation of different SVPWM has been investigated. As explained above in overmodulation mode 2 both the voltage reference as well as the phase reference changes. The Eq (11) are equations for the modified phase angle α^* and modified reference Volatge V_m .

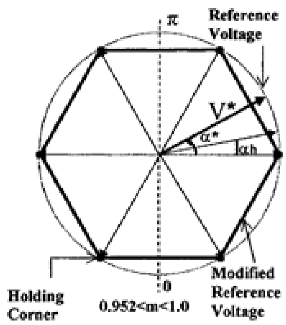

Fig. 9 Operation of SVPWM in overmodulation mode 2

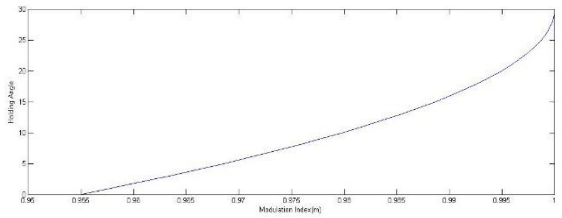

Fig. 10 Holding angle (°) v/s modulation index

$$\begin{aligned} \alpha^* &= 0 && \text{if } 0<\alpha<\alpha_H \\ &= 30 * \frac{\alpha-\alpha_H}{30-\alpha_H} && \text{if } \alpha_H \le \alpha \le 60-\alpha_H \\ &=60 && \text{else} \end{aligned} \tag{11}$$
$$V_m = \frac{0.866}{\cos(30-\alpha_H)}$$

III. SINE PWM(SPWM)

In Sine PWM, three legs of the inverter are switched using individual Sinusoidal reference signal, each reference signal is 120° apart from one another .The advantage of Sine PWM over Space Vector PWM is simplicity of operation. As depicted in Fig. 11, the inverter output voltage is determined in the following [6]:

- When $V_{control} > V_{tri}$, $V_{A0} = V_{DC}/2$
- When $V_{control} < V_{tri}$, $V_{A0} = -V_{DC}/2$

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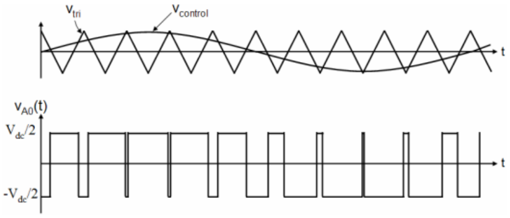

Fig. 11 Operation of SPWM

IV. Simulation and Results

The Software implementation of conventional Space Vector Modulation for a Three phase VSI was implemented in PSIM. The steps involved in the simulation are as follows:

•Three phase to Two phase conversion.

•Sector identification

•Calculation of Ta, Tb and Tc using Eq. no (7)

•Comparing the ref signal Ta, Tb and Tc with the carrier wave, gate pulses for the Three phase inverter is obtained.

The switching frequency used in this case is 3 kHz and Load consists of and RL(R=0.23Ω and L=30.7mH).For sector identification and time dwell calculation C Block form PSIM has been used. The PSIM model for operation (0<m<1.0) is shown in Fig. 12.A look up table is used to store values on non-linear factor fc, for undermodulation fc=1.Fig. 13-Fig. 17 shows the output waveform for modulation index m=0.5, m=0.907 and m=0.94, m=0.98, m=1.

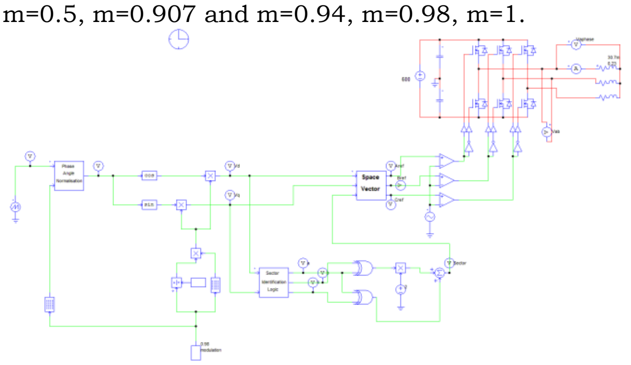

Fig. 12 PSIM model for SVPWM

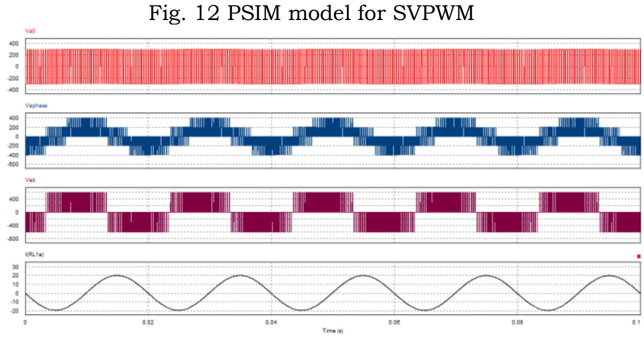

Fig. 13 Output waveforms SVPWM m=0.5

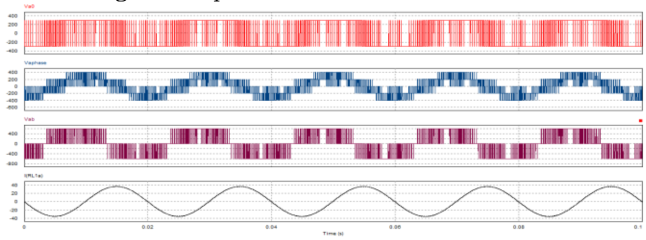

Fig. 14 Output waveforms SVPWM m=0.907

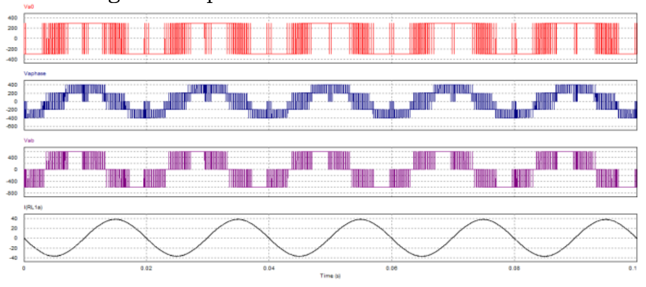

Fig. 15 Output Waveforms SVPWM m=0.94 (overmodulation mode 1)

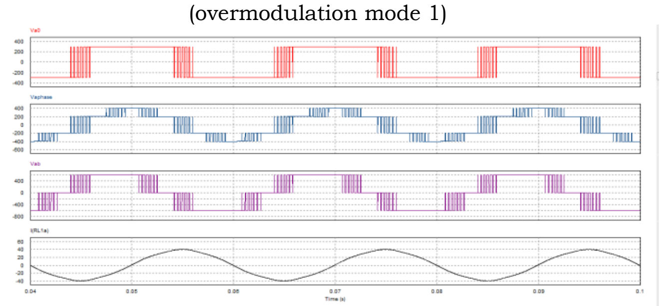

Fig. 16 Output waveforms SVPWM m=0.98 (overmodulation mode 2)

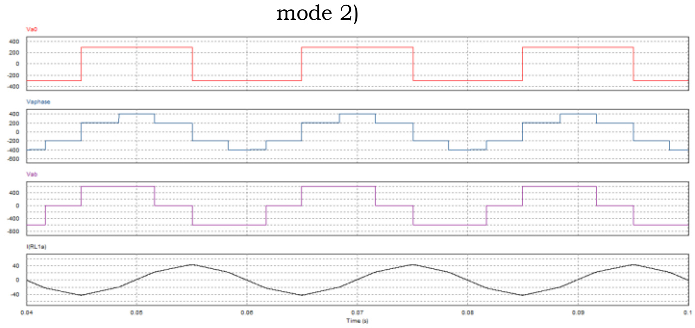

Fig. 17 Output waveform m=1.0

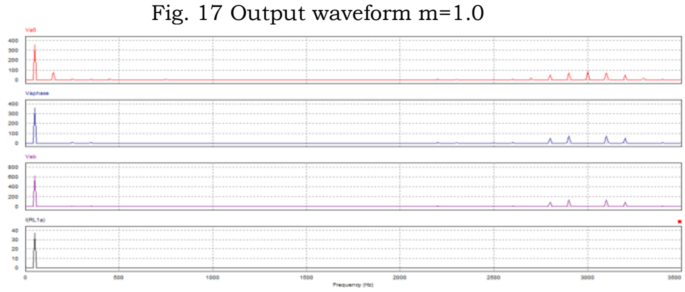

Fig. 18 FFT analysis of output waveforms (m=0.907)

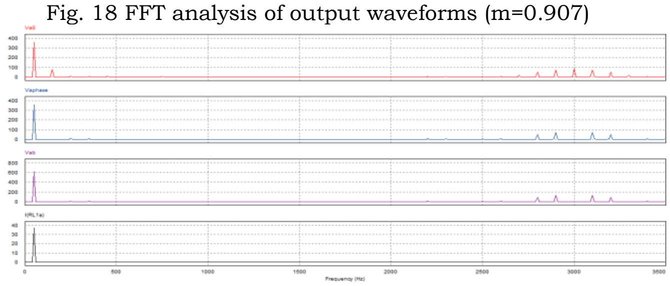

Fig. 19 FFT analysis of output waveforms (m=0.94) (Overmodulation mode 1)

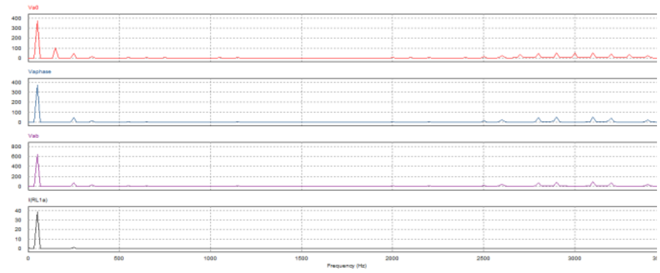

Fig. 20 FFT analysis of output waveforms (m=0.98) (overmodulation mode 2)

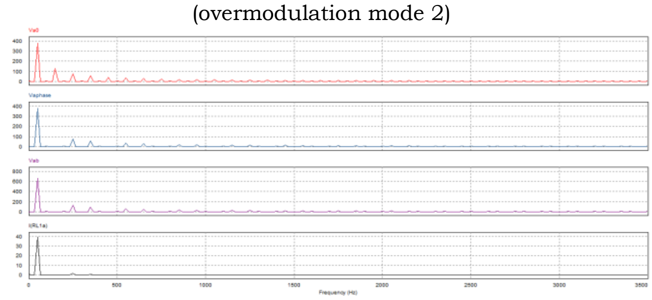

Fig. 21 FFT analysis of output waveforms (m=1)

V. Comparision Between SVPWM and SPWM

Table I shows the comparison between Sine PWM and SVPWM.As can be seen the RMS voltage by Space Vector PWM is higher than Sine PWM, also the harmonics content without any filter is lesser for Space Vector PWM then Sine PWM.

Table I Comparison of SVPWM and Sine PWM

(Voltage)THD	**Sine PWM**	**SVPWM**
	68.8%	52.5%
RMS	444 V	478 V

Conclusion

Using PSIM simulation software packages the simulation study of Two Level Inverter using space vector modulation technique is carried out in this paper. From this paper, the space vector modulation technique concludes to the following:

•Space Vector PWM can be used to generate an averaged-sinusoidal voltage.

•SVM technique utilizes DC bus voltage more efficiently and generates less harmonic distortion in a three phase voltage source inverter.

•The phase-to-center voltage of the Space Vector PWM is not sinusoidal.

•Compared with sinusoidal PWM, space vector PWM can work with a higher modulation index (m>0.907) and the harmonic content of the inverter voltage is less in the space vector PWM than in sinusoidal PWM.

•The SVPWM technique can be further applied to three level, four leg and multilevel inverters. Software implementation used has be extended further to over modulation region i.e. modulation index m>0.907.

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