International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 3, Issue1 (August 2013) PP: 58-66

A Novel Space Vector Modulation (SVM) Controlled Inverter For Adjustable Speed Drive Applications

M.Nagaiah $_{\text{M.Tech,}}$ Gnanatheja Rakesh.V $_{\text{M.Tech,}}$
Assistant Professor EEE Department Sri Venkateswara College Of Engineering, Tirupati.
Assistant Professor EEE Department Sri Venkateswara College Of Engineering, Tirupati.

ABSTRACT---*The induction motor (IM) is fed from three phase bridge inverter which is operated with space vector modulation (SVM) Technique. Among the various modulation strategies Space Vector Modulation Technique is the efficient one because it has better performance and output voltage is more closed to sinusoidal. The main aim of any modulation technique is to obtain variable output having a maximum fundamental component with minimum harmonics. Space Vector PWM (SVPWM) method is an advanced PWM method and possibly the best techniques for variable frequency drive application. The performance of SVM technique and Sine triangle pulse width modulation (SPWM) technique are compared for harmonics, THD, dc bus utilization and Output voltage and observed that SVM has better performance. These techniques when applied for speed control of Induction motor by v/f method for both open loop and closed loop systems it is observed that the induction motor performance is improved with SVM.*

I. INTRODUCTION

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), un-interruptible power supplies (UPS) etc. The main problems faced by the power electronic design engineers are about the reduction of harmonic content in inverter circuits. 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 technique is to fabricate a sinusoidal AC output whose magnitude and frequency could both be restricted.

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. The frequency of the carrier signal is very high compared to the modulating signal.

The magnitude and frequencies of the fundamental component in the line side are controlled by changing the magnitude and frequency of the modulating signal. It is simple and linear between 0% and 78.5% of six step voltage values, which results in poor voltage utilization. Voltage range has to be extended and harmonics has to be reduced.

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

II. SPACE VECTOR PULSE WIDTH 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 circuit model of a typical three-phase voltage source PWM inverter is shown in Figure-1. 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 sinusoidal PWM, based on space vector representation of the voltages in the α-β plane. 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.

III. 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. 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,

$V_a=V_m\sin wt$ (1)

$V_b=V_m\sin(wt-2\pi/3)$ (2)

$V_c=V_m\sin(wt-4\pi/3)$ (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 d-q reference frame that consists of the horizontal (d) and vertical (q) axes as depicted in Figure-2. From

$f_{dqo}=K_s f_{abc}$ (4)

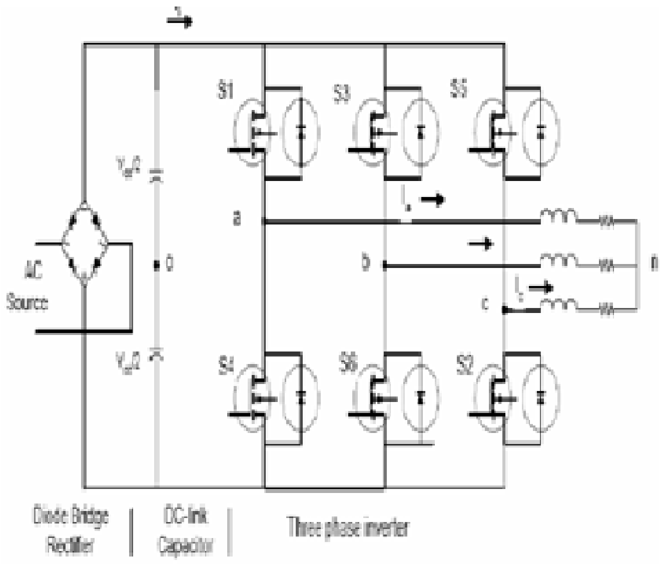


Fig-1: Three Phase Voltage Source Inverter

$$K_s = \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{-\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \qquad (5)$$

$$f_{dqo} = \left[f_d f_q f_0\right]^T, \; f_{abc} = [f_a f_b f_c]^T$$

f denotes either a voltage or a current variable.

As described in Figure-2. 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 and V7). The same transformation can be applied to the desired output voltage to get the desired reference voltage vector Vref 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.

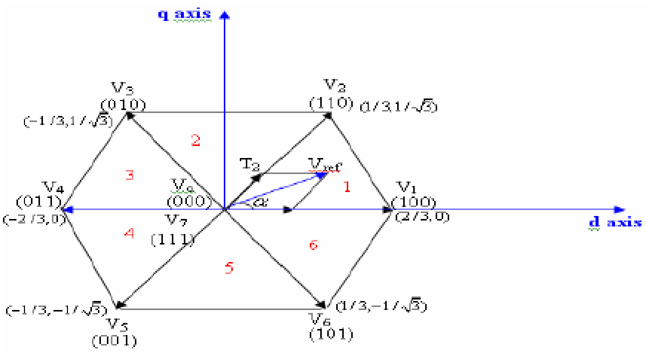


Fig-2: Basic Switching, Vectors and Sectors

TABLE1

Voltage Vectors	Switching Vectors			Line to neutral voltages			Line to Line voltages		
	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
Respective voltages should be multiplied by V_{dc}									

SWITCHING PATTERNS AND OUTPUT VECTORS

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 ($2^3 = 8$). 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. Table-1 gives the details of different phase and line voltages for the eight states.

IV. REALIZATION OF SVPWM

Space vector PWM can be implemented by the following steps:

Step-1:

Determine, Vd, Vq, Vref and the angle (α). From figure-4 Vd, Vq, Vref and the angle (α) can be determined as follows:

$V_d=V_{an}-V_{bn}\cos60^0-V_{cn}\cos60^0$ (6)
$Vq=0-V_{bn}\cos30^0-V_{cn}\cos30^0$ (7)

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

$$|V_{ref}| = \sqrt{V_d^2+V_q^2}$$

$$\alpha = tan^{-1}\frac{V_d}{V_q} = wt = 2\pi ft$$

Where f=fundamental frequency

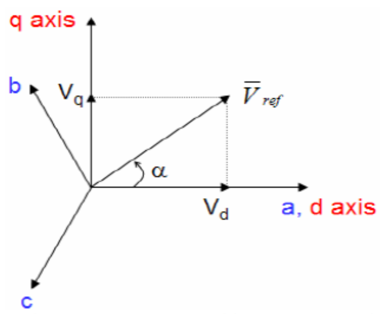


Fig-3: Voltage Space Vector and its Components in (d ,q).

Step-2:
Determine the time duration, T_1, T_2 and T_0 From figure-5 the switching time duration can be calculated as follows:

A. Switching time at sector 1

Assume that Vs is making an angle $0<\alpha<60^0$
Let V1 be applied for time T1 and V2 for T2 and zero vector Vz for TZ.
Volt-sec balance condition gives

$$\int_0^{T_s} V_{ref} = \int_0^{T_1} V_1 dt + \int_{T_1}^{T_1+T_2} V_2 dt + \int_{T_1+T_2}^{T_s} V_0$$

$$\int_0^{T_s} V_{ref} = \int_0^{T_1} V_1 dt + \int_{T_1}^{T_1+T_2} V_2 dt + \int_{T_1+T_2}^{T_s} V_0$$

$$Ts * V_{ref} = (T_1 * V_1 + T_2 * V_2)$$

$$T_s.|V_{ref}|.\left|\begin{bmatrix}\cos\alpha\\ \sin\alpha\end{bmatrix}\right| = T_1.\frac{2}{3}.V_{dc}.\begin{bmatrix}1\\0\end{bmatrix} + T_s\frac{2}{3}.V_{dc}.\begin{bmatrix}\cos\frac{\pi}{3}\\ \sin\frac{\pi}{3}\end{bmatrix}$$

$$T_1 = T_s.a.\frac{\sin(\frac{\pi}{3}-\alpha)}{\sin\frac{\pi}{3}}$$

B. Switching time at sector 2

$$T_2 = T_s.a.\frac{\sin(\alpha)}{\sin\frac{\pi}{3}}$$

$$T_0 = T_s - (T_1 + T_2),$$

Where ($T_s = \frac{1}{f_s}$ *and* $a = \frac{|V_{ref}|}{\frac{2}{3}.V_{dc}}$)

C. Switching time during any sector

$$T_1 = \left(\frac{\sqrt{3}.T_s.|V_{ref}|}{V_{dc}}\right).\sin\left(\frac{n}{3}\pi - \alpha\right) \qquad (8)$$

$$T_2 = \left(\frac{\sqrt{3}.T_s.|V_{ref}|}{V_{dc}}\right).\sin\left(\alpha - \left(\frac{n-1}{3}.\pi\right)\right) \qquad (9)$$

$$\therefore T_0 = T_s - (T_1 + T_2)$$

$$(where\ n = 1 through\ 6 (that\ is\ sector\ 1 to\ sector\ 6,))$$

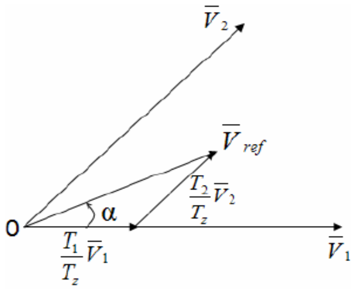


Fig-4: Reference Vector as a Combination of Adjacent Vector as sector-1

Step-3:

Determine the switching time (S1 to S6) The relationship between the effective times and the actual gating times is depicted when the reference vector is located in the Sector-1. In this case the V1 vector is applied to the inverter during T1 interval, and consequently V2 vector is applied during T2 interval. Thus, in general, the switching sequence is given by 0-1-2-7-7-2-1-0 within two sampling periods. With the point of view of the upper switching devices of one inverter leg, the former sequence (0-1-2-7 sequence) is called 'ON' sequence, and the latter (7-2-1-0) is called 'OFF' sequence in this paper. Therefore, the actual switching times corresponding to the case of sector -1 can be written as,

On gating Sequence	Off Gating Sequence
Tga=T0/2+T1+T2	Tga= T0/2
Tgb=T0/2+T2	Tgb =T0/2+T2
Tgc=T0/2	Tgc=T0/2+T1+T2

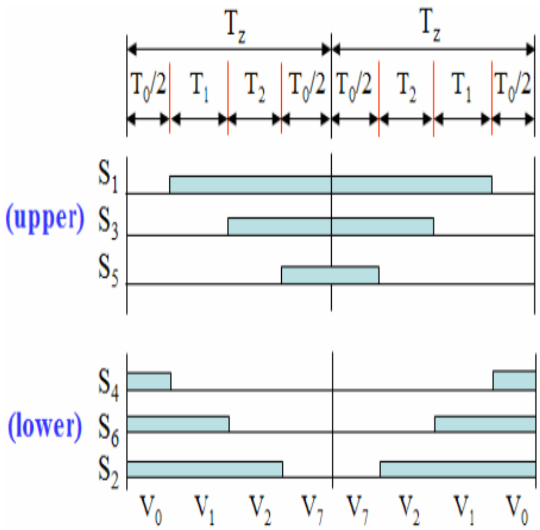


Fig-5: Switching Pulse Pattern

V. SIMULATION OF SPWM

In Sinusoidal PWM three phase reference modulating signals are compared against a common triangular carrier to generate the PWM signals for the three phases. It is simple and linear between 0% and

78.5% of six step voltage values, which results in poor voltage utilization. Finally performance of chaos based SPWM has been compared with SVPWM. The block diagram for Sinusoidal pulse width modulated inverter fed induction motor is shown in Figure-7. The line voltage, line current, speed and torque are shown in Figures 8, 9, 10 and 11 respectively.

VI. SIMULATION OF SVPWM

Space vector PWM is an advanced technique used for variable frequency drive applications. It utilizes dc bus voltage more effectively and generates less THD in the Three Phase Voltage Source Inverter. SVPWM utilize a chaotic changing switching frequency to spread the harmonics continuously to a wide band area so that the peak harmonics can be reduced greatly.

Simulation has been carried out by varying the modulation index between 0 and 1. Finally performance of SVPWM has been compared with conventional Sine PWM.

The Block Diagram of Space Vector Pulse width modulated inverter fed Induction Motor is shown in Figure-12. The speed, torque, and current are shown in Figure 13, 14 and 15 respectively.

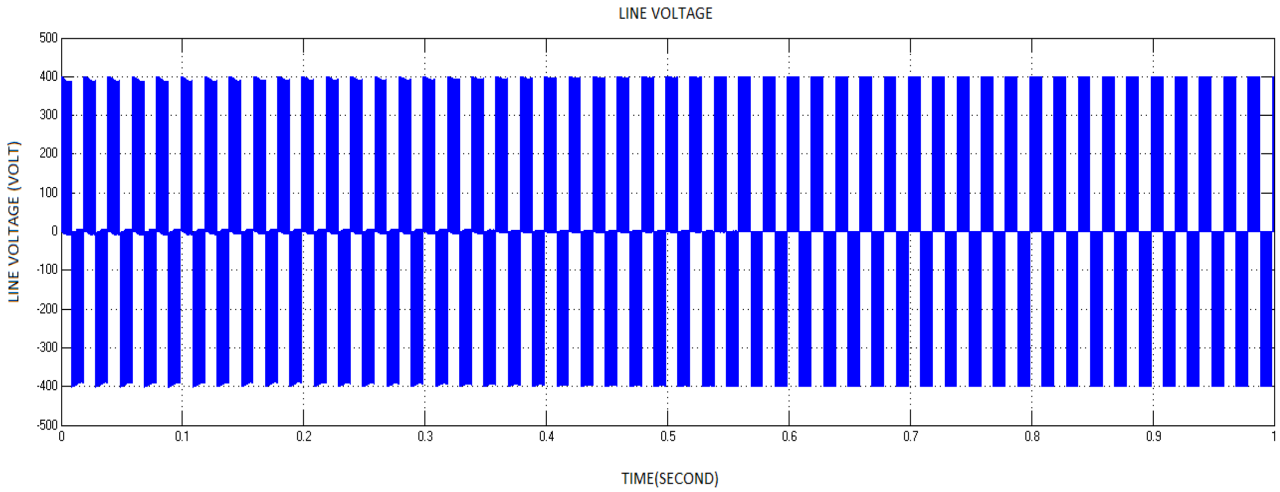


Fig-6: Response of Line Voltage in SPWM

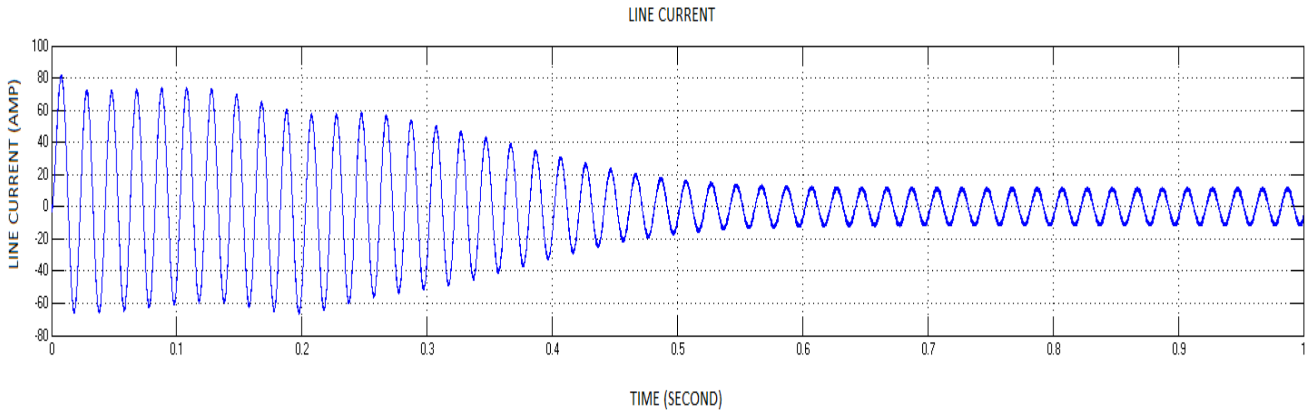


Fig-7: Response of Line Current in SPWM

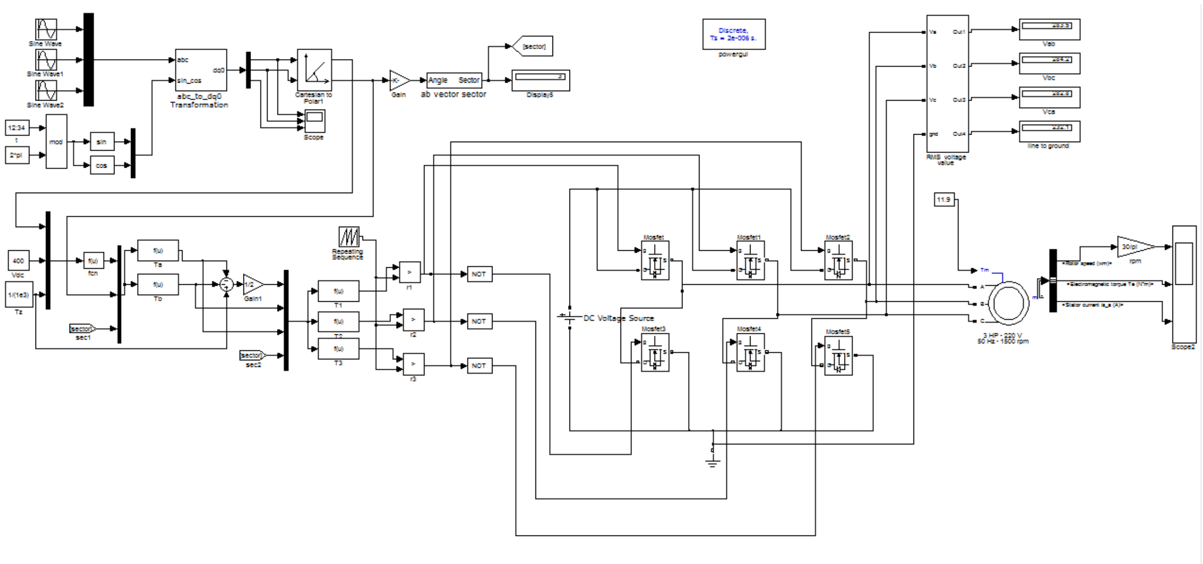


Fig-8: Block Diagram of SVPWM Inverter Fed Induction Motor

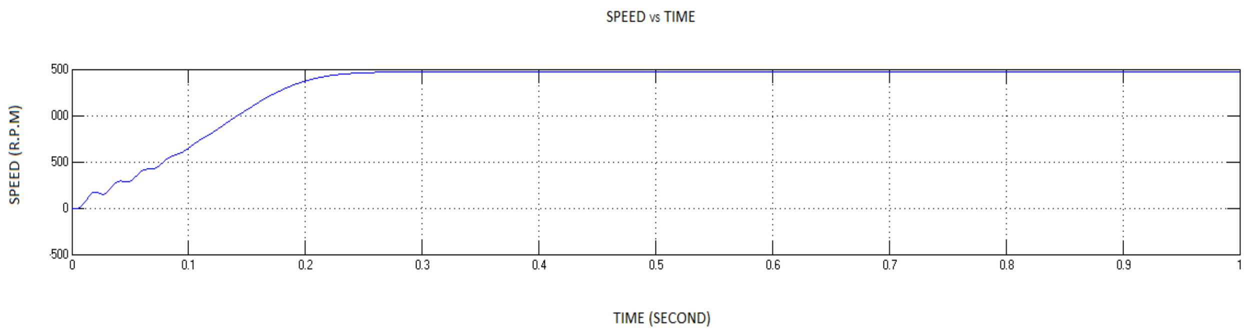


Fig-9: Response Rotor Speed in SVPWM

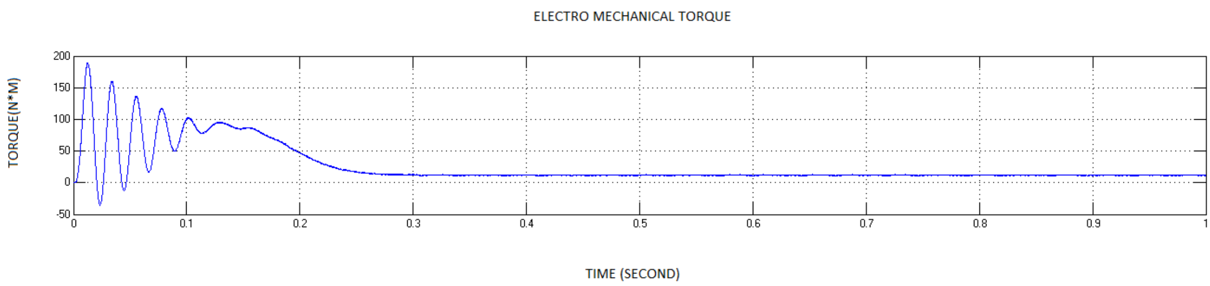


Fig-10: Response of Torque in SVPWM

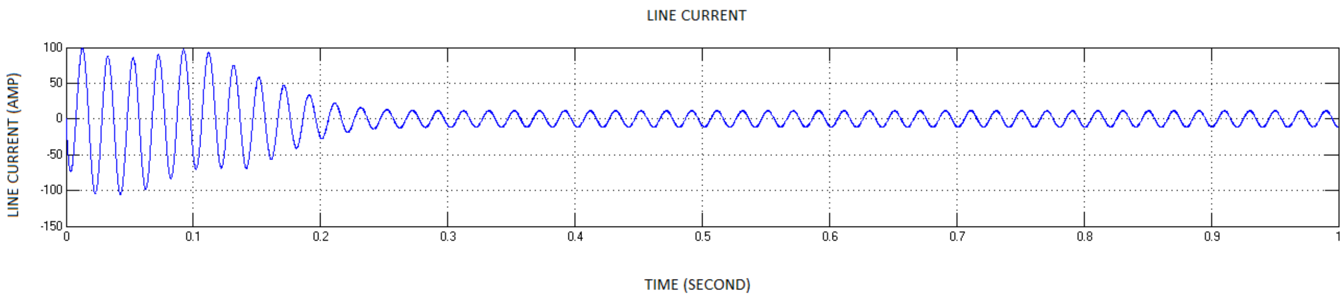
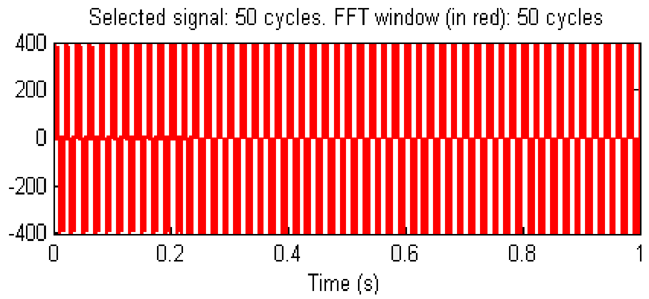


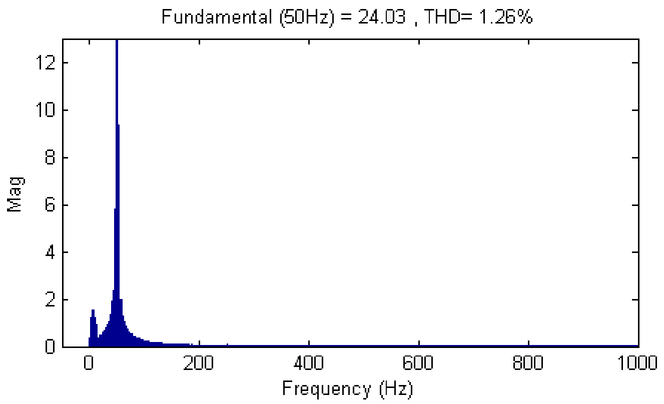
Fig-11: Response of Line current in SVPWM

VII. SIMULATION RESULTS OF SPWM AND SVPWM

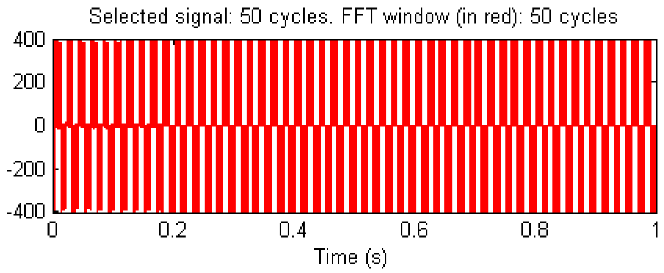
Voltage THD of SPWM

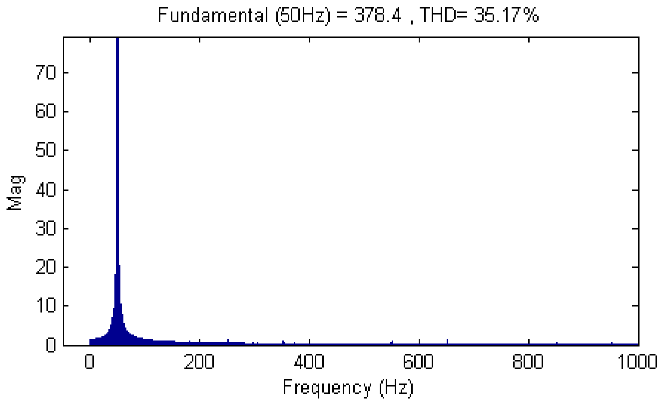


(a) SPWM



VOLTAGE THD OF SVPWM





(b) SVPWM

VIII. CONCLUSIONS

Space vector Modulation 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. In this paper first comparative analysis of Space Vector PWM with conventional SPWM for a two level Inverter is carried out.

The Simulation study reveals that SVPWM gives 15% enhanced fundamental output with better quality i.e. lesser THD compared to SPWM. PWM strategies viz. SPWM and SVPWM are implemented in MATLAB/SIMULINK software and its performance is compared with conventional PWM techniques. Owing to their fixed carrier frequencies fc in conventional PWM strategies, there are cluster harmonics around the multiples of carrier frequency. PWM strategies viz. Sinusoidal PWM and SVPWM utilize a changing carrier frequency to spread the harmonics continuously to a wideband area so that the peaks of harmonics are reduced greatly.

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