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# SIMULATION AND COMPARISON OF SPWM AND SVPWM CONTROL FOR THREE PHASE INVERTER

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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 TCPWM methods such as sine-triangle PWM, three phase reference modulating signals are compared against a common triangular carrier to generate the PWM signals for the three phases. 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. The highest possible peak phase fundamental is very less in sine triangle PWM when compared with space vector PWM. Space Vector Modulation (SVM) Technique has become the important PWM technique for three phase Voltage Source Inverters for the control of AC Induction, Brushless DC, 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 and generates less harmonic distortion when compared with Sinusoidal PWM (SPWM) technique. In this paper first a model for Space vector PWM is made and simulated using MATLAB/SIMULINK software and its performance is compared with Sinusoidal PWM. The simulation study reveals that Space vector PWM utilizes dc bus voltage more effectively and generates less THD when compared with sine PWM.

**Keywords**: PWM, SVPWM, three phase inverter, total harmonic distortion.

## 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 techniques was to fabricate a sinusoidal AC output whose magnitude and frequency could both be restricted.

PWM switching strategies not only addresses the primary issues viz, less THD, effective dc bus utilization etc but also take care of secondary issues like EMI reduction , switching loss, better spreading of Harmonics over the spectrum. 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. 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.

## 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 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; computation intensive PWM method and possibly the best techniques for variable frequency drive application.

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**A space vector PWM**

The circuit model of a typical three-phase voltage source PWM inverter is shown in Figure-1. $S_1$ to $S_6$ 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 $S_1$, $S_3$ and $S_5$ 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. 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.

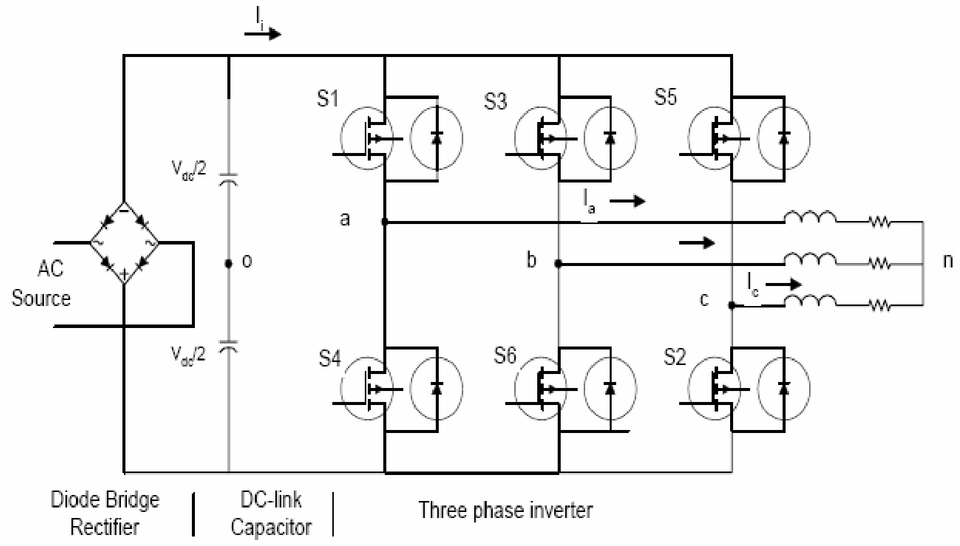


**Figure-1.** Three phase voltage source inverter.

**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,

$$V_a = V_m \mathrm{Sin}\omega t \quad (1)$$

$$V_b = V_m \mathrm{Sin}(\omega t - 2\pi/3) \quad (2)$$

$$V_c = V_m \mathrm{Sin}(\omega t - 4\pi/3) \quad (3)$$

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 equations in the abc reference frame can be transformed into the stationary dq reference frame that consists of the horizontal (d) and vertical (q) axes as depicted in Figure-2. From Figure-2, the relation between these two reference frames is below

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

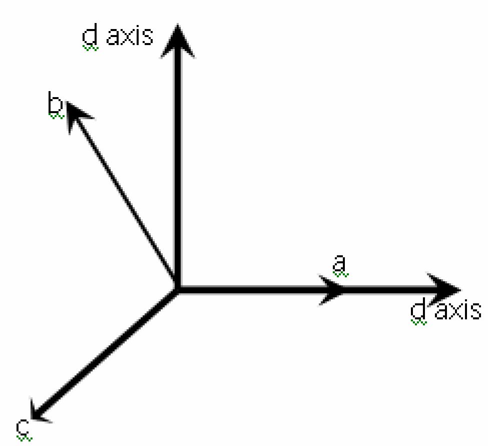


**Figure-2.** The relationship of abc reference frame and stationary dq reference frame.

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$$K_s = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix},\ f_{dq0} = \left[ f_d\, f_q\, f_0 \right]^T,\ f_{abc} = \left[ f_a\, f_b\, f_c \right]^T,$$

and 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 ($V_1$-$V_6$) 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 $V_{ref}$ 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 $V_{ref}$ in the same period

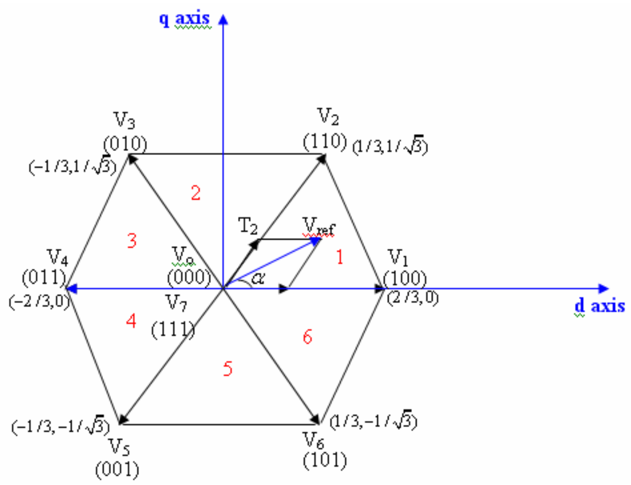


**Figure-3.** Basic switching, vectors and sectors.

## SWITCHING STATES

**Table-1.** Switching patterns and output vectors.

| Voltage vectors | Switching vectors | | | Line to neutral voltage | | | Line to line voltage | | |
|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | $V_{an}$ | $V_{bn}$ | $V_{cn}$ | $V_{ab}$ | $V_{bc}$ | $V_0$ |
| $V_0$ | 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 |

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.

## SOFTWARE IMPLEMENTATION OF SVPWM

Space vector PWM can be implemented by the following steps:

**Step-1:** Determine $V_d$ , $V_q$ , $V_{ref}$ and angle($\alpha$ ).

**Step-2:** Determine the time duration, $T_1$ , $T_2$ and $T_0$

**Step-3:** Determine the switching time of each transistor

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($S_1$ to $S_6$).

**Step-1: Determine $V_d$, $V_q$, $V_{ref}$ and angle($\alpha$)**

From Figure-4, $V_d$, $V_q$, $V_{ref}$ and angle ($\alpha$) can be determined as follows:

$$V_d = V_{an} - V_{bn}\cdot\cos60^\circ - V_{cn}\cdot\cos60^\circ$$

$$= V_{an} - \frac{1}{2}\cdot V_{bn} - \frac{1}{2}\cdot V_{cn} \qquad (6)$$

$$V_q = 0 + V_{bn}\cdot\cos30^\circ - V_{cn}\cdot\cos30^\circ$$

$$= V_{an} + \frac{\sqrt{3}}{2}\cdot\cos30^\circ - \frac{\sqrt{3}}{2}\cdot\cos30^\circ \qquad (7)$$

$$\therefore \begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3}\cdot\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \qquad (8)$$

$$\therefore \left|\bar{V}_{ref}\right| = \sqrt{V_d^{\,2} + V_q^{\,2}} \qquad (9)$$

$\alpha = \tan^{-1}\left(\dfrac{V_d}{V_q}\right) = wt = 2\pi ft$, where $f$ = fundamental frequency.

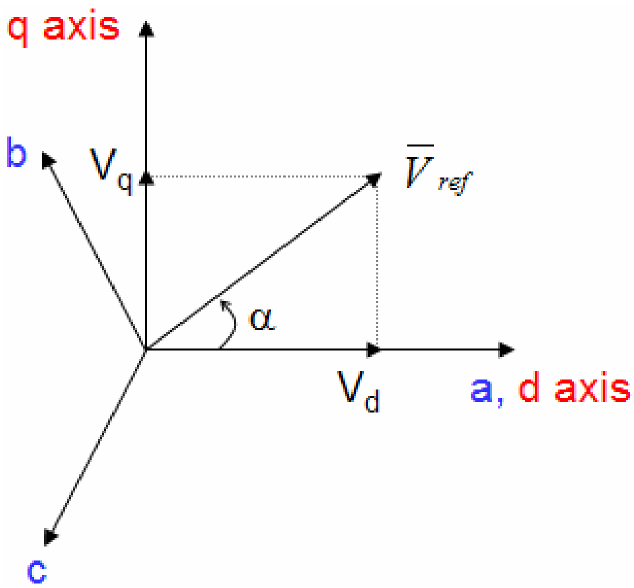


**Figure-4.** Voltage space vector and its components in (d,q).

**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:

Switching time at sector-1

$$\int_0^{T_z} \bar{V}_{ref} = \int_0^{T_1} \bar{V}_1 dt + \int_{T_1}^{T_1+T_2} \bar{V}_2 dt + \int_{T_1+T_2}^{T_z} \bar{V}_0 \qquad (10)$$

$$\int_0^{T_z} \bar{V}_{ref} = \int_0^{T_1} \bar{V}_1 dt + \int_{T_1}^{T_1+T_2} \bar{V}_2 dt + \int_{T_1+T_2}^{T_z} \bar{V}_0 \qquad (11)$$

$$\therefore T_Z\cdot\bar{V}_{ref} = (T_1\cdot\bar{V}_1 + T_2\cdot\bar{V}_2) \qquad (12)$$

$$\Rightarrow T_Z\cdot\left|\bar{V}_{ref}\right|\cdot\begin{bmatrix} \cos(\alpha) \\ \sin(\alpha) \end{bmatrix} = T_1\cdot\frac{2}{3}\cdot V_{dc}\cdot\begin{bmatrix} 1 \\ 0 \end{bmatrix} + T_2\cdot\frac{2}{3}\cdot V_{dc}\cdot\begin{bmatrix} \cos(\frac{\pi}{3}) \\ \sin(\frac{\pi}{3}) \end{bmatrix} \qquad (13)$$

$$\therefore T_1 = T_Z\cdot a\cdot\frac{\sin(\frac{\pi}{3} - \alpha)}{\sin(\frac{\pi}{3})} \quad (\text{Where}, 0 \le \alpha \le 60^\circ) \qquad (14)$$

$$\therefore T_2 = T_Z\cdot a\cdot\frac{\sin(\alpha)}{\sin(\frac{\pi}{3})} \qquad (15)$$

$$\therefore T_0 = T_Z - (T_1 + T_2)\left(\text{where}, T_Z = \frac{1}{f_z} \text{ and } a = \frac{\left|\bar{V}_{ref}\right|}{\frac{2}{3}\cdot V_{dc}}\right) \qquad (16)$$

Switching time during any sector

$$= \frac{\sqrt{3}\cdot T_Z\cdot\left|\bar{V}_{ref}\right|}{V_{dc}}\cdot\sin\left(\frac{n}{3}\pi - \alpha\right) \qquad (17)$$

$$= \frac{\sqrt{3}\cdot T_Z\cdot\left|\bar{V}_{ref}\right|}{V_{dc}}\cdot\left(\sin\frac{n}{3}\pi\cdot\cos\alpha - \cos\frac{n}{3}\pi\cdot\sin\alpha\right) \qquad (18)$$

$$\therefore T_2 = \frac{\sqrt{3}\cdot T_Z\cdot\left|\bar{V}_{ref}\right|}{V_{dc}}\cdot\left(\sin\left(\alpha - \frac{n-1}{3}\pi\right)\right) \qquad (19)$$

$$= \frac{\sqrt{3}\cdot T_Z\cdot\left|\bar{V}_{ref}\right|}{V_{dc}}\cdot\left(-\cos\alpha\cdot\sin\frac{n-1}{3}\pi + \sin\alpha\cdot\cos\frac{n-1}{3}\pi\right) \qquad (20)$$

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

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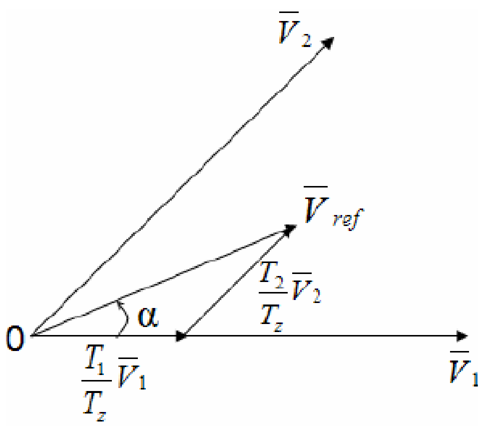
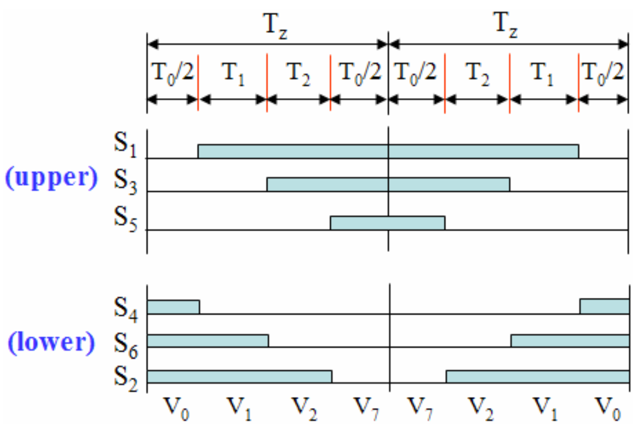
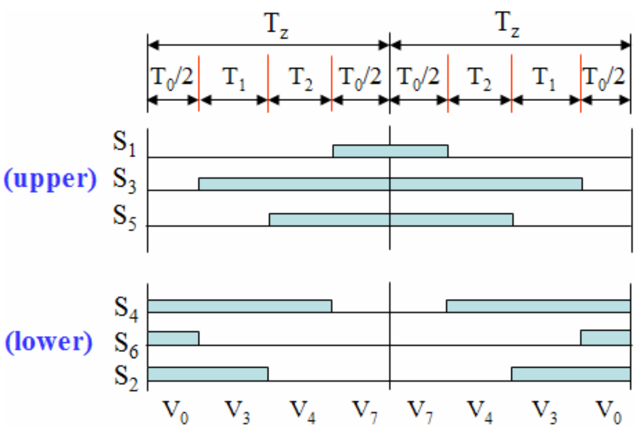



**Figure-5.** Reference vector as a combination of adjacent vectors at sector-1.

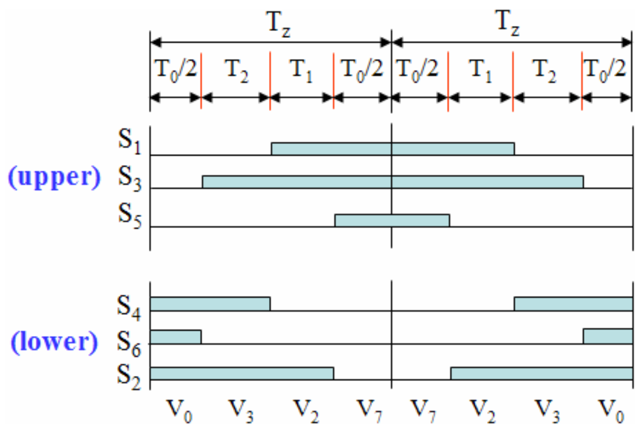
**Step-3: Determine the switching time of each transistor (S1 TO S6)**



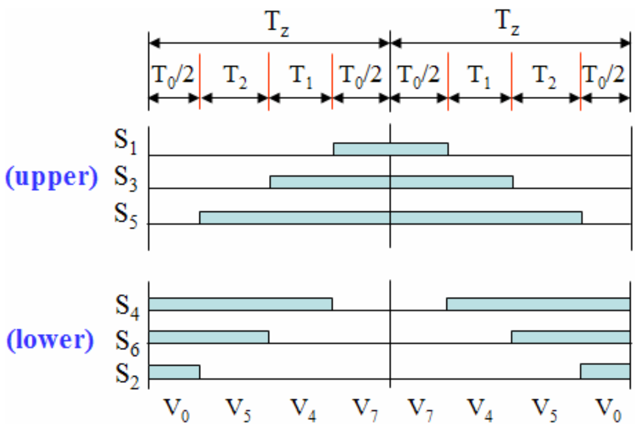

(a) Sector 1



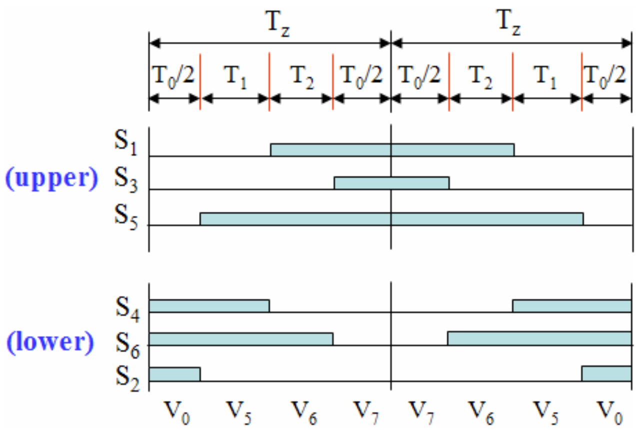

(b) Sector 2




(c) Sector 3




(d) Sector 4




(e) Sector 5

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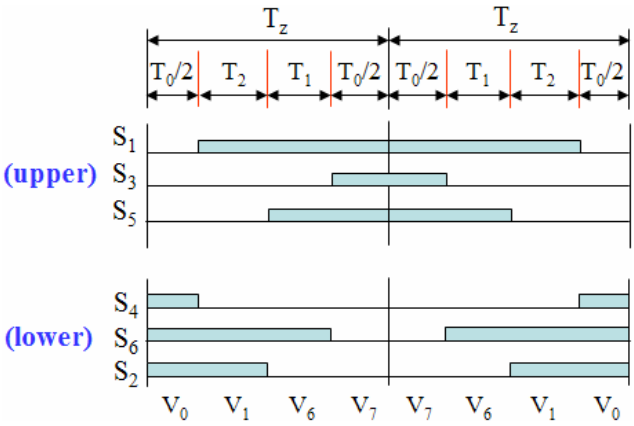


(f) Sector 6

**Figure-6.** Switching pulse pattern for the three phases in the 6 different sectors.

## RESULTS AND DISCUSSIONS

The main aim of any modulation technique is to obtain variable output having maximum fundamental component with minimum harmonics. The objective of Pulse Width Modulation techniques is enhancement of fundamental output voltage and reduction of harmonic content in Three Phase Voltage Source Inverters. In this paper different PWM techniques are compared in terms of Total Harmonic Distortion (THD). Simulink Models has been developed for Sinusoidal PWM (SPWM), Space vector PWM (SVPWM), and Space vector PWM switching Patterns. Simulation work is carried in MATLAB 7.0/Simulink.

The simulation parameters used are:

| | |
|---|---|
| Fundamental frequency | 50 Hz |
| Switching frequency | 10 kHz |
| DC voltage | 600 Volt |
| ODE Solver | ode23tb |

### 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. Frequency in conventional SPWM output waves owing to their fixed switching frequencies. Simulation has been carried out by varying the modulation index between 0 and 1.Finally performance of chaos based SPWM has been compared with SPWM. The block diagram for Sinusoidal pulse width modulated inverter fed induction motor is shown in Figure-7. The line voltage and line current are shown in Figures 8 and 9, respectively.

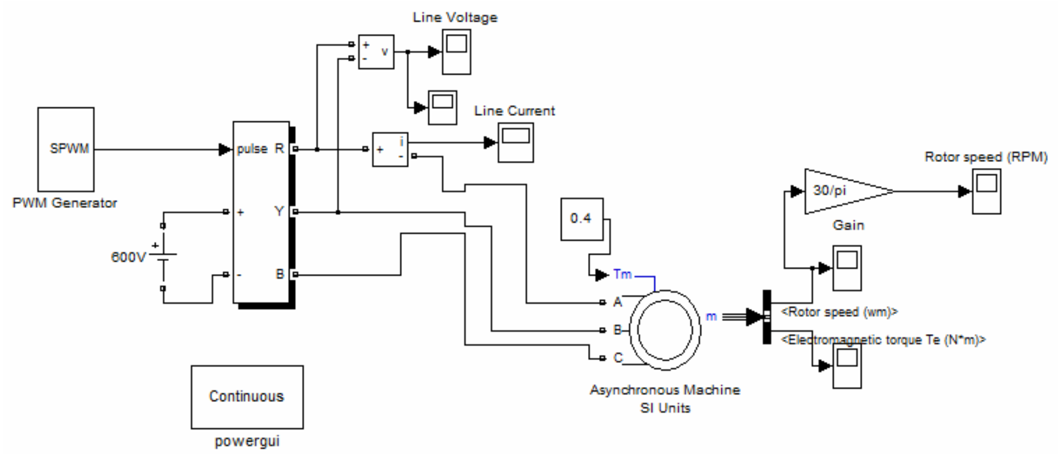


**Figure-7.** Block diagram of SPWM inverter fed induction motor.

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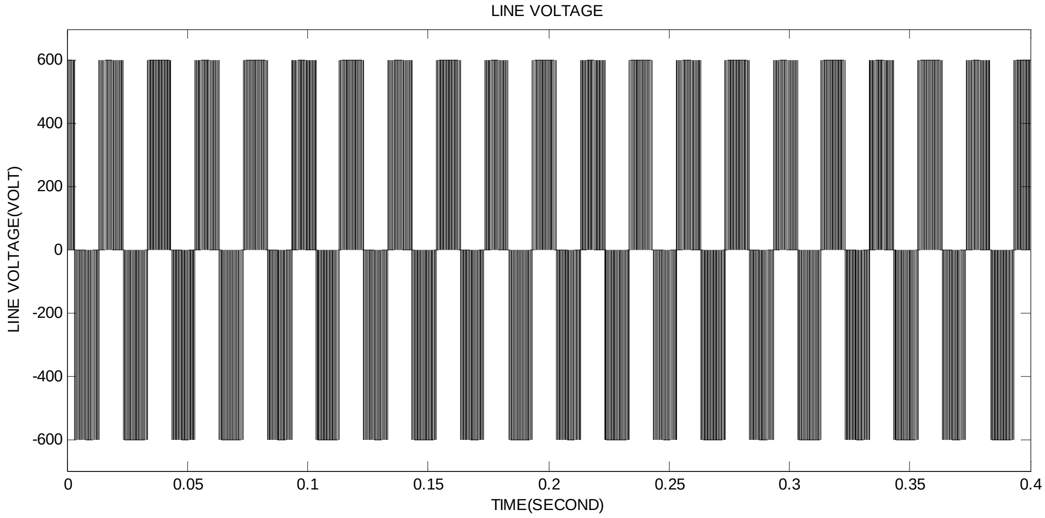


**Figure-8a.** Response of line voltage in SPWM.

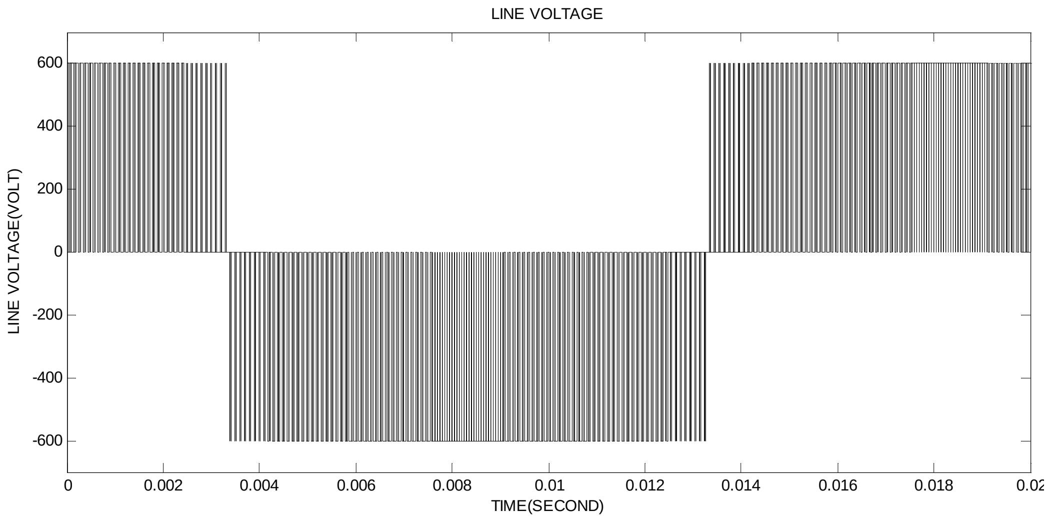


**Figure-8.** Response of line voltage in SPWM.

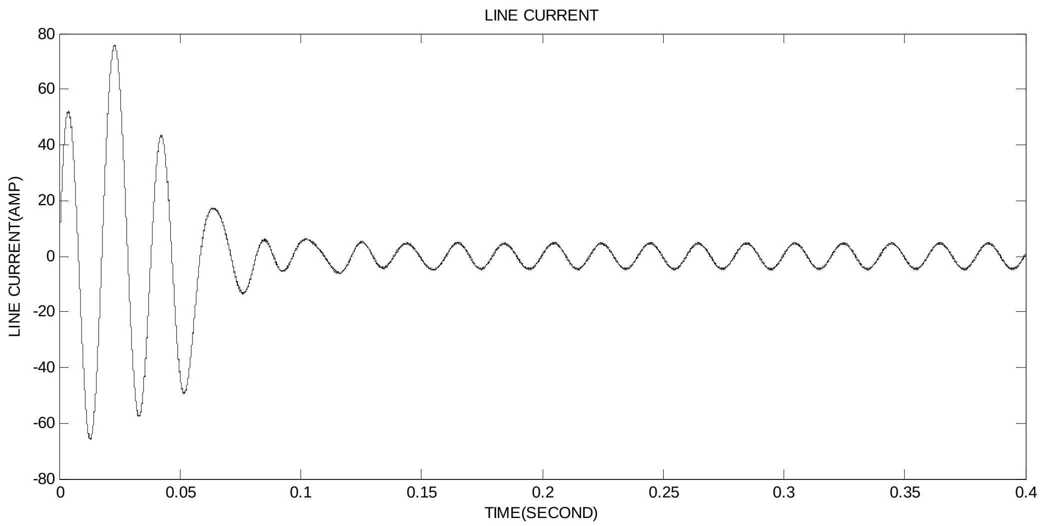


**Figure-9a.** Response of line current in SPWM.

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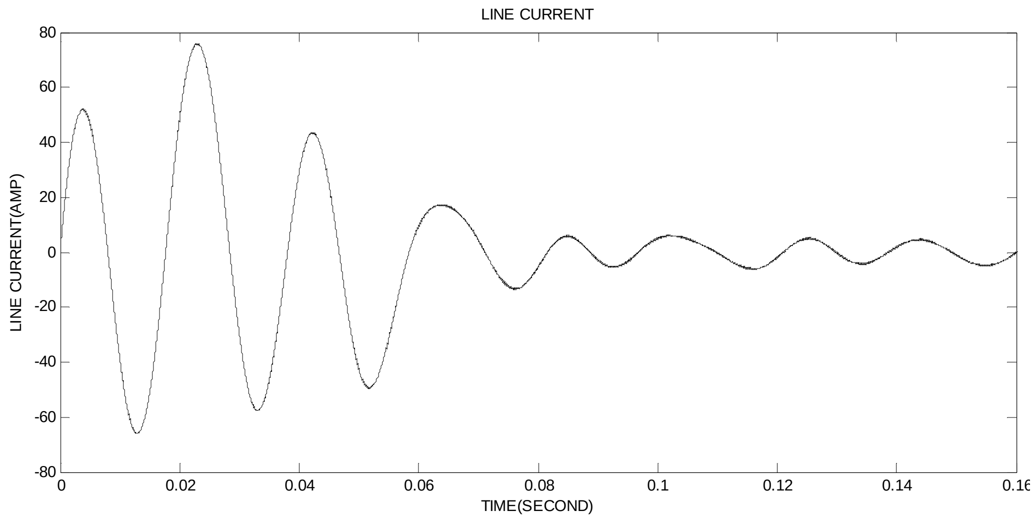


**Figure-9b.** Response of line current in SPWM.

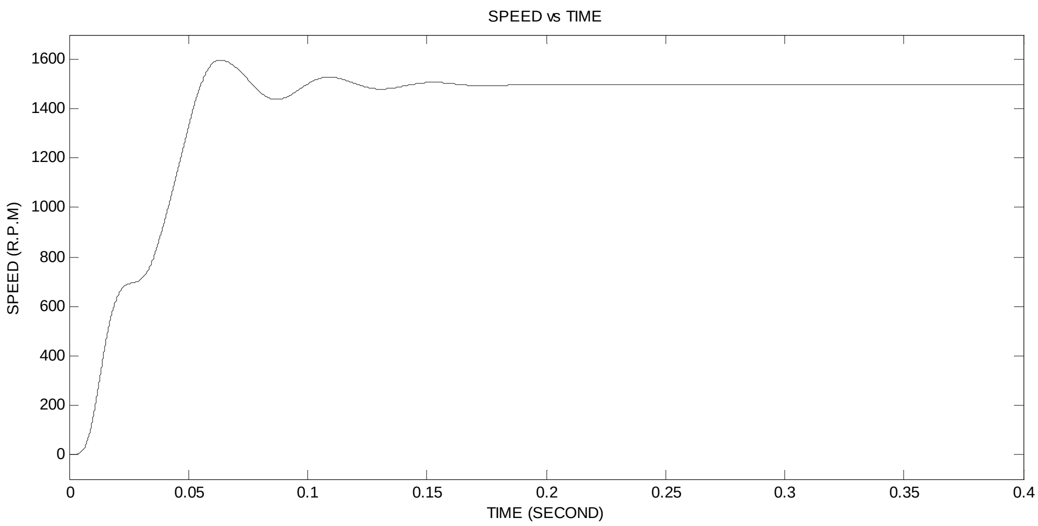


**Figure-10.** Response of rotor speed in SPWM.

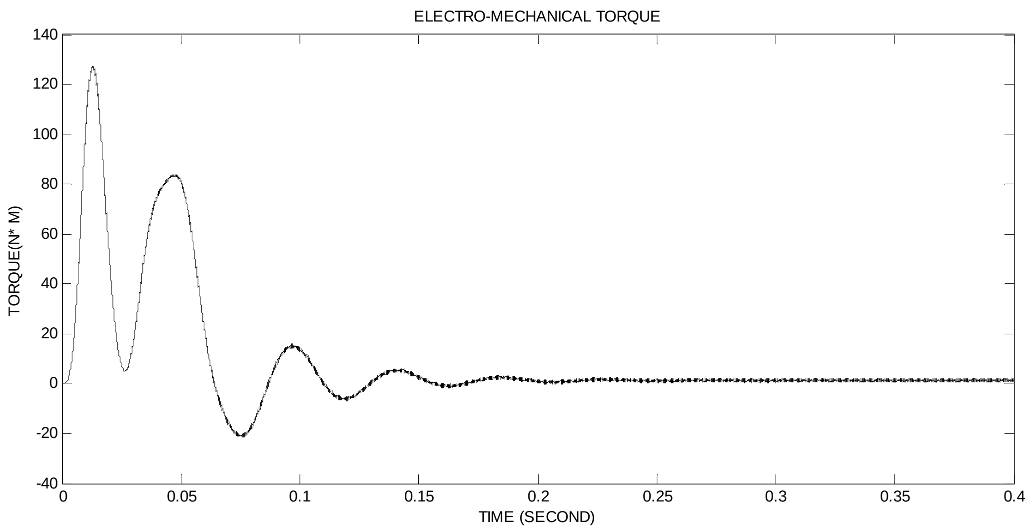


**Figure-11.** Response of torque in SPWM.

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**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 line voltage and line current are shown in Figures 13 and 14, respectively.

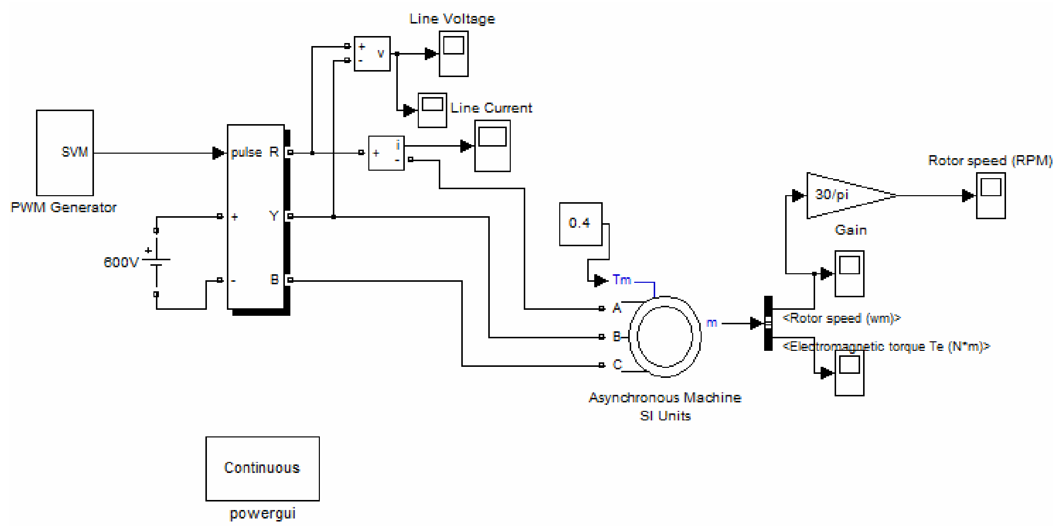
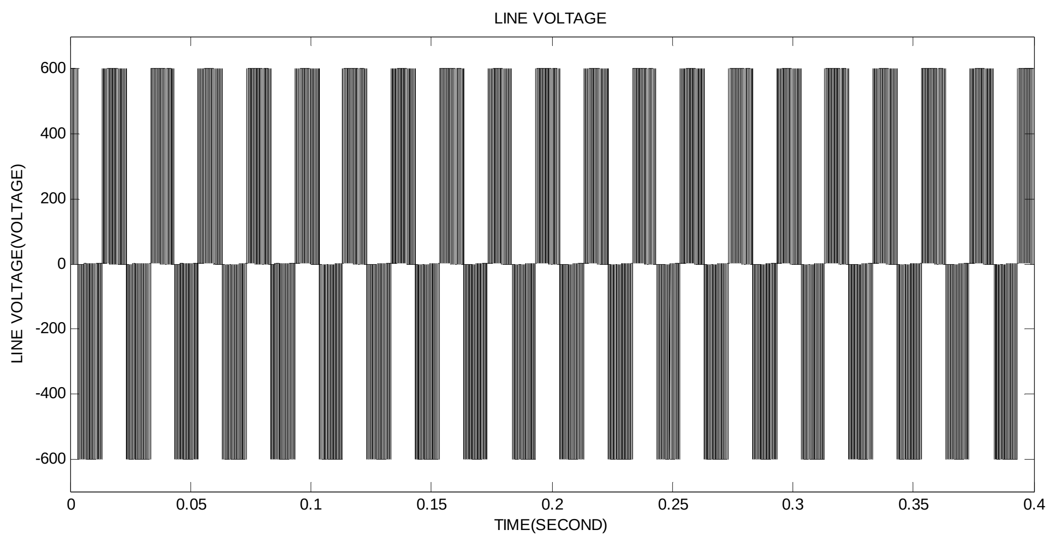



**Figure-12.** Simulink block diagram of space vector PWM.



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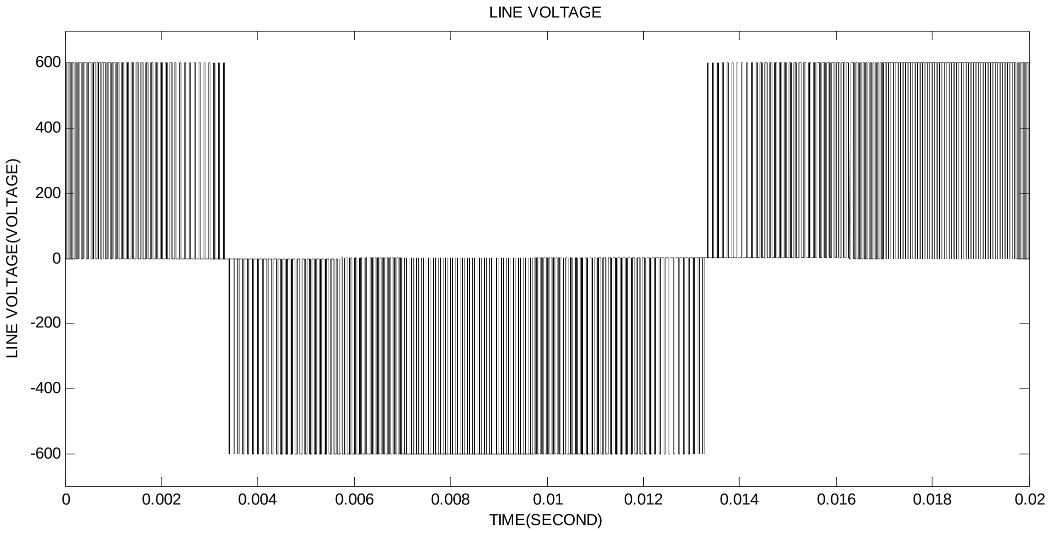


**Figure-13.** Response of line voltage in SVPWM.

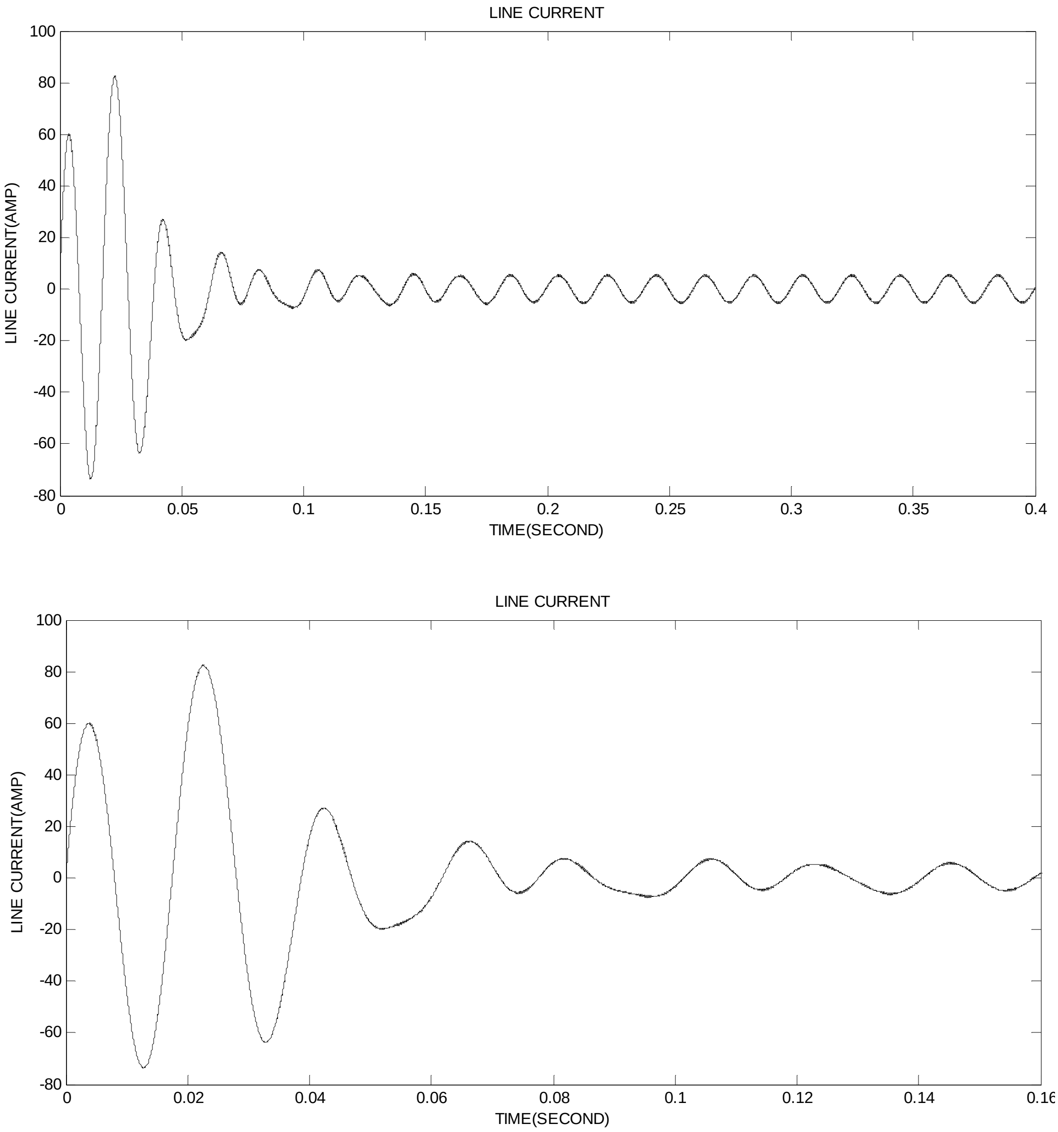


**Figure-14.** Response of line current in SVPWM.

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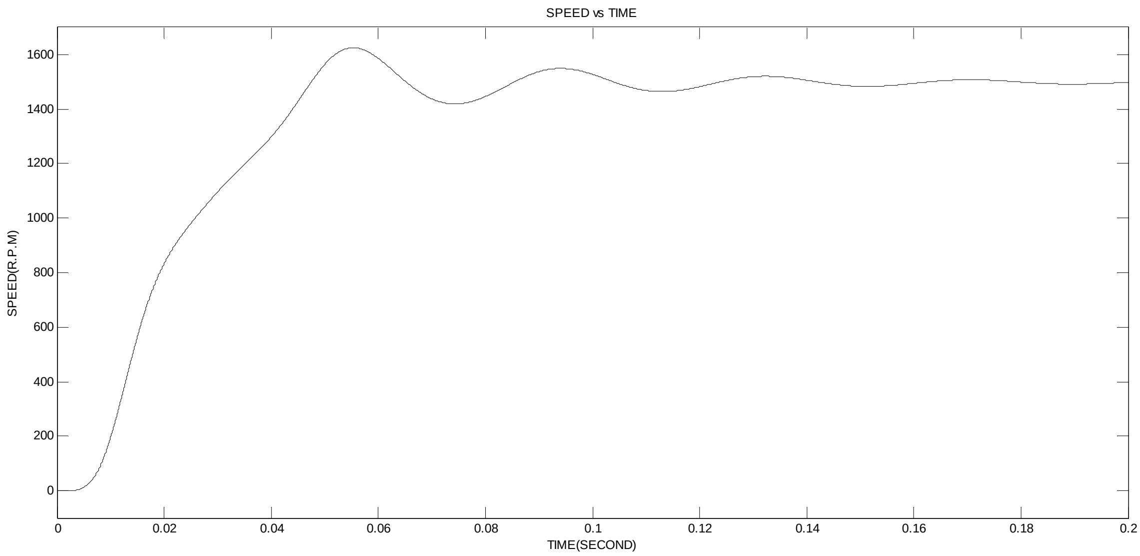


**Figure-15.** Response of rotor speed in SVPWM.

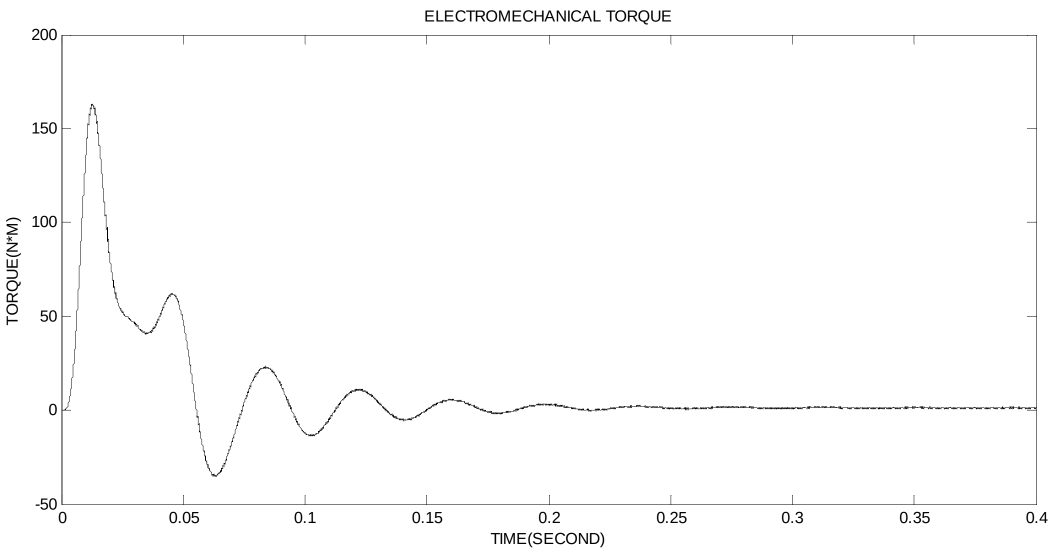


**Figure-16.** Response of torque in SVPWM.

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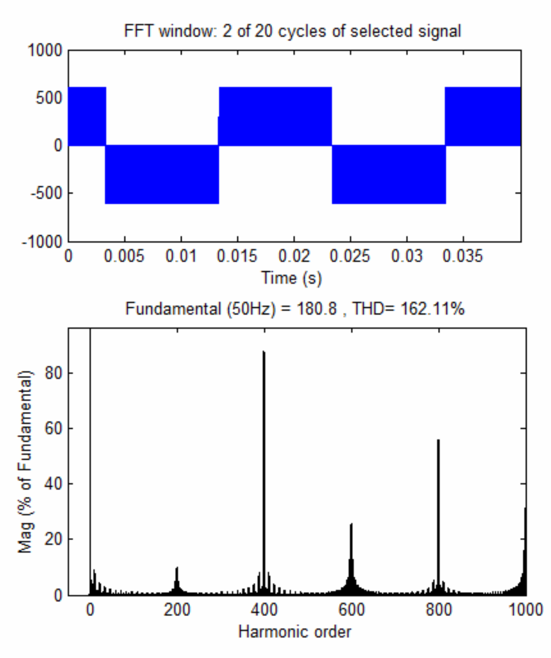
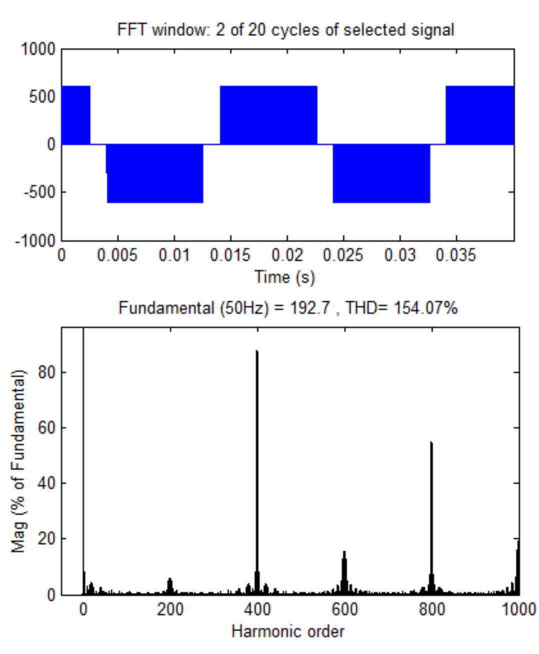
**Simulation results of SPWM and SVPWM**

MODULATION INDEX = 0.4:

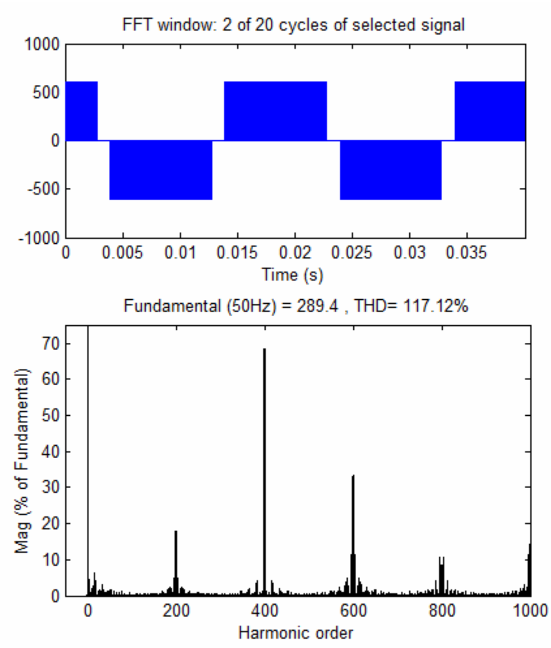



(A) SPWM

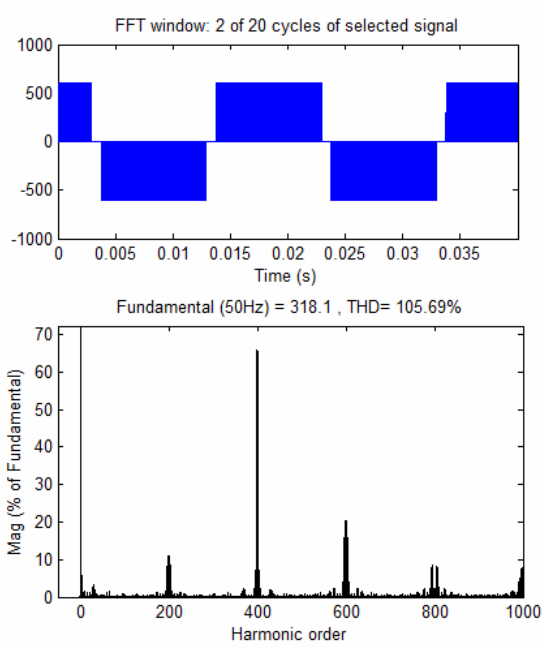



(B) SVPWM

MODULATION INDEX = 0.6:




(A) SPWM




(B) SVPWM

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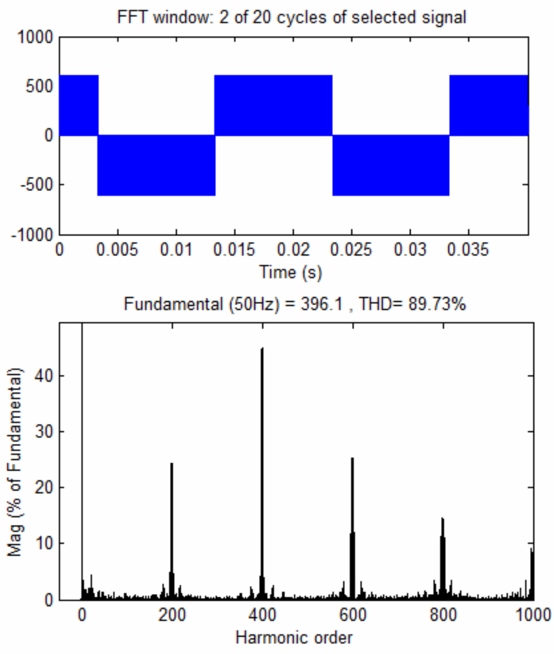
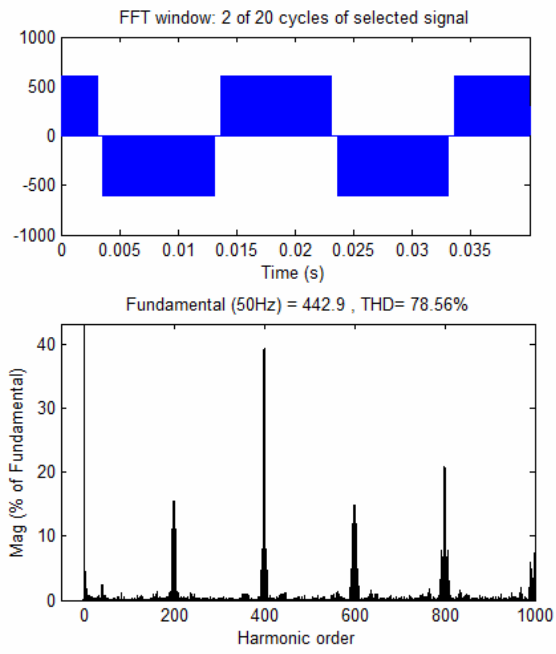
MODULATION INDEX = 0.8:

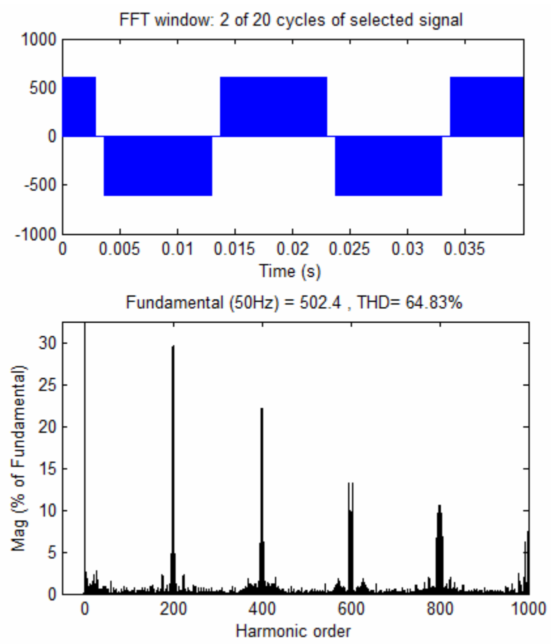



(A) SPWM

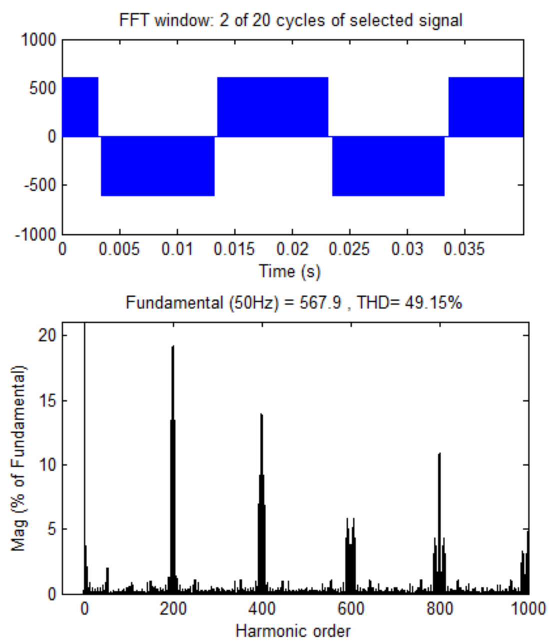



(B) SVPWM

MODULATION INDEX = 1:




(A) SPWM




(B) SVPWM

**Table-2.** Comparisons between SPWM and SVPWM by varying modulation index.

| **Technique** | **SPWM** | | **SVPWM** | |
|---|---|---|---|---|
| **M. I.** (M) | **Output line voltage (peak) volt** | **THD** (%) | **Output line voltage (peak) volt** | **THD** (%) |
| 0.4 | 180.80 | 162.11 | 192.70 | 154.07 |
| 0.5 | 266.50 | 123.35 | 312.20 | 108.78 |
| 0.6 | 289.40 | 117.12 | 318.10 | 105.69 |
| 0.7 | 369.20 | 94.52 | 436.60 | 81.19 |
| 0.8 | 396.10 | 89.73 | 442.90 | 78.56 |
| 0.9 | 472.90 | 70.69 | 552.30 | 53.62 |
| 1.0 | 502.40 | 64.83 | 567.90 | 49.15 |

## 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 $f_c$ 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 peak harmonics are reduced greatly.

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