

# Simulation and Performance of AC Drives Using SVPWM Technique

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**Abstract-** Drives are mainly categorized into constant-speed and variable-speed drives. AC machines have been used in constant-speed applications, where as DC machines were preferred for variable speed drives. Due to the advancement in power semiconductor devices and microprocessors, AC machines are widely used in variable speed drives.

This paper focuses on the simulation and performance evaluation for an ac drive system with Induction motor and PMSM Motor. The focus was based on the simulation of the power circuits using MATLAB/SIMULINK software. The performance of inverter was studied by SVPWM technique. Space Vector Pulse Width Modulation (SVPWM) is a digital technique, which increases the output voltage capability and increases DC bus utilization voltage. The performance of an ac drive system was simulated and evaluated for variable speed operation from no load to rated speed under constant torque operation. The advantages and disadvantages of Induction motor and PMSM are analyzed and presented in this paper

**Keywords-** PWM, SVPWM, THD, Induction motor, PMSM.

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## I. INTRODUCTION

The electrical machine that transforms electrical energy into mechanical energy, and vice-versa, is the workhorse in a drive system. Traditionally, AC machines with a constant frequency sinusoidal power supply have been used in constant-speed applications, where as DC machines were preferred for variable-speed drives. DC machine drive converter and controls are simple and the machine torque response is very fast. Disadvantages are higher cost, higher rotor inertia and maintenance problems with commutator and brushes and do not permit the machine to operate in dirty and explosive environments. The AC motors are light in weight, inexpensive and require less maintenance compared with DC motors. AC motors are now employed in variable-speed drives due to the development of semiconductor converters employing thyristors, power transistors, IGBTs and GTOs.

Sinusoidal PWM is most popular technique used in AC motor control. It employs a triangular carrier wave modulated by a sine wave and the points of intersection determine the switching points of the power devices in the inverter. This method has some disadvantages, such as higher switching losses and Complexity in digital implementation.

At present, the control strategies are implemented in digital systems, and therefore digital modulating techniques are also available. Space Vector Pulse Width Modulation (SVPWM) scheme can be implemented digitally with DSPs. Space vector modulation increases the output voltage efficiently and generates less THD.

## II. SPACE VECTOR PULSE WIDTH MODULATION

Space Vector Modulation (SVM) was generated as a vector approach to pulse width modulation (PWM) for three-phase inverter. It offers extended output voltage capability of the PWM waveforms and prevents unnecessary switching hence less commutation losses. It is a more practiced technique for generating sine wave that provides a higher voltage to the motor with low THD. The main aim of any modulation technique is to attain variable output having a maximum fundamental component with minimum harmonics. Space Vector PWM (SVPWM) method is an advanced PWM method and widely used for variable speed drive application.

## III. A SPACE VECTOR PWM

The space vector modulation is a highly efficient way to generate the six PWM signals necessary at the power stage for two-level inverter. The circuit model of a typical three phase voltage source PWM inverter (two-level inverter) is shown in fig 1.

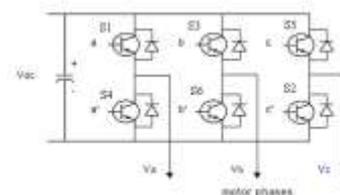


Fig 1. Three-phase Voltage source PWM Inverter

There are 6 power switches,  $S_1$  to  $S_6$  that shape the output which are controlled by the switching variables  $a, a^1, b, b^1, c, c^1$ . When the upper transistor is switched ON then the switching variables  $a$  or  $b$  or  $c$  equal to 1 and the corresponding lower transistor is switched OFF & the switching variable equal to  $a^1$  or  $b^1$  or  $c^1$  equal to 0. Therefore, the ON and OFF states of the upper transistor and  $V_{dc}$  can be used to determinate output voltage.

The line-to-line voltage vector  $[V_{ab} V_{bc} V_{ca}]^t$  is expressed in terms of the switching variable vector  $[a, b, c]^t$  which is represented by equ(1) in the following:

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad \dots(1)$$

Also, the phase voltage vector  $[V_a V_b V_c]^t$  is expressed in terms of the switching variable vector  $[a, b, c]^t$  which is represented by equ (2) in the following

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{1}{3} V_{dc} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad \dots(2)$$

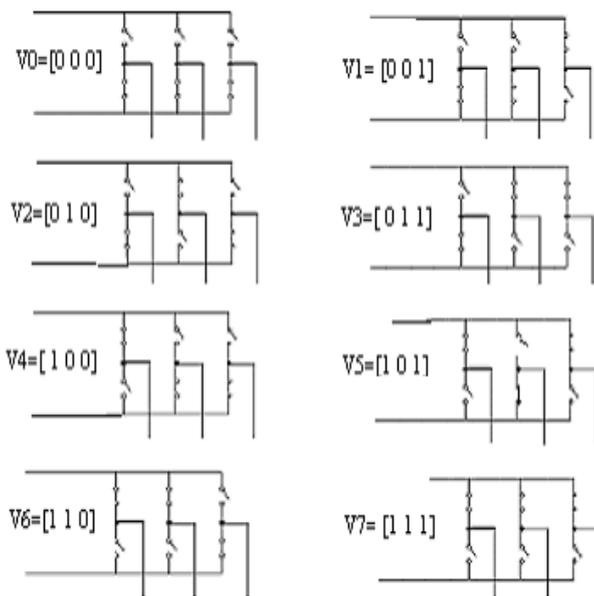


Fig 2. Inverter voltage vectors ( $V_0$  to  $V_7$ )

In Fig 1, there are eight possible combinations of on and off patterns for power switches. The on and off states of the lower transistors are opposite to the upper one and so are easily determined once the states of the upper transistors are determined.

The eight switching states, output line to neutral voltage and output line-to-line voltage in terms of DC-link  $V_{dc}$  are formulated in table 1 by combining equations 1 and 2, and Fig 3 shows the eight inverter voltage vectors( $V_0$  to  $V_7$ ).

Table 1: Switching Vectors, phase voltages and output line to line voltage

Voltage Vectors	Switching Vectors			Line to neutral voltage			Line to line voltage		
	a	b	c	$V_{an}$	$V_{bn}$	$V_{cn}$	$V_{ab}$	$V_{bc}$	$V_{ca}$
$V_0$	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

(Note that the respective voltage should be multiplied by  $V_{dc}$ )

#### IV. SPACE VECTOR CONCEPT

The three phase reference phase voltages  $V_a, V_b,$  and  $V_c$  are calculated from the amplitude of reference voltage space vector and inverter reference frequency. In order to implement SVPWM, the reference phase voltages are transformed to two phase stationary reference frame ( $\alpha$ - $\beta$ ). The relative position of three phases ( $a, b$  and  $c$ ) and two phase stationary ( $d$ - $q$ ) frame which consists of the horizontal ( $d$ ) and vertical ( $q$ ) axes. is shown in Fig 3.

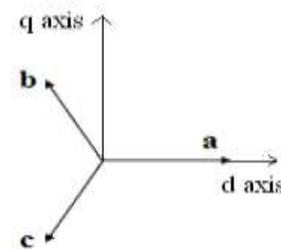


Fig 3. The relationship of abc reference frame & stationary dq reference frame

From this figure, the relation between these two reference frames is below

$$f_{dq0} = K_s f_{abc} \quad \dots(3).$$

where,  $K_s = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix}$ ,  $f_{dq0} = [f_d, f_q, f_0]^T$ ,  $f_{abc} = [f_a, f_b, f_c]^T$ , and  $f$  denotes either a voltage or a current variable.

As described in Fig. 3, 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.

Six non-zero vectors and two zero vectors are framed. Six nonzero vectors ( $V_1 - V_6$ ) shape the axes of a hexagonal as depicted in Fig. 4, and feed electric power to the load. Each section represents  $60^\circ$  of the fundamental cycle. Two zero vectors ( $V_0$  and  $V_7$ ) are at the origin and apply zero voltage to the load.  $V_0, V_1, V_2, V_3, V_4, V_5, V_6,$  and  $V_7$  are considered as basic voltage space vectors. The resultant voltage ( $V_{ref}$ ) is applied to calculate the angular position of the voltage space( $\alpha$ ). The six sectors are selected by an angle  $\alpha$ .

The main aim of space vector PWM technique is to approach the reference voltage vector  $V_{ref}$  using the eight switching states. One simple method 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.

The modulation index depends on amplitude of the voltage space vector  $V^*$ . For constant Dc link voltage, if  $V^*$  increases modulation index also increases and vice-versa. The time duration  $T_1, T_2$  and  $T_0$  for realizing the reference space vector are calculated. The time durations calculated for the each sector are merged to give the final time durations ( $T_1, T_2,$  and  $T_0$ ) of selected switching states.

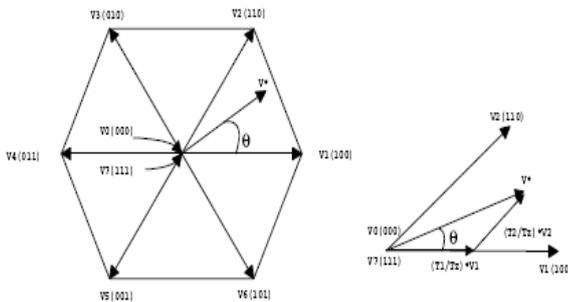


Fig 4. Basic switching vectors and sectors

V. SVPWM CAN BE IMPLEMENTED BY THE FOLLOWING STEPS:

- Step 1:** Determination of  $V_d, V_q, V_{ref},$  and angle ( $\alpha$ )
- Step 2:** Determination of time duration  $T_1, T_2, T_0$
- Step 3:** Determination of the switching time of each transistor ( $S_1$  to  $S_6$ ).

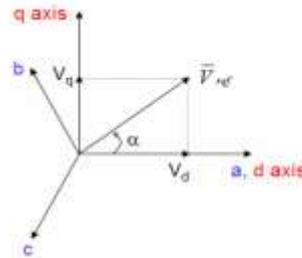
**Step 1: Determination of  $V_d, V_q, V_{ref},$  and angle ( $\alpha$ )**  
 $V_d, V_q, V_{ref},$  and angle ( $\alpha$ ) can be calculated as follows

$$\begin{aligned} V_d &= V_{an} - V_{bn} \cdot \cos 60 - V_{cn} \cdot \cos 60 \\ &= V_{an} - \frac{1}{2} V_{bn} - \frac{1}{2} V_{cn} \\ V_q &= 0 + V_{bn} \cdot \cos 30 - V_{cn} \cdot \cos 30 \\ &= V_{an} + \frac{\sqrt{3}}{2} V_{bn} - \frac{\sqrt{3}}{2} V_{cn} \end{aligned}$$

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

$$\therefore \alpha = \tan^{-1} \left( \frac{V_q}{V_d} \right) = \omega t = 2\pi f t, \text{ where } f = \text{fundamental frequency}$$

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



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

Fig 5. Voltage Space Vector and its components in (d, q)

**Step 2: Determination of time duration  $T_1, T_2, T_0$**

The switching time duration for any sector can be computed as follows:

- Switching time duration at Sector 1

$$\begin{aligned} \int_0^{T_z} \bar{V}_{ref} dt &= \int_0^{T_1} \bar{V}_1 dt + \int_{T_1}^{T_1+T_2} \bar{V}_2 dt + \int_{T_1+T_2}^{T_z} \bar{V}_0 dt \\ \therefore T_z \cdot \bar{V}_{ref} &= (T_1 \cdot \bar{V}_1 + T_2 \cdot \bar{V}_2) \\ \Rightarrow T_z \cdot \sqrt{\bar{V}_{ref}} \begin{bmatrix} \cos(\alpha) \\ \sin(\alpha) \end{bmatrix} &= T_1 \cdot \frac{2}{3} V_{dc} \begin{bmatrix} 1 \\ 0 \end{bmatrix} + T_2 \cdot \frac{2}{3} V_{dc} \begin{bmatrix} \cos(\pi/3) \\ \sin(\pi/3) \end{bmatrix} \end{aligned}$$

(where,  $0 \leq \alpha \leq 60^\circ$ )

$$\begin{aligned} \therefore T_1 &= T_z \cdot a \cdot \frac{\sin(\pi/3 - \alpha)}{\sin(\pi/3)} \\ \therefore T_2 &= T_z \cdot a \cdot \frac{\sin(\alpha)}{\sin(\pi/3)} \\ \therefore T_0 &= T_z - (T_1 + T_2), \left( \text{where } T_z = \frac{1}{f_z} \text{ and } a = \frac{\sqrt{V_{ref}}}{\frac{2}{3} V_{dc}} \right) \end{aligned}$$

Switching time duration at any Sector

$$\begin{aligned} \therefore T_1 &= \frac{\sqrt{3} \cdot T_z \cdot |\bar{V}_{ref}|}{V_{dc}} \left( \sin \left( \frac{\pi}{3} - \alpha + \frac{n-1}{3} \pi \right) \right) \\ &= \frac{\sqrt{3} \cdot T_z \cdot |\bar{V}_{ref}|}{V_{dc}} \left( \sin \frac{n}{3} \pi - \alpha \right) \\ &= \frac{\sqrt{3} \cdot T_z \cdot |\bar{V}_{ref}|}{V_{dc}} \left( \sin \frac{n}{3} \pi \cos \alpha - \cos \frac{n}{3} \pi \sin \alpha \right) \\ \therefore T_2 &= \frac{\sqrt{3} \cdot T_z \cdot |\bar{V}_{ref}|}{V_{dc}} \left( \sin \left( \alpha - \frac{n-1}{3} \pi \right) \right) \\ &= \frac{\sqrt{3} \cdot T_z \cdot |\bar{V}_{ref}|}{V_{dc}} \left( -\cos \alpha \cdot \sin \frac{n-1}{3} \pi + \sin \alpha \cdot \cos \frac{n-1}{3} \pi \right) \\ \therefore T_0 &= T_z - T_1 - T_2, \quad \left( \text{where, } n = 1 \text{ through } 6 \text{ (that is, Sector 1 to 6)} \right) \\ &\quad 0 \leq \alpha \leq 60^\circ \end{aligned}$$

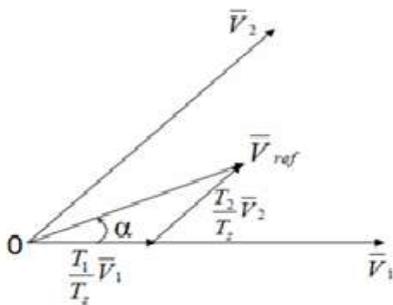


Fig 6. Reference vector as a combination of adjacent vectors at sector1

Step 3: Determination of the switching time of each IGBT (S1 to S6)

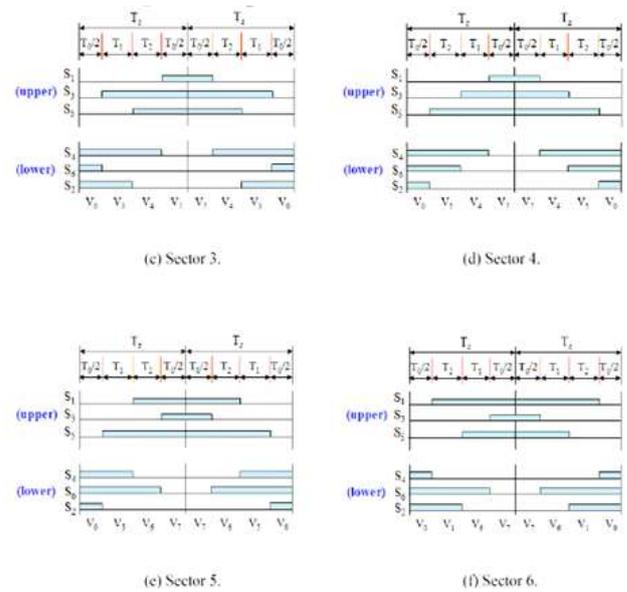
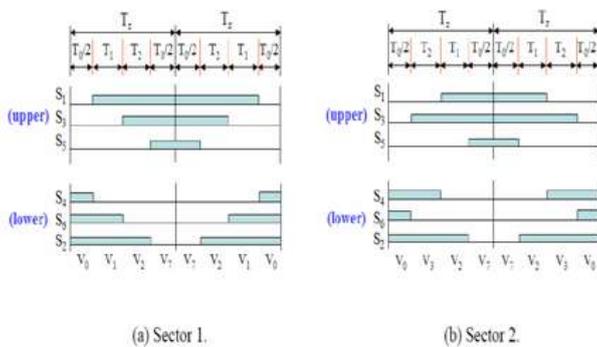


Fig 7. Switching time of each IGBT

The ON state time for each sector is summarized in Table 2, and it can be used to build SVPWM in MATLAB/SIMULINK model.

Table 2. Switching time calculation for each sector

Sector	Upper Switches (S <sub>1</sub> , S <sub>3</sub> , S <sub>5</sub> )	Lower Switches (S <sub>4</sub> , S <sub>6</sub> , S <sub>2</sub> )
1	S <sub>1</sub> = T <sub>1</sub> + T <sub>2</sub> + T <sub>0</sub> /2 S <sub>3</sub> = T <sub>2</sub> + T <sub>0</sub> /2 S <sub>5</sub> = T <sub>0</sub> /2	S <sub>4</sub> = T <sub>0</sub> /2 S <sub>6</sub> = T <sub>1</sub> + T <sub>0</sub> /2 S <sub>2</sub> = T <sub>1</sub> + T <sub>2</sub> + T <sub>0</sub> /2
2	S <sub>1</sub> = T <sub>1</sub> + T <sub>0</sub> /2 S <sub>3</sub> = T <sub>1</sub> + T <sub>2</sub> + T <sub>0</sub> /2 S <sub>5</sub> = T <sub>0</sub> /2	S <sub>4</sub> = T <sub>2</sub> + T <sub>0</sub> /2 S <sub>6</sub> = T <sub>0</sub> /2 S <sub>2</sub> = T <sub>1</sub> + T <sub>2</sub> + T <sub>0</sub> /2
3	S <sub>1</sub> = T <sub>0</sub> /2 S <sub>3</sub> = T <sub>1</sub> + T <sub>2</sub> + T <sub>0</sub> /2 S <sub>5</sub> = T <sub>2</sub> + T <sub>0</sub> /2	S <sub>4</sub> = T <sub>1</sub> + T <sub>2</sub> + T <sub>0</sub> /2 S <sub>6</sub> = T <sub>0</sub> /2 S <sub>2</sub> = T <sub>1</sub> + T <sub>0</sub> /2
4	S <sub>1</sub> = T <sub>0</sub> /2 S <sub>3</sub> = T <sub>1</sub> + T <sub>0</sub> /2 S <sub>5</sub> = T <sub>1</sub> + T <sub>2</sub> + T <sub>0</sub> /2	S <sub>4</sub> = T <sub>1</sub> + T <sub>2</sub> + T <sub>0</sub> /2 S <sub>6</sub> = T <sub>2</sub> + T <sub>0</sub> /2 S <sub>2</sub> = T <sub>0</sub> /2
5	S <sub>1</sub> = T <sub>2</sub> + T <sub>0</sub> /2 S <sub>3</sub> = T <sub>0</sub> /2 S <sub>5</sub> = T <sub>1</sub> + T <sub>2</sub> + T <sub>0</sub> /2	S <sub>4</sub> = T <sub>1</sub> + T <sub>0</sub> /2 S <sub>6</sub> = T <sub>1</sub> + T <sub>2</sub> + T <sub>0</sub> /2 S <sub>2</sub> = T <sub>0</sub> /2
6	S <sub>1</sub> = T <sub>1</sub> + T <sub>2</sub> + T <sub>0</sub> /2 S <sub>3</sub> = T <sub>0</sub> /2 S <sub>5</sub> = T <sub>1</sub> + T <sub>0</sub> /2	S <sub>4</sub> = T <sub>0</sub> /2 S <sub>6</sub> = T <sub>1</sub> + T <sub>2</sub> + T <sub>0</sub> /2 S <sub>2</sub> = T <sub>2</sub> + T <sub>0</sub> /2

VI. MATLAB/SIMULINK MODELING OF SVPWM FOR TWO LEVEL INVERTER

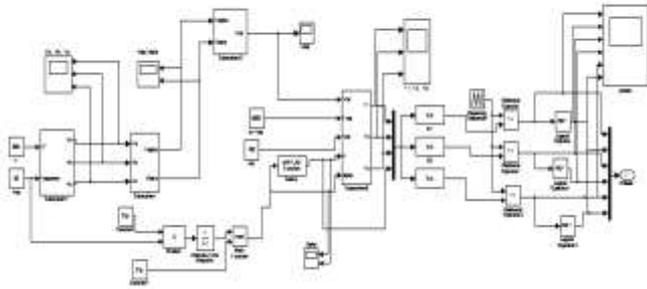


Fig 8. Simulink /subsystem block diagram of SVPWM for two level inverter

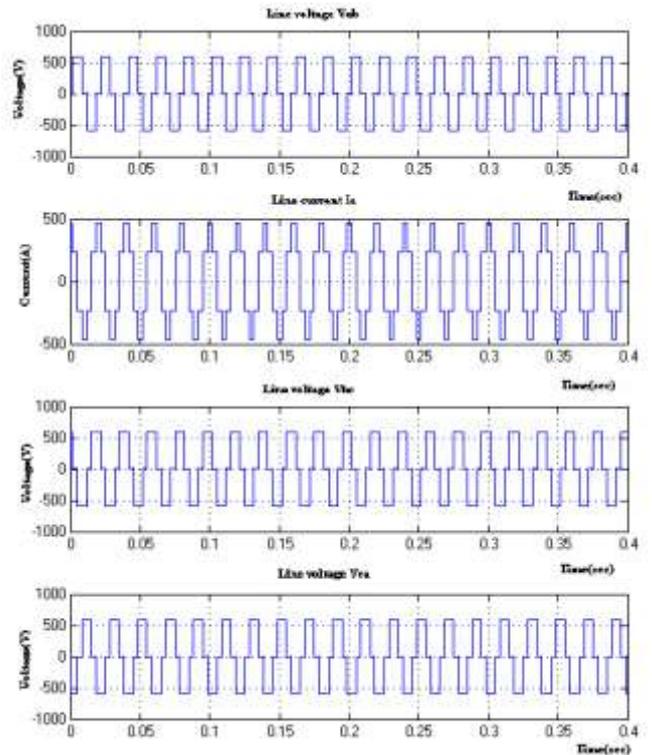


Fig 10. Simulation Results of Output line voltages and Line current for SVPWM inverter without filter

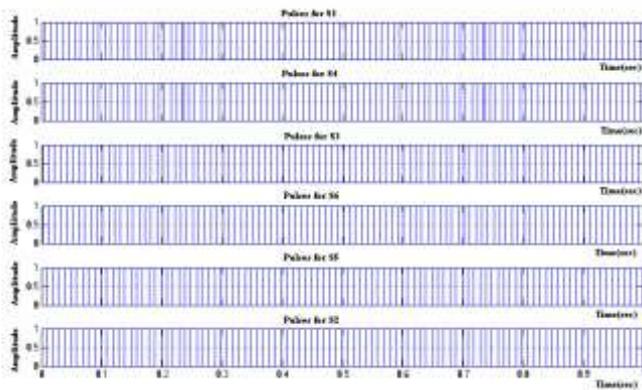


Fig 9. PWM pulses for SVPWM technique

SVPWM algorithms were developed and the conditions to achieve these are derived in terms of inverter states. The PWM signals for two-level inverter can be generated by comparing equivalent DC values of time durations with the symmetrical triangular waveform.

VII. MATLAB/SIMULINK MODEL OF SVPWM INVERTER WITHOUT FILTER

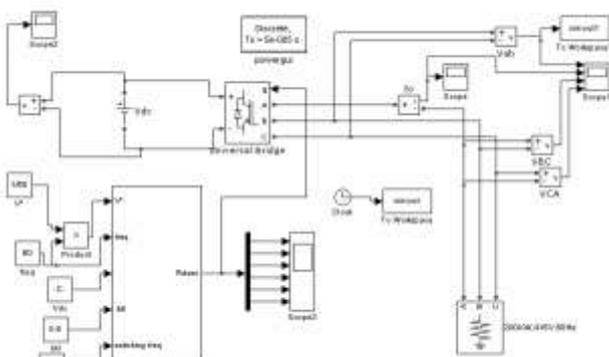


Fig 9. Simulink block diagram of SVPWM inverter without filter

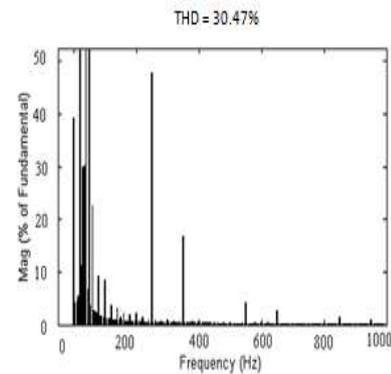


Fig 11. THD of Output line voltages for SVPWM inverter without filter

VIII. CONCEPT OF FILTER

The output voltage wave forms of inverter have either the quasi-square wave form or pulse width modulation wave form. These voltage wave forms contain harmonics. The voltage wave forms of a PWM inverter have a negative impact on the performance of an induction motor in terms of heating and torque pulsations. In order to eliminate these voltage harmonics in wave form, it is necessary to pass them through a suitable filter.

A wide variety of filters are available to improve the output waveform. The main limitations of RLC and LCL filters are they are very expensive and the use of resistance in the filter results energy losses.

The mostly used filter topology for an AC drive system is LC filter. The inductance offers the high impedance to

harmonic voltage. Higher the harmonic member, higher will be the impedance and lower will be the magnitude of the harmonic at the out put. The capacitance offers a shunt path for the harmonic current.

### IX. FILTER DESIGN

In order to be able to connect a standard industrial motor, the motor voltage has to be almost sinusoidal. The filter performance with respect to the motor voltage is determined by its resonance frequency. In order to achieve an almost sinusoidal motor voltage, the resonance frequency should be below the lowest harmonic frequency of the inverter and the voltage resulting with pulse width modulation.

The values of L and C are determined using the following formulas.

$$L = 3 \% V_{ph} / I_{fl} * w$$

$$C = Q / 3 * V_{ph}^2 * w$$

### X. MATLAB/SIMULINK MODEL OF SVPWM INVERTER WITH FILTER

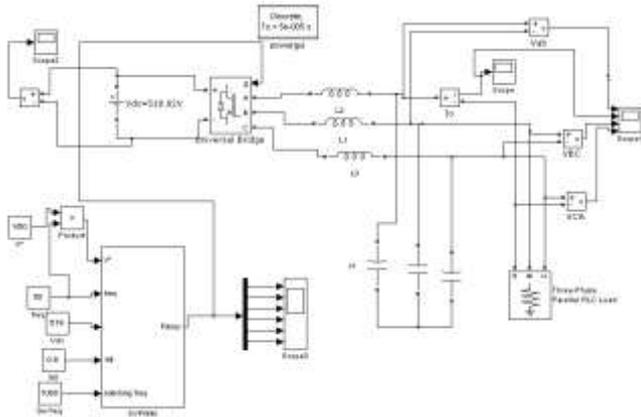


Fig 12. Simulink block diagram of SVPWM inverter with filter

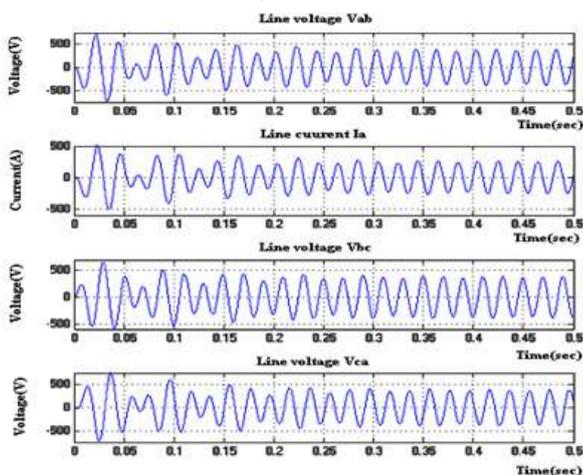


Fig 13. Simulation Results of Output line voltages and Line current for SPWM inverter using filter

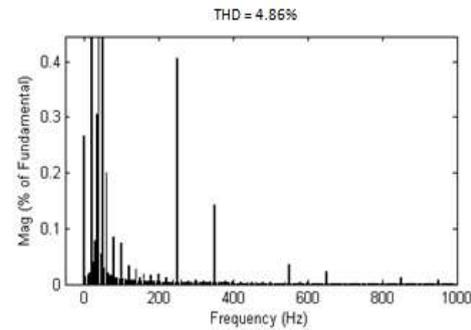


Fig 14. THD of Output line voltages for SVPWM inverter with filter

### XI. AC MACHINES FOR DRIVES

The electrical machine that converts electrical energy into mechanical energy, and vice-versa, is the workhorse in a drive system. Industrial drive applications are broadly classified into constant-speed and variable-speed drives. Traditionally, AC machines with a constant frequency sinusoidal power supply have been used in constant-speed applications, whereas DC machines were preferred for variable-speed drives. DC machine drive converter and controls are simple and the machine torque response is very fast. Disadvantages are higher cost, higher rotor inertia and maintenance problems with commutator and brushes and do not permit the machine to operate in dirty and explosive environments. The AC motors are light in weight, inexpensive and require less maintenance compared with DC motors. AC motors are now employed in variable-speed drives due to the development of semiconductor converters employing thyristors, power transistors, IGBTs and GTOs.

The most widely used AC motors are Induction motors and Synchronous motors. Switching power converters offer an easy way to regulate both the frequency and magnitude of the voltage and current applied to a motor. It results in higher efficiency and performance. The most common principle is the constant V/f principle, which requires that the magnitude and frequency of the voltage applied to the stator of a motor maintain a constant ratio. The magnitude of the magnetic field in the stator is kept at an approximately constant level throughout the operating range. So constant torque producing capability is maintained. When transient response is critical, switching power converters also allow easy control of transient voltage and current applied to the motor to achieve faster dynamic response. The constant V/f principle is considered for this application.

Synchronous motor drives are close competitors to induction motor drives in many industrial applications. They are generally more expensive than induction motor drives, but the advantage is that the efficiency is higher, which tends to lower the life cycle cost.

In a permanent magnet synchronous motor, the dc field winding of the rotor is replaced by a permanent magnet. PMSM has a higher full load efficiency and power factor than an induction motor. Because of low losses, it is

possible to make motors with very high power density and torque to inertia ratios

## XII. MATLAB/SIMULINK MODEL OF SVPWM INVERTER FED AC DRIVE

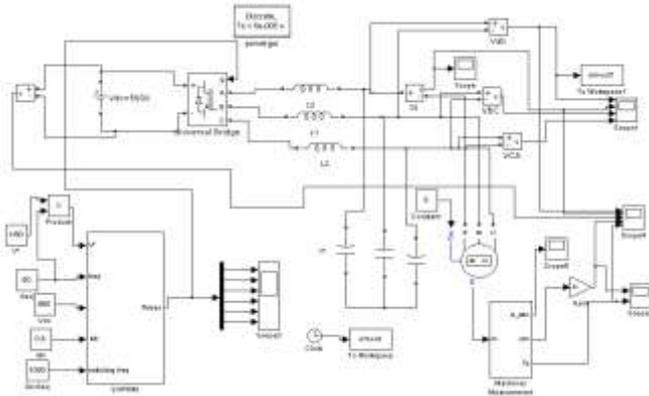


Fig15. Simulink block diagram of SVPWM inverter fed AC drive

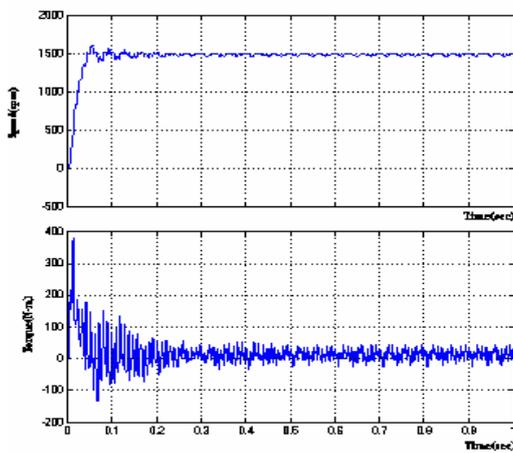


Fig 16. Speed & Torque response under no load for IM drive

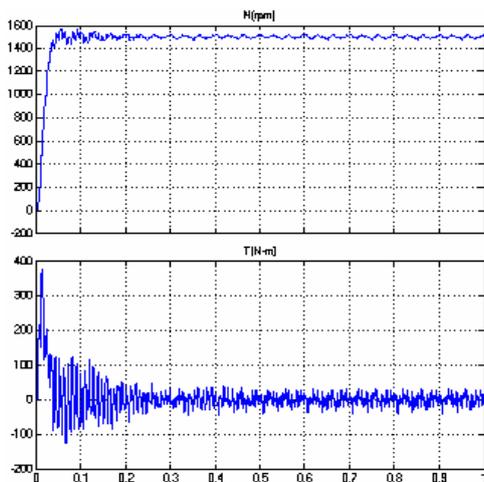


Fig 17. Speed & Torque response under full load for IM drive

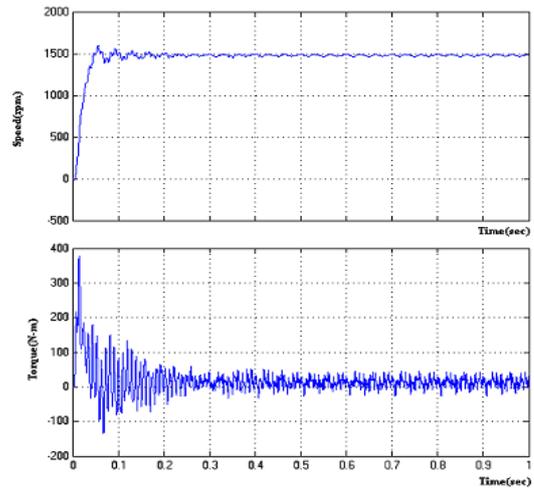


Fig 18. Speed & Torque response under no load for PMSM drive

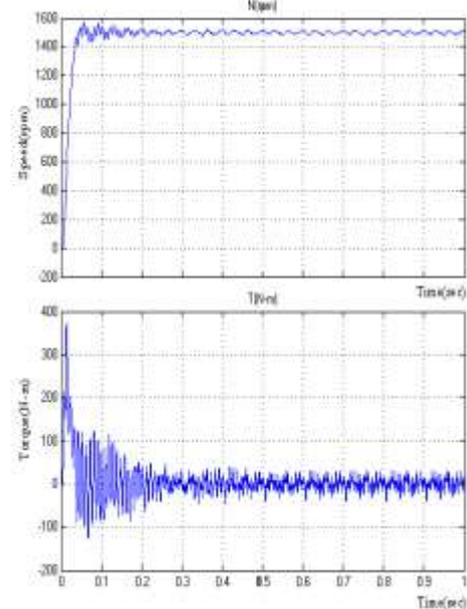


Fig 19 Speed & Torque response under full load for PMSM drive

Table 3: SVPWM inverter fed AC Drive under no load

## XIII. CONCLUSION

From the simulation results it is observed that

THD of output line voltage for SVPWM technique without filter is 30.47%. As the aim is to get low THD with sinusoidal output voltage waveform it is proposed to use an LC filter.

THD of output line voltage for SVPWM technique using filter is 4.86%. It is observed that the THD of the output voltage waveform is reduced using filters.

This sinusoidal inverter output under variable frequency operation with V/f ratio constant was fed to an Induction motor and a PMSM drive. It is observed that the PMSM drive draws lesser stator current compared to its equivalent output power rated induction motor. It is observed from the simulation studies that the speed response

in terms of steady state error and rise time of the IM and PMSM was almost same at the same stator frequency.

Table 3: SVPWM inverter fed AC drive under No load

S.No	Parameters	Induction Motor	PMSM	Remarks
1	VRY(V)	400	400	Same
2	F(Hz)	50	50	Same
3	I <sub>spk</sub> (A)	7	3.8	I <sub>spk</sub> (IM) = 45.72 %I <sub>fl</sub> peak I <sub>spk</sub> (PMSM) = 23.57 %I <sub>fl</sub> peak
4	TL(N-m)	0	0	Rated torque
5	Reference speed(rpm)	1500	1500	Same
6	Steady state Error (rpm)	100	105	Almost same
7	Rise Time(sec)	0.07	0.06	Nearly same

Table 4: SVPWM inverter fed AC drive under full load

S.No	Parameters	Induction Motor	PMSM	Remarks
1	VRY(V)	400	400	Same
2	F(Hz)	50	50	Same
3	I <sub>spk</sub> (A)	13.5	10.88	I <sub>spk</sub> (IM) = 88.18 %I <sub>fl</sub> peak I <sub>spk</sub> (PMSM) = 67.48 %I <sub>fl</sub> peak
4	TL(N-m)	49.73	67.27	Rated torque
5	Reference speed(rpm)	1500	1500	Same
6	Steady state Error (rpm)	0	0	Almost same
7	Rise Time(sec)	0.17	0.14	Nearly same

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