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Simulation and Performance of Induction Motor Drive Using SVPWM Technique

B.Sujatha[1] | D.Sree Meghana[2]

[1]Assistant Professor, Department of Electrical and Electronics Engineering, BVRITH college of Engineering for Women, Nizampet, Hyderabad, India.
[2]UG Student, Department of Electrical and Electronics Engineering, BVRITH college of Engineering for Women, Nizampet, Hyderabad, India.

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ABSTRACT

Due to the advancement in power semiconductor devices and microprocessors, PWM inverters have been used in today’s motor drives. The most commonly used PWM techniques are Sinusoidal pulse width modulation (SPWM) and Space vector pulse width modulation (SVPWM). Sinusoidal PWM technique is complex in digital implementation. Space Vector Pulse Width Modulation (SVPWM) is a digital technique, which increases the output voltage capability and increases DC bus utilization voltage. The output of the inverter can contain large number of voltage harmonics. As aim is to get low THD with sinusoidal output voltage waveform it is proposed to use LC filter. Sinusoidal output waveform is fed to an Induction Motor (IM). An AC drive system performance was simulated and evaluated for variable speed operation from no-load to rated speed under constant torque operation. The performance of motors has been analyzed from no load and full load in this paper. The focus was based on the simulation of power circuits using MATLAB/SIMULINK software.

KEYWORDS: *PWM, SPWM, SVPWM, THD, IM*

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I. INTRODUCTION

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. 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.

To achieve voltage control within in the inverter and to reduce harmonic content in the output voltages, PWM inverters are used.PWM inverter powered motor drives offer better efficiency and higher performances compared to fixed frequency motor drives.

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 higher switching losses and Complexity in digital implementation.

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) is 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. 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.

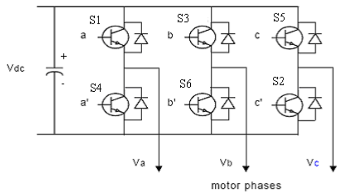


FIGURE 1-Three-phase Voltage source PWM Inverter

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:

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

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

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

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

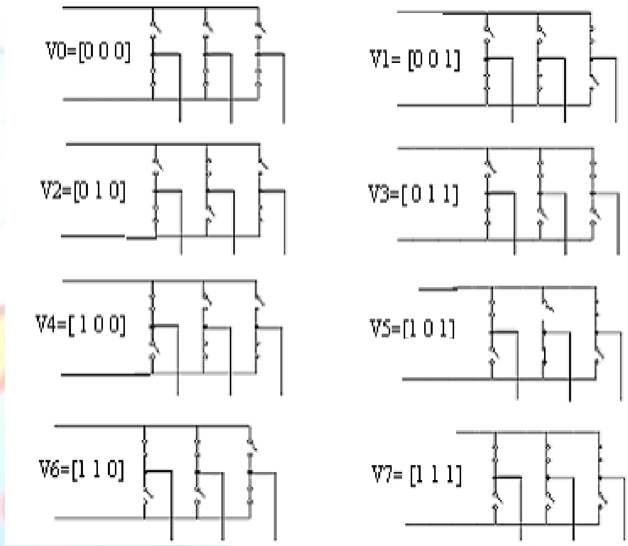


Figure 2-Inverter voltage vectors (V_0 to V_7)

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	Van	Vbn	Vcn	Vab	Vbc	Vca
V0	0	0	0	0	0	0	0	0	0
V1	1	0	0	2/3	-1/3	-1/3	1	0	-1
V2	1	1	0	1/3	1/3	-2/3	0	1	-1
V3	0	1	0	-1/3	2/3	-1/3	-1	1	0
V4	0	1	1	-2/3	1/3	1/3	-1	0	1
V5	0	0	1	-1/3	-1/3	2/3	0	-1	1
V6	1	0	1	1/3	-2/3	1/3	1	-1	0
V7	1	1	1	0	0	0	0	0	0

(Note that the respective voltage should be multipied by Vdc)

IV. SPACE VECTOR CONCEPT

The three phase reference phase voltages Va, Vb, and Vc 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 (α-ß). 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.
From the Fig 3, the relation between these two reference frames is below

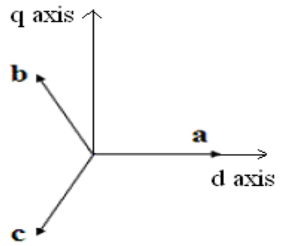


Figure 3-The relationship of abc reference frame & stationary dq reference frame

$$f_{dqo} = K_s\, f_{abc} \quad \ldots(3$$

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 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° 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 (Vref) is applied to calculate the angular position of the voltage space(α). The six sectors are selected by an angle α.

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.

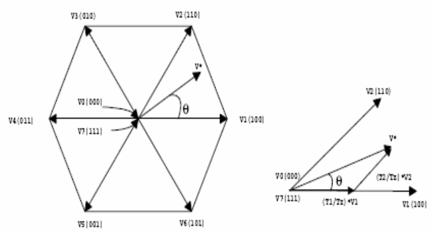


Figure 4-Basic switching vectors and sectors

V. SVPWM can be implemented by the following Steps

Step 1: Determination of V_d, V_q, V_{ref}, and angle (α)
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 (α)

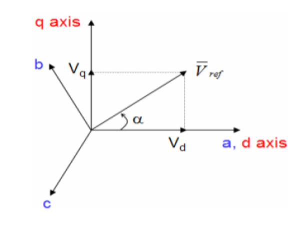
V_d, V_q, V_{ref}, and angle (α) can be calculated as follows

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

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

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

$$\therefore \left|\overline{V}_{ref}\right| = \sqrt{{V_d}^2 + {V_q}^2}$$



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

Figure 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

$$\int_0^{T_z} \overline{V}_{ref} = \int_0^{T_1} \overline{V}_1 dt + \int_{T1}^{T_1+T_2} \overline{V}_2 dt + \int_{T_1+T_2}^{T_z} \overline{V}_0$$

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

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

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

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

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

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

- Switching time duration at any Sector

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

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

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

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

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

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

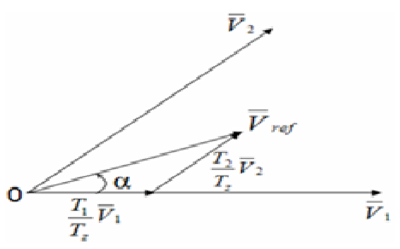
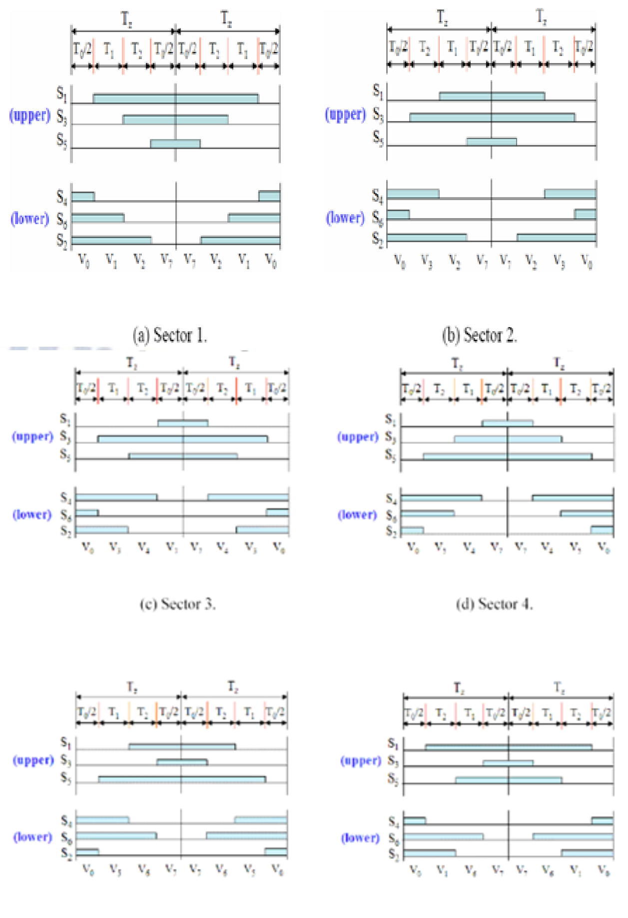


Figure 6-Reference vector as a combination of adjacent vectors at sector1

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



(a) Sector 1. (b) Sector 2.

(c) Sector 3. (d) Sector 4.

(e) Sector 5. (f) Sector 6.

Figure 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.

Table2: Switching time calculation for each sector

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	$S_1 = T_1 + T_2 + T_0/2$ $S_3 = T_0/2$ $S_5 = T_1 + T_0/2$	$S_4 = T_0/2$ $S_6 = T_1 + T_2 + T_0/2$ $S_2 = T_2 + T_0/2$

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

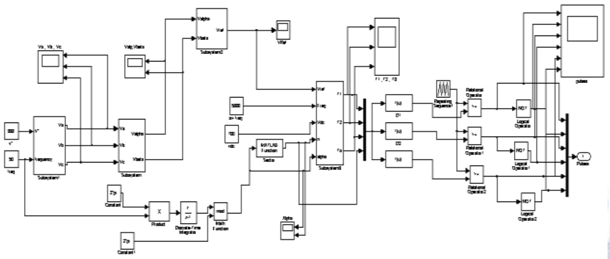


Figure 8-Simulink /subsystem block diagram of SVPWM for two level inverter

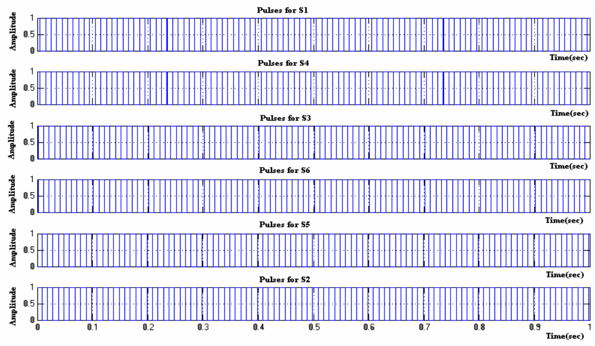


Figure 9-PWM pulses for SVPWM technique

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.

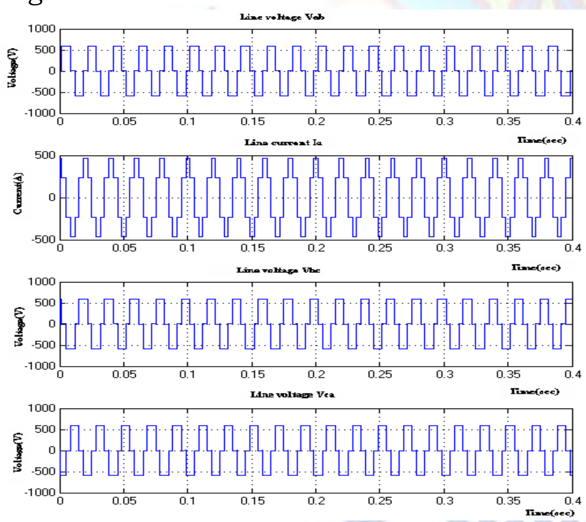


Figure 10-Simulation Results of Output line voltages and Line current for SVPWM inverter without filter

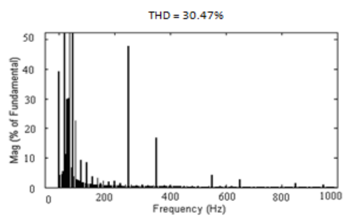


Figure 11-THD of Output line voltage for SVPWM inverter without filter

VII. 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 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 output. The capacitance offers a shunt path for the harmonic current.

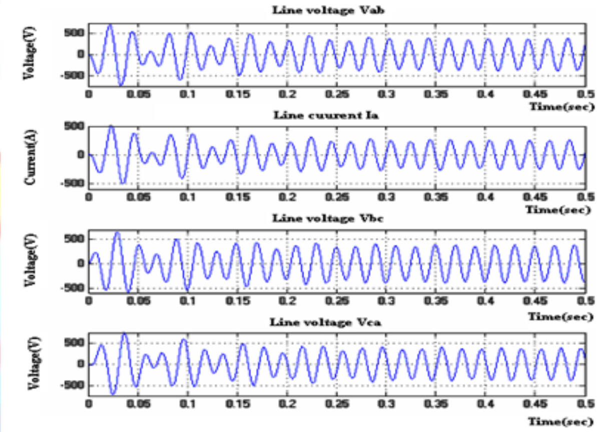


Figure 12-Simulation Results of Output line voltages and Line current for SVPWM inverter with filter

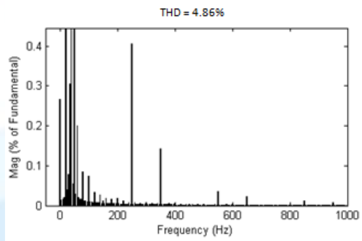


Figure13-THD of Output line voltage for SVPWM inverter with filter

VIII. AC MACHINES FOR DRIVES

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, where as DC machines were preferred for variable-speed drives. DC machine drive converter and controls are simple. But they are higher cost, higher rotor inertia and maintenance problems with commutator and brushes. 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.

Switching power converters regulates both frequency and magnitude of the voltage and current applied to a motor. It results higher efficiency and performance. The most common 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 constant level throughout the operating range. 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.

IX. MATLAB/SIMULINK MODEL OF SVPWM INVERTER FED IM DRIVE

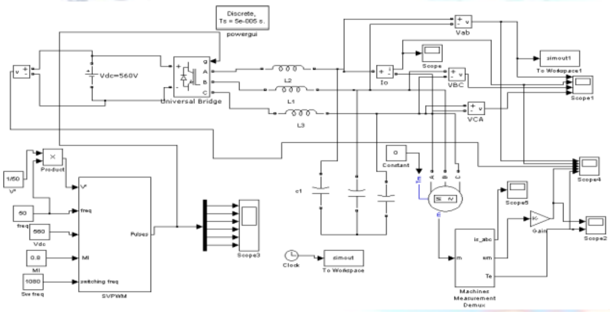


Figure14-*Simulink block diagram of SVPWM inverter Fed IM drive*

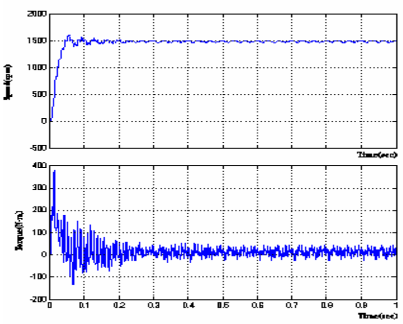


Figure 15-Speed &Torque response under no load for IM drive

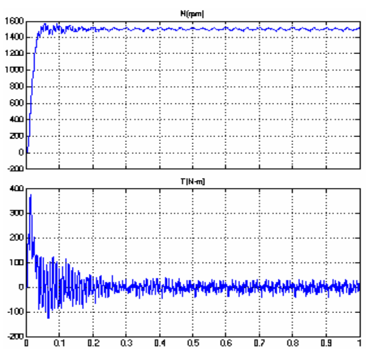


Figure16-Speed &Torque response under full load for IM drive

X. CONCLUSION

From the simulation results it is observed that THD of output line voltage 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 using filter is 4.86%. It is observed that the THD of the output voltage waveform is reduced using filters.

The sinusoidal inverter output under variable frequency operation with V/f ratio constant was fed to an Induction motor drive. It is observed that the IM drive draws lesser steady state error under full load condition.

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