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# Comparative Study of SPWM and SVPWM Based Closed Loop Speed Control of PMSM

**Sudesh Nain**

Assistant Professor, Dept. of EE, Swami Devidayal Institute of Engg. & Technology, Barwala, Haryana, India

**ABSTRACT:** The PMSM motors have been increasingly applied in drive applications due to its simple structure and efficiency. With advances in solid-state power electronic devices and microprocessors, various inverter control techniques employing pulse width modulation (PWM) techniques are becoming increasingly popular in AC motor drive application. These PWM-based drives are used to control both the frequency and the magnitude of the voltage applied to motors. Various PWM techniques have been developed in past two decades. This paper analysis the closed loop speed control of a PMSM with the two PWM techniques namely, sinusoidal PWM and Space vector PWM. Both the control scheme is simulated in the Matlab/Simulink software environment. The simulation result shows that the speed control of PMSM with SVPWM is better than with SPWM technique. It also shows that the whole control system has less harmonic distortion and lower switching losses.

**KEYWORDS:** PMSM, Sinusoidal PWM, Space Vector PWM

## I.INTRODUCTION

Pulse-width modulation (PWM) is a technique where the duty ratio of a pulsating waveform is controlled by another input waveform. The output frequency and voltage is controlled electronically by controlling the width of the pulses of voltage of motor. PWM is commonly used in applications like motor speed control, converters, audio amplifiers etc. For example, it is used to reduce the total power delivered to a load without losses which normally occurs when a power source is limited by a resistive element. PWM is used to adjust the voltage applied to the motor and changing the duty ratio of the switches changing the speed of the motor. There is no single PWM method that is the best suited for all applications and with advances in solid-state power electronic devices and microprocessors. Various pulse width modulation (PWM) techniques have been developed for industrial applications. For these reasons, the PWM techniques have been the subject of intensive research since 1970s.This techniques provides the sequence of width modulated pulses to control power switches. The main advantage of PWM is that power loss in the switching devices is very low. When a switch is off there is practically no current, and when it is on, there is almost no voltage drop across the switch. Power loss, being the product of voltage and current, is thus in both cases close to zero. PWM works also well with digital controls, which, because of their on/off nature,

In this paper the closed loop speed control of a PMSM drive with sinusoidal PWM and Space Vector PWM is analysed. The simulation result shows that SVPWM is a better technique than SPWM.

## II PERMANENT MAGNET SYNCHRONOUS MOTOR CONFIGURATIONS

A permanent magnet synchronous motor (PMSM) is a motor that uses permanent magnets to produce the air gap magnetic field rather than using electromagnets. These motors have significant advantages, attracting the interest of researchers and industry for use in many applications. The PM synchronous motor is a rotating electric machine with classic 3-phase stator like that of an induction motor; the rotor has surface-mounted permanent magnets. In this respect, the PM synchronous motor is an equivalent to an induction motor, where the air gap magnetic field is produced by a permanent magnet, so the rotor magnetic field is constant.PM synchronous motors offer a number of advantages in designing modern motion-control systems. The use of a permanent magnet to generate substantial air gap magnetic flux makes it possible to design highly efficient PM motors. The embedment of magnets in the rotor decides their types. PMSM can be broadly classified on the basis of direction of field flux as follows [1]:

1. Radial field: - Direction of flux is along the radius of motor.
2. Axial field: - Direction of flux is parallel to rotor shaft.

The magnets can be mounted in many ways on the rotor. The radial field version is shown in Figure (1).

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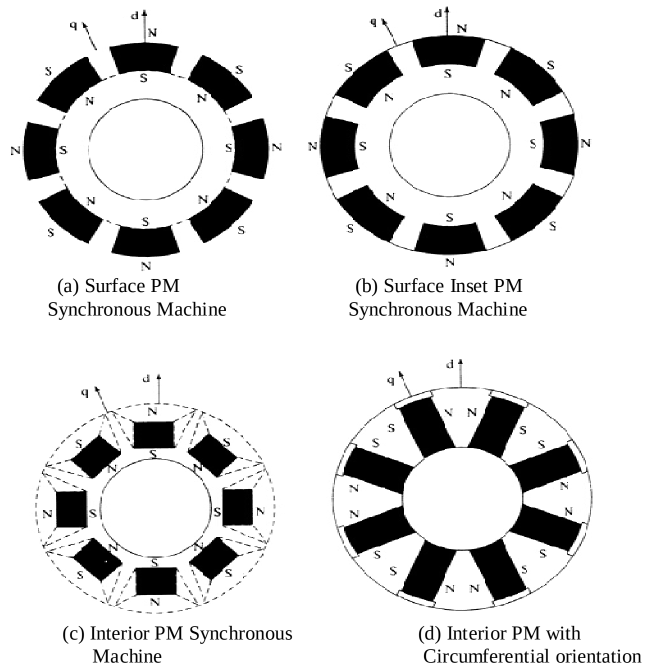


Figure1. Different Configurations of PMSM

The high power density PMSM has surface PMs with radial orientation where as IMPMs are used for high speed applications. Figure 1(a) shows that the magnets are mounted on the surface of outer periphery of the rotor, provides higher air gap flux density and motors are generally known as surface mounted PMSM. These motors are not used for high speed applications generally greater than 300rpm.

Figure 1(b) shows magnets placed in the grooves of the outer periphery provides a uniform cylindrical surface. These are more robust mechanically as compared with surface mounted machines.

Figure 1(c) and Figure 1(d) shows the magnet mounted in the middle of the rotor laminations in radial and circumferential orientations respectively. This construction is used for high speed applications. This type of motor is very complex in construction as compare to surface mounted PMSM. These machines are generally known as interior PMSM [1].

*A. Equations of Permanent Magnet Synchronous Motor*

The model of PMSM without damper winding has been developed on the rotor reference frame using the following assumptions [2]:

1. Saturation is neglected.
2. The induced EMF is sinusoidal.
3. Eddy Currents and hysteresis losses are negligible.
4. There are no field current dynamics.

Voltage equations are given by:

$$V_q = R_s i_q + w_r \lambda_d + \rho \lambda_q \qquad (1)$$

$$V_d = R_s i_d - w_r \lambda_q + \rho \lambda_d \qquad (2)$$

Flux linkages are given by:

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$$\lambda_q = L_q i_q \qquad (3)$$

$$\lambda_d = L_d i_d + \lambda_f \qquad (4)$$

Substituting equation (3) and (4) into (1) and (2)

$$V_q = R_s i_q + w_r (L_d i_d + \lambda_f) + \rho L_q i_q \qquad (5)$$

$$V_d = R_s i_d - w_r L_q i_q + \rho (L_d i_d + \lambda_f) \qquad (6)$$

Arranging equations (5) and (6) in matrix form

The developed torque motor is given by

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\lambda_d i_q - \lambda_q i_d) \qquad (8)$$

The mechanical torque equation is

$$T_e = T_L + B w_m + J \frac{d w_m}{dt} \qquad (9)$$

Solving for the rotor mechanical speed from equation (9)

$$w_m = \int \left(\frac{T_e - T_L - B w_m}{J}\right) dt \qquad (10)$$

And

$$w_m = w_r \frac{P}{2} \qquad (11)$$

In the above equations $w_r$ is the rotor electrical speed where as $w_m$ is the rotor mechanical speed.

The dynamic dq modelling is used for the study of the motor during transient and steady state. It is done by converting the three phase voltages and current to dqo variable by using Park's transformation. Converting the phase voltage variable $V_{abc}$ to $V_{dqo}$ in rotor reference frame the following equations are obtained [2]:

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (12)$$

The inverse transformation is given by :

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - 2\pi/3) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + 2\pi/3) & 1 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} \qquad (13)$$

Where

$\lambda_f$ = rotor magnetic flux

$L_d$ = d-axis stator inductance

$L_q$ = q-axis stator inductance

$R_s$ = stator resistance

$T_e$ = electromagnetic torque

$T_L$ = load torque

$\omega_m$ = mechanical speed

$\omega_r$ = angular speed

$J$ = moment of inertia

$B$ = coefficient of friction

$p$ = no. of pole

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## III. SINUSOIDAL PULSE WIDTH MODULATION (SPWM)

The sinusoidal pulse-width modulation (SPWM) technique produces a sinusoidal waveform by filtering an output pulse waveform with varying width. The desired output voltage is achieved by varying the frequency and amplitude of a reference or modulating voltage. The variations in the amplitude and frequency of the reference voltage change the pulse-width patterns of the output voltage but keep the sinusoidal modulation. As shown in Figure 2, a low-frequency sinusoidal modulating waveform is compared with a high-frequency triangular waveform [3].

In three-phase SPWM, a triangular voltage waveform($V_T$) is compared with three sinusoidal control voltages (Va, $V_b$, and Vc), which are 120° out of phase with each other and the relative levels of the waveforms are used to control the switching of the devices in each phase leg of the inverter.

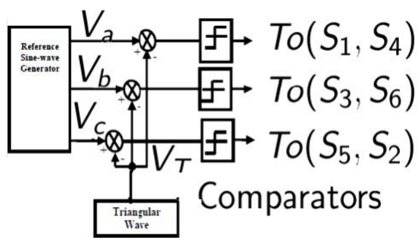


Figure 2 Control Signal Generators for SPWM

A six-step inverter is composed of six switches $S_1$ through $S_6$ with each phase output connected to the middle of each inverter leg as shown in Figure 3. The outputs of the comparators in Figure 2 form the control signals for the three legs of the inverter. Two switches in each phase make up one leg and open and close in a complementary fashion.

That is, when one switch is open, the other is closed and vice-versa. The output pole voltages $V_{ao}$, $V_{bo}$, and $V_{co}$ of the inverter switch between $-V_{dc}/2$ and $+V_{dc}/2$ voltage levels where $V_{dc}$ is the total DC voltage [3].

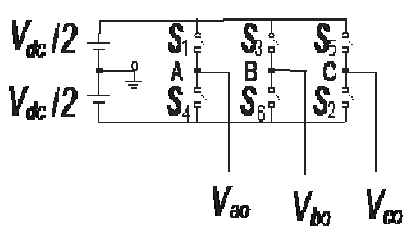


Figure 3 Three-Phase Sinusoidal PWM Inverter

### A. SIMULATION MODEL OF SPWM

Figure 4 shows the simulation model of SPWM for the closed loop speed control of permanent magnet synchronous motor. Here speed is set at 700 r.p.m which is shown by the first block in the system. The proportional integral controller (PI) is used to get the stability in the output which is shown by the second block in the system. In the third block the dq components are converted into abc by using parks transformation. In the next block we use SPWM which designed as below. Figure 5 shows the simulation model of SPWM inverter. Here the phase current $I_{abc}$ and $I_{ref}$ are given as input. These are compared by using the comparators. The output of the comparators is fed to the motor.

The SPWM technique treats each modulating voltage as a separate entity that is compared to the common carrier triangular waveform. A three-phase voltage set ($V_a$, $V_b$, and $V_c$) of variable magnitude is compared in three separate comparators with a common triangular wave of fixed amplitude as shown in the Fig 5. The output of the comparators form the control signals for the three legs of the inverter composed of switch pairs respectively. From these switching signals and the DC bus voltage, PWM phase to neutral voltages can also obtained.

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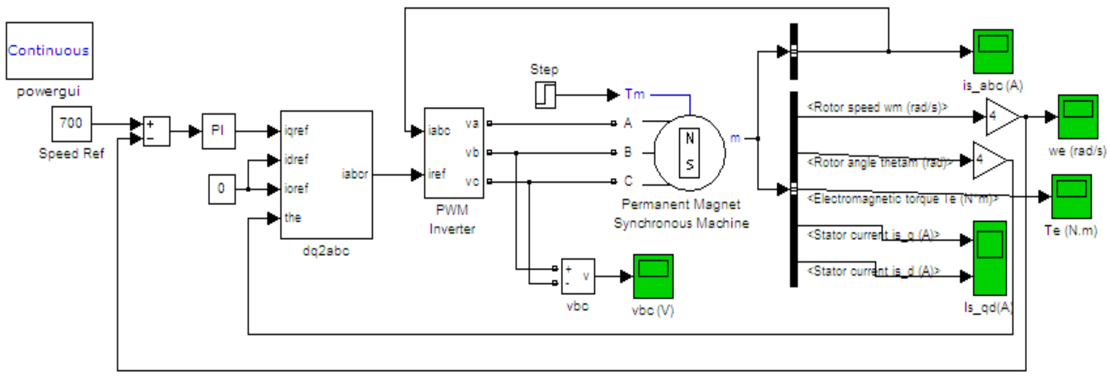


Figure 4 Simulation Model of SPWM Based Speed Control of PMSM

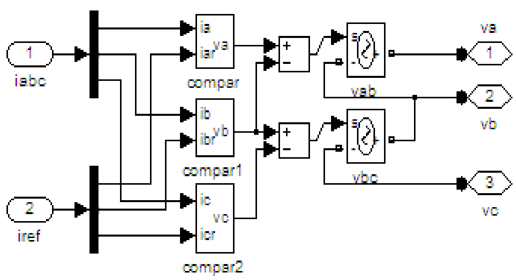


Figure 5 Simulation Model of PWM Inverter

## B. SIMULATION RESULTS OF SPWM

The SVPWM is designed by using MATLAB/SIMULINK software. After the simulation of SPWM model the results can be obtained under two categories:

1. When Load Torque is increasing
2. When Load Torque is decreasing

1. When Load Torque is Increasing

When the sampling period of SPWM is 0.0005s, the DC voltage is 310V, the carrier frequency of SPWM is 20Hz and the reference speed is set at 700 rpm, then this signal is applied to the PMSM. The parameter of the speed regulator is set at $K_i$ =3 and $K_p$=40. The simulation step is 0.04s and the simulation time is 0.2s.At t=0.02s a load torque of 1 Nm is applied. The speed is slightly fluctuated and little change in current drawn by motor. But if we increase the load torque from 1 to 3 Nm at t=0.04s the speed is still constant and phase current is increases. The variation of phase currents, load torque, speed and with the time is shown in Figure 6,7, and 8.

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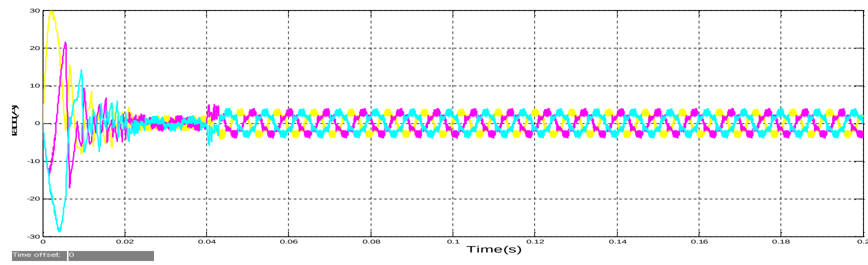


Figure 6 Phase Current Vs Time

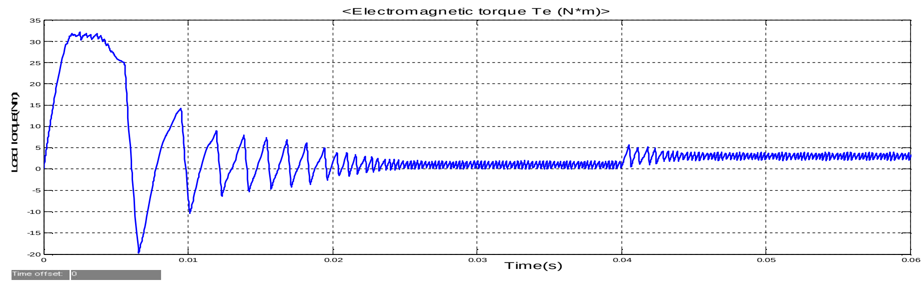


Figure 7 Load Torque Vs Time

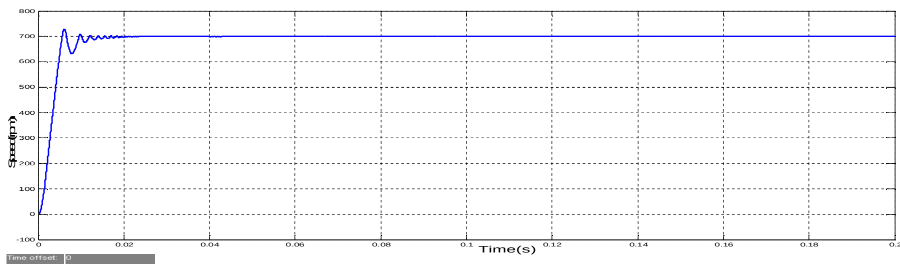


Figure 8 Speed Vs Time

As shown in fig. 6, 7 and 8, at t=0.02s the load torque of 1 Nm is applied then there is slight change in current drawn by the motor and the speed of the motor.But after t=0.04s the load torque is increases from 1 Nm to 3 Nm the current drawn by the motor is increases but the speed of the motor is constant. In this way as the load torque increases the current drawn by the motor increases but the speed of the motor is constant.

2. When Load Torque is Dcreasing

But if decrease the load torque then current drawn by the motor is decreases but the speed is still constant. The variation of phase currents, load torque, speed with time is shown in Figure 9, 10 and 11.

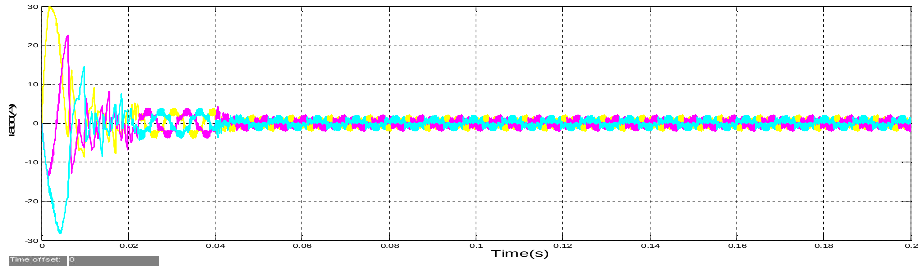


Figure 9 Phase Current Vs Time

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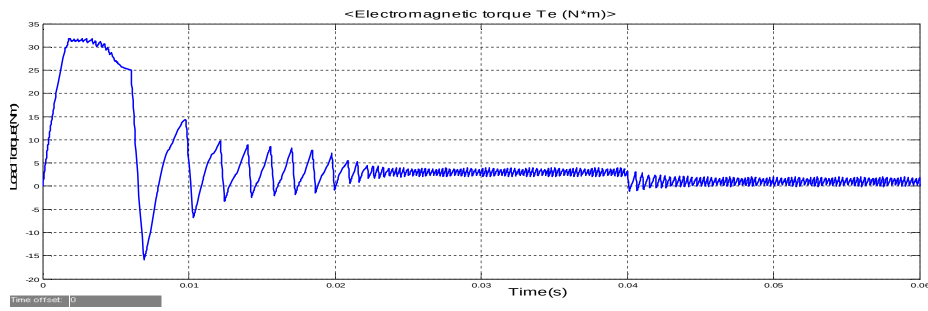


Figure 10 Load Torque Vs Time

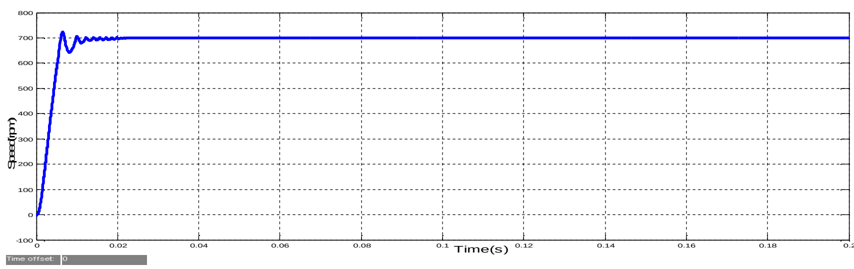


Figure 11 Speed Vs Time

As shown in fig. 9,10 and 11 at t=0.02s a load torque of 3 Nm is applied then a slight change in current drawn by the motor and the speed of the motor. But as the load torque is decreases from 3 Nm to 1 Nm at t=0.04s the current drawn by the motor is decreases but the speed of the motor is constant.

Hence as the load is increases the current drawn by the motor is increases the speed of the motor is constant and vice versa. In this way the speed control of PMSM is achieved by using SPWM.

## IV. SPACE VECTOR PULSE WIDTH MODULATION (SVPWM)

Space vector control is the process to generate a PWM modulation signal for PMSM voltage signal. In this technique the inverse Park's transform has been folded into the SVM routine which simplifies the equation. Each of the three output of inverter can be in one of the two states which allows for $2^3$ =8 possible states of output as shown in Table (I).

SVPWM subjects to generate a voltage vector which is close to a reference circle through different switching modes of inverter [4]. Figure (12) shows the basic diagram of three phase VSI model.

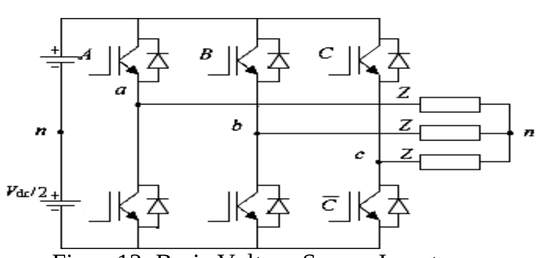


Figure12. Basic Voltage Source Inverter

The space vector of output voltage of inverter can be given as [4]:

$$V_A(S_A,S_B,S_C) = 2V_{dc}(S_A+\alpha S_B+\alpha^2 S_C)/3 \qquad (14)$$

Where $V_{dc}$ is DC bus voltage of inverter and $\alpha$ is $e^{j/20}$.

If the state of upper and lower arm switches is considered 1 and 0 respectively, then the on-off state will have eight possible combination voltage space vectors as shown in Figure 13. T-refers to the operation time of two non-zero voltage vectors in the same zone. $V_0(000)$ and $V_7(111)$ are called zero voltage space vector, while remaining six vectors are known as effective vectors with magnitude of $2V_{dc}/3$.

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| Inverter states | $S_A$ | $S_B$ | $S_C$ | $\frac{V_A}{V_{dc}}$ | $\frac{V_B}{V_{dc}}$ | $\frac{V_C}{V_{dc}}$ |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 1 | -1/3 | -1/3 | 2/3 |
| 2 | 0 | 1 | 0 | -1/3 | 2/3 | -1/3 |
| 3 | 0 | 1 | 1 | -2/3 | 1/3 | 1/3 |
| 4 | 1 | 0 | 0 | 2/3 | -1/3 | -1/3 |
| 5 | 1 | 0 | 1 | 1/3 | -2/3 | 1/3 |
| 6 | 1 | 1 | 0 | 1/3 | 1/3 | -2/3 |
| 7 | 1 | 1 | 1 | 0 | 0 | 0 |

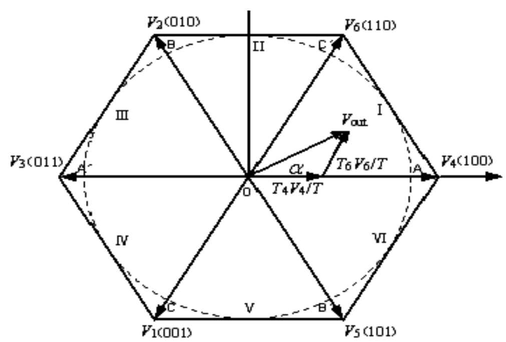


Figure 13.Voltage Space Vector Diagram

### A. **SIMULATION MODEL OF SVPWM**

Figure 14 shows the simulation model for the closed loop speed control of permanent magnet synchronous motor. Here speed is set at 700 r.p.m which is shown by the first block in the system. The proportional integral controller (PI) is used to get the stability in the output which is shown by the second block in the system. In the third block the dq components are converted into abc by using parks transformation. In the next block we use SVPWM which is connected to a PWSM. The parameter of the motor which used in this project are shown in table 2 [4].Here as the load is increases the torque drawn by the motor is also increases but the speed is constant and as the load is decreases the torque drawn by the motor is also decreases but the speed is still constant. In this way the speed control of PMSM is achieved by using SVPWM.

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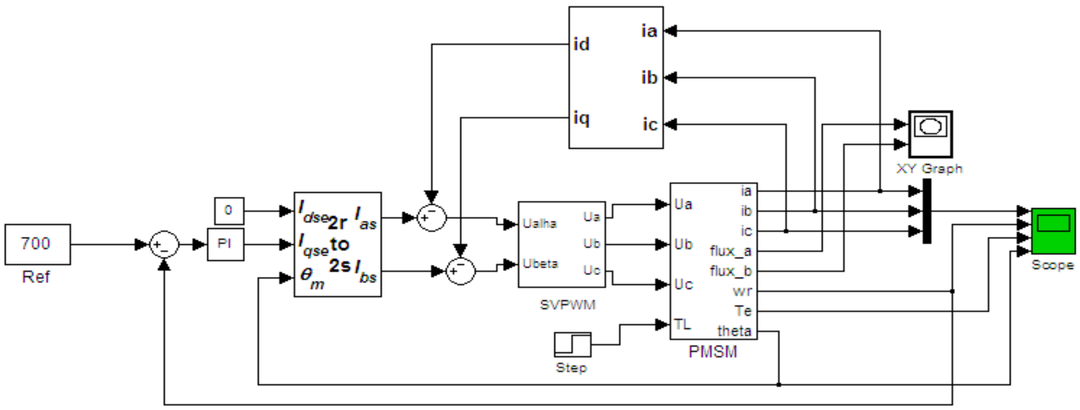


Figure 14 Simulation Model of SVPWM Based Speed Control of PMSM

**Table 2** Parameter of PMSM

| Parameter Name | Parameter Range |
|---|---|
| Power Range | 110W to 550W |
| Moment of Inertia | 0.8 $kgm^2$ |
| Rated Torque | 3.5Nm |
| Voltage Range | 76V to 380V |
| Rated Current | 1.5A |
| Stator Resistance | 2.875 Ω |
| Stator Inductance | 8.5mH |

## B. SIMULATION RESULTS OF SVPWM

The SVPWM is designed by using the MATLAB/SIMULINK software. After the simulation of SVPWM model results can be obtained under two categories:

1. When load torque is increasing.
2. When load torque is decreasing.

1. When Load Torque is increasing

When the sampling period of SVPWM is 0.0005s, the DC voltage is 310V, the carrier frequency of SVPWM is 20Hz and the reference speed is set at 700 rpm, then this signal is applied to the PMSM. The parameter of the speed regulator is set at $K_i$ =40 and $K_p$=500. The simulation step is 0.15s and the simulation time is 0.3s.At t=0.05s a load torque of 5 Nm is applied. The speed is slightly fluctuated and little change in current drawn by motor. But if we increase the load torque from 5 to 8 Nm at t=0.15s then the speed is still constant and phase current is increases. The variation of phase currents ,load torque, speed with the time is shown in Figure 15,16,17.

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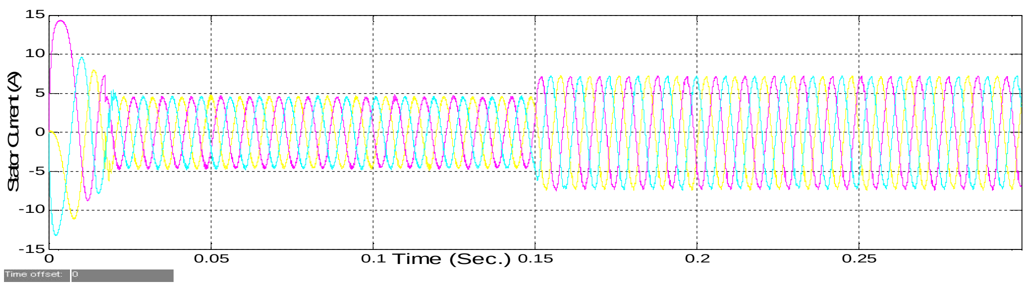


Figure 15 Phase Current Vs Time

As shown in Fig. 15 and Fig. 16, at t=0.05s load torque of 5 Nm is applied then there is slight change in current drawn by the motor. But at t= 0.15s as the load torque is increases from 5 to 8 Nm the current drawn by the motor is also increases.

As shown in Fig. 17, at t=0.05s there is slight variation in speed of the motor. But after it ,at t=0.15s as the load torque is increases from 5 to 8 Nm then the speed is constant. Here the speed is set at 700 rpm. In this way as load torque is increases the current drawn by the motor is increases but the speed is constant.

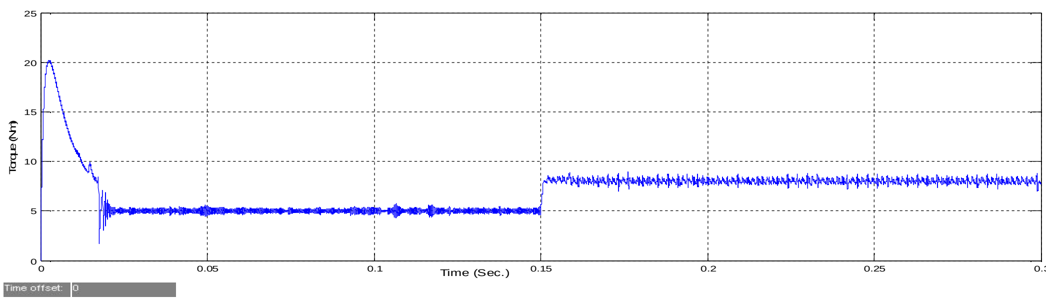


Figure 16 Load Torque Vs Time

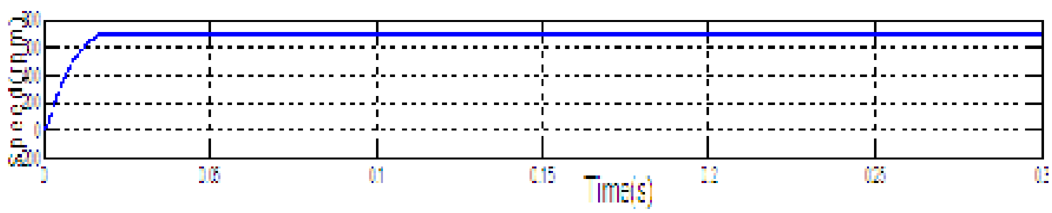


Figure 17 Speed Vs Time

2. When Load Torque is decreasing: - But if decrease the load then current drawn by the motor is decreases but the speed is still constant. The variation of phase currents, load torque, speed and rotor angle with time is shown in Figure 18, 19 and 20.

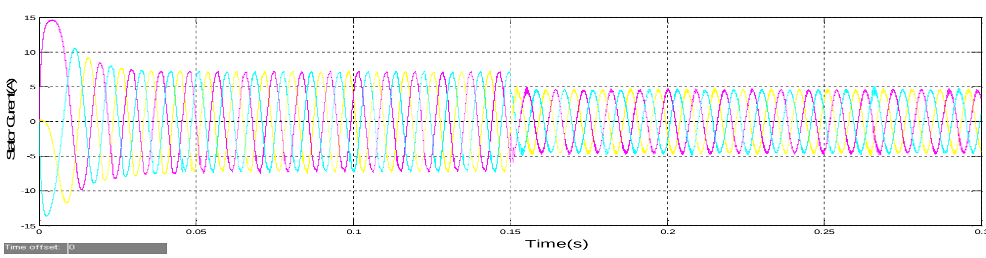


Figure 18 Phase Current Vs Time

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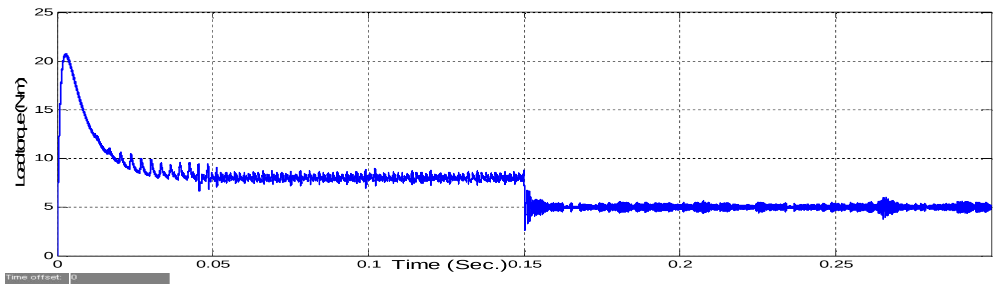


Figure 19 Load Torque Vs Time

At t=0.05s as the load torque is set at 8 Nm there is no change in current drawn by the motor . But at t=0.15s as the load torque is decreases from 8 to 5 Nm then the current drawn by the motor is also decreases which is shown above.

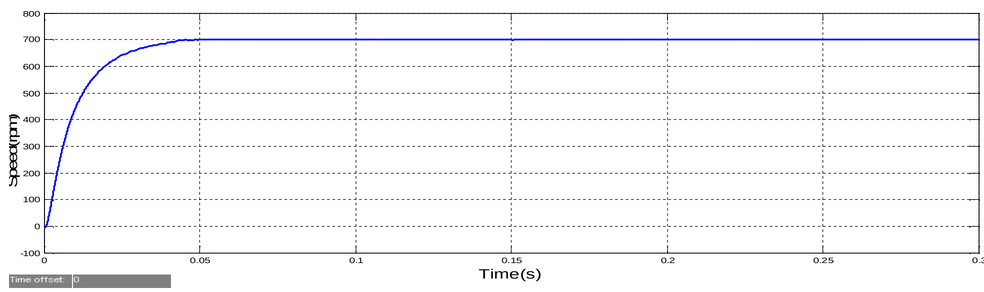


Figure 20 Speed Vs Time

At t=0.05s the load torque is 8 Nm the speed is constant as shown in fig. 20. But at t=0.15s as the load torque is decreases from 8 to 5 Nm but the speed is still constant at 700 rpm. In this way as the load torque is decreases the current drawn by the motor is decreases but the speed is still constant at 700 rpm.In the way the speed control of PMSM is achieved by using SVPWM technique.

## V. COMPARISON

A fast fourier transform (FFT) analysis in MATLAB is used to conduct the harmonic analysis. The harmonic spectrum of the inverter voltage waveforms of these techniques are presented with the different modulation indices. Figure 21 and Figure 22 shows the harmonic spectrum of inverter voltage of SVPWM and SPWM techniques. It is clear from the figures that SVPWM produce less harmonic distortion as compared to SPWM. Hence SVPWM is better technique for the closed loop speed control of PMSM.

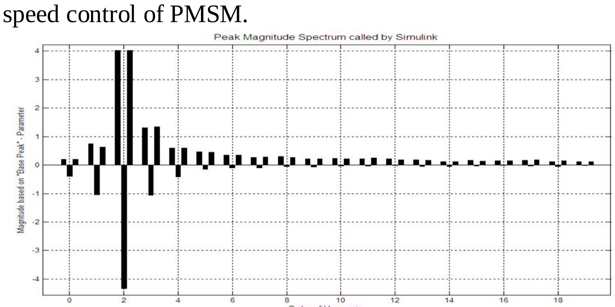


Fig. 21 Harmonic Spectrum of SVPWM

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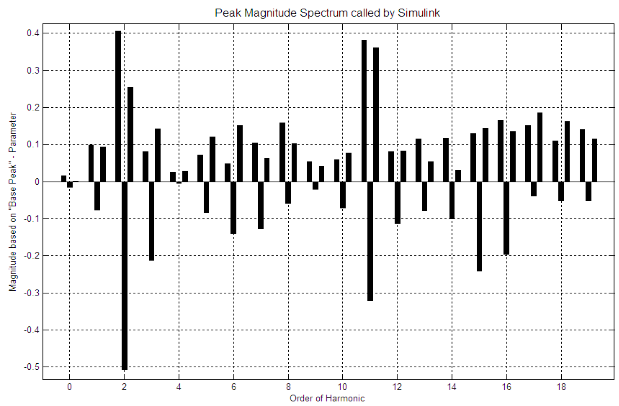


Fig. 22 Harmonic Spectrum of SPWM

## VI. CONCLUSION

This paper has evaluated two different PWM technique, namely SVPWM and SPWM. Here the simulink models for two techniques have been developed and tested in the MATLAB/SIMULINK environment. As seen from the simulation results, the SVPWM has a superior performance as compared to SPWM. The SPWM technique is very popular for industrial converters. It is the easiest modulation scheme to uderstand and implement. This technique can be used in single-phase and three-phase inverters.The SVPWM technique can only be applied to a three-phase inverter and it increases the overall system efficiency. The SVPWM is used for controlling the switching of the machine side converter. Advantages of this method include a higher modulation index, lower switching losses and less harmonic distortion as compared to SPWM [5]. SVPWM research has been widespread in recent years making it one of the most popular methods for three-phase inverters because it has a higher fundamental voltage output than SPWM for the same DC bus voltage. The SVPWM is significantly better than SPWM by approximately 15.5%. However, the SVPWM technique is complex in implementation.

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## BIOGRAPHY

Miss Sudesh Nain – She received her M. Tech. Degree in Electrical Engineering from Hindu College of Engineering, DCRUST, Murthal India in 2013. At present She is working as Assistant professor in Swami Devidayal Institute of Engineering and Technology, Barwala, Panchkula. She received her B.Tech Degree in Electrical Engineering from Haryana College of technology and Management, K.U.K University, Kurukshetra India in 2011