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# Constant Speed Applications for Permanent Magnet Synchronous Motor Drive by Pulse Width Modulation Technique

**[1]M V Ramana Rao, [2]CH Siva Kumar**
[1]Associate Professor, [2]Associate Professor,

[1]Department of Electrical Engineering, University college of Engineering Osmania University, Hyderabad, Telangana, India
[2]Department of Electrical Engineering, University college of Engineering Osmania University, Hyderabad, Telangana, India

***Abstract :*** The growth in the market of PM motor drives has demanded the need of simulation tools capable of handling motor drive simulations it is important to simulate the inverter fed PMSM drive system so that its characteristics under steady state, transient and abnormal conditions can be predicted. This paper presents the details of the Simulink model of permanent magnet synchronous motor drive system. A control circuit employing pulse width modulation technique has been designed such that the PMSM runs at constant speed irrespective of the load torque applied on it. The performance of the motor is tested for different load torques and the speed is observed to follow the reference speed.

***Index Terms*** **-** IGBT, Constant Speed, Permanent Magnet Synchronous Machine, PWM.

## I. INTRODUCTION

The availability of modern permanent magnets (PM) with considerable energy density led to the development of dc machines with PM field excitation in the 1950s. Introduction of PM to replace electro magnets, which have windings and require an external electric energy source, resulted in compact dc machines. The synchronous machine, with its conventional field excitation in the rotor, is replaced by the PM excitation; the slip rings and brush assembly are dispensed with. This contributed to the development of PM synchronous machine. The permanent magnet machines have numerous advantages over other machines that are conventionally used for ac servo drives. The rare earth and neodymium boron PM machine has a lower inertia when compared with an IM because of the absence of a rotor cage; this makes for a faster response for a given electric torque. In other words, the torque to inertia ratio of these PM machines is higher[1]. The PM machine has a higher efficiency than an induction machine. This is primarily because there are negligible rotor losses in permanent magnet machines; the rotor losses in the IM, however, can be considerable, depending on the operating slip. This discussion is applicable to constant flux operation. The IM requires a source of magnetizing current for excitation. The PM machine already has the excitation in the form of the rotor magnet. The need for magnetizing current and the fact that the IM has a lower efficiency necessitates a larger rated rectifier and inverter for the IM than for a PM machine of the same output capacity. The PM machine is smaller in size than an induction motor of the same capacity. Hence, it is advantageous to use PM machines, especially where space is a serious limitation. In addition, the permanent magnet machine weighs less. In other words, the power density of permanent magnet machines is higher. The rotor losses in a PM machine are negligible compared with those in the induction motor. A problem that has been encountered in the machine tools industry is the transferal of these rotor losses in the form of heat to the machine tools and work pieces, thus affecting the machining operation. This problem is avoided in permanent magnet machines.[2]

## II. MODELING OF PMSM

At any time t, the rotating rotor d-axis makes an angle θr with the fixed stator phase axis and rotating stator mmf makes an angle α with the rotor d-axis. Stator mmf rotates at the same speed as that of the rotor.

Voltage equations are given by following 1 and 2 equations

$$V_q = R_s i_q + \omega_r \lambda_d + \rho \lambda_q \quad \textbf{(1)}$$

$$V_d = R_s i_d - \omega_r \lambda_q + \rho \lambda_d \quad \textbf{(2)}$$

Flux Linkages are given by following 3 and 4 equations

$$\lambda_q = L_q i_q \qquad \textbf{(3)}$$

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

Substituting equations 3 and 4 into 1 and 2, we get following equations 5 and 6.

$$V_q = R_s i_q + \omega_r (L_d i_d + \lambda_f) + \rho L_q i_q \qquad \textbf{(5)}$$

$$V_d = R_s i_d - \omega_r L_q i_q + \rho (L_d i_d + \lambda_f) \qquad \textbf{(6)}$$

Arranging equations 5 and 6 in matrix form we get following equation 7

$$\begin{pmatrix} V_q \\ V_d \end{pmatrix} = \begin{pmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{pmatrix} \begin{pmatrix} i_q \\ i_d \end{pmatrix} + \begin{pmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{pmatrix} \qquad \textbf{(7)}$$

The developed torque motor is given by following equation 8

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

The mechanical Torque equation is given by following equation 9

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

Solving for the rotor mechanical speed from equation 9

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

$$\omega_m = \omega_e \left( \frac{2}{P} \right) \qquad \textbf{(11)}$$

In the above equations $\omega^r$ is the rotor electrical speed where as $\omega m$ is the rotor mechanical speed. Above equations are given with respect to rotor reference frame (i.e. w.r.t d-q axis). Equivalent circuits of the motors are used for study and simulation of motors. From the above voltage equations, the equivalent circuit of the motor can be derived [3][4].

## III. SPEED CONTROL OF PMSM

Many applications, such as robotics and factory automation, require precise control of speed and position. Speed Control Systems allow one to easily set and adjust the speed of a motor. The control system consists of a speed feedback system, a motor, an inverter, a controller and a speed setting device[5]. The purpose of a motor speed controller is to take a signal representing the demanded speed, and to drive a motor at that speed. Closed Loop speed control systems have fast response, but become expensive due to the need of feed back components such as speed sensors. The operation of the controller must be according to the speed range. The process can be easily understood with the system flow chart [6][7].

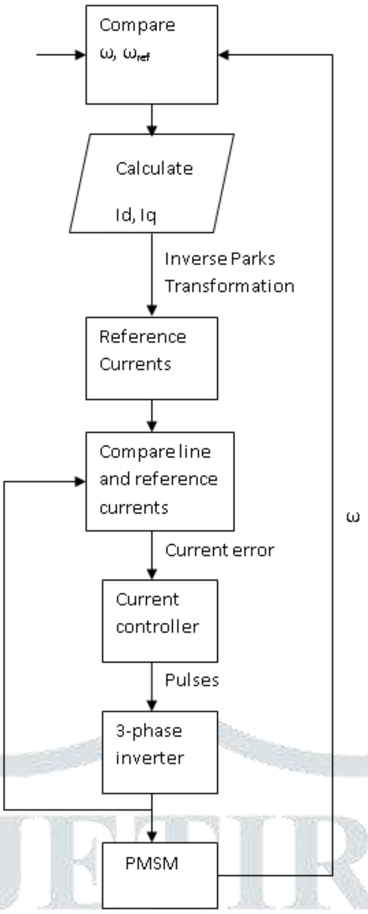

Fig 1 System flow chart

## V. SIMULATION DIAGRAM OF PMSM DRIVE

The PM motor drive simulation was built in several steps like abc phase transformation to dqo variables, calculation torque and speed, and control circuit. The abc phase transformation to dqo variables is built using park's transformation and for the dqo to abc the reverse transformation is used. The simulation diagram shown in fig, 3

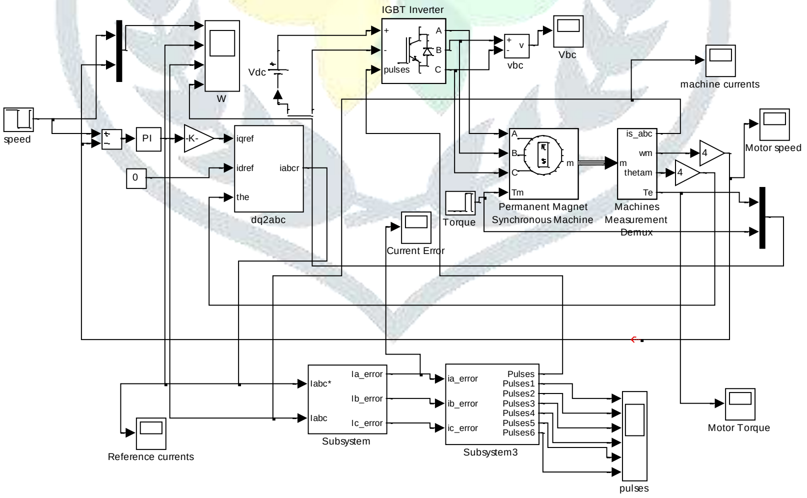

Fig. 2 PM Motor Drive System in Simulink

## IV. RESULTS AND DISCUSSION

**Speed waveforms:**

The system built in Simulink for a PMSM drive system has been tested for different signals of torque and speed. The motor reference speed starts at 200 rpm at time t = 0 sec and drops to 150 rpm at t = 0.1 sec.It remains at that speed till t = 0.2 sec. At t = 0.2 sec the speed is increased to 200 rpm and the speed remains constant thereafter. The actual machine speed can be seen to follow the reference speed. The motor speed waveform and the comparison between motor and reference speeds are as shown in the fig. 3 and fig. 4 respectively.

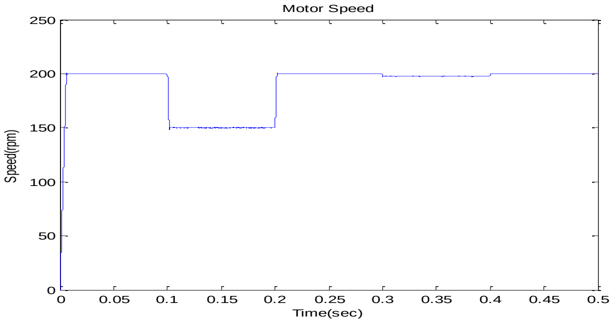

Fig. 3 Waveform of actual motor speed

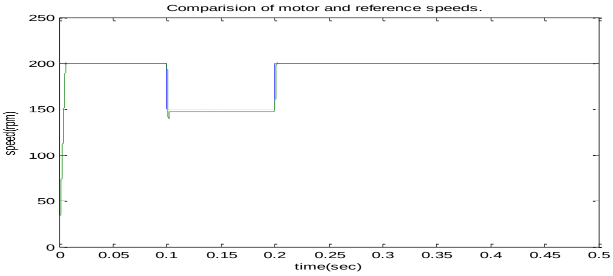

Fig. 4 Comparison of reference and actual speeds

**Torque waveforms:**

Fig. 5 shows the load torque applied to the motor. The motor torque follows the load torque. The load torque is applied at the instant t = 0.3 sec. The magnitude of load torque applied is 3.5 Nm. The load torque remains constant at 3.5 Nm till t = 0.4 sec. The load torque becomes 0 at t = 0.4 sec and remains 0 thereafter. Fig. 6 shows the developed torque of the motor.

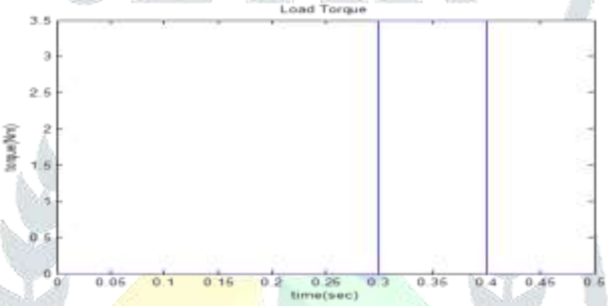

Fig. 5 Load torque

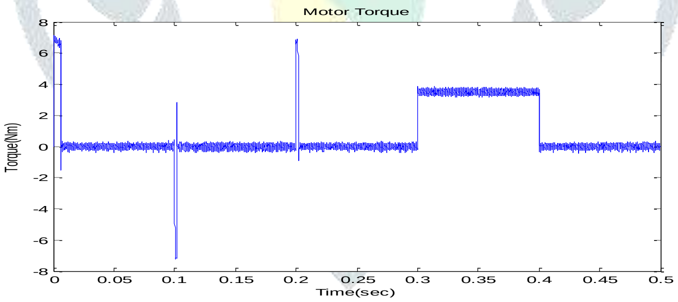

Fig.6 Motor torque

**Current waveforms:**

The reference, actual currents and their difference (error) are shown in figs. 7, 8, and 9. The reference currents are the currents obtained from the speed error. The actual currents are those flowing through the motor windings. The error current is the difference of actual and reference currents. The logic of speed control is to see to it that the actual currents follow the reference currents so that the speed error is zero and the desired speed is obtained. The currents can be seen to be varying with variation in torque since $I_d = 0$ and $I^q$ is the torque producing component and forms an important part of reference currents. It can be seen that the current is non sinusoidal at the starting and becomes sinusoidal when the motor reaches the controller command speed.

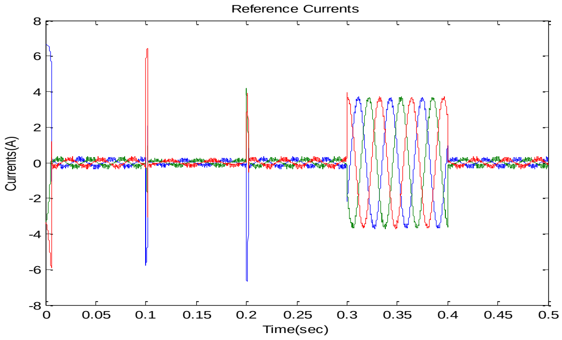

Fig. 7 Reference currents

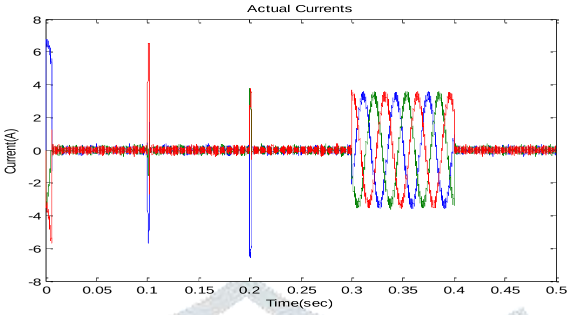

Fig. 8 Actual currents

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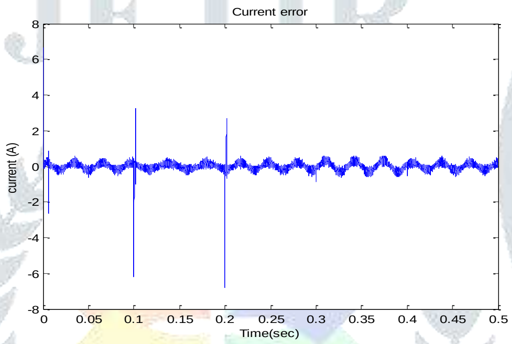

**Fig. 9 Current error waveforms**

**Voltage waveform:**

Fig. 10 shows the inverter output voltage. The voltage waveform shown in the fig. 10 is Vbc, which is the difference between the phase voltages Vb and Vc.It is a stepped waveform as can be seen .The waveforms of other voltages are similar with a phase difference of 120 degrees.

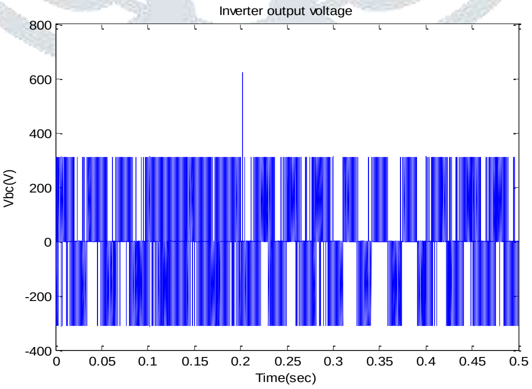

Fig. 10 Inverter output voltage

To summarize, all the waveforms are put together in fig. 11 for better understanding and easier view of their variations, depending on each other. It is observed that obtaining speed control and PMSM runs at constant speed irrespective of the load torque applied on it

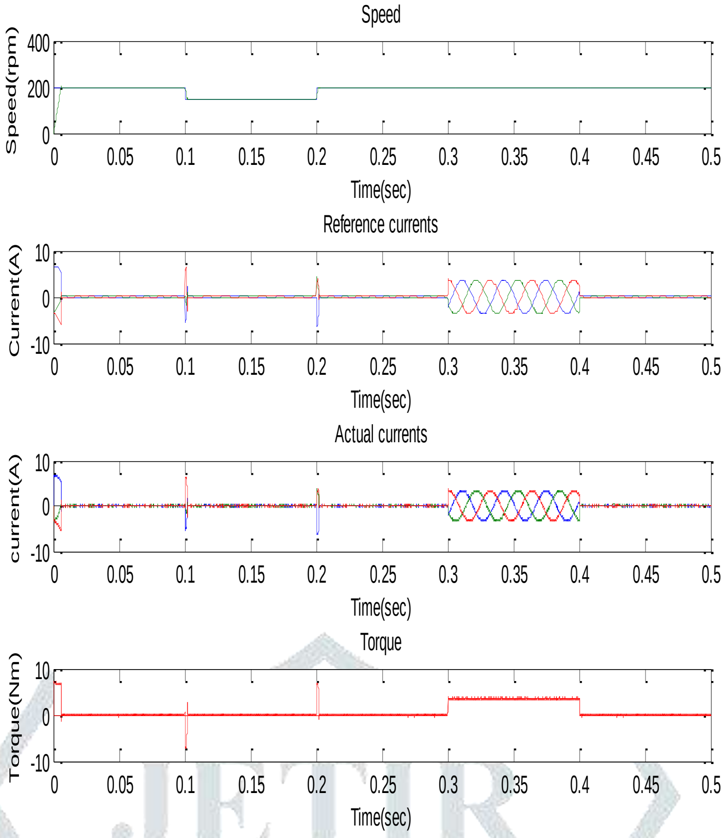

Fig. 11 Speed, torque and current waveforms

## V. CONCLUSIONS

A detailed Simulink model for a PMSM drive system has been developed and operation has been studied. Simulink has been chosen from several simulation tools because of its flexibility in working with analog and digital devices. Mathematical models can be easily incorporated in Simulation and the presence of numerous toolboxes and support guides simplifies the simulation of large system compared to spice. The drive has been designed so as to work at desired speed irrespective of the changes in load torque applied. The speed can be seen to remain at 200 rpm though the torque suddenly increases to 3.5 Nm at t = 0.3 seconds. A control circuit has been developed which makes use of the speed error to calculate reference currents. The difference between these reference currents and the motor currents is used to derive the pulses, to be fed to the IGBT inverter. The output voltage of the inverter is given as input to the permanent magnet synchronous motor, and this ensures that the speed error reduces to zero. The drive can be considered more advantageous over the others as the permanent magnet synchronous motor drive possesses many desired qualities required for constant speed applications,

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