Performance Characteristics of Permanent Magnet Synchronous Motor Fed by Brushless DC Motor & Six Step Inverter Drive Using Conventional PI & PID Controllers

Swarna Daniel*[1], Surya Prakash[2]

Department of Electrical Engineering, Shepherd School of Engineering & Technology, Sam Higginbottom Institute of Agriculture, Technology & Sciences, Deemed University, Allahabad-India

*[*1]Corresponding Author: Email: sprakashgiri0571@yahoo.com*

***Abstract*— This paper analyzes the mathematical model of permanent magnet synchronous motor based on the use of powerful simulation with Matlab modeling capabilities. In the Matlab / Simulink to create a simulation model of PMSM control system can be provide effective means and tools for analysis and design of the servo control system. PMSM is a multivariable, nonlinear and high coupling system. The output torque and stator current present a complicated function relation. Magnetic field can be decoupled to get a good control performance: It was no slip frequency current, less affected by the rotor parameters, easier to implement vector control. The comparative study of speed control of PMSM fed by DC brushless motor drive is presented.**

Keywords— **Permanent magnet synchronous machine, Brushless DC motor, PI & PID Controller, MATLAB**

I. INTRODUCTION

The control of the synchronous machine (SM) must take into account machine specificities: the high order of the model, the nonlinear functioning as well as the coupling between the different variables of control. Furthermore, the machine parameters depend generally on the operating point and vary either on the temperature (resistance), or with the magnetic state of the synchronous machine. These parametric variations modify the performances of the control system when we use a regulator[1].

Using complex control algorithms has become available with the development in microprocessor technology. The applications of vector control for induction and synchronous motors can be given an example of this. As a result of development of various algorithms for system modeling and control applications, induction and synchronous motors are being used in applications where DC motors were used. However, induction motor’s efficiency changes with slip value, it needs reactive current, and not able to produce the high torque / weight ratio which needed for high performance applications such as robotics, therefore different solutions are being studied, and different motor designs have been developed. One of these recently developed motors is the permanent magnet synchronous motor. In applications where high performance is demanded, some properties of the permanent magnet synchronous motor such as high torque, high power, high efficiency and low noise have made it more popular compared to other alternating current motors [1]. Especially because of the high power density, permanent magnet synchronous motor is applicable for areas such as robotics, automation and aeronautics technologies. Since the excitation flux is supplied by the magnets and due to the magnet characteristics and location, permanent magnet synchronous motors have both of a synchronous machine and a direct current machine characteristics. Unloaded conditions, velocity is directly proportional to voltage and inversely proportional to the flux and loaded conditions, it is directly proportional to the current and flux.

Synchronous motors have three phase windings in their stators, just like the induction motors. However, the rotor structure is different. By using permanent magnets in stead of windings on the rotor, disadvantages of the brush and collector are eliminated. Also, since the excitation losses are eliminated, thermal limits are expanded and higher power values can be obtained from a machine of same volume. Using high energy permanent magnets, keeps the air gap flux density at higher values than of wounded machines and eliminates the copper losses of the rotor windings, thus provides the higher efficiency compared to the induction motors at identical power value. Also the motor dimensions are considerably reduced [2]. Permanent magnet synchronous motor is an AC motor that has windings in the stator slots. The flux generated by stator currents is almost sinusoidal. Therefore, the same control methods used for the induction motors can also be used for the permanent magnet synchronous motors [3]. These controls are; V/f control, field oriented control, and direct torque control. The choice of direct torque control from these methods gives advantages such as; faster torque control, high torque at low level speed and high speed sensitivity.

II. PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE SYSTEM AND MODELING

The motor drive consists of four main components, the PM motor, inverter, control unit and the position sensor. The components are connected as shown in figure 1

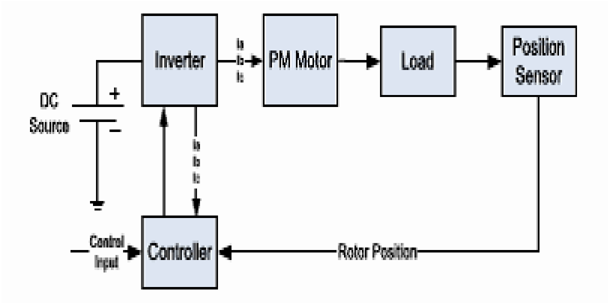

Figure 1 Drive System Schematic

Dynamic Model of Synchronous Motor

Nomenclature

ψsd	d axis stator magnetic flux,
ψsq	q axis stator magnetic flux,
ψM	rotor magnetic flux,
Lsd	d axis stator leakage inductance,
Lsq	q axis stator leakage inductance,
Rs	stator winding resistance,
Te	electromagnetic torque,
p	double pole number,
Lq, Ld	q and d axis inductances
R	Resistance of the stator windings
iq, id	q and d axis currents
vq, vd	q and d axis voltages

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

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:

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

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

Flux Linkages are given by

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

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

Substituting equations 3 and 4 into 1 and 2

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

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

Arranging equations 5 and 6 in matrix form

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

The developed torque motor is being 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

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

Solving for the rotor mechanical speed

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

and

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

In the above equations ω r is the rotor electrical speed where as ω m is the rotor mechanical speed.

Alternate Equation of Torque

$$\psi_{sd} = L_{sd} i_{sd} + \psi_M \qquad (12)$$

$$\psi_{sq} = L_{sq} i_{sq} \qquad (13)$$

$$u_{sd} = R_s i_{sd} + \frac{d}{dt}\psi_{sd} - \omega_r \psi_{sq} \qquad (14)$$

$$u_{sq} = R_s i_{sq} + \frac{d}{dt}\psi_{sq} + \omega_r \psi_{sd} \qquad (15)$$

$$T_e = \frac{3}{2} p (\psi_{sd} i_{sq} - \psi_{sq} i_{sd}) \qquad (16)$$

$$T_e = \frac{3}{2} p \left[\psi_M i_{sq} - (L_{sq} - L_{sd}) i_{sd} i_{sq}\right] \qquad (17)$$

Using transformation equation we get

$$\begin{bmatrix} F_d \\ F_q \end{bmatrix} = \begin{bmatrix} \cos\delta & -\sin\delta \\ \sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} F_x \\ F_y \end{bmatrix} \qquad (18)$$

$$\sin\delta = \frac{\psi_{sq}}{|\psi_s|} \qquad (19)$$

$$\cos\delta = \frac{\psi_{sd}}{|\psi_s|} \qquad (20)$$

is obtained. The expression |ψs|; represents the stator magnetic flux amplitude. When the necessary terms are placed using Figure 1, the following equation is obtained.

$$T_e = \frac{3}{2} p \left[\psi_{sd} \left(i_{sx} \sin\delta + i_{sy} \cos\delta \right) - \psi_{sq} \left(i_{sx} \cos\delta - i_{sy} \sin\delta \right) \right] \tag{21}$$

$$= \frac{3}{2} p \left[i_{sx} \frac{\psi_{sd}\psi_{sq}}{|\psi_s|} + i_{sy} \frac{\psi_{sd}^2}{|\psi_s|} - i_{sx} \frac{\psi_{sd}\psi_{sq}}{|\psi_s|} + i_{sy} \frac{\psi_{sq}^2}{|\psi_s|} \right] \tag{22}$$

$$T_e = \frac{3}{2} p |\psi_s| i_{sy} \tag{23}$$

It is clear that electromagnetic torque is directly proportional to the y-axis component of the stator current [6]. Controlling directly y-axis component of the stator current provides appropriate selection of the voltage switching vectors. Depending on less parameter is the main advantage of stator current control. It is possible to say that in a practical application the estimation technique shown in equation (6) requires saturation-dependent inductances. Therefore in equation (9) direct torque control over the stator current control is more convenient.

Stator magnetic flux vectorψs and rotor magnetic flux vector ψ_M, can be represented on rotor flux (dq), stator flux (xy) reference system as shown in Figure 1. The angle between the stator and rotor magnetic fluxes δ, is the load angle. δ is constant for a constant load torque. In that case both the stator and the rotor fluxes rotate at constant speed. However under different loads δ varies. Either the stator current rotation speed or the variation of δ is controlled in order to control the increase of the torque.

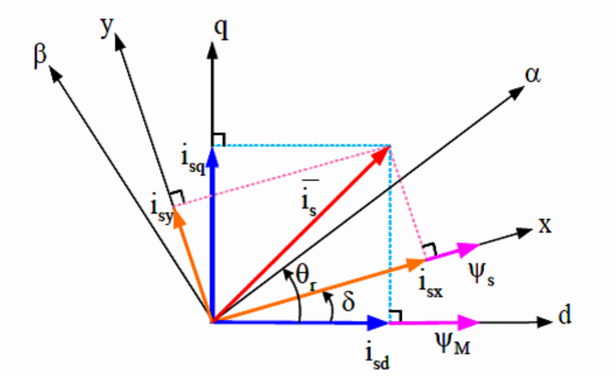

Figure 2. Stator and rotor magnetic fluxes in different reference systems

III. VOLTAGE SOURCE İNVERTER

The power circuit of a three-phase bridge inverter using six switch device is shown in figure 1. The dc supply is normally obtained from a utility power supply through a bridge rectifier and LC filter to establish a stiff dc voltage source [4].

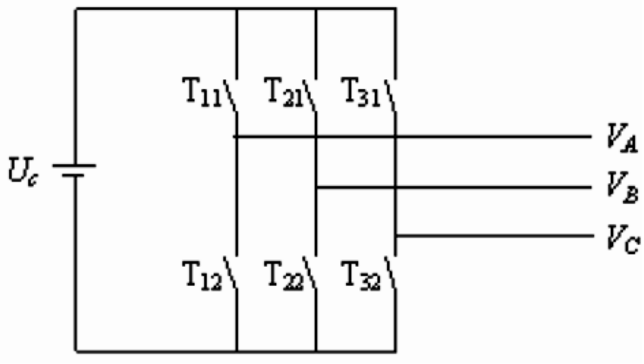

Fig. 3 Voltage source inverter

The switch Tci (*c* ∈{1, 2, 3}, *i*∈{1, 2}) is supposed perfect. The simple inverter voltage can be presented by logical function connexion in matrix form as

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} F_{11} \\ F_{21} \\ F_{31} \end{bmatrix} U_c, \tag{24}$$

where the logical function connexion *F*c1 is defined as: *F*c1 = 1 if the switch Tc1 is closed, *F*c1 = 0 if the switch Tc1 is opened, *c U* is the voltage feed inverter.

IV. SPEED CONTROL OF PM MOTOR

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. A properly designed feedback controller makes the system insensible to disturbance and changes of the parameters. 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.

For a PM motor drive system with a full speed range the system will consist of a motor, an inverter, a controller (constant torque and flux weakening operation, generation of reference currents and PI controller) The operation of the controller must be according to the speed range. For operation up to rated speed it will operate in constant torque region and for speeds above rated speed it will operate in flux-weakening region. In this region the d-axis flux and the developed torque are reduced.

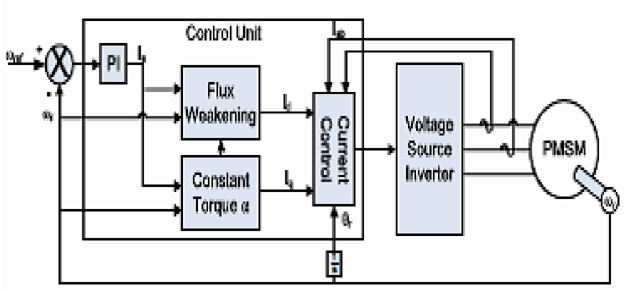

Figure 4 Block Diagram PMSM with controller

PI Controller: Speed controller calculates the difference between the reference speed and the actual speed producing an error, which is fed to the PI controller. PI controllers are used widely for motion control systems. They consist of a proportional gain that produces an output proportional to the input error and an integration to make the steady state error zero for a step change in the input.

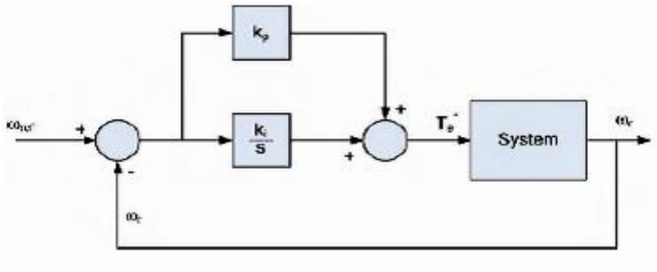

Figure 5(a) PI Controller

PID Controller Structure

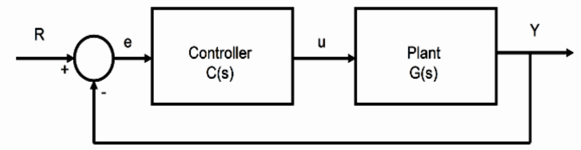

Figure 5(b) PID Controller structure

In this tutorial, we assume the controller is used in a closed-loop unity feedback system. The variable e denotes the tracking error, which is sent to the PID controller. The control signal u from the controller to the plant is equal to the proportional gain (KP) times the magnitude of the error plus the integral gain (KI) times the integral of the error plus the derivative gain (KD) times the derivative of the error[10].

$$u = K_P e + K_I \int e dt + K_D \frac{de}{dt} \qquad (25)$$

PID Controllers are everywhere! Due to its simplicity and excellent if not optimal performance in many applications, PID controllers are used in more than 95% of closed-loop industrial processes.1 It can be tuned by operators without extensive background in Controls, unlike many other modern controllers that are much more complex but often provide only marginal improvement. In fact, most PID controllers are tuned on-site. The lengthy calculations for an initial guess of PID parameters can often be circumvented if we know a few useful tuning rules. This is especially useful when the system is unknown [11].

Speed control of motors mainly consist of two loops the inner loop for current and the outer loop for speed. The order of the loops is due to their response, how fast they can be changed. This requires a current loop at least 10 times faster than the speed loop. Since the PMSM is operated using field oriented control, it can be modeled like a dc motor. The design begins with the innermost current loop by drawing the block diagram. But in PMSM drive system the motor has current controllers which make the current loop. The current control is performed by the comparison of the reference currents with the actual motor currents.

V. RESULTS AND DISCUSSION

According to the proposed vector control of PMSM simulation model, run in Matlab, using the motor parameters are as follows: electrical power P = 2kw, DC voltage Udc =550V, stator windings resistance Rs = 2.875Ω, d-phase winding inductance Ld = 8.5 e-3H, d-axis winding inductance Ld = 805e-3H, the rotor magnetic flux Ψ f =0.175 Wb, moment of inertia J = 0.8 e-3 kg • m ^ 2, the pole number p = 4, magnetic flux density B = 0. Set the total simulation time t = 0.2 s, for the sudden increase in torque test. No load start, t = 0.1s when the additional load Tm = 5N.m, speed is 2000 r / min. Waveforms as follows:

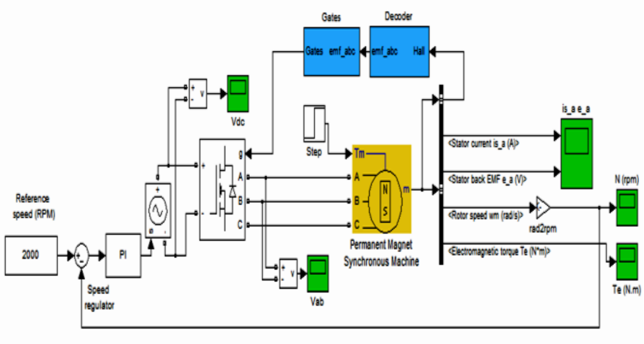

Fig.6 Brushless DC motor fed permanent magnet synchronous motor

The torque climbs to nearly 28 N.m when the motor starts and stabilizes rapidly when the motor reaches the reference value. The nominal torque is applied at t = 0.1 second and the controller reacts rapidly and increases the DC bus voltage to produce the required electric torque. Observe the saw tooth shape of the currents waveforms. This is caused by the six step controller, which applies a constant voltage value during 120 electrical degrees to the motor. The initial current is high and decreases during the acceleration to the nominal speed. When the nominal torque is applied, the stator current increases to maintain the nominal speed. The saw tooth waveform is also observed in the electromotive torque signal Te. However, the motor's inertia prevents this noise from appearing in the motor's speed waveform [7],[8],[9].

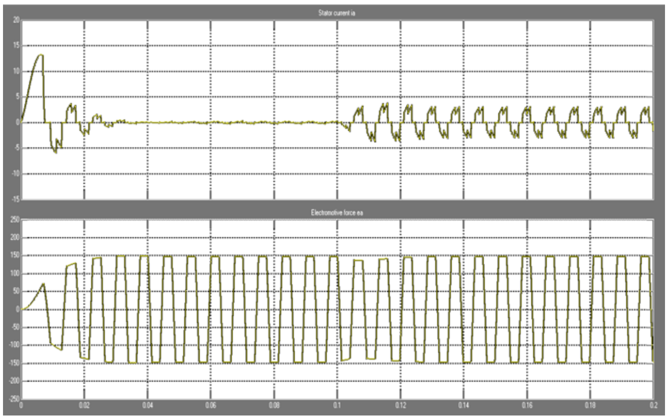

Fig. 7 Response of Stator current Ia and Electromotive force Ea With PI Controller

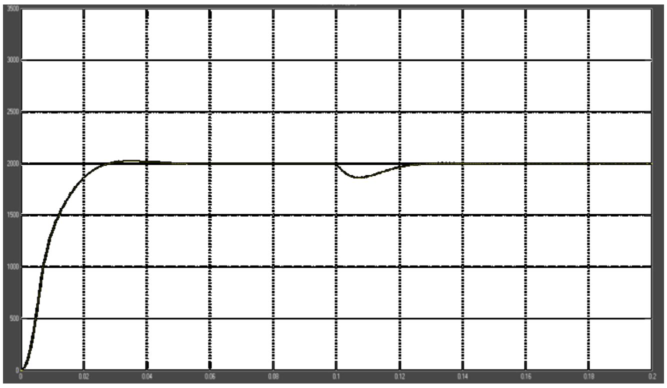

Fig.8 Response of the Rotor speed with step disturbance at 0.1sec with PI controller

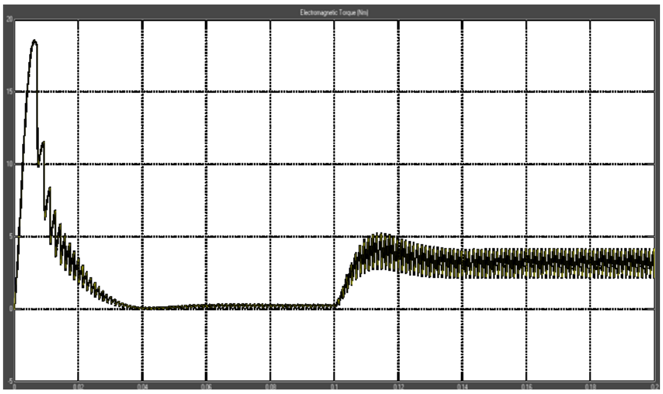

Fig. 9 Change in Electromagnetic torque (Nm) with PI controller

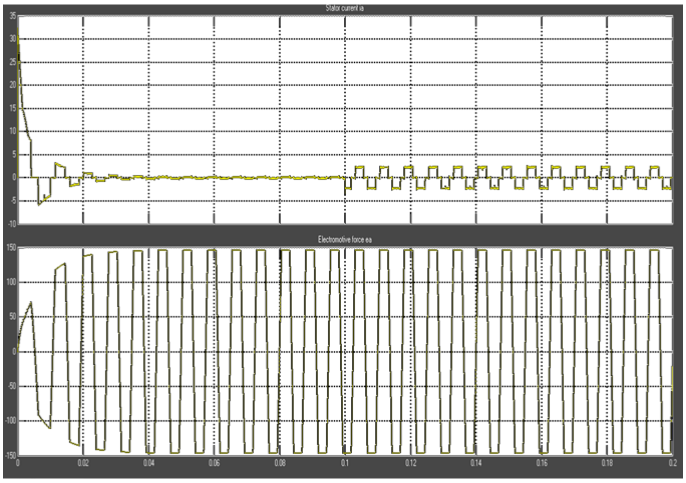

Fig. 10 Response of Stator current Ia and Electromotive force Ea With PID controller

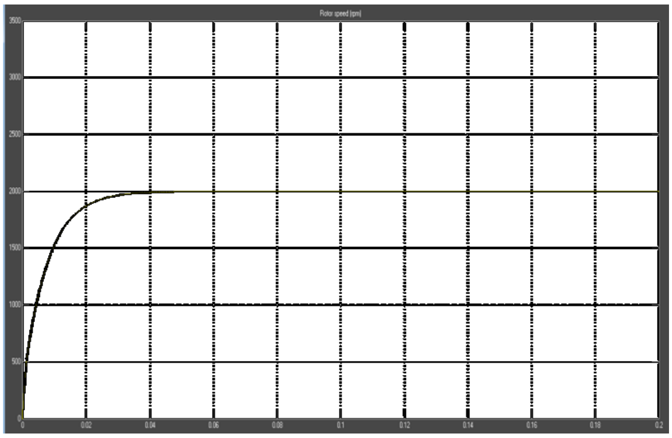

Fig. 11 Response of the Rotor speed with step disturbance at 0.1sec with PID controller

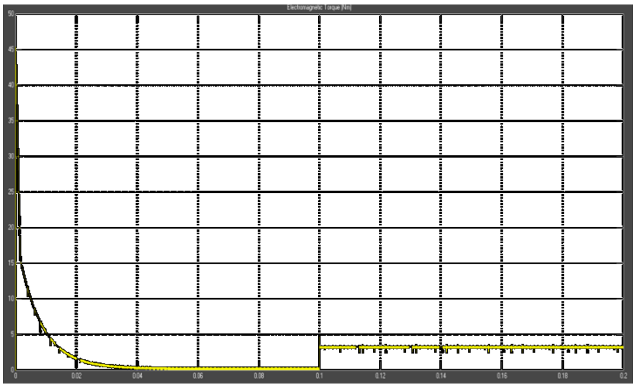

Fig.12 Change in Electromagnetic torque (Nm) with PID controller.

The proposed model demonstrate the use of the Permanent Magnet Synchronous Machine block in motoring mode with a closed-loop control system built entirely with Simulink blocks. The complete system includes a six step inverter block from the Sim Power Systems library. Two control loops are used; the inner loop synchronizes the pulses of the bridge with the electromotive forces, and the outer loop regulates the motor's speed, by varying the DC bus voltage. The mechanical torque applied at the motor's shaft is originally 0 N.m (no load) and steps to its nominal value (5 N.m) at t = 0.1 second.

VI. CONCLUSION

In this paper, Simulink-based simulation of PMSM DC motor fed control system modeling is carried out to control the speed of the motor by using PI and PID controllers. Simulation results show that the system can run smoothly has good static and dynamic characteristics. It provides an effective means and tools for analysis and design of PMSM. By changing the step load at 0.1 sec the disturbances in speed ,electromagnetic torque, stator current and Emf are analyzed with two separate control technique i.e. PI and PID controllers. The responses obtained by PID controller shows the superiority over PI one in complex dynamical system.

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