CHAPTER 3

PMSM DRIVE WITH CONVENTIONAL
PI CONTROLLER

3.1 INTRODUCTION

The Permanent Magnet Synchronous Motor (PMSM) can be controlled as separately excited DC motor by using vector control method. The various control strategies for the control of the inverter fed PMSM drive have provided good steady state response but poor dynamic response. The vector controlled PMSM drive provides better dynamic response and lesser torque ripples. The outer speed control loop and inner current control loop are used in vector controlled PMSM drive system. This chapter depicts the control of PMSM using conventional PI controller. The simulation studies of the drive using traditional proportional controller and PI controller are presented.

3.2 VECTOR CONTROL OF PMSM DRIVE

The vector control technique is one of the most effective techniques for high performance AC drives. Speed control is quite complex due to nonlinearity because of core saturation. Vector control scheme has made the task easy by controlling torque and flux current components separately (Kumar et al 2012). The PMSM can be vector controlled when the machine equations are transformed from the a-b-c frame to the synchronously rotating d – q frame where the sinusoidal quantities become constant. The vector
control separates the torque and flux channels in the machine through its stator excitation inputs. Vector control made the AC drives equivalent to DC drives in the independent control of flux and torque and superior to them in their dynamic performances. The developed torque $T_e$ in DC motor can be expressed as,

$$T_e = K_t I_a \psi_f$$  \hspace{1cm} (3.1)

Where $K_t$ is constant, $I_a$ is the armature current and $\psi_f$ is the field flux linkage which depends on field current $I_f$. Since $I_a$ and $I_f$ are orthogonal and decoupled vectors, the control task becomes much easier for the separately excited DC motor.

$$T_e = (3 \pi) F [\psi_f i_q + (I_\psi - I_{d}) i_d i_q]$$  \hspace{1cm} (3.2)

The torque equation (3.2) of PMSM has two terms: the first term represents the torque produced by the permanent magnet flux $\psi_f$ and the torque producing current component $i_q$. The second term represents the reluctance torque produced by the interaction of inductances $L_d$ and $L_q$ and also the currents $i_d$ and $i_q$. The reluctance torque for the surface mounted PMSM is negligible due to $L_d \equiv L_q$. The torque equation of the surface mounted PMSM becomes linear and hence the control task is easier (Xu et al 2009).

In the case of the interior PMSM, $L_q$ is larger than $L_d$. Also the excitation voltage due to permanent magnets, and the values of the inductances $L_d$ and $L_q$ undergo significant variations in an interior type permanent magnet motor under different steady state and dynamic loading conditions. The torque equation of interior PMSM is nonlinear based on equation (3.2) and control of the drive is complex. In order to operate the PMSM in a vector control scheme with less complexity and efficient strategy
of vector control technique is to make the d-axis current \( i_d \) zero (Molavi et al 2008 and Zang 2010). Then the torque equation becomes linear and is given by,

\[
T_e = \left( \frac{3}{2} \right) P \varphi_r i_q = K_t \varphi_r i_q
\]  

(3.3)

Where, \( K_t = \left( \frac{3}{2} \right) P \) is the constant, the torque expressions of Equations (3.1) and (3.3) are identical and decoupled. Using phasor notations and taking the \( d^f \) axis as a reference phasor, the steady state phase voltage \( V_a \) can be derived from the steady state d - q axis voltage Equation as,

\[
V_a = V_d + jV_q
\]  

(3.4)

Steady state voltage and \( V_d \) and \( V_q \) are given by

\[
V_d = R_s i_d - \omega_r L_{q} i_q
\]  

(3.5)

\[
V_q = R_s i_q + \omega_r (L_{q} i_d + \varphi_f)
\]  

(3.6)

Therefore \( V_a = (R_s i_d - \omega_r L_{q} i_q) + j (R_s i_q - \omega_r (L_{q} i_d + \varphi_f)) \)

\[
= R_s (i_d + j i_q) - \omega_r L_{q} i_q + j \omega_r (L_{q} i_d + \varphi_f)
\]

\[
V_a = R_s I_a - \omega_r L_{q} i_q + j \omega_r (L_{q} i_d + \varphi_f)
\]  

(3.7)

Where the phase current,

\[
I_a = i_d + j i_q
\]  

(3.8)

Based on the equation 3.7, the vector diagram of PMSM is shown in Figure 3.1.
Figure 3.1 Vector diagram of PMSM

The stator current can be controlled by controlling the d axis and q axis current component. If $i_d$ is set to zero in vector control scheme, all the flux linkages are oriented in d axis and is shown in Figure 3.2. The torque is the function of q axis current component and constant torque is obtained by making $i_q$ as constant based on equation (3.3) (Sharma et al 2008). With $i_d = 0$ for constant torque control, the steady state voltage is given by the following equations:

$$V_q = R_s i_q + j \omega_r \phi_f$$  \hspace{1cm} (3.9)

$$V_d = -\omega_l l_{x_q} i_q$$  \hspace{1cm} (3.10)

$$V_a = R_s i_q + j \omega_r \phi_f - \omega_l l_{x_q} i_q$$  \hspace{1cm} (3.11)
3.3 CURRENT CONTROLLED VSI FED PMSM DRIVE

In the PMSM vector control method, q axis current provides the desired torque. The current controlled VSI fed PMSM drive with current controller, speed controller and inverter is shown in Figure 3.3. The speed controller generates the torque command q axis reference current $i_{q}^*$ based on the error between reference speed and actual speed. In order to obtain the simplified nonlinear dynamic model of the PMSM, the d- axis reference current $i_{d}^*$ is set to zero (Ren et al 2007 and AmarnathTiwari 2011).

![Figure 3.3 Block Diagram of Current Controlled PMSM Drive](image-url)
The reference phase currents $i_a^*$, $i_b^*$ and $i_c^*$ are generated from the d and q axis command currents using Park’s transformation. The current controller generates the control signals to the inverter by comparing the actual current and reference current and drives the motor to follow the reference speed due to the feedback control. The motor currents and rotor position signal are taken as feedback signal to operate the motor in a vector control scheme. The current controlled voltage source Pulse Width Modulated (PWM) inverter is usually preferred for the PMSM drive because of its quick response and accurate control, compared to the conventional voltage control scheme.

### 3.3.1 Speed Controller

The error between the reference speed and actual speed is processed in the speed controller which in turn generates the command or reference torque

$$
\Delta T_e = J \frac{d}{dt} (\Delta \omega_m) + B \Delta \omega_m
$$

(3.12)

Integrating Equation (3.12) gives the total change in torque as,

$$
T_e = J\Delta \omega_m + B \int \Delta \omega_m \, dt
$$

(3.13)

Equation (3.13) represents the PI algorithm for the speed controller and it may be written as

$$
T_e^* = K_p \Delta \omega_m + K_i \int \Delta \omega_m \, dt
$$

(3.14)

Where $K_p$ is the proportional constant, $K_i$ is the integral constant and $\Delta \omega_m = \omega_m^* - \omega_m$ the speed error between the reference speed $\omega_m^*$ and the actual motor speed $\omega_m$. In Laplace domain Equation (3.14) can be written as,
\[
T_e = K_p + \frac{K_i}{s} \Delta \omega_m(s)
\]  

(3.15)

3.3.2 Vector Rotator

The vector rotator is used to transform the rotating rotor reference frame quantities into the stator reference frame. The d axis reference currents \(i_d^*\), q axis reference current \(i_q^*\) and the rotor position \(\theta_r\) are taken as input and three-phase reference currents \(i_a^*, i_b^*, i_c^*\) are generated using Park transformation. The transformation is done in two steps: first the synchronously rotating d-q axis quantities are transformed to the stationary d-q axis and then the stationary d-q axis quantities are transformed to the a-b-c phase quantities.

3.3.3 Current Controller

The current controller is used to force the motor currents to follow the command currents and drives the motor to follow the reference speed using the feedback control. The current controller generates firing pulses to drive the inverter by comparing the actual current and reference current. Among the various current controller schemes, the hysteresis current controller and PWM current controller are the most commonly used current controllers for high performance drive applications due to their simplicity.

3.3.3.1 PWM Current Controller

Pulse Width Modulated (PWM) current controllers are widely used and the switching frequency is usually kept constant. PWM controllers are based on the principle of comparing a triangular carrier wave of desired switching frequencies and are compared with error of the controlled signal. The reference current signal generated in the controller and the actual motor current produces the error signal. The resultant voltage controlled signal,
controls the gates of the voltage source inverter to generate the desired output and the controller will respond based on the error.

If the error command is greater than the triangle waveform, the inverter leg is held switched to the positive polarity (upper switch on). When the error command is less than the triangle waveform, the inverter leg is switched to the negative polarity (lower switch on). This will generate a PWM signal shown in Figure 3.4. The inverter leg is forced to switch at the frequency of the triangle wave and produces an output voltage proportional to the current error command. The nature of the controlled output current consists of a reproduction of the reference current with high frequency PWM ripple superimposed.

![Figure 3.4 PWM signal](image)

**3.3.4 Voltage Source Three – Phase Inverter**

Voltage source inverters (VSI) are used to convert a DC voltage to AC voltage of variable frequency and magnitude. The current controlled VSI is used to drive the PMSM. The output voltage obtained from the inverter could be of fixed or variable frequency. If the DC input voltage to the inverter is constant by controlling the gain of the inverter, it is possible to control the output voltage. Pulse Width Modulation (PWM) technique are used to vary the gain of the inverter to obtain variable output.
Three phase inverters consist of six power switches connected to a DC voltage source as shown in Figure 3.5. \(V_a\), \(V_b\) and \(V_c\) are the output voltages applied to the stator windings of a motor. The inverter switches \(Q_1\) to \(Q_6\) decides the output which are controlled by PWM control signals. In case of AC motor control, turn-on of upper line inverter switches requires turn off of the lower line switches and vice versa.

The line voltages can be derived from the phase voltages as

\[
V_{ab} = V_{an} - V_{bn} \quad (3.16)
\]

\[
V_{bc} = V_{bn} - V_{cn} \quad (3.17)
\]

\[
V_{ca} = V_{cn} - V_{an} \quad (3.18)
\]

where,

\(V_{ab}\), \(V_{bc}\) and \(V_{ca}\) are the line voltages and \(V_{an}\), \(V_{bn}\)and \(V_{cn}\) are the phase voltages.

![Figure 3.5 Three Phase Inverter](image-url)
3.4 TRANSFER FUNCTION MODEL OF PMSM DRIVE

The closed transfer function of the system is necessary for the design of controllers. Using the d axis stator voltage equation, the block diagram representation of PMSM in d axis is shown in Figure 3.6.

![Figure 3.6 Block diagram of PMSM in d – axis](image)

The block diagram representation of PMSM in q axis is shown in Figure 3.7(a) by using stator voltage equation, torque equations and mechanical equation.

![Figure 3.7 (a) Block diagram of PMSM in q – axis](image)

The block diagram representation of PMSM in q-axis by including torque equation, moment of inertia and frictional co-efficient is shown in Figure 3.7(b).
Figure 3.7(b) Block diagram of PMSM in q – axis with mechanical constants

In case of surface mounted PMSM, the direct axis inductance \( L_d \) and quadrature axis inductance \( L_q \) are equal and hence the block diagram of surface mounted PMSM can be modified as shown in the Figure 3.7(c)

Figure3.7(c) Block diagram of surface mounted PMSM in q – axis

3.5 CONVENTIONAL PI CONTROLLERS

A Proportional Integral (PI) controller is a feedback controller mostly used in industrial control systems. In linear control, PI control systems, PI control scheme is widely applied due to their relative simple implementation (Li & Liu 2009). The traditional controller tries to minimize the error between the measured and desired outputs. These PI controllers were used to control and maintain the processes.
They were designed and implemented using current error, past error and rate of change of error. Today’s process industries have wide application of PI controllers to control temperature, pressure, flow rate, tank level, speed and current etc. The use of PI controllers provides accurate control under different process conditions. Basically PI control algorithm is a simple mathematical equation based controller used to evaluate the controlled variables. The controller is designed to minimize the error by adjusting the process control inputs.

The working of a PI controller can be described as for instance, if speed is the controlled variable, then it is measured and fed back to the controller. Based on the set value and the current value, the error is generated. The error value is examined with the PI algorithm. Finally, the controller issues the necessary commands and alters the process inputs such that the error is eliminated. The phenomenon of PI control is iterative in nature. The PI algorithms provide straightforward correlations between the process and responses. Along with these advantages the other features are the easy to use and tune. The structure of the PI controller can be P or PI.

The values of the parameters proportional and integral constants are chosen as numerical values in order to tune the controller. The reaction of the proportional constant is based on the current error; the integral constant’s reaction is based on the total recent errors. The sum of these two actions is used to adjust the process. By tuning the parameters in the PI controller algorithm, the controller can provide control action designed for specific process requirements. The general block diagram representation of PI controller is shown in the Figure 3.8.
Based on the requirement, one or two control actions may be used to provide necessary system control. A PI controller can be used as P or PI controller in the absence of the respective control actions. PI controllers are mostly used in the feedback control system. Transfer function block diagram of PI controller is shown in the Figure 3.9.

The P controller utilizes the gain $K_p$ and produces the output value which is proportional to the current error value. By adjusting the gain value $K_p$ the response of the controller can be adjusted. The higher value of proportional gain results in a large change in the output for a given change in the error. If the proportional gain is too high, the system becomes unstable. In contrast, a small gain results in a less output response for a large input error,
and less sensitive controller. The P controller is governed by the Equation (3.19).

\[ P_{out} = K_p e(t) \quad (3.19) \]

In a PI Controller, with the proportional band \( K_p \) the controller produces the output proportional to the error and the integral action produces the output proportional to the amount of time the error is present. Proportional controller causes an offset and increasing the \( K_p \) value will make the loop go unstable. The integral action eliminates the offset. The absence of integral term prevents the system from reaching the target value and the PI controllers are commonly used. The PI controller is governed by the Equation (3.20).

\[ P_{out} = K_p e(t) + K_i \int e(t) \quad (3.20) \]

### 3.5.1 Controller Tuning

Tuning of PI or PID controller is the change in control parameters to the optimum values for the desired control response. PID controllers can provide acceptable control using default tunings, but performance can be improved by careful tuning, and performance may be unacceptable with poor tuning. PID tuning is a difficult problem to satisfy the complex criteria such as stability, settling time etc. The tuning methods based on the optimization techniques ensure good stability and robustness in the recent research field. Vaishnav & Khan (2010) and Namazov & Basturk (2010) presented various tuning techniques for PID controllers.

#### 3.5.1.1 Manual Tuning

The knowledge about the controlled process is necessary for controller tuning. In manual tuning of PID controller, initially \( K_i \) and \( K_d \) values are set to zero and \( K_p \) is increased until the output of the system
oscillates. Then the $K_p$ is set to half of the value obtained to produce the above and $K_i$ is increased until the system gets less steady state error. The higher value of $K_i$ will lead to instability. Then $K_d$, is increased to acceptable value without causing oscillations and to obtain quick response to reach its reference value. The values of $K_p$, $K_i$ and $K_d$ are adjusted to get optimum value in order to obtain system response with less over shoot, less steady state error and good stability. The effects of change in the parameters are shown in the Table 3.1.

**Table 3.1 Effects of change in tuning parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rise Time</th>
<th>Overshoot</th>
<th>Settling Time</th>
<th>Steady State Error</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_p$</td>
<td>Decrease</td>
<td>Increase</td>
<td>Small Change</td>
<td>Decrease</td>
<td>Degrade</td>
</tr>
<tr>
<td>$K_i$</td>
<td>Decrease</td>
<td>Increase</td>
<td>Increase</td>
<td>Decrease Significantly</td>
<td>Degrade</td>
</tr>
<tr>
<td>$K_d$</td>
<td>Minor Decrease</td>
<td>Minor Decrease</td>
<td>Minor Decrease</td>
<td>No Effect In Theory</td>
<td>Improved if $K_d$ is Small</td>
</tr>
</tbody>
</table>

### 3.5.1.2 Ziegler- Nichols tuning rule

Ziegler- Nichols tuning rule provides a practical approach to tune a PID controller. Based on this rule, a PID or PI controller is made as proportional controller mode and the $K_p$ value is adjusted to make the control system in continuous oscillations. The corresponding gain is named as the ultimate gain ($K_u$) and the period of oscillation is named as the ultimate period ($P_u$). The PID controller parameters are obtained from $P_u$ and $K_u$ using the Ziegler- Nichols tuning Table as given below.
Table 3.2 Ziegler- Nichols tuning rule

<table>
<thead>
<tr>
<th>Controller</th>
<th>$K_C$</th>
<th>$T_i$</th>
<th>$T_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>$K_u/2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PI</td>
<td>$K_u/2.2$</td>
<td>$P_u/1.2$</td>
<td></td>
</tr>
<tr>
<td>PID</td>
<td>$K_u/1.7$</td>
<td>$P_u/2$</td>
<td>$P_u/8$</td>
</tr>
</tbody>
</table>

The important step of Ziegler- Nichols tuning method is to determine the ultimate gain and ultimate period. But determination of the ultimate gain and period experimentally is time consuming. PID online self tuning using particle swarm optimization for vector control PMSM drive was presented by Cao et al (2010).

3.5.2 Transfer function Model of PMSM with PI controller in q-axis

The current controller or regulator is a very important part of the field oriented based control system. The torque current has to be properly controlled. The closed loop transfer function is necessary for the design of PI controllers. The objective of the design is to determine proportional gain $K_p$, integral gain $K_i$ and integral time $T_i$ so as to achieve a good closed loop response. From the block diagram of PMSM, using q-axis voltage equation, torque equation and mechanical equation, the block diagram of current loop in q-axis with PI controller is obtained as shown in Figure 3.10. The transfer function between torque component and q-axis voltage $V_q$ is

$$\frac{i_q}{V_q} = \frac{1}{R_s+L_s} = \frac{1/R_s}{1+\left(\frac{L_q}{R_s}\right)s}$$ (3.21)

$$\frac{L_q}{R_s} = \tau_{eq} = \text{Electrical time constant in q-axis}$$
The delay associated with inverter time constant is less when compared to q-axis current time constant ($\tau_q$) and can be neglected. The transfer function between torque component current $i_q$ and its reference $i_q^*$ using block diagram shown in Figure 3.10 is given by

\[
\frac{i_q}{i_q^*} = \frac{K_p(T_1s+1)}{T_1l_q s^2 + T_i (R_e + K_p)s + K_p}
\]

(3.22)

3.5.3 Transfer function Model of PMSM with PI controller in d-axis

The block diagram of current loop in d-axis with PI controller is shown in Figure 3.11. The transfer function between flux component $i_d$ and d-axis input voltage $V_d$ is given by

\[
\frac{i_d}{V_d} = \frac{1}{R_s + L_s} = \frac{1}{\frac{L_d}{R_s}} \frac{1}{1 + \left(\frac{L_d}{R_s}\right)s}
\]

(3.23)

where $\frac{L_d}{R_s} = \tau_d = \text{Electrical time constant in d-axis}$

![Figure 3.11 Block diagram of d axis loop with PI controller](image-url)
The transfer function between flux component $i_d$ and its reference $i_{d}^*$ is given by

$$\frac{i_d}{i_{d}^*} = \frac{K_P(T_i s + 1)}{T_i L_d s^2 + T_i (R_s + K_P) s + K_P}$$  \quad (3.24)$$

$$\frac{i_d}{i_{d}^*} = \left(\frac{K_P}{T_i L_d}\right)\frac{1}{s^2 + \left(\frac{R_s + K_P}{L_d}\right)s + \left(\frac{K_P}{T_i L_d}\right)}$$  \quad (3.25)$$

3.6 SIMULATION MODEL OF PMSM DRIVE

It is usual practice to simulate the drive system to predict the performances of the drive before real-time implementation. The simulation of the proposed complete drive has been carried out using MATLAB simulation software. The simulation allows investigation of both transient and steady state performance of the drive. For simulation, the motor parameters and command speed are given as inputs and the outputs are the instantaneous current, voltages, speed and torque. In the simulation, the inverter transistors are modelled as ideal controlled switches with zero turn-on and turn-off time and hence the switches of each inverter leg have a complementary switching state. The Simulink model of the complete drive system is shown in Figure 3.12.

![Simulink model of PMSM drive](image-url)
The simulation model contains different blocks such as command-current generator, current controller, inverter and PMSM module. These are known as the subsystems. Each subsystem consists of many blocks, which perform specific functions. The specifications of the PMSM used for simulation are tabulated in Table 3.3.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator Resistance ($R_s$)</td>
<td>1.4Ω</td>
</tr>
<tr>
<td>Direct axis inductance ($L_d$)</td>
<td>6.6 mH</td>
</tr>
<tr>
<td>Quadrature axis inductance ($L_q$)</td>
<td>5.8 mH</td>
</tr>
<tr>
<td>Moment of Inertia (J)</td>
<td>0.00176 Kg.m²</td>
</tr>
<tr>
<td>Number of poles (P)</td>
<td>6</td>
</tr>
</tbody>
</table>

### 3.7 SIMULATION RESULTS AND INFERENCES

The closed loop PMSM drive system with traditional P and PI controllers are tuned for the various values of proportional gain ($K_p$) and integral gain ($K_i$) values. The speed error is processed by these controllers and the appropriate command is given to the PWM generator, which in-turn controls the output of the inverter. The output voltage of the inverter is fed as input voltage to the armature of the motor. When the input voltage varies, the speed of the PMSM also varies.

#### 3.7.1 Simulation Results of P Controller

The simulation results are carried out at different operation conditions such as at no load, full load and low command speeds. The simulation results are also carried out under disturbance conditions such as step change in command speed and sudden change in load.
Figure 3.13 No load speed response of P controller

Figure 3.14 Speed responses with change in load with P controller
Figure 3.15 Restoration speed response under load with P controller

In no load conditions, the peak overshoot, steady state error and settling time are obtained and the response of the drive in no load mode is depicted in Figure 3.13. The response of the drive with sudden change in load is shown in Figure 3.14. The parameters such as speed drop at step change in load for 3 Nm, restoration time to reach the reference speed are obtained and shown in Figure 3.15. The PMSM drive system using traditional controllers has been simulated and results have been presented. To examine the robustness of the drive, the performances are observed under various speed values. The peak overshoot, steady state error, and settling time are observed and measured.

The analysis has been made by varying the gain values and observing the transient and steady state parameters of the system. From the simulated responses for various gain values and set speed of 1000 rpm, the parameters of the system are measured and tabulated in Table 3.4. The performance characteristics of the drive for various values of proportional gain are plotted and shown in Figure 3.16.
Table 3.4 P controller performances

<table>
<thead>
<tr>
<th>S.No</th>
<th>Proportional Gain ($K_p$)</th>
<th>Peak Overshoot(%)</th>
<th>Steady State Error(%)</th>
<th>Settling Time $T_s$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4</td>
<td>00</td>
<td>1.84</td>
<td>0.015</td>
</tr>
<tr>
<td>2</td>
<td>0.8</td>
<td>1</td>
<td>1</td>
<td>0.02</td>
</tr>
<tr>
<td>3</td>
<td>1.2</td>
<td>2.2</td>
<td>0.6</td>
<td>0.02</td>
</tr>
<tr>
<td>4</td>
<td>1.6</td>
<td>2.8</td>
<td>0.4</td>
<td>0.03</td>
</tr>
<tr>
<td>5</td>
<td>2.0</td>
<td>3.3</td>
<td>0.35</td>
<td>0.04</td>
</tr>
<tr>
<td>6</td>
<td>2.2</td>
<td>3.6</td>
<td>0.3</td>
<td>0.05</td>
</tr>
<tr>
<td>7</td>
<td>2.3</td>
<td>3.7</td>
<td>0.25</td>
<td>0.1</td>
</tr>
<tr>
<td>8</td>
<td>2.4</td>
<td>3.8</td>
<td></td>
<td>System oscillates</td>
</tr>
</tbody>
</table>

Figure 3.16 (Continued)
Figure 3.16 Performance characteristics of P controller
(a) Overshoot (b) Steady state error (c) Settling time

The drive system parameters are measured for various speeds with $K_p=1.2$ and tabulated in Table 3.5. Figure 3.17 illustrates speed Vs overshoot characteristic performance of P controller.

Table 3.5 P controller performances for $K_p=1.2$

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Ref Speed (rpm)</th>
<th>Proportional Gain $K_p=1.2$</th>
<th>Settling Time $T_s$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Peak Overshoot (%)</td>
<td>Steady State Error (%)</td>
</tr>
<tr>
<td>1</td>
<td>300</td>
<td>8.30</td>
<td>0.670</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>5.00</td>
<td>0.600</td>
</tr>
<tr>
<td>3</td>
<td>800</td>
<td>2.75</td>
<td>0.624</td>
</tr>
<tr>
<td>4</td>
<td>1000</td>
<td>2.20</td>
<td>0.600</td>
</tr>
<tr>
<td>5</td>
<td>1200</td>
<td>1.67</td>
<td>0.580</td>
</tr>
<tr>
<td>6</td>
<td>1500</td>
<td>1.20</td>
<td>0.600</td>
</tr>
<tr>
<td>7</td>
<td>1800</td>
<td>1.00</td>
<td>0.670</td>
</tr>
<tr>
<td>8</td>
<td>2000</td>
<td>0.75</td>
<td>0.650</td>
</tr>
</tbody>
</table>
Figure 3.17 Overshoot characteristic of P controller for various speeds

3.7.2 Simulation Results of PI Controller

An extensive simulation has been done to predict the performance of the drive. The Figure 3.18 illustrates the no load speed response for 1000 rpm with proportional gain $K_p$ as 1.2 and integral gain $K_i$ as 0.6. The overshoot in speed response of the drive is shown in Figure 3.19. The corresponding q axis command current and actual 3 phase motor current are shown in Figures 3.20 and 3.21 respectively.

Figure 3.18 No load speed response with PI
Figure 3.19 Overshoot in speed response with PI

Figure 3.20 q axis current command with PI

Figure 3.21 Three phase current
The response of the drive system is simulated for various integral values of gain by keeping proportional gain $K_p=1.2$ and the readings are tabulated in Table 3.6. The Figure 3.22 illustrates the speed response of the drive with step change in load. The drive system is started at no load and constant load of 5 Nm applied at $t=0.1$ sec. The performance of the drive is also investigated for sudden change in command speed and Figure 3.23 shows the speed response of the system for two speed level.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Integral Gain ($K_i$)</th>
<th>Peak Overshoot %</th>
<th>Steady State Error %</th>
<th>Settling Time ($T_s$) sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2</td>
<td>2.3</td>
<td>0.5</td>
<td>0.02</td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
<td>2.4</td>
<td>0.45</td>
<td>0.02</td>
</tr>
<tr>
<td>3</td>
<td>0.6</td>
<td>2.5</td>
<td>0.40</td>
<td>0.02</td>
</tr>
<tr>
<td>4</td>
<td>0.8</td>
<td>2.6</td>
<td>0.30</td>
<td>0.02</td>
</tr>
<tr>
<td>5</td>
<td>1.0</td>
<td>2.7</td>
<td>0.20</td>
<td>0.02</td>
</tr>
<tr>
<td>6</td>
<td>1.2</td>
<td>2.7</td>
<td>0.15</td>
<td>0.02</td>
</tr>
<tr>
<td>7</td>
<td>1.4</td>
<td>2.8</td>
<td>0.10</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 3.6 PI controller performance for variable $K_i$

Figure 3.22 Speed responses under change in load with PI
Figure 3.23 Speed responses for change in speed command with PI

The performance parameter of PMSM drive such as peak overshoot, steady state error and settling time are observed and Table 3.7 gives simulation results for various speeds. The characteristic curves are obtained from the simulation results and it is shown in Figure 3.24.

Table 3.7 PI controller performance

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Ref Speed</th>
<th>Peak Overshoot %</th>
<th>Steady State Error %</th>
<th>Settling Time (T_s) sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>300</td>
<td>11.67</td>
<td>0.5</td>
<td>0.012</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>7.6</td>
<td>0.5</td>
<td>0.014</td>
</tr>
<tr>
<td>3</td>
<td>800</td>
<td>3.75</td>
<td>0.5</td>
<td>0.016</td>
</tr>
<tr>
<td>4</td>
<td>1000</td>
<td>3.5</td>
<td>0.5</td>
<td>0.02</td>
</tr>
<tr>
<td>5</td>
<td>1200</td>
<td>3.33</td>
<td>0.416</td>
<td>0.022</td>
</tr>
<tr>
<td>6</td>
<td>1500</td>
<td>2</td>
<td>0.233</td>
<td>0.025</td>
</tr>
<tr>
<td>7</td>
<td>1800</td>
<td>1.88</td>
<td>0.333</td>
<td>0.027</td>
</tr>
<tr>
<td>8</td>
<td>2000</td>
<td>2</td>
<td>0.325</td>
<td>0.028</td>
</tr>
</tbody>
</table>
Figure 3.24 Performance characteristics of PI controller
(a) Overshoot (b) Steady state error (c) Settling time
3.7.3 Inference

The Table 3.2 depicts the properties of P controller. The analysis shown in Figure 3.16 implies that when the proportional gain value is increased, the overshoot is increased. The increase in proportional gain value decreases steady state error and settling time. The system output leads to oscillator behaviour if $K_p$ is greater than 2.2. The system becomes unstable if the value of $K_p$ is higher and it is necessary to select the optimum value of proportional gain to improve the stability of the drive system.

Based on the response of the PI controller system, it is obvious that for a fixed value proportional gain ($K_p$), increase in the value of integral gain ($K_i$) increases peak overshoot and decreases the steady state error. In the PI controller system, the important quality of integral gain is the steady state error and from the tabulated results of PMSM drive system, it is evident that the steady state error is reduced with increase in the integral gain values. It is clear that the current is non sinusoidal at starting and becomes sinusoidal when the motor reaches the controller command speed at steady state. As Figure 3.15 and 3.22 illustrates, at $t=0.1$ sec, speed decreases while positive load torque is applied and it shows that P and PI controller cannot obtain a rapid recovery of speed under external load disturbance.

3.7.4 Problem Associated with Conventional Controllers

The traditional controllers face several problems in the real time implementation as most of the real time systems are nonlinear. In the PMSM, the fields are made of permanent magnets and these permanent magnets have their own capability of producing the fixed magnet field. Hence PMSM drive with traditional controller is affected by integral anti windup problems, which leads to increase in peak overshoots. With respect to speed control in the presence of load disturbance, higher the proportional gain of PI controller
increases the overshoot with oscillatory speed response to reach its steady state value.

3.8 SUMMARY

The robustness of the PMSM drive against load variation, change in step input speed demand and performances for various speeds with well known PI speed controller was investigated in this chapter. By using vector control method, PMSM drive is simulated with P and PI controller and performances are analyzed. The speed of the motor is regulated by using traditional P and PI controller. For performance study, the responses of the system for various values of gains are simulated and their characteristics are plotted and compared. The transient parameters such as peak overshoot, settling time and steady state error are noted, tabulated and analyzed. The speed response of the drive under sudden change in load was observed. In addition to the speed response, q axis current command, command phase current and actual motor current was observed under no load and load.