CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The electric motors are electromechanical machines, which are used for the conversion of electrical energy into mechanical energy. The foremost categories of AC motors are Asynchronous and Synchronous motors. The Asynchronous motors are called singly excited machines i.e. the stator windings are connected to AC supply whereas the rotor has no connection from the stator or to any other source of supply. The power is transferred from the stator to the rotor only by mutual induction, owing to which the asynchronous motors are called as induction machines.

The synchronous motors require AC supply for the stator windings and DC supply for the rotor windings. The motor speed is determined by the AC supply frequency and the number of poles of the synchronous motor, the rotor rotates at the speed of the stator revolving field at synchronous speed, which is constant. The variations in mechanical load within the machine’s rating will not affect the motor’s synchronous speed (Bimbra 2004a).

One of the types of synchronous motor is the PMSM. The PMSM consists of conventional three phase windings in the stator and permanent magnets in the rotor. The purpose of the field windings in the conventional synchronous machine is carried out by permanent magnets in PMSM. The
conventional synchronous machine requires AC and DC supply, whereas the PMSM requires only AC supply for its operation. One of the greatest advantages of PMSM over its counterpart is the removal of dc supply for field excitation as discussed by Bose (1996).

The development of PMSM has happened due to the invention of novel magnetic materials and rare earth materials. PMSM give numerous advantages in scheming recent motion management systems. Energy efficient PMSM are designed due to the availability of permanent magnet materials of high magnetic flux density.

2.2 PERMANENT MAGNET MATERIALS

The performance of the PMSM are directly related to the properties of the permanent magnetic materials, Adequate knowledge on the selection of permanent magnet material ensures good performance of PMSM as discussed by Aydin (2004). In the past, hardened steel was used for manufacturing magnets. The advantage of hardened steel magnet is that it is easy to magnetize. However, the drawbacks are the low flux density and tendency to easily demagnetize and degradation of its flux density due to aging.

In modern years, new magnet materials like as Samarium Cobalt (SmCo) First generation rare earth magnet, Strontium Ferrite or Barium Ferrite (Ferrite), Aluminum Nickel and Cobalt alloys (ALNICO), and Neodymium Iron-Boron (Second generation rare earth magnet) (NdFeB) are used for making permanent magnets. The flux density versus magnetizing field for the above magnets is shown in Figure 2.1.
The rare earth magnets are classified into two varieties. They are Neodymium Iron Boride (NdFeB) magnets and Samarium Cobalt (SmCo) magnets. SmCo magnets has higher flux density than the NdFeB magnets, but they are very expensive. NdFeB magnets are the most familiar rare earth magnets and it is now used in the permanent magnet motors.

The Figure 2.2 shows a hysteresis (B-H) curve of a permanent magnet material suitable for PM machines.
2.3 SYNCHRONOUS MOTOR AND PMSM

In Synchronous motors the rotor rotates at the speed of stator revolving field. The speed of the revolving stator field is called as synchronous speed. The synchronous speed \( (\omega_s) \) can be found by the frequency of the stator input supply\( (f_s) \), and the number of stator pole pairs\( (p) \). The stator of a three phase synchronous motor consists of distributed sine three phase winding, whereas the rotor consists of the same number of \( p \)-pole pairs as stator, excited by permanent magnets or a separate DC supply source as given by Krishnan (2001).
When the synchronous machine is excited with a three phase AC supply, a magnetic field rotates at synchronous speed develops in the stator. The synchronous speed of this rotating magnetic field is shown by the Equation (2.1).

\[ N = \frac{120 \, f_s}{P} \text{ rpm} \quad (2.1) \]

Where,
- \( N \) - Synchronous speed,
- \( f_s \) - Frequency of AC supply in Hz,
- \( P \) - Number of poles,
- \( p \) - pole pairs and it is given by \((P/2)\).

2.3.1 Classification of Synchronous A.C. Motors

The synchronous AC motors are classified into a number of different types based on its construction and working. The following are the different types of synchronous motors.

- Salient pole
- Non salient pole (round or cylindrical rotor)
- Permanent magnet (surface, inset, buried/interior, imprecated rotor)
- Reluctance motor (synchronous reluctance, switched reluctance)
- Stepping motor (variable reluctance, permanent magnet, hybrid)

The general classification of electric motors is shown in Figure 2.3.
2.3.2 Types of PMSM

The PMSM are classified based on the direction of field flux as follows,

1. Radial field
2. Axial field

In radial field, the flux direction is along the radius of the machine. The radial field permanent magnet motors are the most commonly used. In axial field, the flux direction is parallel to the rotor shaft. The axial field permanent magnet motors are presently used in a variety of numerous applications because of their higher power density and quick acceleration.

The permanent magnets can be placed in many different ways on the rotor of PMSM as discussed by Krishnan (2001) and Bose (2002). The
Figures 2.4 and 2.5 shows the permanent magnets mounted on the surface of the outer periphery of rotor laminations. This type of arrangement provides the highest air gap flux density, but it has the drawback of lower structural integrity and mechanical robustness. Machines with this arrangement of magnets are known as Surface mount PMSMs.

One other types of placing the permanent magnets in the rotor, is embedding the permanent magnets inside the rotor laminations. This type of machine construction is generally referred to as Interior PMSM and it is shown in the Figures 2.6 and 2.7.

![Figure 2.4 Surface Permanent Magnet](image1)
![Figure 2.5 Surface Inset Permanent Magnet](image2)
The development of this arrangement is more difficult than the surface mount or inset magnet permanent magnet rotors. The inset permanent magnet rotor construction has the advantages of both the surface and interior permanent magnet rotor arrangements by easier construction and mechanical robustness, with a high ratio between the quadrature and direct-axis inductances, respectively.

The surface PMSM with radial flux are generally applied for applications which require low speed operations. These machines have the advantage of high power density than the other types of PMSM. The interior PMSM are used for applications which require high speed.

The principle of operation is identical for all the types of PMSM, in spite of the types of mounting the permanent magnets in the rotor.

The important significance of the type of mounting the permanent magnets on the rotor is the variation in direct axes and quadrature axes.
inductance values, which is explained below. The primary path of the flux through the permanent magnets rotor is the direct axis. The stator inductance when measured in the position of permanent magnets aligned with stator winding is called as direct axis inductance. The quadrature axis inductance is measured by rotating the magnets from the already aligned position (direct axis) by 90 degrees, in this position the iron (inter polar area of the rotor) sees the stator flux. The flux density of the permanent magnet materials is presently high and its permeability is almost equal to that of the air, such that the air gap between the rotor and stator of PMSM can be treated as an extension of permanent magnet thickness. The reluctance of direct axis is always greater than the quadrature axis reluctance, since the effectual air gap of the direct axis is several times that of the real air gap looked by the quadrature axis.

The significance of such an uneven reluctance is that the direct axis inductance is greater than the quadrature axis inductance and it is shown in Equation (2.2)

\[ L_d > L_q \] (2.2)

Where \( L_d \) is the inductance along the direct to the magnet axis and \( L_q \) is the inductance along the axis in quadrature to the magnet axis.

2.3.3 Rotor Position Sensor

The operation of permanent magnet synchronous motors require rotor position sensors to be mounted in the rotor shaft during its operation. The requirement of knowing the rotor position is essential for commutation of inverter switches and production of continuous rotation of the rotor of PMSM. There are four types of rotor position sensors used for the measurement of position of rotor. They are linear variable differential transformer,
potentiometer, optical encoder and resolvers. The most commonly used rotor position sensors for PMSM are optical encoders and resolvers. Depending on the function and performance required by the user, a rotor position sensor with the necessary accuracy can be selected for PMSM.

2.3.3.1 Optical Encoders

The most well-liked type of encoders for rotor position sensors is the optical encoder, and it is shown in Figure 2.8, as discussed by National-Instruments (2006). It consists of a rotating disk with coded patterns of opaque and transparent sectors at the periphery, a LED light source, and a light sensor or photo detector. The rotating disk is mounted on the shaft of PMSM, As the rotating disk rotates, the patterns in the disk disrupt the light emitted onto the light sensor, The light sensor generates a digital pulse or output signal with respect to the coded patterns. There are two types of optical encoders, they are incremental encoder and absolute encoder.

![Figure 2.8 Optical Encoder](image)

2.3.3.2 Incremental Encoders

Incremental encoders are simple in construction and also have good accuracy in finding the rotor position. However, the greatest disadvantage is
the lack of information at the rest position of the motor. To get the rotor position information during the rest position of motor, the motor must be kept stopped at the starting point. The most familiar category of incremental encoder has two code tracks (channel A and channel B) on a disk, with two sectors 90° degrees out of phase. The output channels A and B are used to sense the direction of rotation and the position of the rotor as depicted in the Figure 2.9, as discussed by National-Instruments (2014). If output signal from the channel A leads to channel B, the disk and motor are then rotating in a clockwise direction. If the output signal from channel B leads channel A, the disk and the motor are then rotating in a counter-clockwise direction. By looking at the relative phase of the output signals of channel A and channel B and the number of pulses, the rotor position and the direction of rotation can be identified.

![Figure 2.9 Quadrature Encoder Channels and Outputs](image)

### 2.3.3.3 Absolute Encoders

The absolute encoder has an unique code disc pattern for each position. The unique codes are related to the output bits (n) of the absolute encoder. It can capture the correct position of the rotor with accuracy directly connected to the number of output bits (n) of the encoder. The absolute
encoder is shown in the Figure 2.10, as discussed by BEI-Technologies (2011). It provides an output of unique code pattern signifying each rotor position for each independent track. On the encoder disc an individual light sensor is mounted to derive the code of the rotor position. The output from the individual light sensor or photo detectors can be HIGH during light or LOW during dark depending on the code patterns in the disc for a particular rotor position. The greatest advantage of absolute encoders is that it can give the rotor position information even if the motor is at rest (stop).

![Figure 2.10 Absolute Encoder](Image)

Absolute encoders are applicable in the areas where the devices are inactive for a certain time period or the devices move at a slow rate. Absolute encoders are insisted in systems that must retain rotor position information through a power failure or power outage. Applications of such areas are cranes, valves, telescope, spill way gate control and flood gate control.

### 2.3.3.4 Position Resolver

As position resolvers work on the principle of transformer, it is called a rotary transformer. The position resolvers look like small motors. It
consists of stator and movable rotor, the stator windings are placed in laminated iron stack which is fixed, the rotor windings are placed on a laminated iron stack which is movable. The coefficient of coupling among the stator and rotor varies with the shaft position.

Typically resolvers have a pair of windings on the stator and a winding on the rotor, the stator winding pairs are positioned at right angles to each other. When the rotor winding is excited with a reference AC signal, the stator winding pair produce AC output voltages that differ in amplitude according to the sine and cosine of shaft position of PMSM. The position resolver is shown in Figure 2.11, as given in Freescale Semiconductor (2005).

![Figure 2.11 Position Resolver](image)

### 2.4 NECESSITY FOR RESEARCH ON PMSM

The requirement of variable speed drives with respect to single speed drives are necessary in today’s modern world. The requirement of variable speed drives changed the field of motor which is used in such drives. Till the last decade, the induction motor and Direct Current motor have dominated as mechanical energy conversion devices but now they are being replaced by BLDC and PMSM in the category of power application which
ranges between 0-5kW. The applications of PMSM motors between 0-5 kW are Robotics and factory automation (servo drives), printers/plotters, tape drivers, washers, blowers, compressors, Power steering, ventilation and air conditioning.

**PMSM have the following advantages over DC motors**

- Higher power density and smaller size
- Sparkless operation (used in hazardous environment)
- Higher speed
- Less audible noise
- Longer life
- Better heat transfer

**PMSM have the following advantages over induction motors**

- Higher power density, resulting in smaller size
- Higher efficiency
- Better heat transfer
- Higher power factor

**Demerits of PMSM**

- Complex control.
- Demagnetization of the rotor magnet due to ageing.
- Reduction of torque production due to demagnetization of rotor magnet.
- Maintenance is often required for rotor magnet.
The above comparison shows that the PMSM is superior to the induction motor and direct current machines. The above discussion justifies the choice made in the present research towards the need for research on PMSM.

2.5 APPLICATIONS OF PMSM

Robotics and factory automation (servo drives)
- Pick and place robots (Motion control)
- Positioning tables
- Automatic guided vehicle
- Power supply inverters

Computer and office equipment
- Copier and microfilm machines
- Printers/plotters
- Tape drivers

Appliances
- Washers
- Blowers
- Compressors

Automotive control
- Power steering
- Anti-lock brakes
- Suspension controls
HVAC

- Heating
- Ventilation and air conditioning

### 2.6 MODELING OF PMSM

For proper simulation and analysis of the system, a complete modelling of the drive model is essential. The motor axis has been developed using d-q rotor reference frame theory as shown in Figure 2.12, as given by Pillay & Krishnan (1988). At any particular time t, the rotor reference axis makes an angle \( \theta_r \) with the fixed stator axis and the rotating stator mmf creates an angle \( \alpha \) with the rotor d axis. It is viewed that at any time t, the stator mmf rotates at the same speed as that of the rotor axis.

![Figure 2.12 Motor Axis](image)

**Figure 2.12 Motor Axis**
The required assumptions are obtained for the modelling of the PMSM without damper windings.

1) Saturation is neglected.
2) Induced EMF is sinusoidal in nature.
3) Hysteresis losses and Eddy current losses are negligible.
4) No field current dynamics.

Voltage equations from the model are given by,

\[ V_q = R_s i_q + \omega_r \lambda_d + \rho \dot{\lambda}_q \]  
\[ V_d = R_s i_d - \omega_r \lambda_q - \rho \dot{\lambda}_d \]  

Flux linkages are given by,

\[ \lambda_q = L_q i_q \]  
\[ \lambda_d = L_d i_d + \dot{\lambda}_f \]  

Substituting Equations (2.5) and (2.6) into (2.3) and (2.4)

\[ V_q = R_s i_q + \omega_r (L_d i_d + \dot{\lambda}_f) + \rho L_q i_q \]  
\[ V_d = R_s i_d - \omega_r L_q i_q + \rho (L_d i_d + \dot{\lambda}_f) \]  

Arranging Equations (2.7) and (2.8) in matrix form,

\[
\begin{bmatrix}
V_q \\
V_d
\end{bmatrix} = 
\begin{bmatrix}
R_s + \rho L_q & \omega_r L_d \\
-\omega_r L_q & R_s + \rho L_d
\end{bmatrix} 
\begin{bmatrix}
i_q \\
i_d
\end{bmatrix} + 
\begin{bmatrix}
\omega_r \dot{\lambda}_f \\
\rho \dot{\lambda}_f
\end{bmatrix} \tag{2.9}
\]

The developed torque motor is being given by,
The mechanical torque equation is,

\[ T_e = \frac{3}{2} \left( \frac{P}{2} \right) (\lambda_{sd}i_{qd} - \lambda_{qd}i_{sd}) \]  

\[ (2.10) \]

Solving for the rotor mechanical speed form Equation (2.11)

\[ \omega_m = \int \left( \frac{T_e - T_L - B\omega_m}{J} \right) dt \]  

\[ (2.12) \]

\[ \omega_m = \omega_r \left( \frac{2}{P} \right) \]  

\[ (2.13) \]

In the above equations \( \omega_r \) is the rotor electrical speed, \( \omega_m \) is the rotor mechanical speed.

2.6.1 Parks Transformation and Dynamic d-q Modeling

The dynamic d-q modelling of the system is used for the study of motor during transient state and as well as in the steady state conditions. It is achieved by converting the three phase voltages and currents to dqr axis variables by using the Parks transformation (Bose 2002).

Converting the phase voltages variables \( V_{abc} \) to \( V_{dqo} \) variables in rotor reference frame axis are illustrated in the equations,
Convert $V_{dqo}$ to $V_{abc}$

$$
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
\cos(\theta_r) \cos(\theta_r - 120) \cos(\theta_r + 120) & \cos(\theta_r) \sin(\theta_r - 120) \sin(\theta_r + 120) & \cos(\theta_r) \\
\sin(\theta_r) \cos(\theta_r - 120) \cos(\theta_r + 120) & \sin(\theta_r) \sin(\theta_r - 120) \sin(\theta_r + 120) & \sin(\theta_r) \\
1/2 & 1/2 & 1/2
\end{bmatrix} \begin{bmatrix}
V_q \\
V_d \\
V_o
\end{bmatrix}
$$

(2.14)

2.6.2 Equivalent Circuit of PMSM

Equivalent circuit is essential for the proper simulation and designing of the motor. It is achieved and derived from the d-q modelling of the motor using the voltage equations of the stator. From the assumption, rotor d axis flux is represented by a constant current source which is described through the following equation,

$$\lambda_f = L_{dm} i_f$$

(2.16)

Where, $\lambda_f$ - Field Flux Linkage

$L_{dm}$ - d-axis Magnetizing Inductance

$i_f$ - Equivalent Permanent Magnet Field Current.

The Figure 2.13 shows the equivalent circuit of PMSM without damper windings.
2.7 PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE SYSTEM

The motor drive essentially consists of four main components such as the PMSM, the inverter, the main control unit and the position sensor. Interconnections of the components are shown in Figure 2.14.

![Figure 2.14 Components Permanent Magnet Synchronous Motor Drive](image)

2.7.1 Inverter

For variable frequency and magnitude, Voltage Source Inverters are devices which convert the constant DC voltage level to variable AC
voltage. As specified in the function, these inverters are commonly used in Adjustable speed drives.

Figure 2.15 shows a voltage source inverter with a supply voltage $V_{dc}$ and with six switches. The frequency of the AC voltage can be variable or constant based on the applications (Bose 1996, The MathWorks Incorporation 2013).

![Figure 2.15 Voltage Source Inverter with DC Supply and Load (PMSM)](image)

**Figure 2.15 Voltage Source Inverter with DC Supply and Load (PMSM)**

Three phase inverters consist of a DC voltage source and six power ON/OFF switches connected to the PMSM as shown in Figure 2.15. Selection of the inverter switches must be carefully done based on the necessities of operation, ratings and the application. There are several devices available in the market and these are thyristors, Bipolar Junction Transistors (BJTs), MOS Field Effect Transistors (MOSFETs), Insulated Gate Bipolar Transistors (IGBTs) and Gate Turn Off thyristors (GTOs). The list of the devices with their respective power switching capabilities is shown in Table 2.1. It has been inferred that MOSFETs and IGBTs are preferred in the industry because
of its advantages that the MOS gating permits high power gain and control advantages. MOSFET is considered to be universal power ON/OFF device for low power and low voltage applications, whereas IGBT has wide acceptance in the motor drive applications and other application in the low and medium power range. The power devices when used in motor drives applications require an inductive motor current path provided by antiparallel diodes when the switch is turned off. Inverters with antiparallel diodes are shown in Figure 2.16 (Bimbra 2004b).

![Inverter with IGBTs and Antiparallel Diodes](image)

**Figure 2.16 Inverter with IGBTs and Antiparallel Diodes**

**Table 2.1 Devices Switching Speed and Power Capacity**

<table>
<thead>
<tr>
<th>Device</th>
<th>Switching Speed</th>
<th>Power Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>THYRISTOR</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>MOSFET</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>BJT</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>IGBT</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>GTO</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>
2.7.2 Control Techniques of PMSM

Many techniques based on both motor designs and control techniques that have been proposed in literature to diminish the torque ripples in the PMSM. And is shown in Figure 2.17.

2.7.3 Scalar Control

One way of controlling AC motors for variable speed applications is through the open loop scalar control, which represents the most popular control strategy of squirrel cage AC motors. It is presently used in applications where information about the angular speed need not be known. It
is suitable for a wide range of drives as it ensures robustness at the cost of reduced dynamic performance. Typical applications are pump and fan drives and low-cost drives. The main idea of this method is the variation of the supply voltage frequency inattentively from the shaft response (position, angular speed). The magnitude of the supply voltage is changed according to the frequency in a constant ratio. The motor is then in the condition where the magnetic flux represents the nominal value and the motor is neither over excited nor under excited. The major advantage of this simple method is running in a sensorless mode because the control algorithm does not need information about the angular speed or actual rotor position. On the contrary, the significant disadvantages are the speed dependence on the external load torque, mainly for PMSM, and the reduced dynamic performances.

2.7.4 Vector Control

The vector control of PMSM allows separate closed loop control of both the flux and torque, thereby achieving a similar control structure to that of a separately excited DC machine, as discussed by Novotny & Lipo (1998).

2.7.4.1 Direct Torque Control (DTC)

The DTC is one of the high performance control strategies for the control of AC machine. In a DTC drive applications, flux linkage and electromagnetic torque are controlled directly and independently by the selection of optimum inverter switching modes of operation. To acquire a faster torque output, low inverter switching frequency and low harmonic losses in the model, the selection is made to restrict the flux linkages and electromagnetic torque errors within the respective flux and torque hysteresis bands. The required optimal switching vectors can be selected by using the
optimum switching voltage vector look-up table. This can be obtained by simple physical considerations involving the position of the stator-flux linkage space vector, the available switching vectors, and the required torque flux linkage.

### 2.7.4.2 Field Oriented Control (FOC) of PMSM

For the Control of PM motors, FOC technique is used for synchronous motor to evaluate as a DC motor. The stator windings of the motor are fed by an inverter that generates a variable frequency variable voltage scheme. Instead of controlling the inverter frequency independently, the frequency and phase of the output wave are controlled using a position sensor as shown in Figure 2.8.

FOC was invented in the beginning of 1970s and it demonstrates that an induction motor or synchronous motor could be controlled like a separately excited DC motor by the orientation of the stator mmf or current vector in relation to the rotor flux to achieve a desired objective. For the motor to behave like a DC motor, the control needs knowledge of the position of the instantaneous rotor flux or rotor position of permanent magnet motor. This needs a resolver or an absolute optical encoder. Knowing the position, the three phase currents can be calculated. Its calculation using the current matrix depends on the control desired. Some control options are constant torque and flux weakening. These options are based in the physical limitation of the motor and the inverter. The limit is established by the rated speed of the motor, at which speed the constant torque operation finishes and the flux weakening starts as shown in Figure 2.18 as shown by Novotny & Lipo (1998). From the literature it has been found that the best control for PMSM to make it to behave like a DC motor using decoupling control is known as
Vector control or Field oriented control. The torque components of flux and currents in the motor are separated by the vector control through its stator excitation.

**Figure 2.18 Steady State Torque Versus Speed**

From the dynamic model of the PMSM, the vector control is derived.

Assuming the line currents as input signals,

\[ i_a = I_m \sin(\omega t + \alpha) \]  \hspace{1cm} (2.17)

\[ i_b = I_m \sin(\omega t + \alpha - \frac{2\pi}{3}) \]  \hspace{1cm} (2.18)

\[ i_c = I_m \sin(\omega t + \alpha + \frac{2\pi}{3}) \]  \hspace{1cm} (2.19)
Writing the above Equations (2.17) to (2.19) in the matrix form,

\[
\begin{pmatrix}
i_a \\
i_b \\
i_c
\end{pmatrix} = \begin{pmatrix}
\cos(\omega_r t + \alpha) \\
\cos(\omega_r t + \alpha - \frac{2\pi}{3}) \\
\cos(\omega_r t + \alpha + \frac{2\pi}{3})
\end{pmatrix} \begin{pmatrix}
I_m
\end{pmatrix}
\] (2.20)

Where \(\alpha\) is the angle between the rotor field and stator current phasor, \(\omega_r\) is the electrical rotor speed.

Using the Park’s transformation, the currents obtained in the previous cycle are transformed to the rotor reference frame axis with the rotor speed \(\omega_r\). Since \(\alpha\) is fixed for a given load torque, the \(q\) and \(d\) axis currents are fixed in the rotor reference frames. These constant values are made similar to the armature and field currents in the separately excited DC machine. The \(q\) axis current is distinctly equivalent to the armature current of the DC machine. The \(d\) axis current is field current, but not in its entirety. It is only a partial field current; the other part is contributed by the equivalent current source representing the permanent magnet field. Thus, the \(q\) axis current is known as the torque producing component and the \(d\) axis current is called the flux producing component of the stator currents.

Substituting Equation (2.20) in (2.14) and obtaining \(i_d\) and \(i_q\) in terms of \(I_m\) as follows,

\[
\begin{pmatrix}
i_q \\
i_d
\end{pmatrix} = I_m \begin{pmatrix}
\sin \alpha \\
\cos \alpha
\end{pmatrix}
\] (2.21)
Using Equations (2.3), (2.4), (2.10) and (2.21) the electromagnetic torque equation is obtained as given below,

\[
T_e = \frac{3}{2} \cdot \frac{P}{2} \left[ \frac{1}{2} (L_d - L_q) I_m^2 \sin 2\alpha + \lambda_f I_m \sin \alpha \right]
\]  

(2.22)

Where \(L_d\) and \(L_q\) are the d and q axis synchronous inductances. Each of the two terms in the equation has a useful physical interpretation. The first “magnet” torque term is independent of \(i_d\) but is directly proportional to the stator current component \(i_q\). In contrast, the second reluctance torque term is proportional to the \(i_d\) and \(i_q\) current component product and to the difference of the inductance values.

As the Equation (2.22) shows that the torque depends on the rotor type and its inductances \(L_d\), \(L_q\) and on permanent magnets mounted on the rotor. The non-salient PMSM have surface mounted magnets on the rotor and the reluctance term disappears since \(L_q\) equals \(L_d\). On the contrary, the electromagnetic torque is more dominated by the reluctance component when permanent magnets are interior mounted and the rotor’s saliency causes a difference in \(L_q\) and \(L_d\).

(i) **Constant torque operation scheme**

Constant torque control strategy is derived from field oriented control scheme where the maximum possible torque is desired at all times like the separately excited DC motor (Novotny & Lipo 1998, Freescale semiconductor 2006, Texas Instruments Incorporation 1999a). It is performed by making the torque producing current \(i_q\) equal to the supply current \(I_m\). This results in selecting the \(\alpha\) angle to be 90° degrees according to
Equation (2.21). By making the \( i_d \) current equal to zero the torque equation can be rewritten as,

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

(2.23)

Assuming that,

\[
k_t = \left( \frac{3}{2} \right) \left( \frac{P}{2} \right) \lambda_f
\]  

(2.24)

The torque is given by,

\[
T_e = k_t \cdot i_q
\]  

(2.25)

Like the DC motor, the torque is dependent of the motor current.

A PMSM drive system with a full speed range will have a motor, an inverter unit, a controller with constant torque and flux weakening operation, PI controller and generation of reference line currents as shown in Figure 2.19.

Based on the speed range of the load, the operation of the controller is performed. For operation upto its rated speed, it will be operated in the constant torque region and for speeds above the rated speed of operation it will be operated in the flux weakening region. In this region of operation, the \( d \) flux axis and then the developed torque get reduced or minimized. The process is illustrated using a flow diagram in Figure 2.20.
Figure 2.19 Block Diagram of FOC of PMSM-Constant Torque Operation
Figure 2.20 Flow Diagram of FOC of PMSM-Constant Torque Operation
2.8 LITERATURE SURVEY

Pillay & Krishnan (1989) presented the PMSM which was one of several types of permanent magnet AC motor drives available in the drives industry. The motor had a sinusoidal flux distribution. The application of vector control as well as complete modeling, simulation, and analysis of the drive system were given. State space models of the motor and speed controller and real time models of the inverter switches and vector controller were included. The machine model was derived for the PMSM from the wound rotor synchronous motor. All the equations were derived in rotor reference frame and the equivalent circuit was presented without dampers. The damper windings were not considered as the motor was designed to operate in a drive system with field-oriented control. Performance differences due to the use of Pulse Width Modulation (PWM) and hysteresis current controllers were examined. Particular attention was paid to the motor torque pulsations and the speed response and experimental verification of the drive performance were given.

In order to minimize the torque ripples, many methods based on proper motor design and active control schemes, have been proposed by Jahns & Soong (1996) and Panda et al (2008). Even though the proper motor design is most effective in minimizing torque ripples, there are instances where it is insufficient to achieve the required level of torque ripple reduction.

In active control technique, unwanted pulsating current components which lead to torque pulsations are removed or neutralized by actively controlling the stator excitation to generate a sinusoidal current such that a ripple free smooth torque is produced. Such active control techniques are torque controller using Integral Variable Structure Control studied by Chung et al (1998).
Batzel & Lee (1998) improvised a method to estimate the rotor position using pseudo sensorless approach. The authors suggested two methods of excitation of the motor which include the six step excitation and the sinusoidal excitation. In six step excitation, the Hall effect sensors are mounted on the rotor to evaluate the position of the rotor using back emf method. In sinusoidal excitation, a higher resolution rotor position sensor is used for this technique to obtain the position of the rotor. This approach is used when there is a requirement for a smooth torque response at the output. This approach when used with the hall sensors could reduce the torque pulsations for a sinusoidal wound PMSM. It has been found that this technique could trail the position of the rotor effectively using sinusoidal excitation. A high resolution position sensor such as an encoder could replace the feedback of Hall sensors when sinusoidal commutation is used. This method is suitable for motion control applications such as weapons, tools and bottle industries. The main disadvantage of this method is that the addition of external position sensor makes the system complex.

Production of reference current based on Fourier analysis is known as Harmonic injection method to cancel the current harmonics so that torque ripples are cancelled out is studied by Favre et al (1993), Joachim & Lothar (1996) and Chapman et al (1999). The disadvantages of these methods are that they rely on the assumption that sufficient data is available about the motor.

Rahimi et al (2010), proposed a new on-line three phase reference currents modification method based on Fourier analysis and harmonic identification to reduce torque pulsations and current harmonic noises in PMSM driven by field oriented control algorithm. The new effective schemes based on active filters are presented to minimize the current harmonic noises and torque pulsation but these are not cost beneficial to motor drive
applications and increases the complexity of the control system. As a comparison with the other methods, the proposed approach provides significant effects to obtain optimal motor drive without any complexity. In this study, a harmonic suppression control scheme which constituted a simple generation method of compensation signals for feedback control based on Fourier expansion and harmonic injection strategy have been presented, and also the variables and parameters represented in the rotor reference frame, with the assumptions that the PMSM is unsaturated and eddy currents and hysteresis losses are negligible. By using the proposed scheme, all the current harmonic orders generated by the inverter and hysteresis current controller are almost eliminated and subsequently torque ripple factor improved up to 80%.

Colamartino et al (1999) and Madani et al (1995), studied the shape of the injected current with an additional constraint of minimization of ohmic losses, but they have not concentrated on switching harmonics and voltage harmonics of power inverter which is a major source of harmonics in PMSM.

The inverter output filter system is proposed to reduce harmonics of PMSM by Sozer et al (2000) and Gulez et al (2007b) but they have the disadvantages of circulating current between the inverter output and filter elements, tuning of filters not suitable for variable speed or load applications.

Petrovic et al (2000) proposes a new feedback structure for torque ripple minimization in PMSM drive. The structure has an improved and newly adopted feedback model with slight variation from the conventional model. The main advantages of the model are that it has been found compatible and suitable for control applications. All the parameters of the model structure have physical interpretation, and can be measured directly by
using a numerical reliable technique. Also, it has been found that a speed tracking unit is installed to reduce the torque ripples. The main issues that introduce an upper speed limit were found to be the sampling of the controller inputs and holding of the outputs. The lower speed limit mainly occurs due to increased delay in speed measurement. Several approaches for extending these limits are also discussed in the paper. The results show that there is a significant reduction of 6th (by 27 dB) and 12th (by 4 dB) torque harmonics in the output response.

PM Synchronous Motor Drive demo circuit in The MathWorks Incorporation (2011), used the AC6 block of SimPowerSystems library. It modelled a permanent magnet synchronous motor drive with a braking chopper. The PM synchronous motor was fed by a PWM voltage source inverter, which was built using a Universal Bridge Block. The speed control loop used a PI regulator to produce the flux and torque references for the vector control block. The vector control block computed the three reference motor line currents corresponding to the flux and torque references and then fed the motor with these currents using a three-phase current regulator. Motor current, speed, and torque signals were available at the output of the block.

The demo circuit in Simulink for Permanent magnet synchronous motor fed by PWM inverter had a three-phase motor rated 1.1 kW, 220 V, 3000 rpm in The MathWorks Incorporation (2010). The PWM inverter was built entirely with standard Simulink blocks. Its output went through Controlled Voltage Source blocks before being applied to the PMSM block's stator windings. Two control loops were used. The inner loop regulated the motor's stator currents. The outer loop controlled the motor's speed. Line to line voltages, three phase currents, speed and torque were available at the output of the scope blocks.
The active filter design to reduce or compensate harmonics in the supply side by injecting harmonics into the line current has been proposed by Fujita et al (2000), Rivas et al (2003), Detjen et al (2001) and Gulez et al (2008), which has no effect on the current supplying the load. Moreover, they are complicated in design, and online filter tuning causes more complexity and hardware implementation is relatively expensive.

Islam et al (2009) proposes Skewing designs for the reduction of torque ripples and cogging torque reduction in permanent magnet synchronous motor drive with surface mounted permanent magnets. The effects of the slot/pole combinations and various magnet shapes on the harmonic content of the output torque responses are estimated. It has been found that the torque ripple reduction in the PMSM drive using improved step skewed magnet is a good method but this technique requires adequate attention in the selection of the shape of the magnets. Torque ripple reduction using skewing is more effective in machines as it has a higher optimum skew angle, such as in 9-slot/6-pole and 12-slot/8-pole machines. Another major disadvantage found in these designs is that torque ripple in some motors will increase even after magnet skew, if the magnet shape is not designed carefully. Finite Element Analysis shows that the skewing with steps does not necessarily reduce the torque ripple but may cause it to increase for certain magnet designs and configurations.

A $H_\infty$ model matching two-degree-of-freedom control with adaptive torque ripple cancellation for direct-drive systems under parameter and load uncertainties for PMSM is investigated by Bogosyan et al (2007) but this method’s hardware implementation is relatively expensive and complicated design.

The main causes of torque pulsations are due to the introduction of cogging torque and the non-sinusoidal flux density distribution in the air gap.
The main cause for the non-sinusoidal flux density distribution is that the rotor permanent magnet field is variable under the condition of demagnetization, induces this effect of distribution. The torque ripples fluctuate from time to time with the position of the rotor and are redirected by speed pulsations, which influence the PMSM drive efficiency and performance. To estimate flux magnitude, an extended Kalman filter is built by using the state variables, such as stator current and PM flux. This extended Kalman filter method can be used to accurately track the flux linkage of the motor. Xi Xiao & Changming Chen (2010) proposed a current compensation method to moderate the negative influence caused by demagnetization of the permanent magnets. The compensated currents are derived from the estimated flux linkage. The proposed method has been applied to reduce the torque ripple of synchronous reluctance with permanent magnet motor and it could reduce the 6th and 12th flux linkage harmonics.

Ma & Li (2011) proposed open type and closed type PID type iterative learning control for linear systems and proved that it can speed up the convergence of the tracking error and the controller parameters the PID-type learning algorithm.

Hao Zhu et al (2012) proposed a control scheme for minimizing the non-sinusoidal flux density distribution in the PMSM motor drives. The DTC scheme of permanent-magnet synchronous motors receives growing attention due to its merits in reducing the current controllers and quicker dynamic response output than the other motor control algorithm schemes. This means that large stator voltage and current harmonic contents exist in the PM motors. Since the variation of motor electromagnetic torque is related to the voltages that are applied to the motor by analysing the relationships between the stator flux, torque, and voltages such a scheme is proposed. A torque dynamic equation is developed for the analysis of torque real time behaviour.
The prediction scheme uses incremental changes in the stator flux and the stator current, together with voltage vectors to achieve accurate torque control. Instead of using the increment of stator flux magnitude that might introduce deviation to the calculation, voltage vector is directly handled in the prediction of voltage control angle. The control voltage is accurately oriented according to the rotor flux vector. This scheme simplifies the calculation and improves the accuracy of calculation. Combined with flux control criteria that follows the principle of DTC, the voltage vector control angle is carefully selected to deliver high control performance of both the torque and the stator flux.

Jezernik et al (2013) proposed a field-programmable gate array implementation of a variable structure system predictive sequential switching control strategy, as applied to a permanent magnet synchronous machine. In the case of AC motor drives, in contrast to the conventional vector control where the inverter is not taken into consideration by the controller, the proposed control integrates the inverter model and the inverter states. It allows obtaining faster torque dynamics than the vector control algorithms. The main design specifications are a reduced switching frequency and simple hardware implementation. A predictive sliding mode controller has been developed, designed as finite-state machine, and implemented with a FPGA. This new logic FPGA torque and speed controller has been developed, analysed, and experimentally verified. The predictive current VSS control strategy introduced is very simple and powerful, and advantageously considers the discrete nature of power inverters, and the digital controller.

Flieller et al (2014) proposed a self-learning solution for minimizing the torque ripples which are caused due to the non sinusoidal flux density distribution of the permanent magnets based on Artificial Neural Network framework. To calculate the optimal currents are introduced from
geometrical considerations which are based on Lagrange optimization. These currents are obtained from the two hyper planes enclosed which depend on the structure of the machine. The author has tried to reduce the presence of harmonics in the cogging torque and the back EMF through Adaline neural structure algorithm. Here in this scheme, the two signals speed and torque are given to the two neural blocks, where one is for optimal current calculation and the other is for the generation of these currents via a VSI. The main disadvantage found in this method is the use of Adaline neural algorithm which makes the training process complex.

Heydari et al (2009) proposed a predictive Field Oriented Control of PMSM Using Fuzzy Logic. This method estimates the desirable electrical torque to track mechanical torque at fixed speed operation of PMSM. The estimated torque is used to calculate the reference current based on FOC. In order to increase the performance of the traditional SVM, Predictive Current Control (PCC) is established as switching pattern modifier. In addition, to manage the uncertainty of the estimated values and their error, a fuzzy inference system is cooperated with the proposed FOC-SVM-PCC controller. The performance of the above technique is evaluated in terms of torque, current ripple and transient response to step variations of the torque command.

Kadjoudj et al (2007) studied about the Fuzzy Rule Based Model Reference Adaptive Control for PMSM Drives. The objective of the Model Reference Adaptive Fuzzy Control (MRAFC) is to change the rules definition in the direct Fuzzy Logic Controller (FLC) and rule base table according to the comparison between the reference model output signal and system output. Owing to the improved algorithm, it has fast learning features and good tracking characteristics even under severe variations of the system parameters. In this scheme, the error and error change measured between the motor speed
and the output of the reference model are applied to the MRAFC. The latter will force the system to behave like the signal reference by modifying the knowledge base of the FLC or by adding an adaptation signal to the fuzzy controller output. High performances and robustness have been achieved by using the MRAFC.

Sergaki et al (2008) studied about the online electromagnetic loss mimimization of PMSM Drives and also to improve the online efficiency in PMSM drives for both transient and steady state operation. The power losses are calculated as the difference between the measured input DC-link power and drive's output power. Variables in the operating characteristics of the PMSM, such as DC input voltage/current and actual speed are inputs to the fuzzy control system, making the control system independent of any specific load. The system used in the present research combines two fuzzy logic designed efficiency controllers which are introduced as Fuzzy (1) and Fuzzy (2) controllers to generate the magnetizing current (d-axis component of the stator current). They are separately activated during the steady and transient state respectively. The FLC prototypes were created and tested using MATLAB Simulink simulations.

Soliman & Elbuluk (2008) presented a method for improving the reduction of torque ripple in PMSM drives under Direct Torque Control (DTC) using a FLC. A DTC PMSM drive using conventional two and three states of torque error, and a FLC were simulated using the SimuLink package. The results showed that the DTC/FLC gives a better dynamic performance regarding torque and flux ripples, and speed performance than the conventional DTC that has two and three level hysteresis torque controllers.

Hasanien (2010) presented a digital observer controller for PMSM. The digital observer controller is used for torque ripple minimization of this type of motors. The dynamic response of the PMSM with the proposed
controller is studied during the starting process under the full load torque and under load disturbance. The effectiveness of this digital observer controller is then compared with that of the conventional PI controller.

Patil et al (2010) proposed the Fuzzy Adaptive Control (FAC) for speed control of PMSM drive. In this novel approach output scaling factor of Fuzzy controller is tuned through adaptation mechanism. The idea is to have a control system that will be able to achieve improvement in tracking set point change and rejection of load disturbance. High performances and robustness have been achieved by using the FAC. This has been illustrated by the results of simulation and comparisons with other controllers such as PI, Classical and Fuzzy adaptive controller based on tuning of input and output scaling factors.

Uddin (2011) proposed an adaptive-filter-based Torque Ripple Minimization (TRM) of a FLC for speed control of an IPM motor drive. A simple and effective first-order digital infinite impulse response filter is utilized to reduce the torque ripples introduced by the FLC. A simulation model for vector control of an FLC based IPM motor drive incorporating the TRM technique is developed in SIMULINK under MATLAB. The complete drive is also experimentally implemented using digital signal processor board DS1102 for a laboratory 1-hp IPM motor. The performance of the FLC based IPM drive is significantly improved.

The steady state torque is instantaneously controlled via the proportional type iterative learning controller using the Previous Cycle Feedback (PCF) algorithm by Qian et al (2004) and Lam et al (1999) and the results show that torque ripple minimization is better, the scheme is simple to implement, can be added to any existing controller and does not require accurate knowledge of the motor parameters. However, they have not
concentrated on switching harmonics and voltage harmonics of power inverter which is a major source of harmonics in PMSM.

In all the above works, none of them have considered a real FOC of PMSM drive system operating at constant torque.

2.9 MOTIVATION AND SCIENTIFIC CONTRIBUTIONS

Qian et al (2004) studied the two periodic torque ripple minimization schemes using Iterative Learning Controller (ILC) implemented in time domain and frequency domain. The performances of both ILC control schemes have been evaluated through experimental investigations. Test results presented demonstrate improvements in the steady-state torque response and therefore validate the effectiveness of both the proposed ILC schemes in suppressing the torque ripple. The scheme is simple to implement, can be added to any existing controller and does not require accurate knowledge of the motor parameters. They have concentrated on torque ripples which are periodic in nature like cogging torque, flux harmonics and current offset error. However, the authors have not concentrated on switching harmonics and voltage harmonics of power inverter which is a major source of harmonics in PMSM which motivated to develop a ILC along with less switching harmonics techniques like HPWM and SVPWM respectively to reduce the torque ripples present in FOC of PMSM operating at constant torque.

Gaur et al (2008) proposed Artificial Neural Network based speed Controller and Speed Estimation of Permanent Magnet Synchronous Motor and analysed the performance of ANN based system using SIMULINK under MATLAB by evaluating it for various disturbances to substantiate the ANN control and estimation of the speed. The author does not consider a real drive system simulation in SIMULINK under MATLAB, operating at constant
torque and flux weakening regions. This motivated to develop a new torque control scheme operating at constant torque, which is based on ANN with minimum torque ripples so as to suit the application requirements.

Li et al (2010) proposed an application of computational intelligence technique like Fuzzy Logic to reduce the torque ripples associated with the direct torque control in PMSM. The traditional hysteretic comparator is replaced by FLC. The zero voltage vectors effective time is determined by the FLC output with the help of torque error magnitude and flux error magnitude. Thus, the arrangement of switching time of inverter switches resulted in reducing the torque ripples. The effectiveness of the method is verified by the results of the simulation. The author considered only Direct Torque Controller but field oriented vector controller is better than its performance, which motivated to develop a new FLC for field oriented PMSM operating at constant torque.

The scientific contributions of the present research can be summarized as follows

1. A two instantaneous FOC techniques operating at constant torque, namely, ILC with HPWM and ILC with SVPWM respectively to reduce torque ripples in PMSM have been proposed. Here, ILC using the PCF algorithm in combination with reduction in switching harmonics and voltage harmonics with the help of space vector modulation of inverter in the FOC of PMSM to minimize the torque ripples is presented. In this system the torque reference is compared with the actual torque and the output is given to the torque controller. Here, this PI torque controller is replaced by ILC controller and the output of this controller will be the torque error. The PMSM stator currents $i_a, i_b, i_c$ are applied as input to the Clarke transformation, which outputs a two co-ordinate time variant system $i_\alpha$ and $i_\beta$. This $i_\alpha$ and $i_\beta$ are
applied as input to park transformation which outputs a two co-ordinate time invariant system currents $i_{ad}, i_{sq}$. By using these values of currents $i_{ad}, i_{sq}$ the $V_{sqref}, V_{sdref}$ are calculated. The calculated $V_{sqref}, V_{sdref}$ values are essential information for the park inverse transformation and its output is given to the SVPWM generator to produce the pulses to the inverter. By proper switching of the inverter switches, harmonics will be reduced in PMSM drives which will further reduce the torque ripples in the PMSM drive. The results of the simulation show that the proposed ILC with SVPWM method shows better torque reduction in comparison with ILC with HPWM and all the existing methods.

2. Artificial Neural Network (ANN) Controller with SVPWM based FOC of PMSM operating at constant torque has been proposed to reduce torque ripples.

In the present research, an application of ANN based controller for PMSM in the in-direct vector controller to minimize the torque ripples is presented. In this system the torque reference is compared with the actual torque and the output is given to ANN controller. From the stator currents $i_a, i_b, i_c$ are applied to the Clarke transformation and Park transformation the output will be the synchronous current $i_{ad}, i_{sq}$. By using these values the actual torque is calculated and compared with the reference torque. The output is given to the park inverse transformation and the output is given to the SVPWM generator to produce the pulses to the three phase inverter. The feed-forward artificial neural network structure is composed of one input layer, one output layer and three hidden layers. The structure of three hidden layer having three neurons gives satisfactory results. The input layer accepts the present torque error and previous torque error as inputs. The output layer gives $i_{sqref}$ as output. The output of the ANN controller will be the $i_{sqref}$ which is used to control the torque.
The results of the simulation of ANN with SVPWM based FOC of PMSM drive shows that the proposed ANN Controller with SVPWM based FOC of PMSM is superior to the existing control methods in minimizing the torque ripples.

3. The following two instantaneous FOC techniques operating at constant torque, namely, Fuzzy Logic Controller (FLC) with HPWM and FLC with SVPWM respectively are proposed to reduce torque ripples in PMSM.

The drawbacks of the Proportional plus Integral (PI) controllers is fixed proportional gain and integral time constant. The performance of the PI controllers are affected by parameter variations, load disturbances and speed variations. These problems can be overcome by the FLC, which do not require any mathematical model and are based on the linguistic rules obtained from the experience of the system operator.

In this study, the conventional PI torque controller is replaced by FLC controller and the output of this controller will be the torque error. The inputs to the FLC are Torque error and change in torque error and the output is torque limit .Each of the inputs and output contains seven membership functions with 49 rules. The PMSM stator currents \( i_a, i_b, i_c \) are applied as input to the Clarke transformation, which outputs a two co-ordinate time variant system \( i_x, i_y \). This \( i_x \) and \( i_y \) are applied as input to park transformation which outputs a two co-ordinate time invariant system currents \( i_{d}, i_{q} \). By using these values of currents \( i_{d}, i_{q} \), the \( V_{sqref}, V_{sdref} \) are calculated. The calculated \( V_{sqref}, V_{sdref} \) values are essential information for the park inverse transformation and its output is given to the SVPWM generator to produce the pulses to the inverter. The SVPWM is employed to overcome the periodic torque pulsations generated by hysteresis controllers. The results of the
simulation shows that the proposed FLC with SVPWM based FOC of PMSM has lesser torque ripples than the all the proposed methods.

The experimental verification is done for the proposed method i.e. FLC with SVPWM based FOC of PMSM. The design analysis of the above controller is implemented in FPGA controller SPARTAN 3A DSP. The results of the simulation are validated with experimental results in PMSM prototype.