CHAPTER 5

ONLINE PARAMETER ESTIMATION AND IMPLEMENTATION OF MTPA CONTROL

5.1 INTRODUCTION

One of the most advanced control techniques for optimizing the torque is MTPA control. The performance of the MTPA control scheme relies on the knowledge of motor parameters. Hence, the effective implementation of proposed MTPA controller is achieved with suitable online parameter estimation algorithm.

The machine parameters can be estimated in offline as illustrated by Kim et al (2002) and Yasser et al (2006). These techniques are computationally intensive and can not be used for online parameter estimation. Such calculations are usually unreasonable in real time.

In this chapter, the implementation of proposed MTPA control along with parameter estimation is discussed for the developed prototype machine. This method is capable of identifying the d and q axes inductances and the back emf due to PM. The hardware implementation of MTPA control strategy along with online parameter estimation is also discussed. A detailed experimental study is carried out with the prototype drive.
5.2 MACHINE MODEL FOR PARAMETER ESTIMATION

Consider the phase model of prototype machine developed in chapter 4. Applying Park’s transformation and transforming abc variables as given by equation (4.14) into dq variables are obtained (Rahman and Little 1984, Rahman and Osheiba 1990).

\[ v_{sd} = r_s i_{sd} + D\lambda_{sq} - (1-s)\omega_r \lambda_{sq} \]
\[ v_{sq} = r_s i_{sq} + D\lambda_{sq} + (1-s)\omega_r \lambda_{sd} \]
\[ 0 = r_{rq} i_{rq} + D\lambda_{rq} \]
\[ 0 = r_{rd} i_{rd} + D\lambda_{rd} \]
\[ \lambda_{sd} = L_{sd} i_{sd} + L_{md} i_{rd} + \lambda_p \]
\[ \lambda_{sq} = L_{sq} i_{sq} + L_{mq} i_{rq} \]
\[ \lambda_{rd} = L_{md} i_{sd} + L_{rd} i_{rd} + \lambda_p \]
\[ \lambda_{rq} = L_{rq} i_{rq} + L_{mq} i_{sq} \]

In steady state, d and q axis equations of a cage-rotor IPMSM are obtained by substituting derivative terms and transient current becomes zero in equation (5.1).

\[ v_{sd} = r_s i_{sd} - \omega_r \lambda_{sq} \]
\[ v_{sq} = r_s i_{sq} + \omega_r \lambda_{sd} \]
\[ \lambda_{sd} = L_{sd} i_{sd} + \lambda_p \]
\[ \lambda_{sq} = L_{sq} i_{sq} \]

Normally, \( \lambda_p \) is considered as known sinusoidal waveform with constant amplitude. Whereas the measured back emf due to PM of prototype machine shows that it is non-sinusoidal mainly due to the machine having low
stator slot number and rectangular shape of inserted magnet. Figure 5.1 shows the non-sinusoidal back emf of phase ‘a’ and the corresponding normalized harmonic contents. As can be seen, the fundamental and fifth harmonic components are significant while other higher order harmonics are negligible. When considering the effect of non-sinusoidal back emf, equation (5.2) is rewritten in terms of Fourier series as given by (Hendershot and Miller 1994)

\[
\begin{align*}
    v_{sd}^r &= r_s i_{sd}^r - \omega r \lambda_{sq}^r \\
    v_{sq}^r &= r_s i_{sq}^r + \omega_r \lambda_{sd}^r \\
    \lambda_{sd}^r &= L_{sd} i_{sd}^r + \lambda_p + \lambda_p \sum_{n=1}^{\infty} [K_{6n-1} + K_{6n+1}] \cos(6n\theta) \\
    \lambda_{sq}^r &= L_{sq} i_{sq}^r - \lambda_p \sum_{n=1}^{\infty} [K_{6n-1} - K_{6n+1}] \sin(6n\theta) \\
    \text{where } n &= 1, 2, \ldots
\end{align*}
\]

The fundamental component of the magnet flux linkage ($\lambda_p$) in (5.3) is considered to be constant, since the machine operates within the magnetization region. The coefficient $K_n$ denotes the normalized magnitude of the $n^{th}$ component of the magnet flux linkage with respect to the fundamental harmonics. $K_n$ is considered to be constant because its value is defined by the shape of back emf and not by its magnitude.

Using multiple reference frame technique (Chapman et al 1999), the estimation of machine parameters can be easily estimated as discussed in the following section.
Figure 5.1 (a) Back emf due to PM at 1500rpm (b) Percentage harmonics of line to line back emf due to PM
5.3 MULTIPLE REFERENCE FRAME TECHNIQUE

In multiple reference frames, the dq-axes variables can be transformed into another reference frame rotating at ‘xr’ times the rotor speed is given by

\[
T_{dq}^{xr} = \begin{bmatrix}
\cos((x-1)\theta) & -\sin((x-1)\theta) \\
\sin((x-1)\theta) & \cos((x-1)\theta)
\end{bmatrix} T_{dq}^{r}
\]

(5.4)

where \( T_{dq}^{r} \) can be the stator voltage, current or flux linkage.

Applying (5.4) to (5.3) yields the voltage equations in the ‘xr’ reference frame, which may be expressed by

\[
\begin{align*}
V_{sd}^{xr} &= r_s i_{sd}^{xr} - x \omega_r \lambda_{sq}^{xr} \\
V_{sq}^{xr} &= r_s i_{sq}^{xr} + x \omega_r \lambda_{sd}^{xr}
\end{align*}
\]

(5.5)

Transform dq frame flux linkages into xr reference frame as given by

\[
\begin{align*}
\lambda_{sd}^{xr} &= L_{sd} i_{sd}^{xr} + \lambda_p \cos((x-1)\theta) + \\
& \quad \lambda_p \sum_{n=1}^{\infty} K_{6n-1} \cos((x-1+6n)\theta) + K_{6n-1} \cos((x-1+6n)\theta) \\
\lambda_{sq}^{xr} &= L_{sq} i_{sq}^{xr} + \lambda_p \sin((x-1)\theta) + \\
& \quad \lambda_p \sum_{n=1}^{\infty} K_{6n-1} \sin((x-1+6n)\theta) - K_{6n-1} \sin((x-1+6n)\theta)
\end{align*}
\]

(5.6)

Equation (5.6) is used in literature for minimizing the torque ripple of IPMSM drive. In this research work, the same model is used to estimate the machine parameters.
5.4 PARAMETER ESTIMATION ALGORITHM

The parameter estimation algorithm for PM-assisted Synchronous reluctance machine is proposed by Niazi et al (2007). In this section, it can be extended to estimation of prototype machine parameter also. Particularly at high speed, the variation of \( R_s \) is relatively small in estimation of \( L_{sq} \) and very small in estimation of \( L_{sd} \) (Niazi et al, 2007). Hence, \( R_s \) may be considered as a constant system parameter. The rest of the parameters be estimated by using the multiple reference schemes. The parameters to be estimated are \( L_{sd}, L_{sq} \) and \( \lambda_p \). The online estimation of these three parameters requires three equations. The first two equations in (5.7) can be written in the fundamental harmonic reference frame by substituting \( n=1 \) and \( x=0 \) in equation (5.5). The third equation can be written in the fifth harmonic reference frame by substituting \( n=1 \) and \( x= -5 \) in (5.5),

\[
\begin{align*}
  v_{sd} - r_s i_{sd} &= -\omega_r L_{sq} i_{sq} \\
  v_{sq} - r_s i_{sq} - \omega_r \lambda_p &= \omega_r L_{sd} i_{sd} \\
  v_{rsq}^5 - r_s i_{sq}^5 - 5\omega_r K_{5}\lambda_p &= 5\omega_r L_{sd} i_{sd}^5
\end{align*}
\]

These three equations will help to estimate \( L_{sd}, L_{sq} \) and \( \lambda_p \). In order to reject the high order harmonics from the measured signals, low pass filter is necessary. Figure 5.2 shows the block diagram of the control system along the proposed parameter estimator.
5.5 EXPERIMENTAL SETUP

The schematic block diagram of the experimental setup of the prototype cage-rotor IPMSM is shown in Figure 5.3. The corresponding photographic view of the complete drive system is shown in Figure 5.4.
The IPMSM drive control consists of system hardware and control software. The drive hardware includes a fully digitally controlled IGBT-based VSI with necessary gate driver circuit, position encoder with scaling circuits, current and voltage sensors with necessary scaling circuits, and dSPACE DS 1104 controller board. The controller board is equipped with
a compact host add-on card based on Texas instruments 32-bit floating-point processor TMS320C31 as a main processor and the TMS320P14 as a slave processor, analog-to-digital converters, digital I/O’s and digital-to-analog converters. The gate driver circuit consists of EXB840 driver chip. Each gate driver has an optical isolation in its initial stage to isolate the control circuit from the power circuit. As per the proposed MTPA algorithm, six gating pulses are generated in digital environment. The actual speed, reference speed, voltage and current signals are scaled by their respective signal conditioning circuits and are brought in the acceptable range of 0-5V. The speed ranges from +3000rpm to -3000rpm. Hall Effect closed loop current and voltage sensors are used for measuring currents and voltages, respectively.

The components of the control software, namely, the speed controller, limiter, online parameter estimation, MTPA controller and PI current controller are implemented through the DSP processor. The software code controller algorithm is implemented through SIMULINK environment. It serves as control and display.

In order to implement the control algorithm, various tasks such as acquiring input signals, parameter estimation and generation of reference current are performed in sequence. These tasks are sequenced by the use of appropriate Interrupt Service Routine (ISR). The sampling frequency of the current and voltage signals is kept at 10 kHz. While sampling the input signals for the present cycle, reference signals generated from the previous cycle are outputted. The flowchart describing the implementation of estimation algorithm is shown in Figure 5.5.
Figure 5.5 Flow chart of the software for implementation of MTPA algorithm
5.6 SIMULATION AND EXPERIMENTAL RESULTS

The simulation was done using the inverter fed prototype machine. Using the current controlled PWM voltage source inverter circuit, experimental measurements of voltage and currents are performed under constant speed. The values of \( L_{sd} \) and \( L_{sq} \) are obtained from equation (5.2) over the entire operating region and the same has been shown in Figure 5.6. However, effect of variation in flux linkage from magnet has been ignored in the simulation due to the complexity of the model.

To satisfy the computed results of parameter estimation, it is necessary to remove the higher order harmonic components from the measured currents and voltages. By using low pass analog filter, the fundamental and fifth harmonic components of \( d \)-axes voltages and currents are computed and the same has been substituted with equation (5.6) for estimating \( L_{sd}, L_{sq} \) and \( \lambda_p \). The inability of analog filter introduces oscillations in measured signals and the same can be reflected in the parameter estimation as shown in Figure 5.7. This can be improved by using digital filter instead of analog filter.

![Figure 5.6 Measured dq axes inductances as a function of current components](image-url)
Figure 5.7 Experimental results of dq axes inductances and rotor flux linkages
To satisfy MTPA control, initially the motor operates at steady state speed in 500rpm with a load 1.0Nm. Then, at t=1.0 sec, the reference speed is increased to 800rpm. The corresponding speed and torque graph are shown in Figure 5.8. As seen from Figure 5.8(a), the experimental speed response takes a long time to reach set values because of high inertia on the motor. The ripple in the steady state speed of the experimental result is due to the poor resolution of speed measurement. It can be observed from Figure 5.8(b), when the motor speed is increased from 500rpm to 800rpm, the dip in torque may occur. The developed MTPA control action recovers the same back into the set value. Since, the cogging torque of the prototype machine was unknown, the pulsation in the torque is more in the experimental result.

To demonstrate the load perturbation on the same drive, the load on the motor shaft is gradually increased from 0.5 Nm to 1.0 Nm via DC generator. Figure 5.9 presents the corresponding simulation and experimental results.

Figure 5.9(a) shows a stator phase current on a time scale. The step variation in torque from simulation and from experimental is shown in Figure 5.9(b) and the corresponding effect in speed is shown in Figure 5.9(c). It can be seen that the transient behaviour of the experimental results are varies from simulated results because the computation of proposed MTPA control algorithm neglects the transient effect. However, the magnitude of steady state current, torque and speed in these plots are same.
Figure 5.8 Time variation of (a) Speed (b) Torque when speed is increased from 500rpm to 800rpm
Figure 5.9  Time variation of (a) Stator phase current (b) Torque (c) Speed when load is increased from 0.5Nm to 1.0Nm
5.7 CONCLUSION

Interior permanent magnet synchronous motor can offer better torque capability. However, to utilize the maximum efficiency of the motor knowledge of the motor parameters is necessary.

Variation of the IPMSM parameters was shown and a simple practical method for estimation of the motor parameters was presented. It is noticed that the implemented MTPA controller includes the effects of the saturation as well as the variation of magnet flux due to the change of temperature. This feature assures the robustness of the MTPA controller against the variations of the motor parameters.

Simulation and experimental results of the proposed technique validate the effectiveness of the proposed controller and prove the feasibility of the proposed method.