CHAPTER 6

SIMULTANEOUS CONTROL OF ROTOR TORQUE AND ROTOR POWER IN A FIELD-ROTOR INTERIOR PERMANENT MAGNET SYNCHRONOUS MOTOR

6.1 INTRODUCTION

In a specific application like rotational antenna or turret system which requires electric power to electronic equipment mounted on the rotating assembly, a suitable electromechanical machine can provide simultaneous action of mechanical rotation and electric power transfer. Masoud et al (2005) have suggested that a Salient Pole Synchronous Motor (SPSM) can be used to provide mechanical torque along with electrical power delivered to the rotor mounted load. However, the amount of torque production using SPSM depends only on saliency, which is very less. It can be improved by using field-rotor IPMSM. Xiaogang and Lipo (2000) proposed a field-rotor interior permanent magnet synchronous motor, which is a combination of IPMSM and SPSM without damper winding. It has the features of PM and synchronous machine. The permanent magnets provide constant air gap flux and the excitation poles act as the flux regulator to adjust the air gap flux distribution.

In this research work, maximum torque per flux scheme that is introduced in chapter 3 is used for simultaneous control of torque to a rotor mounted load and electric power transfer to equipment mounted on the rotor in a field-rotor IPMSM. Evaluation of simultaneous control of rotor torque and rotor power is performed in two ways. Firstly, the simulation of the motor
with flux control algorithm is performed. Secondly, real time model of field-rotor IPMSM with flux control algorithm is programmed on DSP add-on card (dSPACE DS1104).

6.2 PROBLEM STATEMENT

Consider the field-rotor IPMSM structure as shown in Figure 6.1. It has both PM poles and excitation poles on rotor and retains the conventional three-phase stator winding. In the absence of field excitation, a field-rotor IPMSM enables to produce torque, as equivalent to IPMSM. At the same time, the unexcited field winding induces a field voltage \( (v_f) \) across the winding. Suppose a load resistance \( (R_L) \) is connected across the field winding, a load current \( (i_f) \) will flow at the user defined frequency \( (f_p) \). According to Lenz’s law, the power will be transferred to the load with a negative sign. This technique eliminates the need for slip rings. Thus, a field-rotor IPMSM can be used to generate torque without field excitation and also transmit contactless power to the rotor mounted electronic equipment.

![Figure 6.1 Structure of 4 pole, 3 phase, field-rotor IPMSM](image-url)
The main objective of this chapter is to extend the MTPF scheme introduced in chapter 3, for simultaneous control of torque and rotor power extraction in a field-rotor IPMSM drive.

6.3 TRIPLE MODE OPERATION

A field-rotor IPMSM model can be operated in the triple modes of operation viz, motor action, transformer action and the combination of these two actions (Masoud et al 2005). The machine equations are considered in dq reference frame for the derivation of MTPF control algorithm in the following section.

6.3.1 Basic Equations

The equivalent circuit of field-rotor IPMSM in dq reference frame is shown in Figure 6.2

Figure 6.2 Equivalent circuit of field-rotor IPMSM with unexcited field winding (a) d-axis (b) q-axis
and the corresponding voltage and flux linkage equations are given by

\[
\begin{align*}
    v_{sd} &= r_s i_{sd} + D \lambda_{sd} - \omega_r \lambda_{sq} \\
    v_{sq} &= r_s i_{sq} + D \lambda_{sq} + \omega_r \lambda_{sd} \\
    v_f' &= -R_f i_f' + p \lambda_f' = i_f' R_L' \\
    \lambda_{sd} &= L_{sd} i_{sd} - L_{md} i_f' + \lambda_p \\
    \lambda_{sq} &= L_{sq} i_{sq} \\
    \lambda_f' &= -L_f i_f' + L_{md} i_{sd}
\end{align*}
\] (6.1)

Then, the electromagnetic torque is given by

\[
T_e = \frac{3 P}{2 L_{sq} L_{sd}} \left[ L_{sq} \lambda_p \lambda_{sq} - (L_{sq} - L_{sd}) \lambda_{sq} \lambda_{sq} - L_{sq} L_{md} \lambda_{sq} i_f' \right] 
\] (6.2)

In order to extend MTPF scheme, equation (6.2) can be transformed into stationary reference frame with the help of a well-known coordination transformation matrix to yield

\[
T_e = \frac{3 P |\lambda_s|}{4L_{sd} L_{sq}} \left[ 2 \lambda_p L_{sq} \sin \delta - |\lambda_s| (L_{sq} - L_{sd}) \sin 2\delta - 2L_{md} i_f' L_{sq} \sin \delta \right]
\] (6.3)

Equation (6.3) clearly implies that three different modes of operation are possible in the absence of external field excitation. They are

1. Mechanical Power Transfer (Mode 1)
2. Electrical Power Transfer (Mode 2)
3. Simultaneous Electrical and Mechanical Power Transfer (Mode 3)
In mode 1, when there is no rotor power extraction, the maximum possible excitation torque ($T_{\text{emax}}$) can be obtained by substituting $i_r' = 0$ in equation (6.3). In mode 2, when there is no excitation torque, the stator current can be augmented with higher frequency component to induce voltages across the field winding. An expression for maximum field current $i_f'_{\text{(max)}}$ is obtained by substituting $T_c=0$ in equation (6.3). In mode 3, the field current is a continuous function of time and constant stator flux magnitude and then the machine operates in combination of both modes simultaneously as shown in Figure 6.3.

![Figure 6.3 Rotor electric power versus torque triangle](image)

### 6.3.2 Proposed Reference Flux Generation

Masoud et al (2005) have presented a method for determining the reference stator current in the triple mode operation for the SPSM. In this research work, the expression for reference flux is derived for triple mode of operation in field-rotor IPMSM. Let the desired electromagnetic torque ($T_c^*$) and desired referred field current ($i_f'^*_{\text{}}$) be defined by user. Let it be assumed that $i_f'^*$ is sinusoidal given by

$$i_f'^* = I_f' \sqrt{2} \sin (\omega pt)$$

(6.4)
Substituting equation (6.4) with equation (6.1), \( i_{sd}^* \) is obtained.

\[
i_{sd}^* = I_0 + \frac{L_f'}{L_{md}} I_f' \sqrt{2} \sin(\omega_p t) - \left[ \frac{R_f' + R L'}{\omega_p L_{md}} \right] I_f' \sqrt{2} \cos(\omega_p t) \tag{6.5}
\]

The dc level component \( I_0 \) in equation (6.5) ensures that \( i_{sd}^* \) is positive and prevents a discontinuity in the q-axis stator current. The maximum value assigned to \( I_0 \) is determined by increasing the maximum of \( i_{sd} \). The d-axis flux linkage in equation (6.1) relates \( \lambda_{sd}^* \) to \( i_f^* \) and \( i_{sd}^* \)

\[
\lambda_{sd}^* = L_{sd} I_0 + I_f' \sqrt{2} \left[ \left( \frac{L_f' L_{sd} - L_{md}}{L_{md}} \right)^2 \sin(\omega_p t) - L_{sd} \left[ \frac{R_f' + R L'}{\omega_p L_{md}} \right] \cos(\omega_p t) \right] + \lambda_p
\tag{6.6}

Similarly \( \lambda_{sq}^* \) is obtained with the condition \( (\lambda_{sd}^* - L_{sq} i_{sd}^*) \neq 0 \) as

\[
\lambda_{sq}^* = \frac{T_e^*}{\frac{3 P}{2} \frac{1}{L_{sq} L_{sd}} \left[ L_{sq} \lambda_p - (L_{sq} - L_{sd}) \lambda_{sq}^* - L_{sq} L_{md} i_f' \right]}
\tag{6.7}

It is seen that equation (6.6) relates \( i_f^* \) and \( \lambda_{sd}^* \) and equation (6.7) relates \( T_e^* \) to \( \lambda_{sq}^* \). Hence, the simultaneous control of torque and rotor power extraction is achieved by implementing equation (6.6) and equation (6.7) in real time.

### 6.4 DIRECT TORQUE CONTROL

The basic principle of DTC is to select proper voltage vectors, based on the required stator flux vectors, which in turn maintains the torque
and rotor power at the set values. The block diagram of field-rotor IPMSM drive for triple mode of operation is shown in Figure 6.3 wherein the number of coordinate transformation is reduced as compared with current control method (Masoud et al 2005).

The digital output of the hysteresis controllers for flux linkage ($\Phi$) and torque ($\tau$) is calculated based on the equation (6.9)

$$\text{If } |\lambda_\phi| \leq |\lambda_s^*| - |\Delta\lambda_s| \text{ Then } \phi = 1 \text{ else } \phi = 0$$

$$\text{If } |T_e| \leq |T_e^*| - |\Delta T_e| \text{ Then } \tau = 1 \text{ else } \tau = 0 \quad (6.9)$$

$$\text{If } |T_e| \leq |T_e^*| - |\Delta T_e| \text{ Then } \tau = 1 \text{ else } \tau = 0$$

Figure 6.4 Block diagram of field-rotor IPMSM drive for triple mode operation
Table 6.1 Optimal Voltage Vector Selection

<table>
<thead>
<tr>
<th>Desired effect</th>
<th>Voltage Vector Depending on Sector</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>θ (1)</td>
</tr>
<tr>
<td>Φ=1</td>
<td></td>
</tr>
<tr>
<td>τ =1</td>
<td>V_2</td>
</tr>
<tr>
<td>τ =-1</td>
<td>V_6</td>
</tr>
<tr>
<td>Φ=0</td>
<td></td>
</tr>
<tr>
<td>τ =1</td>
<td>V_3</td>
</tr>
<tr>
<td>τ =-1</td>
<td>V_5</td>
</tr>
</tbody>
</table>

6.5 SIMULATION RESULTS

The DTC algorithm of a field-rotor IPMSM drive is simulated in Matlab/Simulink environment. The machine parameters are listed in Appendix 3. The simulation results provide the maximum limit of torque and electrical power to the rotor.

6.5.1 Maximum Mechanical Power Transfer

The maximum possible torque is determined by substituting $i_1'=0$ in equation (6.3). Then, the machine behaves like IPMSM without power extraction from field winding. Figure 6.5 illustrates that the available torque is a function of stator flux linkage and load angle. Figure 6.6 shows the variation of $T_e$ alternating between 0.5Nm to -0.5Nm with $P_L=0$. The simulated result implies that the technique is capable of reversing the torque direction, while there is no effect on the amount of electric power transferred to the rotor mounted load. The associated operating point which is assigned in the closed loop algorithm is $I_0=6.2A$, $R_L=16.5\Omega$. 
Figure 6.5 Electromagnetic torque against flux linkage and load angle

Figure 6.6 Mode 1 (a) Electromagnetic torque (b) Referred rotor current
6.5.2 Maximum Electrical Power Transfer

The maximum power transferred to the rotor mounted load can be calculated by using maximum power transfer theorem. According to the theorem, the maximum power transfer will occur only when the load resistance is equal to the magnitude of the impedance of the direct axis equivalent circuit.

In this case $T_e^* = 0$Nm, $I_0 = 6.2$A, $i'_f = 1.767$A, $f_p = 50$Hz and $R_L = 16.5\Omega$. As it can be seen from Figure 6.7, the maximum value of $i'_f$ is obtained by operating the machine solely as a transformer with certain stator flux perturbation frequency of 50Hz and no shaft torque. Theoretically, increasing $f_p$ provides more power. However, any increase in $f_p$ leads to more iron loss and decrease in mutual inductance.

6.5.3 Simultaneous Electrical and Mechanical Power Transfer

When the machine works in combined mode, there will be a two frequency component viz. supply frequency and perturbation frequency in the stator current. The stator current with supply frequency can able to produce electromagnetic torque. At the same time, stator current with perturbation frequency induces voltages in the rotor. By varying the frequency of stator current electrical and mechanical power transfer is achieved simultaneously.

The assigned values for simultaneous control of constant torque and rotating secondary transformer action are $T_e^* = 0.5$Nm, $I_0 = 6.2$A, $i'_f = 1.8$A to $1.1$A $f_p = 50$Hz and $R_L = 16.5\Omega$. The simulated results shown in Figure 6.8 indicate that any variation in rotor electric power is not affected by torque.
Figure 6.7 Mode 2 (a) Electromagnetic torque (b) Referred rotor current

Figure 6.8 Mode 3 (a) Electromagnetic torque (b) Referred rotor current
6.6 EXPERIMENTAL RESULTS

To confirm validity of the developed control algorithm, a hardware in loop simulation for field-rotor IPMSM is developed with the help of dSPACE DS 1104. The practical results use the same assigned values as the simulation algorithm. The hardware in simulation loops are found to match with simulation results.

Figure 6.9 shows the response for maximum torque variation, -0.5Nm to 0.5Nm under \( i_i' = 0 \). The oscillation in the torque response is due to the inability of the PI controller to track the reference current.

When the machine can run at no load condition, Figure 6.10 shows the maximum amount of electric power transferred to the resistive load connected to the rotor terminal. In this case, there is no change in electromagnetic torque as shown in Figure 6.10.

The assigned values for validating the mode 3 operation are \( T_e^* = 0.5 \text{Nm}, f_p = 50 \text{Hz} \) and \( i_i' = 1.7 \text{A} \). Figure 6.11(a) shows the reference signals generated from the processor for which equation (6.6) and (6.7) are programmed in assembly code. Figure 6.11(b) shows the actual stator flux along the d and q axis, respectively. The d axis stator flux has been modulated with perturbation frequency, which is independent of torque. Whereas, the q axis stator flux is sinusoidal so that the vector product of flux and current is constant. Hence, the maximum torque is achieved.
Figure 6.9 Maximum torque response when $i_f'=0$

Figure 6.10 Maximum power transfer when $T_e=0$

Figure 6.11 dq-axes stator flux linkages (a) Reference flux (b) Actual flux
6.7 CONCLUSION

The application of flux control scheme in field-rotor IPMSM drive has been explored. It is mathematically proved that the motor with unexcited field winding can deliver rotor torque and rotor power simultaneously. The analysis shows that the machine can operate in three modes viz, torque mode, transformer mode and combination of these two modes. The experimental results confirm that the proposed algorithm can independently control both electromagnetic torque and electric power transferred to the rotor mounted load. The main drawback of the proposed control scheme is its high sensitivity to the variation of machine parameter. The MTPF algorithm can be augmented with appropriate parameter estimation technique to include the effect of parameter variation. However, the number of parameters to be estimated is more when compared to IPMSM drive and hence MTPF-based estimation of machine parameters is yet to be investigated.