Torque Estimation Using Precise Calculations of Inductance and Iron loss Mathematization

Gyu-Won Cho *, and Gyu-Tak Kim *

Abstract – The torque was calculated with inductance and iron loss. Because the linkage flux can change the inductance, and q-axis current can change the iron loss. Therefore, precise estimation of torque can achieve with the inductance and iron loss detail calculations. So, in this paper, the d, q-axis inductance was verified through CVCT(Current Vector Control Test) and DCT(Direct Current Test). Also in the iron loss calculation, the prediction of all areas of current magnitude, phase angle and speed was very difficult. And LUT(Look-Up Table) was spent time and resource largely. Therefore, iron loss mathematization was proposed according to current magnitude, phase angle and speed. Also, characteristics of IPMSM were comprised of analyzed and experimental values.

Keywords: d, q-axis inductance, Iron loss-mathematization, Torque, Linkage flux

1. Introduction

Generally, operating characteristics of IPMSM (Interior Permanent Magnet Synchronous Motor) were estimated with d, q-axis equivalent circuit. If a calculation of non-linear parameters was exactly performed, it is known as an efficient method [1]-[2].

However, the inductance values of the d, q-axis vary nonlinearly under different operating conditions because the magnitude and phase angle of the input current can change the magnetic flux distributions, and the saturation of magnetic materials in the motor can change the machine reluctance [3]. Therefore, estimation of the detailed d, q-axis inductance is very important.

Non-linear parameters were applied to LUT (Look-Up Table), because non-linear parameters calculation was relatively difficult and delicate. But, the iron loss was largely changed according to current magnitude, phase angle and speed by iron core’s magnetic field variation [4]. Also, usually, the iron loss resistances were calculated at particular input state, and those results were applied to an equivalent circuit by LUT. And, estimation of operating characteristics by field-weakening control, voltage and current limits was very complicated parameters. And, LUT took lots of time and resource.

Therefore, in this paper, the inductance was calculated through a CVCT and DCT and the results were compared and studied. Also, the iron loss mathematization was proposed according to current magnitude, phase angle and speed. Because, the iron loss should respond very quickly to variation of input parameters. Also, characteristics of IPMSM were comprised of analyzed and experimental values.

2. Estimation of d, q-axis Inductance

Table 1 shows the motor specification. The d, q-axis inductance was calculated by the voltage equation and vector diagram of IPMSM from formula [5]. So, numerical formula of inductance was described as the d, q-axis current variation according to linkage flux change.

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Speed (rpm)</td>
<td>3000</td>
</tr>
<tr>
<td>Rated Torque (Nm)</td>
<td>1.85</td>
</tr>
<tr>
<td>Pole/Slot</td>
<td>8/12</td>
</tr>
<tr>
<td>Air-gap Length (mm)</td>
<td>1</td>
</tr>
<tr>
<td>Winding Type</td>
<td>Concentrated winding</td>
</tr>
<tr>
<td>Br (T)</td>
<td>1.3</td>
</tr>
<tr>
<td>Stack Length (mm)</td>
<td>45</td>
</tr>
<tr>
<td>Stator Diameter (mm)</td>
<td>83.6</td>
</tr>
<tr>
<td>Phase resistance(ohm)@75°C</td>
<td>0.0235</td>
</tr>
</tbody>
</table>

Fig. 1 shows a linkage flux change according to current phase angle. The d-axis current was increased by the increased current phase angle. And, total linkage flux was decreased, and phase gap became smaller, because q-axis
current was decreased.

\[
\begin{bmatrix}
  v_d \\
  v_q
\end{bmatrix} = \begin{bmatrix}
  R_s + \rho L_d & -\omega L_q \\
  \omega L_d & R_s + \rho L_q
\end{bmatrix} \begin{bmatrix}
  i_d \\
  i_q
\end{bmatrix} + \begin{bmatrix}
  0 \\
  \omega \phi_a
\end{bmatrix}
\]

\[
L_d = \frac{v_q - R_q i_q - \omega \phi_a}{\omega q} \\
L_q = \frac{-v_d + R_d i_d}{\omega q}
\]

Fig. 2 shows the experimental equipment. Fig. 3 shows the result of CVCT. For the average error of the inductance, \(L_d\) was as much as 2.92% and \(L_q\) was 4.5%. The error is caused by the fundamental wave detection of PWM, location alignment of the encoder, temperature rise of the permanent magnet and etc.

2.2 Direct Current Test (DCT)

The DCT method fixes the rotor. Thereafter, the power supply was cut off after enough a flow of direct current. Then, the waveform, at which the current is reduced to 0, was measured. In this case, the iron loss is not included, which is advantageous. In addition, interference between the \(d\), \(q\)-axes does not occur, because the direct current is applied. However, the current phase angle cannot be considered. Therefore, the device can be arrest at \(i_d=0\) or \(i_q=0\) positions. The formula of the inductance by stationary rotor is obtained by (3) ~ (6).

\[
\int V_D(t)dt - \int R_s i_d(t)dt = L_d i_0 \frac{d}{dt}
\]

\[
L_d = \frac{\int 0}{\frac{2}{3}} \int V_D(t)dt + \int R_s i_d(t)dt
\]

Fig. 4 shows DCT experimental equipment. Fig. 5 shows a comparison of the inductance by the DCT and the analysis is values. In \(L_d\), 6.4% error was generated and 0.8% was generated in \(L_q\). The magnetic flux’s path of \(q\)-axis was simpler than that of \(d\)-axis, and the air-gap is located at the both sides of the axis center. Therefore, the lineup is very sensitive. It is hard to say that error was not generated in \(L_q\). But, the PM was located at magnetic path of \(d\)-axis and, the lineup is very difficult. The error of \(d\)-axis was generated more than \(q\)-axis.
The result of CVCT and FEM

Fig. 4. DCT experimental equipment

Fig. 5. DCT Comparison of result

Fig. 6. The average of inductance according to current

3. The Iron Loss Mathematization

The iron loss equation has certain current magnitude, phase angle and speed conditions. Therefore, iron loss was changed by frequency according to operating speed by load condition and flux-density according to current phase angle.
in the iron core. In that case, the iron loss should be evaluated repeatedly. Much time and resource were needed with this calculation method. Especially, IPMSM has the widely operating speed area like a field-weakening control, so disadvantages must be overcome in IPMSM.

Fig. 7 shows the iron loss mathematization progress. The iron loss equation was transformed with a formula of speed. And then, the iron loss mathematization according to current phase angle was performed. Finally, the iron loss was recalculated by formula of current magnitude.

![Fig. 7. Flow chat of iron loss mathematization](image)

Fig. 8 shows the iron loss variation according to speed, current magnitude and phase angle.

The formula according to the current phase angle, speed can be obtained by (7).

Here, \( N_s \) is the operating speed, \( \beta \) is the current phase angle, \( I \) is current, \( z_0 \sim z_2 \) are intercept of each equation, \( A_1 \sim A_k \) are mathematization coefficients. So, the iron loss was transformed with the equation according to speed, current magnitude and phase angle. Consequently, the iron loss was very simply calculated from input parameters such as speed, current and current phase angle. It was very powerfully advantage on the calculation of operating characteristics.

\[
W_i = (z_0 + (A_1 \cdot \beta) + (A_2 \cdot \beta^2)) + ((z_1 + (A_3 \cdot \beta) + (A_4 \cdot \beta^2))N_s + (z_2 + (A_5 \cdot \beta) + (A_6 \cdot \beta^2))N_s^2 \]

where, \( z_0 = a + (b \cdot I) \),
\[
z_1, z_2, A_1, A_2, A_3, A_4, A_5, A_6 = a + (b \cdot I) + (c \cdot I^2) \]

Fig. 9 shows the comparison of LUT and mathematization of the iron loss. The error was generated under 1%. The output characteristic experiment was performed by measurement of output power and input power.

Fig. 10 shows variation of total torque. When the maximum torque generation, the torque was 1.87(Nm) at current phase angle 10°. It result was recalculated from 1.92(Nm) of torque without iron loss. Because, q-axis current was decreased by an iron loss current.

![Fig. 8. Iron loss variation according to speed each current](image)
encoder pulse.

The torque experimental results are shown in Fig. 13. From the results, the maximum torque was generated at a current phase angle of 10°. As a result, the torque calculation using precise inductance and iron loss does not include the error almost.

![Fig. 11. Experimental equipments](image1)

![Fig. 12. Measured waveforms of voltage, current and encoder pulse](image2)
5. Conclusion

In this paper, the torque was estimated by inductance and iron loss. So, inductance of IPMSM was precisely calculated by CVCT and DCT. The average value of inductance was computed by supplement of strengths and weaknesses about CVCT and DCT. And the adequacy of inductance calculation was verified by comparison of experiment with calculation of torque. And the iron loss was transformed for simply calculation in variation operating condition.

The inductance and iron loss directly affect the torque calculation. So, calculations of inductance and iron loss were performed for precise torque estimation. The motor of vehicle has characteristics of low turn and largely diameter of conductor due to low voltage and high current. Therefore, a measurement error and a calculation error were constrainedly generated due to very tiny inductance. But in this paper, the inductance by current magnitude and current phase angle was calculated by two experimental methods. So, analyzed and experimental value was almost same, and satisfactory results were obtained.

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References


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