Magnetic Saturation and Iron Loss Influence on Max Torque per Ampere Current Vector Variation of Synchronous Reluctance Machine

Huai-Cong Liu*, Hyun-Seok Hong*, Sang-Hwan Hann**, Ju Lee* Hangyang University*, Kyungil University**

Abstract - Synchronous Reluctance Motor (SynRM) has a simple structure with high efficiency and without rotor conductor loss. Therefore, it is better than induction motor for electric vehicle (EV) on aspect of efficiency. SynRM usually operates on the constant torque region using maximum torque per ampere (MTPA) control which is adopted due to rotor structure limitation. Thus, the accurate current angle is crucial for motor control. However, finite element analysis (FEA) program is not sufficient exactly to regard how the iron loss and magnetic saturation influences on the current angle. Consequently, this paper proposed a method to calculate the current angle with consideration of iron loss.

1. Introduction

The electromagnetic torque of the SynRM only generates a reluctance torque which can be calculated with d-q axis inductance in the rotor reference frame and the stator d-q axis current. If d-axis and q-axis inductance is constant that MTPA controller will be very simple. But in fact d-axis and q-axis inductance varies not only with the magnetic saturation but also SynRMs are known to possess magnetic non-linearity and considerable iron loss, which make it difficult to realize MTPA control and maximum efficiency control.

This paper presents a method to calculate the transient characteristics of SynRM considering both core loss and magnetic saturation, which influence on inductance and current vector changed of MTPA control. It is using an equation for a circuit model with equivalent core loss.

The accuracy of the proposed method was verified under various operating conditions with computer simulation and testing with a 75 kW SynRM drive system. As an example, experimental results demonstrate the analysis is closer to the actual motor's characteristics of efficiency.

2. Determination of motor parameters

In 2009 the EU commission implemented a new directive called EN 60034-30:2009 which divides electrical rotating motors in classes depending on power output and efficiency. The different class ranges from IE1 which is standard efficiency to IE6 which is super premium efficiency for each class efficiency the losses are reduced by 20%, but selling rate increase of 30%.

A 75kw IE4 class SynRM for test only sustained at synchronous speed is presented throughout this paper. First, the size of the machine is conducted and its performance is investigated including the flux density, self-and mutual-inductances, electrical torque and torque ripple by the finite element method in the software. In SynRM, the flux barriers in the rotor core can change various parameters of the motor. The rotor rib, shape and geometry, also including the barriers geometrical arrangement which are based on the previous work where several optimization methods are exercised to enhance the motor performance (torque density, spatial harmonics and torque ripple)[2]. After optimization, the design parameters are obtained, as presented in Table 1.

In general, SynRM using current control expects its output and efficiency through analysis of ideal sinusoidal current sources. Analysis of the 7.5kw class SynRM d-q axis inductances are variable due to the magnetic saturation. Therefore, this phenomenon has changed MTPA current angle from 45° to 60°.

2.1 Magnetic saturation analysis

Inductances are highly affected by the level of saturation in the SynRM due to high amount of core in both d and q-axis flux paths. Saturation, mainly in the machine d-axis, reduces Ld and consequently torque for a certain current, see point A in Fig. 2. By increasing the current angle (θb) the d-axis current is reduced to point B.

Therefore the level of saturation and air gap flux density are reduced also Ld and torque are increased and compensated. This also means, for example, inductances in d and q-axis are not only a function of stator current but also a function of the current vector.

**TABLE 1** Design parameters for SynRM

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dia. of stator</td>
<td>267</td>
<td>mm</td>
</tr>
<tr>
<td>Dia. of rotor</td>
<td>168</td>
<td>mm</td>
</tr>
<tr>
<td>Depth</td>
<td>200</td>
<td>mm</td>
</tr>
<tr>
<td>Core material</td>
<td>50PN470</td>
<td></td>
</tr>
<tr>
<td>Air gap</td>
<td>0.5</td>
<td>mm</td>
</tr>
<tr>
<td>Resistance of coil</td>
<td>0.4</td>
<td>Ω</td>
</tr>
<tr>
<td>Rated Current</td>
<td>12.5</td>
<td>Arms</td>
</tr>
<tr>
<td>Poles</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Slots</td>
<td>36</td>
<td></td>
</tr>
</tbody>
</table>

*Fig 1* IEC 60034-30 efficiency standard for a 4-pole, 60 Hz motor.

*Fig 2* Saturation compensation by current angle control.
As a result, current vector for different current loadings is shown in Fig.3. The simulation result shows that magnetizing characteristic of d-q axis in SynRM becomes no-line when phase current was bigger than 5A. While rated current of the machine is 12.5A, MTPA operating point of rated current angle changed.

![Figure 3](image-url)  
**Fig 3** As function of current vector and for different stator current, for the design geometry

### 2.2 Modeling of core loss resistance

Core loss in a SynRM motor can be modeled with a resistance, in order to derive motor equations based on the d-q axes equivalent circuit analysis (ECA) in Fig.4. Rm considered as iron loss is connected parallel with speed voltage.

\[ R_m = \frac{V^2}{2} \left(\frac{\omega L_m}{W_p}\right) \]  

Where: V is induced electromotive force of each phase, \( \omega \) is electric angular velocity of SynRM and Wp is iron loss. SynRM with equivalent iron loss resistance, which is originated from the equivalent coreloss, would be the basis on accurate torque estimation for MTPA control. The SynRM model with the iron loss circuit is depicted as Fig.5. Current idm and idqm is different from a terminal current id and idq. That means in theory, need to use idm and idqm to calculate mechanical torque and it is given in steady state by Eq.(2/3)

\[ V_{es} = R_m \left[ I_{ds} \right] + (1 + R_m / R_a) \left[ V_{ds} \right] + p \left[ L_m \right] \left[ I_{ds} \right] \]  

\[ V_{es} = 0 - \omega \theta \left[ I_{ds} \right] \]  

\[ \beta = \arctan \left( \frac{I_{ds}}{I_{d}} \right) \]  

**Fig 4** Magnetization as a function of applied field

In which:
- \( I_{ds} \): currents of equivalent iron loss circuit in d-q axis
- \( R_m \): Resistance of equivalent iron loss
- \( R_a \): Resistance of phase coil
- \( L_d, L_q \): inductances of equivalent iron loss circuit in d-q axis

New current vector would be solved by means of trigonometric function with Eq.4

A process is shown in Fig.6. In order to modeling equivalent circuit, all parameter can be gated from MTPA FEM analysis.

![Figure 5](image-url)  
**Fig 5** Current vector diagram of SynRM

![Figure 6](image-url)  
**Fig 6** Current angle calculation process

Idm and idqm influence on MTPA current vector variation of 7.5KW SynRM is shown in Fig7

![Figure 7](image-url)  
**Fig 7** Current angle shifts due to iron loss

The experimental value of current angle is 58° and the simulation value is 57.6°, which shows that these two values are relatively similar. However, 2D simulation cannot consider the harmonic wave of current source and leakage reactance of end turn. Therefore, torque of ECA is bigger than experimental data.

**Table 1** Comparison of ECA and experimental data

<table>
<thead>
<tr>
<th>ECA/ Experimental data</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current angle</td>
<td>57.6 / 58°</td>
<td>deg.</td>
</tr>
<tr>
<td>Torque</td>
<td>41.08 / 40.37</td>
<td>Nm</td>
</tr>
</tbody>
</table>

4. Conclusion

This paper illustrated the influences of core loss for the current vector with consideration of ECA.

ECA method calculated the transient characteristics of SynRM considering both iron loss and magnetic saturation influence on current angle of MTPA control. Experimental results demonstrate the analysis is closer to the actual motor’s characteristics.

[Reference]