동기형 릴럭턴스 전동기 MTPA 제어시 자기포화 및 철손의 영향

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

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Abstract - Synchronous Reluctance Motor (SynRM) has a simple structure with high efficient 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

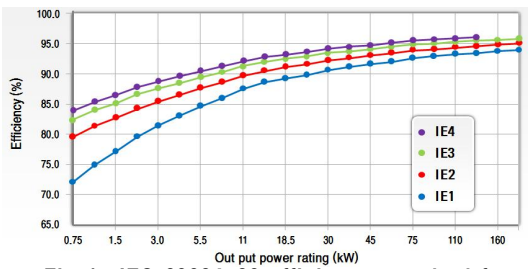
The electromagnetic torque of the SynRM only generates a reluctance torque which can be calculated with d-q axis inductance in the rotor reference frame and the stator d-q axis current. If d-axis and q-axis inductance is constant that MTPA controller will be very simple. But in fact d-axis and q-axis 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 7.5 kW SynRM drive system. As an example, experimental results demonstrate the analysis is closer to the actual motor's characteristics

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 IE4 which is super premium efficiency for each efficiency class the losses are reduced by 20%, but selling rate increase of 30%. In Fig1. The different classes are illustrated for a 4-pole, 60 Hz motor. The directive from 2009 states among other things that from 2015 the lowest efficiency class manufactured in the European Union shall be IE3.[1]



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

A 7.5kw 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.

<TABLE I> Design parameters for SynRM

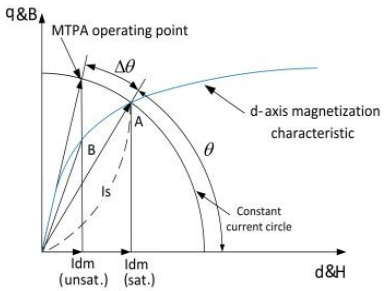
Parameters	Value	Unit
Dia. of stator	267	mm
Dia. of rotor	168	mm
Depth	200	mm
Core material	50PN470	
Air gap	0.5	mm
Resistance of coil	0.4	Ω
Rated Current	12.5	Arms
Poles	4	
Slots	36	

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 variables due to the magnetic saturation. Therefore, this phenomenon has changed MTPA current angle from 45º to 60º.

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.

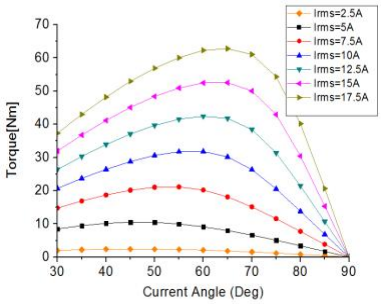
Saturation, mainly in the machine d-axis, reduces Ld and consequently torque for a certain current, see point A in Fig. 2. By increasing the current angle (ΔΘ) the d-axis current is reduced to point B.



<Fig 2> Saturation compensation by current angle control

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.

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 .



<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 Rm, 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.

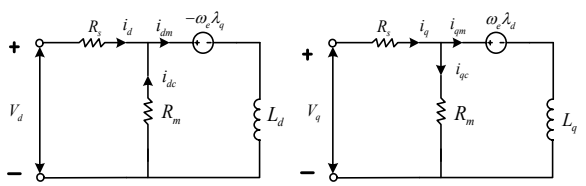
$$R_m = \frac{V_s^{\,2}}{W_c} = \frac{(\omega_e \lambda_a)^2}{W_c} \qquad (1)$$

Where: Vs is induced electromotive force of each phase, ωe is electric angular velocity of SynRM and Wc is iron loss.

SynRMs with equivalent iron loss resistance, which is originated from the equivalent coreless, 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 iqm is different from a terminal current id,iq. That means in theory, need to use idm and iqm to calculate mechanical torque and it is given in steady state by Eq(2),(3)

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = R_s \begin{bmatrix} i_{dm} \\ i_{qm} \end{bmatrix} + (1+\frac{R_s}{R_m}) \begin{bmatrix} V_{dm} \\ V_{qm} \end{bmatrix} + p \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_{dm} \\ i_{qm} \end{bmatrix} (2)$$

$$\begin{bmatrix} V_{dm} \\ V_{qm} \end{bmatrix} = \begin{bmatrix} 0 & -\omega L_q \\ \omega L_d & 0 \end{bmatrix} \begin{bmatrix} i_{dm} \\ i_{qm} \end{bmatrix} (3)$$



(a)d-axis equivalent circuit (b) q-axis
<Fig 4> Magnetization as a function of applied field

In which
Idm,iqm : currents of equivalent iron loss circuit in d-q axis
Rs : Resistance of equivalent iron loss
Ra: Resistance of phase coil
Ld,Lq : inductances of equivalent iron loss circuit in d-q axis

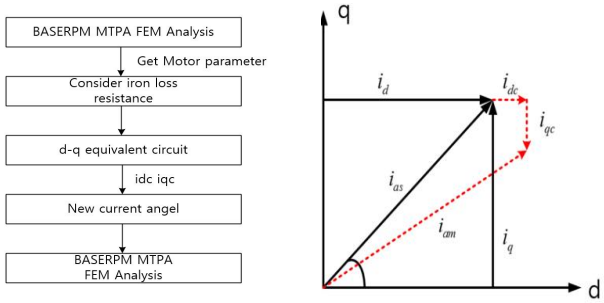
New current vector would be solved by means of trigonometric function with Eq.4

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

$$\beta = \arctan \frac{i_{dm}}{i_{qm}} (4)$$

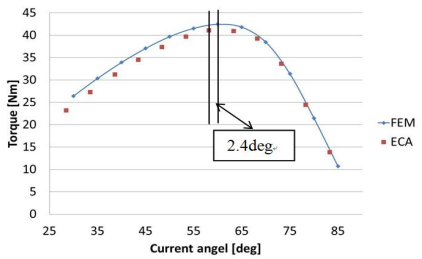
3. Experiment

Fig.8 shows the experimental configuration includes target motor. Load tests were carried out and the result was shown in Table 2.

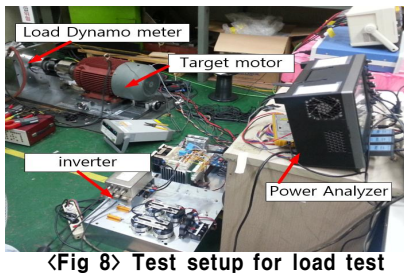


<Fig 5> Current vector diagram of SynRM
<Fig 6> Current angle calculation process

Idm and iqm influence on MTPA current vector variation of 7.5Kw SynRM is shown in Fig7



<Fig 7> Current angle shifts due to iron loss



<Fig 8> Test setup for load test

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 ii> Comparison of ECA and experimental

ECA/ Experimental data	Value	Unit
Current angle	57.6 / 58	deg.
Torque	41.08/40.37	Nm

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 influenced on current angle of MTPA control. Experimental results demonstrate the analysis is closer to the actual motor's characteristics.

[Reference]

[1] The Commission of the European Communities, Commission regulation (EC) No 640/2009 (July 2009).

[2] Nicola Bianchi, Silverio Bolognani, Diego Bon, and Michele Dai Pré, "Rotor Flux-Barrier Design for Torque Ripple Reduction in Synchronous Reluctance and PM-Assisted Synchronous Reluctance Motors". IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 45, NO. 3, PP 921- 928 .MAY/JUNE 2009saturation and iron loss," IEEE Trans. Ind. Appl., vol. 27, pp. 977 - 985, Sep./Oct. 1991.