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Efficiency Evaluation of PMASynRM *versus* SynRM Using a Coupled Finite Element Method and Preisach Modeling

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This paper deals with the efficiency evaluations in a synchronous reluctance motor (SynRM) *versus* a permanent magnet assisted SynRM (PMASynRM), using a coupled transient finite element method (FEM) and Preisach modeling, which is presented to analyze the characteristics under the effects of saturation and hysteresis loss. We herein focus on the efficiency evaluation relative to hysteresis loss and copper loss on the basis of load conditions in a SynRM and PMASynRM. Computer simulation and experimental results for the efficiency, using a dynamometer, show the propriety of the proposed method and the high performance of the PMASynRM.

Keywords : FEM, Preisach modeling, SynRM, PMASynRM, efficiency evaluations

1. Introduction

In high-speed applications of a synchronous reluctance motor (SynRM), hysteresis loss can become the major cause of power dissipation. Whereas in other kinds of machines a rough estimation of hysteresis loss can be accepted, its importance in a SynRM justifies a greater effort in its precise calculation. The Preisach model is now generally accepted to be a powerful hysteresis model and is, therefore, intensively studied for SynRM analysis [1, 2].

By adding a proper quantity of permanent magnets, the torque density and power factor of the SynRM can be greatly increased [3]. This is called the Permanent Magnet Assisted Synchronous Reluctance Motor (PMASynRM).

However, it follows that PMASynRM is more saturated than SynRM due to the additional magnet flux density. Select papers discussing the influence of hysteresis loss on a machine have been presented.

References [4] and [5] investigated the steady state characteristics of inductances using a coupled finite element method (FEM) and Preisach modeling in a PMASynRM.

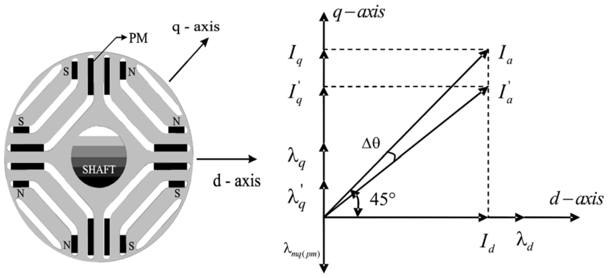
Reference [6] developed the efficiency evaluation method relative to hysteresis loss and copper loss on the basis of load condition, using a coupled finite element method and Preisach modeling in a SynRM.

In this paper, a coupled finite element analysis and Preisach modeling for a PMASynRM and SynRM are presented and characteristic analyses and efficiency evaluations performed under the effects of saturation and hysteresis loss.

This paper specifically focuses upon the efficiency evaluation relative to hysteresis loss and copper loss on the basis of load conditions in a SynRM *versus* PMASynRM scenario.

In addition, the TMS320C31 DSP and dynamometer were installed and equipped as the experimental devices for the experiments herein performed.

Computer simulation and experimental results for the efficiency showed the propriety of the proposed analysis



(a) (b)

Fig. 1. (a) Rotor cross-section; (b) phasor diagram of the PMASynRM.

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method and the high performance of the PMASynRM.

2. Modeling and Principle of PMASynRM

2.1. Principles of PMASynRM for high power applications

A cross-sectional view of the PMASynRM is shown in Fig. 1(a).

The q-axis inductance can theoretically be made to approach zero. The compensating flux can normally be obtained by ferrite magnets since L_q is sufficiently low. Fig. 1(b) shows a phasor diagram, including the effects of a permanent magnet in which the q-axis flux is assumed to be completely canceled.

One should notice that the PMASynRM can be obtained at a current amplitude and angle value lower than those predicted by a normal SynRM for the same torque density, as shown in Fig. 2. The proposed form of the rotor magnets is a guarantee that the counteract effects of the q-axis current can spatially increase output power.

2.2. Governing equation of PMASynRM and SynRM

Maxwell's equations can be written as:

$$\nabla \times \vec{H} = \vec{J}_0 \tag{1}$$

$$\nabla \cdot \vec{B}=0 \tag{2}$$

$$\vec{B} = \frac{1}{\upsilon_0}\vec{H} + \vec{M}, \qquad \vec{B} = \frac{1}{\upsilon_0}\vec{H} + \vec{M}_{PM}, \tag{3}$$

where $\vec{M}$ and $\vec{M}_{PM}$ are the magnetization of the magnetic material and permanent magnet with respect to magnetic intensity. Both $\vec{H}$ and $\vec{M}_{PM}$ were removed in the SynRM. The magnetic vector potential $\vec{A}$ and the equivalent magnetizing current $\vec{J}_m$ and $\vec{J}_{PMm}$ are expressed as follows:

$$\vec{B}=\nabla \times \vec{A} \tag{4}$$

$$\vec{J}_m=\upsilon_0(\nabla \times \vec{M}),\ \vec{J}_{PMm}=\upsilon_0(\nabla \times \vec{M}_{PM}) \tag{5}$$

The governing equation derived from Eq. (1)-(5) is given by:

$$\upsilon_0(\nabla \times \nabla \times \vec{A})=\vec{J}_0+\vec{J}_m+\vec{J}_{PMm} \tag{6}$$

2.3. System matrix

The system matrix can be written as:

$$[K^{(e)}]\{A^{(e)}\}+\{F^{(e)}\}+\{M^{(e)}\}+\{M_{PM}{}^{(e)}\}=0\,. \tag{7}$$

The magnetization $\{M\}$ is calculated by Preisach modeling. The overall model is therefore described by the following matrix:

$$[K]\{A\}+\{F\}+\{M\}+\{M_{PM}\}=0 \tag{8}$$

2.4. Application of the Preisach model

Magnetization $\{M\}$ can be expressed as a scalar model because the rotor synchronously rotates according to the input current angle. Therefore, it can be supposed that the domain in the stator is an alternating field with reference to the x- and y-axes. Both B and H of the domain in the rotor are constant and in a rotating field, but it is an alternating field with reference to the x- and y-axes [1-5]. It is natural that M and H, both calculated on the same axis, have the same vector direction:

$$\begin{aligned} M(t) &= \iint_{\alpha \ge \beta} \mu(\alpha,\beta)\gamma_{\alpha\beta}(H(t))\,d\alpha d\beta \\ &= \iint_{S^+(t)} \mu(\alpha,\beta)\,d\alpha d\beta - \iint_{S^-(t)} \mu(\alpha,\beta)\,d\alpha d\beta \end{aligned} \tag{9}$$

A more convenient treatment of this model is obtained by substitution of the Everett plane for Preisach's:

$$E(\alpha,\beta)=\iint_{\alpha \ge \beta} \mu(\alpha,\beta)\gamma_{\alpha\beta}(H(t))\,d\alpha d\beta \tag{10}$$

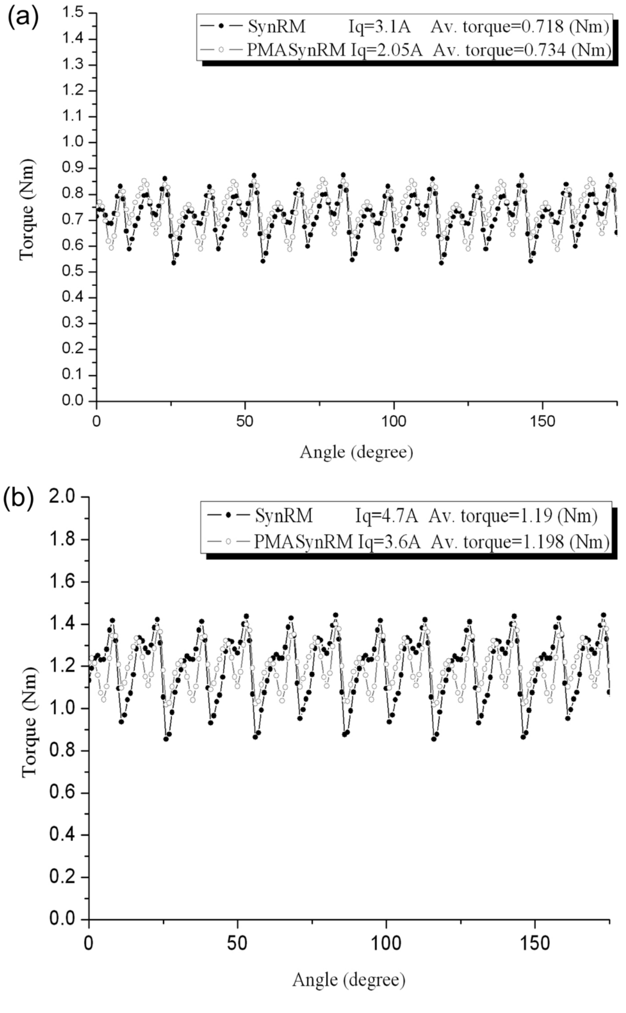

Fig. 2. Torque characteristics of: (a) SynRM; (b) PMASynRM (load: 8.0 and 12.0 kg-cm).

In the Everett plane, the distributions of M, which are accepted from experimental data of material S40 and a ferrite magnet, are described in Gaussian units.

3. Results and Discussion

Figs. 2 and 3 show the torque characteristics of SynRM

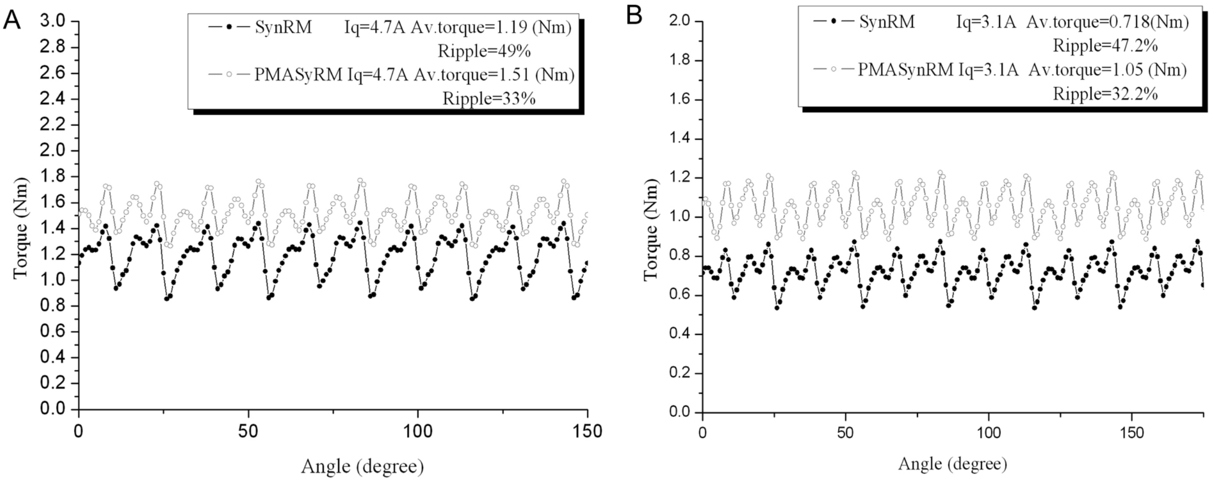

Fig. 3. Torque characteristics of: (a) SynRM; (b) PMASynRM (the same i_q).

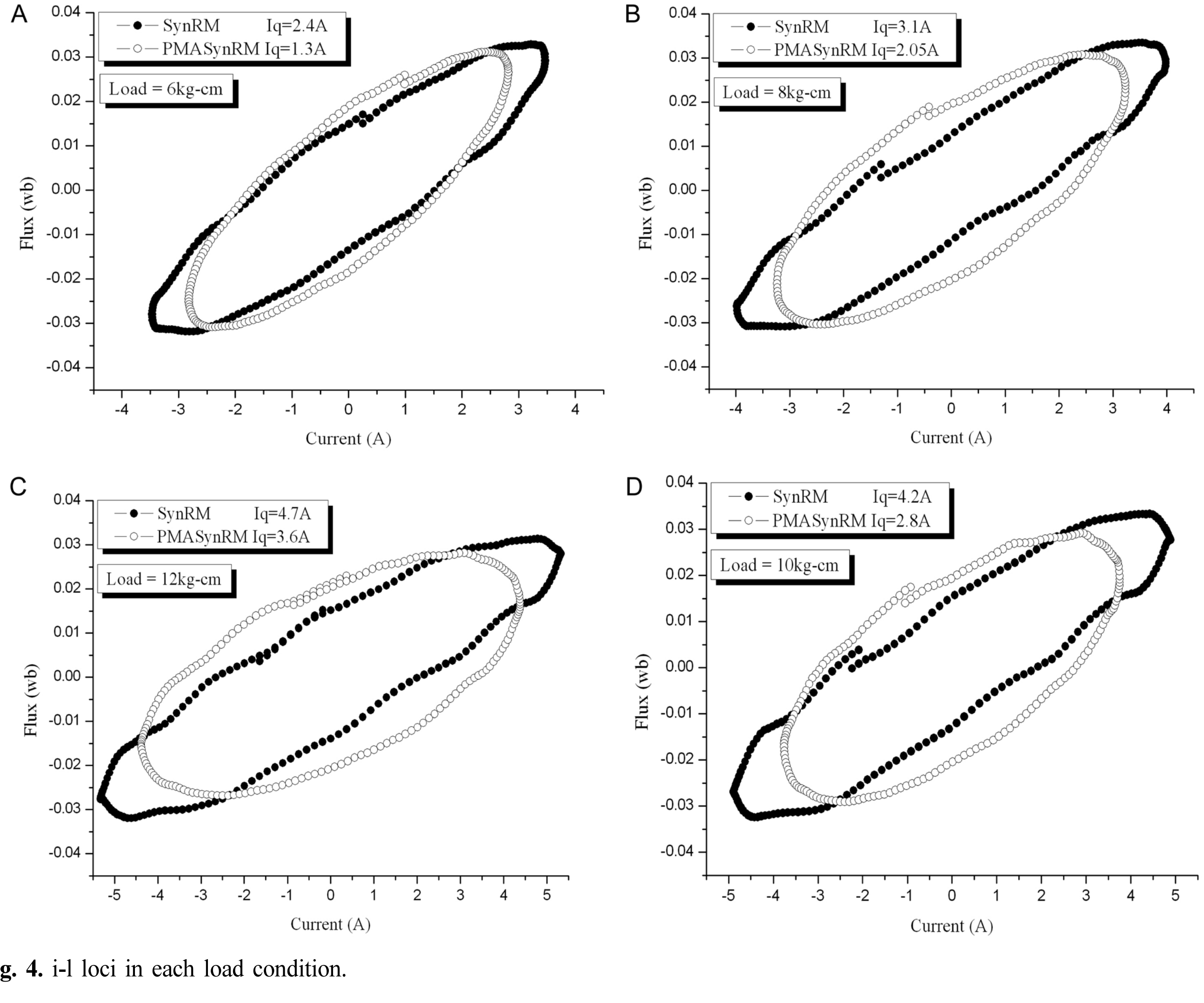

Fig. 4. i-l loci in each load condition.

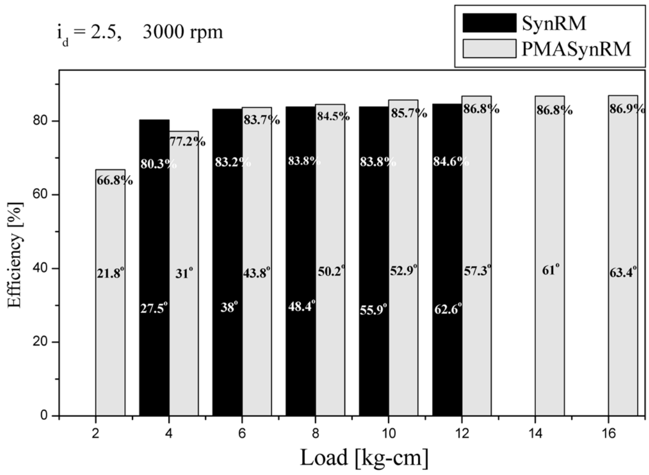

Fig. 5. Efficiency, current angle, and runaway point of PMASynRM and SynRM according to load in the experimental test.

and PMASynRM at loads of 8.0 and 12.0 kg-cm, with the same respective input current conditions. Fig. 4 shows the i-λ loci characteristics according to each load condition characteristic of the SynRM and PMASynRM, respectively.

Whereas average torque density has the same value according to the same load conditions, current magnitude and torque ripples of SynRM are larger than those of PMASynRM, as shown in Fig. 2 and 3.

The q-axis inductance can theoretically be made to approach zero in PMASynRM. The compensating flux can normally be obtained by ferrite magnets since L_q is sufficiently low. While L_d is decreased only by saturation, L_q is decreased by the additional counteracting flux of P.M. in PMASynRM. Therefore, the torque densities of SynRM for the same current of PMASynRM were lower than those of PMASynRM, as shown in Fig. 3.

Experimental comparisons are given with efficiency and current angle characteristics of the normal synchronous reluctance motor (SynRM) and those of PMASynRM, according to the load as shown in Fig. 5. The hysteresis loss can be calculated by the area of the i-l loci times the frequency, and the copper loss by resistance times the rms value square of the phase current.

Other losses include eddy current, mechanical, and stray load. These losses are denoted in Table 1.

It is noted that the output powers in the simulation are the same as those developed in the experimental tests. Therefore, the phase currents are similar to the experimental.

Fig. 6 shows each loss ratio to the total loss in each load condition. Whereas in hysteresis loss, the increase in the current due to increasing load should be somewhat enlarged (no load loss), their rate in hysteresis loss should be reduced under higher efficiency conditions.

However, the increasing copper loss rate of SynRM was larger than those of PMASynRM because of high current for the same torque dissipations, as shown in Fig. 2 and 3 and Table 1. While the hysteresis loss rate of PMASynRM has a higher percentage than those of SynRM, the hysteresis loss values are similar.

For the purpose of reason analysis, a hysteresis response analysis of the teeth and yoke element in the PMASynRM and SynRM was performed, when the current i_d is 4 [A], 25 Hz (same conditions).

From the analysis, the magnitude of hysteresis in stator teeth was larger than those in the yoke, as shown in Fig. 7 and 8. Moreover, PMASynRM is more saturated than SynRM, but has similar hysteresis characteristics in spite of the permanent magnet.

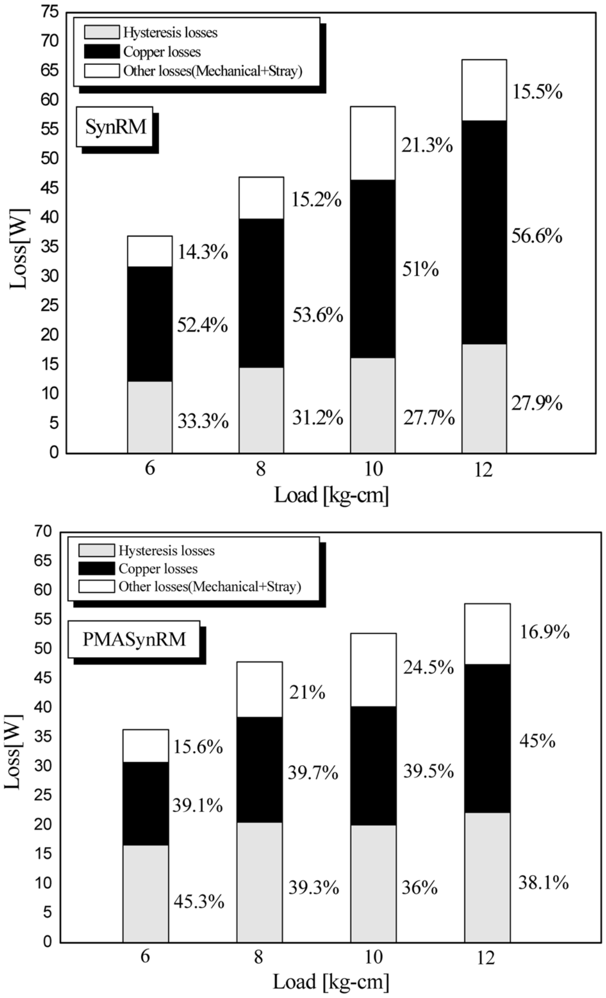

Fig. 6. Loss analysis in each load condition of SynRM and PMASynRM.

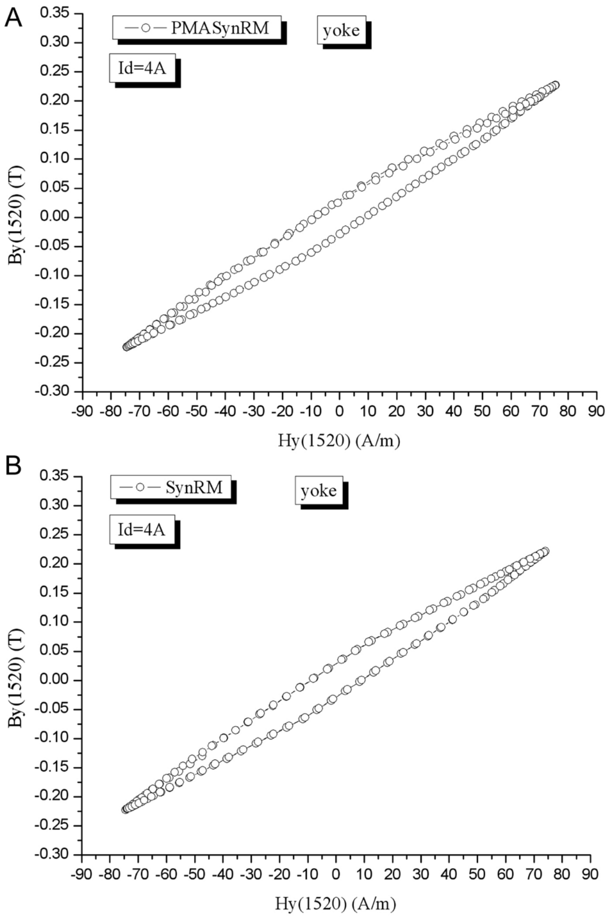

Fig. 7. B-H curve in the yoke of: (a) PMASynRM; (b) SynRM.

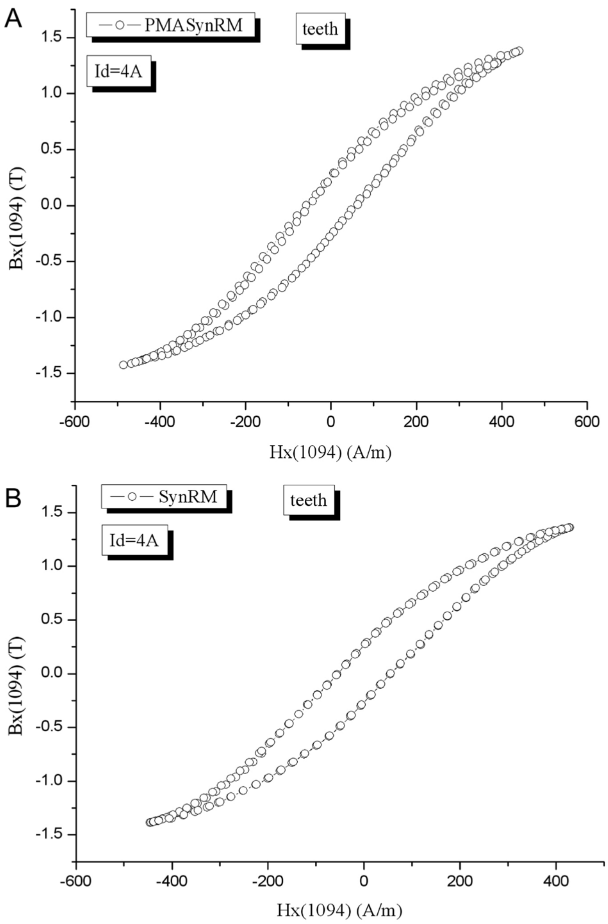

Fig. 8. B-H curve in the teeth of: (a) PMASynRM; (b) SynRM.

Table 1. Comparison of Loss in Synrm and Pmasynrm.

Load (kg/cm)	Efficiency (%)	Core Losses (W)	Copper Loss (W)	Other Losses (W)	Phase Current (A)
		SynRM			
6	83.2	12.33	19.38	5.29	4.06
8	83.8	14.67	25.2	7.13	4.63
10	83.8	16.34	30.11	12.55	5.06
12	84.6	18.68	37.9	10.42	5.6
		PMASynRM			
6	83.7	16.34	14.06	5.6	3.46
8	84.5	17.68	17.87	9.45	3.9
10	85.7	18.34	20.14	12.52	4.14
12	86.8	21.34	25.19	9.47	4.63

4. Conclusions

A characteristic analysis method has been proposed that is suited for efficiency evaluation of machines with magnetic non-linearity.

The i-l loci, which is total hysteresis loss and copper loss of a SynRM and PMASynRM (except mechanical loss, eddy current loss, and stray load loss, which are other losses in this paper) were investigated quantitatively on the basis of the proposed analysis method and experimental test.

In the PMASynRM, L_q was reduced by inserting permanent magnets in the direction of the counteracting q-axis flux, resulting in an increased L_d-L_q and L_d/L_q.

It was also found that the increased L_d-L_q and L_d/L_q could help improve torque density and power factor. Furthermore, it was confirmed that the PMASynRM results in high output power performance through experimental and numerical study.

With the developed analysis method, combined with the problem of vibration and eddy current loss, a more precise analysis of efficiency and power factor of an electromagnetic machine is possible and useful to the change of a motor’s structure, material, and development of the control algorithm for high efficiency performance.

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