Characteristics of a Novel Segment Type Switched Reluctance Motor using Grain-Oriented Electric Steel

Yudai Matsuo[*], Tsuyoshi Higuchi, Takashi Abe (Nagasaki University)
Yasuhiro Miyamoto, Motomichi Ohto (Yaskawa Electric Corporation)
Tel: +81-95-819-2547 – Fax: +81-95-819-2558 – e-mail: thiguchi@nagasaki-u.ac.jp

Abstract — The authors developed a novel segment type switched reluctance motor (SRM) as a rare earth less motor. The torque was increased by 40% and radial force was decreased by 76% compared with the same size VR type SRM. In this paper we propose a new type rotor using grain-oriented electric steel for the segment core. We compare the torque and efficiency characteristics with a non-oriented electric steel type by a finite element method and show effectiveness of the new type rotor

I. INTRODUCTION

A switched reluctance motor (SRM) is expanding its application area, such as high speed application, oil pressure pumps, home electric appliances, etc, because of its adequate mechanical strength, simple structure, maintenance free and low cost. However, it remains for us to improve performance characteristics and reduce acoustic noise and vibration [1] [2].

We previously proposed a novel segment type SRM in which the segment core was embedded in an aluminum rotor block [3] [4] in order to increase the mechanical strength and easy manufacturing compared with usual segment type SRM as well as to improve the torque performance and reduce the vibration and acoustic noise compared with conventional VR type SRM.

In this paper we propose using grain-oriented electric steel as the rotor segment core. We compare the torque and efficiency characteristics with the usual non-oriented electric steel type one by the FEM. The results show effectiveness of the new type rotor.

II. SEGMENT TYPE SRM

A. Construction and characteristics

Fig. 1 shows a construction of the novel segment type SRM. Segment cores are embedded in the aluminum rotor block and the stator has full pitch three phase windings. Fig. 2 shows torque waveform of the SRM simulated by finite element method (FEM). The maximum torque of the segment type SRM is twice as that of a same-sized VR type SRM. The average torque is increased by 40%. Also, the radial force is smaller and so the vibration and acoustic noise are smaller because four poles among the six poles are always excited, the iron loss is low because the magnetic path is short[4]. Fig. 3 shows the power factor and efficiency of a 2.2 kW, 1,800rpm test machine. It is shown that the efficiency is about 77 % between 400 W and 1700 W.

B. Design of segment type SRM

In this section, we design the rotor of segment type SRM to improve torque and efficiency characteristics by the FEM. Fig. 4 shows input current waveform. In consideration of the current waveform, we set lead angle and end angle for 7.5 deg. Table I shows analysis condition of it. The rotational speed is 1800 rpm, current is 8 A and space factor is 50%.

Fig. 5 shows design parameters in the rotor design. In this analysis, non-oriented electric steel is used for the rotor segment core. β_w shows surface width of the segment core, β_{uw} shows bottom width of the segment core, H_{seg} shows height of the segment core.
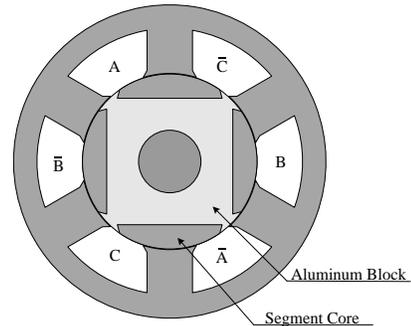

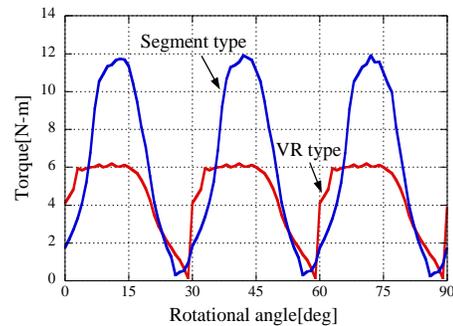Fig. 1. Construction of segment type SRM
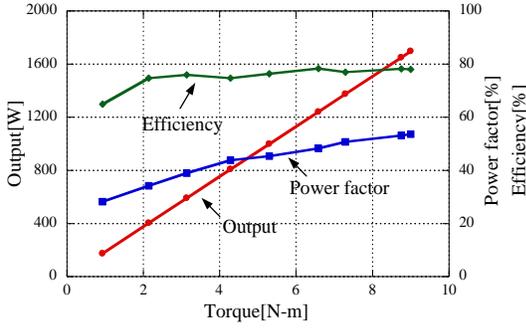

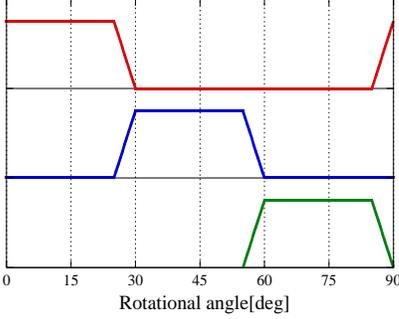Fig. 2. Torque waveform of SRM

Fig. 3. Characteristics of test machine

Fig. 4. Input current waveform

TABLE I
ANALYSIS CONDITION

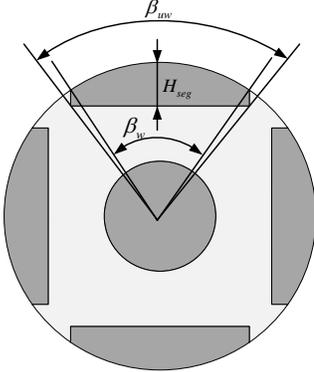| Rotational speed[rpm]	1800
Current[A]	8
Space factor[%]	50
Width of analysis step[deg]	0.25
Number of elements	about 10,000

Fig. 5. Analysis parameter

C. Construction and characteristics

In this section, we simulated the effect of varying these design parameters on the torque and efficiency characteristics.

Fig. 6 shows a rotor design result. Table II shows the optimized parameters; β_w is 78.0 deg, β_{uw} is 58.0 deg, H_{seg} is 12.7 deg. The rotor diameter equals to the test machine. Shape and width of the bottom part of the segment core has little effect on the torque characteristics.

The average torque of the new design is 6.332N-m, it is increased by 4.8 % compared with a test machine of 6.044 N-m. Also, an eddy current loss, generated on the aluminum rotor block, is decreased by 17.9 % for the reason that the linkage flux to the aluminum block is decreased because of increasing surface width of the segment core β_w.

III. GRAIN-ORIENTED ELECTRIC STEEL

In this section, we examine the effect of using grain-oriented electric steel for the rotor core on the torque and efficiency.

A. 3D magnetization characteristics

Grain-oriented electric silicon steel sheet, it is manufactured as polycrystalline substance which has axis of easy magnetization [100] coincided with the rolling direction. Fig. 7 shows 3D magnetization characteristics of grain-oriented electric steel. It has axis of easy magnetization [100], axis of neutral magnetization [110], axis of hard magnetization [111].

B. 2D magnetization characteristics

In this paper, we use Maxwell2D for electromagnetic FEM software. So we consider 2D magnetization characteristics of the grain-oriented electric steel as shown in Fig.8 (a).
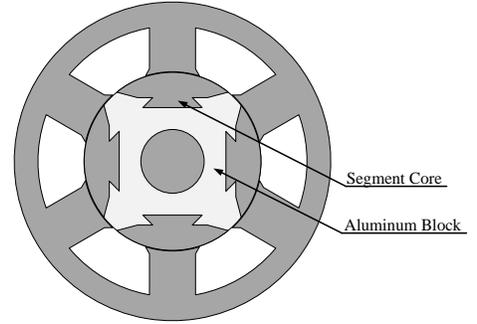

Fig. 6. Result of rotor design

TABLE II
PARAMETERS OF ROTOR DESIGN

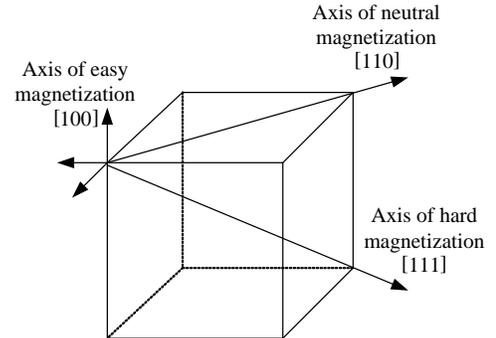| Rotor diameter[mm]	89.4
β_w [deg]	78.0
β_{uw} [deg]	58.0
H_{seg} [mm]	12.7

Fig. 7. 3D magnetization characteristics

It includes the rolling direction and the vertical direction. But the magnetization of thickness direction is neglected because the thickness of the steel sheet is very thin. We use a 2D B-H curve of the grain-oriented electric steel sheet, shown in Fig. 8 (b). It is shown that the magnetization of the rolling direction is larger than the vertical direction.
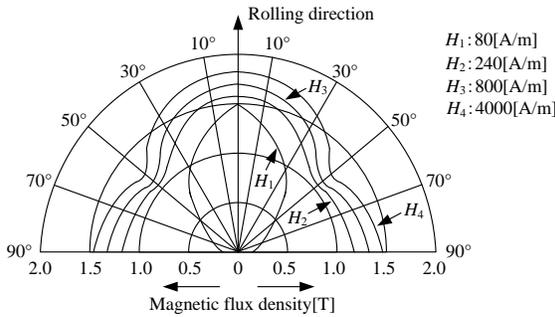
IV. SEGMENT TYPE SRM USED GRAIN-ORIENTED ELECTRIC STEEL

In this section, we examine about the model using grain-oriented electric steel for the segment rotor cores. Fig. 9 shows the direction of magnetization in the segment core. We set it so that the rolling direction is similar to the direction of flux linkage. Here, we use a constant permeability determined from the non-liner magnetization characteristics, because our non-liner analysis isn't able to use the B-H curve with 2 parameters. We calculate the relative permeability μ_s from the saturation magnetic flux density B_s and the saturation magnetic field intensity H_s.
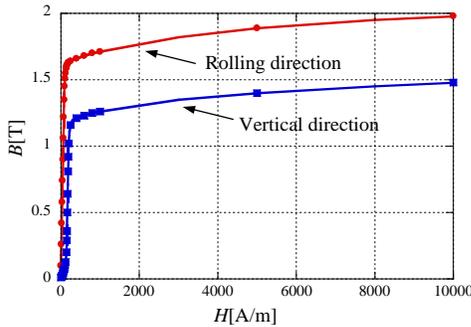
$$B_s = \mu_s H_s \qquad (1)$$

We confirmed on the analysis of the model using non-oriented electric steel that the computed results with constant permeability agrees well with the results with non-liner magnetization model.

Table III shows the relative permeability μ_s. The value of rolling direction is about 8500, vertical direction is about 3800.

V. COMPARISON OF CHARACTERISTICS

A. Torque characteristics

Table IV shows the torque characteristics when a test machine is compared with the new designed model. The average torque of the new design model (6.332N-m) is increased by 4.8 % compared with a test machine (6.044N-m). The new design using the grain-oriented electric steel (6.592N-m) is increased by 4.1 % compared with the non-oriented electric steel type (6.332N-m). It is shown that the torque is improved by the new type rotor using grain-oriented electric steel.

B. Efficiency characteristics

We calculate efficiency using Equation (2). We consider following losses; eddy current loss on the aluminum rotor block, iron loss, copper loss, mechanical loss, stray load loss.

$$\eta = \frac{P}{P + P_e + P_i + P_c + P_s + P_m} \times 100 \, [\%] \qquad (2)$$

P :Output, $\quad P_e$:Eddy current loss, $\quad P_i$:Iron loss,
P_c :Copper loss, $\quad P_s$:Stray load loss, $\quad P_m$:Mechanical loss

On each models, copper losses P_c are equal each other because the stator and MMF are same. Copper losses P_c are 53.6 W each other, where winding resistance is 0.883Ω for one phase, current is 4.5 A$_{rms}$. Each stray load loss P_s is 17.9 W that is estimated to 30 % of the copper loss P_c.

(a) 2D magnetization characteristics

H_1 : 80[A/m]
H_2 : 240[A/m]
H_3 : 800[A/m]
H_4 : 4000[A/m]

(b) B-H curve

Fig. 8. Grain-oriented electric steel
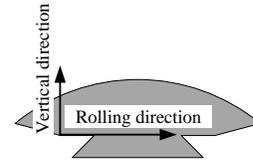
Fig. 9. Direction of magnetization

TABLE III
RELATIVE PERMEABILITY μ_s

	B_s	H_s	μ_s
Rolling direction	1.6	150	8500
Vertical direction	1.2	250	3800

TABLE IV
TORQUE CHARACTERISTICS

	Average torque[N-m]
Non-oriented model (Test machine)	6.044
Non-oriented model (New design)	6.332
Grain-oriented model (New design)	6.592

Equation (3) formulates the iron loss P_i per 1 kg. Iron loss P_i in 3 types of stator is equal because the core material is same.

$$w_f = B^2 \left\{ \sigma_h \left(\frac{f}{100} \right) + \sigma_e d^2 \left(\frac{f}{100} \right)^2 \right\} \text{ [W/kg]} \qquad (3)$$

Table V shows the iron parameter and constant. It shows thickness, coefficient of hysteresis loss σ_h, coefficient of eddy current loss σ_e and its density.

Table VI shows the loss and efficiency. The iron loss P_i of the segment core with grain-oriented electric steel is 88.4 W. It is decreased by 19.2 % compared with the non-oriented electric steel one of 109.4 W.

Next, we examine about eddy current loss P_e which developed in the aluminum block. They are calculated by the FEM. The eddy current loss P_e of the model with grain-oriented electric steel is 111.1 W. It is decreased by 7.0 % compared with non-oriented electric steel one of 119.4 W. It will be caused by that the linkage flux to an aluminum block is decreased by using grain-oriented electric steel.

We examine the efficiency for each model. The efficiency η of the model with grain-oriented electric steel is 81.0 %. It is increased by 2.8 % compared with the non-oriented electric steel one of 78.8 %. The results show effectiveness of the new type rotor using grain-oriented electric steel.

TABLE V
IRON PARAMETER AND CONSTANT

	Thickness [mm]	σ_h	σ_e	Density [kg/dm³]
Non-oriented electromagnetic steel strip JIS C 2552	0.5	2.35	14.1	7.7
Grain oriented electromagnetic steel strip JIS C 2553	0.3	0.39	11.3	7.65

σ_h: Coefficient of hysteresis loss σ_e: Coefficient of eddy current loss

TABLE VI
LOSS AND EFFICIENCY

	Eddy current loss[W] (aluminum)	Iron loss [W]	Efficiency [%]
Non-oriented model (Test machine)	145.4	109.4	77.0
Non-oriented model (New design)	119.4	109.4	78.8
Grain oriented model (New design)	111.1	88.4	81.0

VI. CONCLUSIONS

In this paper, we analyzed the new type rotor using grain-oriented electric steel segment core. The average torque is increased by 4.1 % and the efficiency is increased by 2.8 % compared with using non-oriented electric steel. Also, the eddy current loss which developed on an aluminum block is decreased by 7.0 % and the iron loss is decreased by 19.2 %. These results show effectiveness of the new type rotor using grain-oriented electric steel.

Next time, we will show you the 3-D analytical results and experimental results for the new designed rotor with grain-oriented electric steel shown in Fig. 10.

VII. REFERENCES

[1] T. J. E. Miller, Ed., "Switched Reluctance Motors and their Control", Lebanon, OH: Magna Physics/Oxford University Press, 1993.
[2] T. J. E. Miller, Ed., "Electronic Control of Switched Reluctance Motors", ser. Newnes Power Engineering Series. Oxford, U.K.: Newnes, 2001.
[3] J. Oyama, T. Higuchi, T. Abe, and N. Kifuji : "Novel Switched Reluctance Motor with Segment Core Embedded in Aluminum Rotor Block", IEEJ Trans. IA, Vol.126, No4, pp.385-390, 2005.
[4] J. Oyama, T. Higuchi, T. Abe, and K. Tanaka: "The Fundamental Characteristics of Novel Switched Reluctance Motor with Segment Core Embedded in Aluminum Rotor Block", Journal of Electrical Engineering & Technology, Vol. 1, No.1, pp. 58-62, 2006.

Fig. 10. Rotor with grain-oriented electric steel