Comparative Study of Stator Core Composition in Transverse Flux Rotary Machine

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Abstract – This paper deals with the comparison of magnetic characteristics in transverse flux rotary machine according to different stator core composition with the same rotor. Three different stator designs are considered in the analysis according to the material composition of inner and outer stator cores. Electromotive force (EMF), inductance, torque, and core losses are calculated by three-dimensional finite element analysis. Calculated and measured results of back-EMF according to the analysis models in dependency on speed are presented.

Keywords: Core losses, Soft magnetic composite, Electromotive force, Transverse flux machine

1. Introduction

Recently, soft magnetic composite (SMC) has been developed as an alternative magnetic material to reduce the iron losses in electric machine. Moreover, SMC gives additional degrees of electric machine designing freedom, especially when the magnetic flux has to flow three-dimensionally in the magnetic parts. However, SMC exhibits lower saturation flux densities and permeability than silicon steel [1]–[4].

With silicon steel, magnetic circuits are established by stacking magnetic sheets. In these magnetic circuits, the magnetic flux has to flow in parallel to the sheet steel surface. Such configuration with silicon steel exhibits very good magnetic properties; however, the geometries of possible magnetic circuits are limited because of the anisotropy of the laminated electrical steel and the manufacturing constraints [1], [3].

This paper attempts to find a good composition with these two representative materials, SMC and silicon steel, to achieve high-power density and to reduce core losses in the transverse flux rotary machine (TFRM) with three-dimensional magnetic flux paths. Three analysis models are presented. These three models share an identical rotor; however, three different types of stator are used depending on materials: SMC only, silicon steel only, and a combination of SMC and silicon steel. The conditions of the three analysis models are the same, except for stator core materials. The electromagnetic parameters for each model are computed with three-dimensional finite element analysis

(FEA). Electromotive force (EMF), inductance, torque, and core losses are obtained with computation results of the time-domain three-dimensional magnetic fields. The three analysis models are fabricated, and EMFs of each model are measured to confirm the core losses depending on material. The most suitable stator core composition is selected from the analysis and experiment results.

2. Analysis Models

2.1 Permanent Magnet Excited TFRM

Fig. 1 shows the conceptual configuration of one phase in a permanent magnet (PM)-excited TFRM and the magnetic flux path by current excitation. The PMs on rotor are arranged and magnetized in circumferential direction (Fig. 1(a)) to concentrate the magnetic flux to the rotor core. SMC is used as rotor core material because it is able to easily form a three-dimensional magnetic flux path; however, the magnetic permeability and saturation flux density of SMC are lower than those of laminated silicon steel.

The one-phase stator consists of a coil and the stator core. The stator core is divided into two parts: inner and outer cores. The inner and outer cores are called yoke and teeth, respectively. The teeth are again divided into upper and lower parts again, and the lower teeth are shifted by a half pole-pitch with respect to upper teeth to create skewing effect. Fig. 1(b) shows flux path on cross-section of “A” in Fig. 1(a) when current flows counterclockwise.

2.2 Analysis Models

Three kinds of analysis models are dealt according to the material composition of inner and outer stator cores. Table

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1 shows the three analysis models: SM (SMC core Model), SLM (SMC and Laminated silicon steel core Model), and LM (Laminated silicon steel core Model). The configurations are shown in Fig. 2. The left-side figures in Fig. 2 are the conceptual drawings of three analysis models, and the right-side pictures are their actual objects. For the model SLM, the combination of SMC for inner core and silicon steel for outer core is only considered. The opposite case is omitted because the characteristics can be deduced from the results of the three models. When making teeth of LM model, the original shape is the same as the teeth of SLM model. However, a slit is formed in the teeth of LM model (Fig. 2(c)) to improve the motor characteristics. The effect is explained in experimental results of the next section. The active dimensions of the three models are the same, and the dimensions are shown in Table 2.

Generally, lamination is not modeled to reduce computation time in the FEA process. However, in this paper, the lamination is expressed in the analysis to compare the eddy current loss depending on core state. The stator core is modeled as a solid core when modeling SMC core, whereas it is modeled as layers when modeling laminated silicon steel core. To reduce the number of elements and save computation time, the lamination is expressed with a few layers, not the actual number of laminated sheets, and with insulating boundary condition instead of air gap between layers [5]–[6]. Layers separated by the insulating boundary condition are only electrically isolated, not magnetically or mechanically.

2.3 Analysis Conditions

Specifications of the prototype, including magnetic material information, are listed in Table 3. The conductivity information of magnetic material is based on catalogs of each material product. Each material is purchased based on this information, and sample cores are made to measure both AC and DC b–h curves. Core losses are measured according to variations of both frequency and peak magnetic flux density by the Epstein test method. Fig. 3 shows the measured results of DC b–h curves and a part of core loss data curves. Fig. 3(b) is from one of thirteen samples with different cross-sectional areas [7].

The summarized and compared results for measured core losses are shown in Table 4. The eddy current loss of SMC is lower than that of silicon steel in accordance with representative characteristics of SMC; however, the hysteresis loss is larger. Therefore, total core loss of SMC is larger than that of silicon steel at the condition of the same frequency and flux density under low-frequency domain less than 1 kHz. The measured core loss data are used when total core loss is calculated for the analysis models, and the conductivities are used to calculate eddy current loss.

Fig. 1. Conceptual drawing of one phase in a TFRM; (a) a drawing in section of a TFRM, and (b) flux path on the cross-section of A

(a) Model SM and its actual object (one-phase core)

(b) Model SLM (without slits in teeth) and its actual object (two-phase cores)

(c) LM model (with slits in teeth) and its actual object (lower teeth + yoke)

Fig. 2. Conceptual drawings and assembly

Table 1. Analysis models

Analysis model	Material	
	Inner core (yoke)	Outer core (teeth)
SM	SMC	SMC
SLM	SMC	Silicon steel
LM	Silicon steel	Silicon steel

Table 2. Main dimensions

Rotor outer diameter	206 mm
Stator outer diameter	145 mm
Stator inner diameter	86 mm
Axial length	112 mm
Air-gap length	0.5 mm

Table 3. Specifications of an analysis model

	Quantity	Values and details
Stator	Material 1 (conductivity)	SMC (2500 S/m)
	Material 2 (conductivity)	Laminated silicon steel (3,000,000 S/m)
	No. of phases	2
	No. of turns	90 turns/phase
	Rated MMF	620 AT
Rotor	Material	Core: SMC PM Nd-Fe-B (Br=1.23 T, Hc=-964 kA/m)
	No. of pole	60
	Rated speed	300 rpm (150 Hz)

Br=residual induction; Hc=coercive force

3. Magnetic Characteristics

3.1 Analysis Results

Three-dimensional magnetic field FEA was conducted to calculate the electromagnetic parameters and core losses. The commercial software Maxwell was used for the calculation. Fig. 4 shows a three-dimensional analysis model. EMF, inductance, torque, and core losses are obtained by computation results of the time-domain magnetic fields at rated current. The analysis results are shown in Table 5. The value of eddy current loss is normalized based on a value of LM to avoid confusion. Here, because eddy current loss is calculated by a roughly laminated analysis model, the calculated values are not guaranteed; they are used only for comparison.

For both core loss and eddy current loss, SM has the smallest value. This may be because the flux density variation according to time is different from one another, and this is analogized with the torque wave difference (Fig. 5). In other words, the loss of SMC core in SM can be relatively lower because of less harmonic distortion and less peak flux density.

Table 4. Measured eddy current and hysteresis losses

Condition	Loss (W/KG)	SMC (somaloy700) section: 6.7×6.7 mm ²	Silicon steel (S23) Thickness: 0.5 mm
60 Hz 1.0 T	Eddy	0.12	0.94
	Hysteresis	5.27	2.02
200 Hz 0.5 T	Eddy	0.34	1.93
	Hysteresis	5.68	2.57
400 Hz 0.5 T	Eddy	1.35	7.72
	Hysteresis	11.57	4.45

(a) b-h curves

(b) Core losses of SMC core sample (6.7×6.7 mm²)**Fig. 3.** Magnetic characteristics of core materials **Fig. 4.** Basic analysis model for three-dimensional FEA: (a) configuration of analysis model; (b) flux density distribution in stator

Fig. 5. One-phase torque of three analysis models for rated MMF and rated speed

Table 5. Comparisons of characteristics at rated speed

	Quantity	Unit	SM	SLM	LM
0% MMF	EMF	V	167	176	179
	Core loss	W	0.002	41.5	43.5
	Normalized eddy current loss (NC/C/S)	NC	0.2	56.4	100
		C		6.7	10.8
		S		6.5	8.1
100% MMF	Inductance (min/max)	Min Max	14.3 /16.7	14.6 /17.4	15.1 /18.2
	Torque	Nm	31.5	32.3	32.7

NC/C/S=not considering lamination, considering lamination, and considering lamination and slit, respectively

Depending on considering lamination and slit state, the eddy current loss calculation results are changed. In analysis model, the thickness of layer is 2.5 mm, whereas the real thickness of sheet is 0.5 mm. If the area is reduced five times, the core loss can be reduced a minimum of five times. However, confirming the fact by analysis necessitates considerable time and effort to; therefore, it is verified experimentally.

Based on the analysis results, the comparison of the three models can be expressed by a sign of inequality: (1) parameters related to output power (EMF, torque, inductance): $SM < LSLM < LM$; and (2) eddy current loss and total core losses: $SM < LSLM < LLM$.

3.2 Experimental Results

Fig. 6 shows measured EMF according to rotor speed (frequency) variation for all three analysis models, as shown in Fig. 2. The EMF values are normalized because the numbers of turns are different from one another when the three models are fabricated. In the ideal case, the normalized EMF value is 100 at a speed of 600 rpm. The SM and LM with slit model EMF values are similar to the ideal case; however, the EMF of SLM without slit is severely nonlinear.

The EMF values are presented in Table 6 for more detailed comparison. The basis of normalized EMF value is

(a) EMF of SM model

(b) EMF of SLM model (without slit in teeth)

(c) EMF of LM model (with slits in teeth)

Fig. 6. Comparison of measured EMF (dotted line, ideal curve; solid line, measured curve)

Table 6. Comparison of measured EMF (Normalized Value)

Model	Stator core material (yoke+teeth)	100 rpm	300 rpm	600 rpm
–	Ideal case (assumption)	17	50	100
SM	–	17	50	98
SLM	Without slit	14	34	57
LM	Without slit	15	39	66
	With slit	17	50	100

the same as in Fig. 6. Whereas the voltage drop is 2% for SM at a speed of 600 rpm, the other two models using laminated silicon steel have severe voltage drop of 34% and 43% because of core losses in stator outer core. This is a very significant result because the core loss is too big, despite the fact that the cores are laminated considering flux path.

To reduce the core losses, slits are formed on outer core in LM. The slit is mechanical, and electrical separation creates smaller eddy current loops. This seems a very effective solution because the voltage drop is 0 in LM with slit. Therefore, the sign of inequality for the total core losses of three models is changed as follows: (2') estimated total core losses from voltage drop: SLM>>SM>LM (with slit).

4. Conclusions

Three-dimensional magnetic field FEA was conducted to calculate the electromagnetic parameters and core losses of the three models. In the analysis, the SM model yielded the best efficiency because of the low core losses. When the two models, SLM and LM, had slits, the eddy current loss was reduced. However, the amount of core loss reduction was too slight to reach the loss of the SM.

The experimental results show different results. When EMF was measured, the SLM and LM without slit exhibited severe voltage drop. When the slits were added to the LM, the voltage drop was eliminated. These results imply that the slits reduce the core losses significantly, and that they affect the core losses more than that predicted in the analysis. The experimental results yield that the performance of LM with slit is better than that of SM after all.

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