Calculation of Core Loss of a Transverse Flux Motor with SMC Stator Core and Mild Steel Rotor Yoke

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***Abstract*—This paper presents the numerical computation of core losses in a permanent magnet transverse flux motor (TFM) with soft magnetic composite (SMC) stator core and mild steel rotor yoke based on modified core loss models and finite element magnetic field analysis. The coefficients for the core loss models are obtained by curve-fitting measurements on samples, and the magnetic flux density patterns in the motor are obtained by stepping finite element analysis (FEA) while operating conditions are considered. The calculations of the motor core losses agree with the measured values on the TFM prototype.**

***Index Terms*—Magnetic losses, magnetic cores, soft magnetic materials, electromagnetic devices, electric machines.**

I. INTRODUCTION

SMC (soft magnetic composite) materials and their application in electromagnetic devices have attracted strong research interests in the past two decades [1]. By taking the advantage of the material's powder nature and the matured highly-productive powder metallurgical technology, a lot of work has been conducted to investigate the application potential of low cost mass production of electrical devices [2]. On the other hand, researchers studied the performance improvement of electrical appliances by using the material's unique properties like three-dimensional (3-D) magnetic isotropy and negligible eddy current loss [3]-[4].

For the best use of the material, SMC electromagnetic devices are often designed to operate at 300-400 Hz and the core loss is comparable to the copper loss. This is quite different from the conventional laminated machines with operating frequency of 50 Hz or 60 Hz, in which the copper loss dominates. Therefore, accurate calculation of core loss is crucial for developing high performance SMC devices [5].

This paper presents the calculation of core losses of a prototype transverse flux motor (TFM) with SMC stator [6]. Time stepping finite element analysis (FEA) is conducted to find out the flux density patterns in each element of the machine core at different operating conditions. A modified model, which can consider the effect of any type of flux density pattern, is applied to calculate the motor core loss for the particular operating condition. The calculations agree with the experimental results on the TFM prototype.

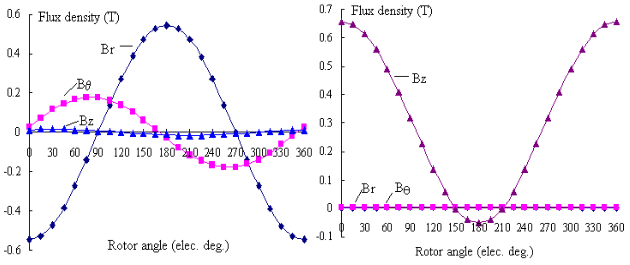
II. MAGNETIC FILED FEA OF THE TFM PROTOTYPE

Fig. 1 shows the photos of the studied SMC TFM prototype [6]. The internal stator consists of three stacks of SMC core, which are shifted by 120 electrical degrees to each other, and each is wound by a phase winding of concentrated coil. The external rotor is made of mild steel yoke and permanent magnets (PMs) glued on the inner surface of the yoke. The major dimensions of the motor include 80 mm of stator outer diameter, 93 mm of effective stator axial length, and 1 mm of main air gap length. The motor was designed to operate at 300 Hz, delivering rated power of 640 W at 1800 rev/min under an optimum brushless DC control scheme.

3-D magnetic field FEA has been conducted to compute the flux density (B) distribution in the motor under various operating conditions, and work out the B pattern in each element when the rotor rotates. Fig. 2 shows a no-load B pattern in a typical stator tooth element and one in a typical rotor yoke element. As shown in Fig. 2(a), the B loci in the SMC stator are basically rotational and 3-D with non-negligible component in any direction. However, the B loci in the rotor yoke elements, as shown in Fig. 2(b), are basically one-dimensional (1-D) along the axial direction (z-axis) only, i.e. the magnetic field along the radial (r-axis) or circumferential (θ-axis) direction is negligible. The calculations also show that the flux density in PMs is almost constant, so the core loss in the PMs is ignored in this work.


(a) (b)

Fig. 1. Photo of the SMC TFM prototype: (a) stator; (b) rotor



(a) (b)

Fig. 2. No-load B in a typical element in (a) stator tooth, (b) rotor yoke

III. CORE LOSS MODELS

To calculate the core losses under rotational B loci, Zhu and Ramsden presented a comprehensive model for calculating the rotational hysteresis loss in laminated sheet steel machines [7]. The formulations are extended to calculate the core losses of this SMC machine, as summarized below.

When the magnetic material is under 1-D sinusoidal B excitation, the so-called alternating core loss is computed by

$$P_a = C_{ha} f {B_P}^h + C_{ea}(fB_P)^2 + C_{aa}(fB_P)^{3/2}, \tag{1}$$

where f is the excitation frequency, B_P is the magnitude of the sinusoidal B, and C_{ha}, C_{ea}, C_{aa} and h are alternating core loss coefficients.

When the material is under two-dimensional (2-D) circularly rotating B excitation, the so-called rotational core loss is computed by

$$P_r = P_{hr} + C_{er}(fB_P)^2 + C_{ar}(fB_P)^{3/2}, \tag{2}$$

$$\frac{P_{hr}}{f} = a_1\left[\frac{1/s}{(a_2+1/s)^2+a_3^2} - \frac{1/(2-s)}{[a_2+1/(2-s)]^2+a_3^2}\right], \tag{3}$$

$$s = 1 - \frac{B_P}{B_s}\sqrt{1-\frac{1}{a_2^2+a_3^2}}, \tag{4}$$

where B_P is the magnitude of the circular B, B_s is the material's saturation flux density, and C_{er}, C_{ar}, a_1, a_2 and a_3 are rotational core loss coefficients.

When the material is under 2-D elliptically rotating B excitation, the core loss is computed by

$$P = P_r R_B + (1-R_B)^2 P_a, \tag{5}$$

where $R_B=B_{min}/B_{maj}$ is the axis ratio, B_{min} and B_{maj} are the values of the major and minor axes of the ellipse respectively, and P_r and P_a are the corresponding rotational and alternating core losses when $B_P=B_{maj}$.

IV. CORE LOSS CALCULATION IN THE TFM PROTOTYPE

A. *Core loss at no-load*

As described in Section II, the B pattern in each element can be obtained by time-stepping FEA. In general, the B pattern is an irregular 3-D loop. The 1-D alternating and 2-D rotating loci can be seen as special cases of the 3-D loop.

In each element, the flux density can be divided into three components along the r-, θ- and z- axes, and each component can be expressed by a series of harmonics using Fourier series. It can be verified mathematically that each harmonic forms an elliptical loop in a 2-D plane. Therefore, (1)-(5) can be used to calculate the core loss caused by each harmonic in each element. The coefficients in the formulae can be derived by curve-fitting the measurements on a cubic SMC sample under 1-D sinusoidal B excitations and 2-D circular excitations [8].

It can be derived mathematically that the total loss is the sum of all the harmonic losses. Then the core loss in the SMC stator is

$$P_{smc} = \sum_{e=1}^{Ne}\sum_{k=1}^{\infty}\left[P_{rk}R_{Bk} + (1-R_{Bk})^2 P_{ak}\right], \tag{6}$$

where Ne is the number of SMC elements used for conducting the FEA, and k is the order of B harmonic with frequency of kf, where f is the frequency of the fundamental component.

In the mild steel rotor yoke, the B patterns are alternating along the z direction only, so only (1) may be required. The alternating coefficients are obtained by curve-fitting the data provided by the material manufacturer, which were measured by using a ring sample with 1-D sinusoidal excitation.

With the above procedure, the core loss in the machine at no-load was computed as 63.3 W at 1800 rev/min, including 29.0 W in the SMC stator and 34.3 W in the mild steel yoke.

B. *Core loss under load*

The magnetic field distributions were solved with both PM and stator current excitations. At the rated load and the optimum brushless DC control, the stator core loss was computed as 56.5 W and the rotor yoke core loss was 63.8 W, and hence the total core loss was 120.3 W.

C. *Core loss measurement*

The core loss at no-load was measured as 68.2 W by using the dummy rotor method, which is 4.9 W larger than the calculated value. The 7.2% error may be caused by the losses in the PMs and endplates, which were not calculated.

Based on various power and loss measurements and the assumption that the mechanical loss at any load is the same for a particular speed, the motor core loss at the rated load was derived as 131.2 W, which is 8.3% larger than the calculation.

V. CONCLUSION

This paper computed the core loss in a transverse flux motor with soft magnetic composite stator and mild steel rotor yoke. It is noted that the approach can be easily adapted for other types of machines with other magnetic materials.

More detailed analysis and results will be presented in the full manuscript.

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