Research on High Speed Permanent Magnet Machine Power Loss and Demagnetization Analysis

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This paper investigates a 150 kW, 17000 rpm high speed permanent magnet machine (HSPMM) power loss and anti-demagnetization analysis by finite element method (FEM). In order to evaluate the machine iron loss with high precision, the improved analytical method considering both harmonics and rotational flux effects is utilized for iron loss calculation; rotor eddy current loss is investigated and discussed with machine structure effects from both stator and rotor sides; moreover, the optimized rotor is also proposed to reduce rotor eddy current loss for HSPMM; the machine PM demagnetization characteristics are studied, while the optimized machine structure and rotor configuration are proposed and researched to improve HSPMM anti-demagnetization capacity. More results about machine performance analysis and optimization will be carried out in the full paper.

***Index Terms*—Demagnetization, finite element method, high speed PM machine, power loss.**

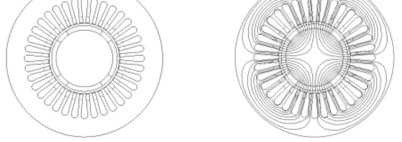
I. INTRODUCTION

HIGH SPEED electrical machines have been widely utilized in industrial application with great interests, and the permanent magnet (PM) machines are considered as reasonable and valuable choices due to their advantages of high power density, high efficiency and compact size [1]. The power loss, which acting as major heat source for high speed PM machine (HSPMM), has a critical effect on machine performance: high core loss is induced due to high fundamental frequency [2]; rotor eddy current loss heats the rotor directly and causes temperature rise due to high power loss density with a limited thermal dissipation area on the rotor side [3]. As PM is vulnerable to be demagnetized and the PM irreversible demagnetization results in serious degradation to machine performance, the optimal PM machine structures that improve machine capability of withstanding irreversible demagnetization is always desirable. The demagnetization behavior is investigated for a flux switching PM machine in [4], while the rotor with cut magnets can be found utilized to decrease the demagnetization area for a 7 MW interior permanent magnet wind generator [5].

In this paper, a 150 kW, 17000 rpm HSPMM is designed with its power loss investigated by finite element method (FEM): the iron loss is calculated with rotational magnetization and harmonics effects considered; the influence of machine structure on rotor eddy current loss is also analyzed; HSPMM performance due to PM demagnetization is illustrated with optimized machine structure to increase machine anti-demagnetization capability researched.

II. MACHINE STRUCTURE

The cross-section of 36 slot 4 pole HSPMM is shown in Fig.1, while its magnetic flux lines distribution with rated speed under no load also displayed. The stator core is composed by 0.2 mm low cost lamination steel while a carbon fiber sleeve is placed on the rotor outer surface for rotor mechanical integrity during high speed operation.



(a) Cross-section (b) Flux line distribution

Fig. 1. HSPMM structure and flux line distribution.

III. POWER LOSS ANALYSIS

Iron loss can be calculated based on the amplitude of flux density B_m in steel core and frequency f as below (Meth 1):

$$P_{iron} = k_h f B_m^{\alpha} + k_c f^2 B_m^2 + k_e f^{1.5} B_m^{1.5} \qquad (1)$$

where k_h, k_c and k_e are the coefficients of hysteresis loss (P_h), eddy current loss (P_c) and excess core loss (P_e) which can be obtained from the Epstein test results for steel core. However, for practical HSPMM, the waveform is with harmonic components rather than an ideal sinusoidal one; moreover, the iron loss is affected by both alternation flux and rotational flux in the steel core. So in order to precisely evaluate the iron loss for HSPMM, the magnetic flux density variation in each region of the machine is obtained and decomposed into a series of elliptical loci through Fourier analysis, and the iron loss can be calculated as follows (Meth 2):

$$P_{iron} = \sum_{k=1}^{N} k_h k f (B_{k\max}^{\alpha} + B_{k\min}^{\alpha}) + \sum_{k=1}^{N} k_c (kf)^2 (B_{k\max}^2 + B_{k\min}^2) + \qquad (2)$$
$$\frac{1}{T}\int_0^T k_e \left(\left| \frac{dB_r(t)}{dt} \right|^2 + \left| \frac{dB_t(t)}{dt} \right|^2 \right)^{\frac{3}{4}} dt$$

where B_{kmax}, B_{kmin} are the major and minor axes of k order harmonic elliptical magnetic field locus; $B_r(t)$, $B_t(t)$ are radial and tangential components of the magnetic field; T is the time period. The HSPMM iron loss calculated with two methods are compared in Table I. As can be found the extra loss considering both harmonics and rotational field effects by meth 2 is 135.6 W (accounts for around 12.5% in the total iron loss) higher than that calculated by conventional method when the machine with rated speed, which proves their necessity for HSPMM iron loss calculation with high precision.

TABLE I

HSPMM IRON LOSS CALCULATION

Speed (rpm)	Meth 1(W)				Meth 2 (W)			
	P_h	P_c	P_e	P_{iron}	P_h	P_c	P_e	P_{iron}
8000	228.9	100.7	1.2	330.8	245.2	123.6	1.8	370.6
17000	486.4	454.8	4.7	945.9	521.3	554.6	5.6	1081.5

The rotor eddy current loss is mainly induced by spatial and temporal harmonics in the machine, and time-stepping FEM with field-circuit coupling is employed to calculate the rotor eddy current loss. The eddy current loss affected by stator slot number for HSPMM at rated condition is shown in Fig.2. All the machines have the same rotor structure, stator slot opening width and conductors per phase with core axial length slightly adjusted to achieve the same largest output torque when machines excited by the same power supply. With different magnetic harmonics in machines, the eddy current loss distribution changes significantly, as eddy current loss in PMs is higher than sleeve when the slot number is small; it is suggested to utilize the stator structure with more slots to reduce rotor eddy current loss. Table II compares the rotor eddy current loss as a function of stator slot opening width for 36-slot HSPMM at rated condition. The eddy current loss gets increased if widening slot opening width, while such increased loss is mainly due to sleeve, as sleeve is near to slot openings in distance and its loss is vulnerable to stator slot dimension.

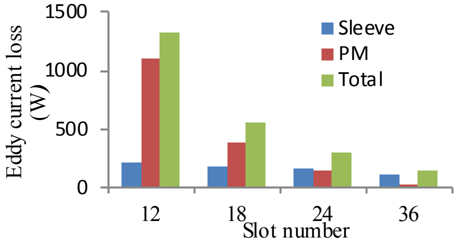
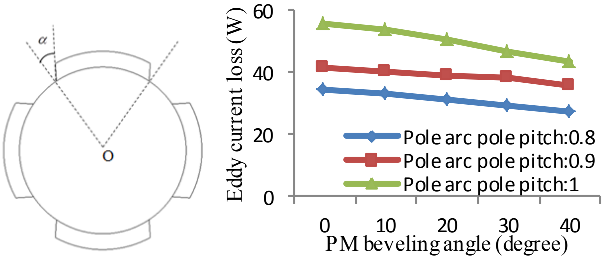


Fig. 2. Eddy current loss under different stator slot numbers.

TABLE II

EDDY CURRENT LOSS WITH SLOT OPENING WIDTH

Slot opening width	Sleeve (W)	PM (W)	Total (W)
3 mm	50.9	27.7	78.6
5 mm	86.9	34.2	121.1
7 mm	157.2	44.2	201.4



(a) Rotor PM beveling angle (b) Eddy current loss in PM

Fig. 3. Rotor PM beveling.

The rotor eddy current loss can be reduced by beveling PM edges while the beveling angel is defined as Fig.3 (a), and the PM eddy current loss with beveling angle and PM pole arc pole pitch is shown in Fig.3 (b): the PM thickness gets thicker to maintain the same output power as the un-beveling one. It can be found rotor beveling method can effectively decrease the PM eddy current loss for HSPMM.

IV. PM DEMAGNETIZATION

The PM demagnetization results in serious machine performance degradation. Fig. 4 presents the HSPMM output torque at cruel condition as PM temperature up to 180℃ from 100℃ during the period of 4.5 ms to 10 ms. It can be found the machine torque after temperature variation cannot recover to its previous one when the windings are excited by 3 or 4 times rated current in amplitude, due to the demagnetization induced by high temperature and over current. The PM demagnetization level can be reflected by demagnetization ratio, which is defined as the PM remanence flux density loss after demagnetization with the original one. Fig.5 compares the demagnetization ratio of different stator slot numbers for the 4-pole HSPMM with overload in harsh conditions. It can be found the HSPMM with larger slot number per phase per slot proves a better anti-demagnetization capability. Rotor can also be optimized to improve the machine anti-demagnetization capability and it will be detailed in the full paper.

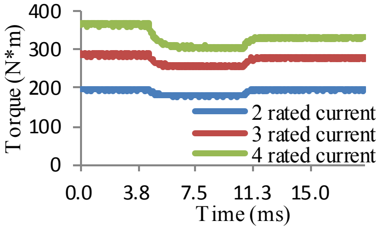
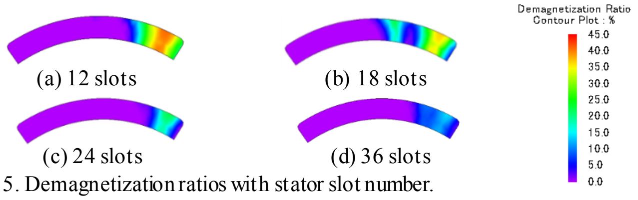


Fig. 4. Machine output torque performance with temperature variation.



(a) 12 slots (b) 18 slots

(c) 24 slots (d) 36 slots

Fig. 5. Demagnetization ratios with stator slot number.

V. CONCLUSION

HSPMM iron loss is calculated with improved method for high precision. The rotor eddy current loss is studied with machine structures. The HSPMM with larger slot number per phase features a better anti-demagnetization capability.

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