Loss Calculation and Demagnetization Analysis for a High Speed Permanent Magnet Electrical Machine

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This paper presents a MW high speed permanent magnet synchronous machine (PMSM) for compressor application. In order to assess the iron loss of PMSM with high precision, it is calculated with improved analytical method considering both harmonics and rotational magnetic field effects in steel core; rotor eddy current loss is calculated including machine structure influences by time-stepping Finite Element Method (FEM); demagnetization behavior of the high speed PMSM is also evaluated based on FEM; while the optimized machine structures are also proposed and investigated for the improvement of anti-demagnetization capability when the high speed PMSM under overload operation; the MW high speed PMSM is also prototyped and tested; More detailed analyses with the prototype and experimental results will be presented in the full paper.

***Index Terms*—Demagnetization, finite element method, high speed PMSM, power loss**

I. Introduction

HIGH SPEED PMSMs are extensively utilized in direct drive system applications with great interests due to their advantages including high power density, compact size and high efficiency [1][2]. Iron loss for high speed PMSM is obviously increased due to the machine high fundamental frequency; rotor heat radiation capability is limited as sleeve is applied around the rotor to retain the surface mounted magnets during high speed operation range, and the rotor eddy current loss acts as heat source effecting PM performance, which is of great importance; the air friction loss also acts considerable proportion in the total power loss [3]. As PMs are vulnerable to be demagnetized due to material property and it is desirable to find solutions to improve the PM machine demagnetization withstanding ability [4][5]. In this paper, a MW 18000 rpm high speed PMSM is designed and researched with its power loss analyzed; the machine demagnetization performance is investigated with FEA and the optimized machine structures to improve anti-demagnetization performance are studied; the high speed PMSM is also prototyped; further analysis and experimental results will be given in the full paper.

II. Loss Calculation for High Speed PMSM

The 27 slot 4 poles MW 18000 rpm PMSM is designed as shown in Fig 1 with non-metal sleeve around inner rotor surface for mechanical integrity during high speed operation;

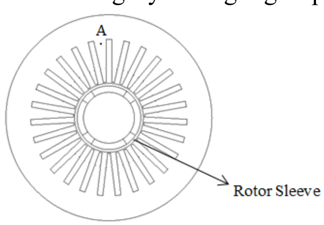
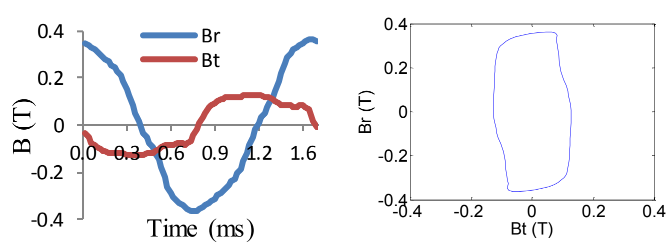


Fig. 1. High speed PMSM structure

Conventionally, the iron loss can be calculated by Bertotti's model that depending on the flux density amplitude B_m as (1) which can be found applied for high speed PM machine [6]:

$$P_{fe} = P_h + P_c + P_e = k_h f (B_m)^{\alpha} + k_c (fB_m)^2 + k_e (fB_m)^{1.5} \quad (1)$$

where f is frequency; k_h, k_c and k_e are the hysteresis loss, eddy current loss and excess core loss coefficients, respectively. For the high grade steel sheets, k_e is so small that the excess loss term can be neglected for the researched PMSM [7]; however, the flux density waveform in practical machine core is not an ideal one with harmonic components; moreover, rotational loss due to rotational magnetization in core should also be considered, as function (1) only regards the iron loss from alternating magnetic field. Fig 2 presents the radial (Br) and tangential (Bt) flux density waveforms for a point in stator teeth bottom (as point A shown in Fig 1 (a)) and the magnetization locus for the point. So in order to precisely evaluate the iron loss for high speed PMSM, 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 components can be predicted more accurately by considering both harmonics and rotational magnetic field effects in improved iron loss calculation method as (2):



(a) Radial and tangential flux density waveform (b) Magnetization
Fig. 2. Flux density and magnetization locus for point A

$$\begin{cases} P_h = \sum_{k=1}^{N} k_h k f (B_{k\max}^{\alpha} + B_{k\min}^{\alpha}) \\ P_c = \sum_{k=1}^{N} k_c (kf)^2 (B_{k\max}^2 + B_{k\min}^2) \end{cases} \quad (2)$$

where $B_{k\max}$, $B_{k\min}$ are the major and minor axes of k order harmonic elliptical field locus. Table I compares the iron loss results of the PMSM at different speeds calculated with the two methods. The iron loss due to harmonics and rotational magnetic field accounts for considerable proportion in the total iron loss of high speed PMSM with high frequency magnetic field, and it is necessary to account for the practical magnetic flux density waveform in the steel core for iron loss estimation with high precision by considering harmonics and rotational field effects.

TABLE I
IRON LOSS WITH DIFFERENT METHODS FOR HIGH SPEED PMSM

Speed	Conventional (W)			Improved (W)		
(rpm)	Hys	Edd	Iron Loss	Hys	Edd	Iron Loss
12000	1983	1044	3027	2191	1254	3445
18000	2975	2348	5323	3283	2820	6103
21000	3471	3198	6669	3828	3836	7664

Due to the high power density per unit and small heat dissipation area for high speed PMSM, rotor eddy current loss, which comes from the temporal and spatial harmonics, heats rotor and affects PMSM performance. Rotor eddy current loss can be calculated by time-stepping FEM. As high mechanical strength sleeve material applied around the surface-mounted PM, Table II and Table III present the sleeve and PM eddy current loss with sleeve parameters for the machine at rated condition. As can be found with the increase in sleeve conductivity, the PM loss is slightly decreased while the sleeve loss is dramatically increased; reducing sleeve thickness with mechanical permission at high speed operation can cut down rotor eddy current loss.

TABLE II
SLEEVE EDDY CURRENT LOSS (W) WITH SLEEVE PARAMETERS

Sleeve	Sleeve conductivity (S/m)			
thickness (mm)	$1*10^4$	$2*10^4$	$3*10^4$	$4*10^4$
6	397	791	1182	1571
7	731	1457	2177	2892
8	1328	2646	3954	5251

TABLE III
PM EDDY CURRENT LOSS (W) WITH SLEEVE PARAMETERS

Sleeve	Sleeve conductivity (S/m)			
thickness (mm)	$1*10^4$	$2*10^4$	$3*10^4$	$4*10^4$
6	1157	1144	1131	1118
7	1144	1128	1113	1099
8	1121	1103	1087	1070

III. DEMAGNETIZATION ANALYSIS

PM experiences characteristic changes in relation to temperature rise and armature reaction field, and it is desirable to improve the machine ability to withstand demagnetization especially for high speed PMSM. Therefore, in this study, the circuit-based FEM calculation is utilized to investigate the demagnetization characteristics of the PMSM, and the distribution and level of PM demagnetization can be evaluated by demagnetization ratio, defined as the PM remanence flux density loss after demagnetization with the original one.

Composite pole spacer can be utilized to increase the machine anti-demagnetization capability for PMSM, as shown in Fig. 3, as two layers of spacer material (magnetic and non-magnetic) filled between the adjacent PMs. Fig.4 compares the PM demagnetization ratio for the rotor without and with such pole spacer structure when the machine with overload at 140℃. It can be observed from the results that the machine rotor with composite pole spacer structure can effectively decrease the PM demagnetization level and area for the high speed PMSM in harsh condition.

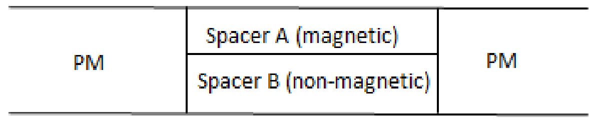
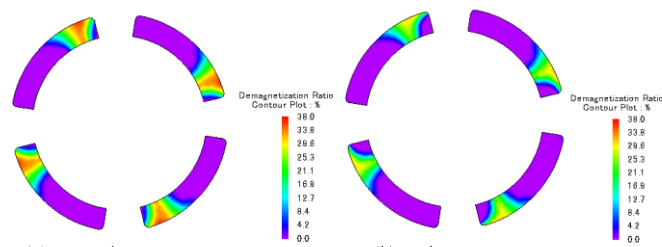


Fig. 3. Composite pole spacer structure.



(a) No pole spacer structure (b) Pole spacer structure

Fig. 4. Demagnetization ratio

IV. CONCLUSION

This paper investigates the power loss and demagnetization analysis for a MW, 18000 rpm high speed PMSM: In order to accurately evaluate the iron loss, both harmonics and rotational magnetic field are considered. Then the eddy current loss for the machine with rotor retaining sleeve parameters are considered comprehensively. The demagnetization for high speed PMSM is studied with composite pole spacer structure proposed to improve the machine anti-demagnetization capability in harsh conditions. The MW high speed PMSM is also prototyped and tested. More analysis and research with experiment will be presented in the full paper.

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