Ultra High Speed Motor Supported by Air Foil Bearings for Air Blower Cooling Fuel Cells

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Abstract — This paper presents the development of an ultra high speed permanent magnet synchronous motor(PMSM) that produces output shaft power of 15 kW at 120,000 rpm with the 93% efficiency. The design of electrical machine is interdisciplinary. The design process of electric machines involves continuous iterations of electromagnetic, thermal, structural, and rotor dynamic design and analysis. This paper introduces a rotor with shrink fit, its structural analysis and rotor dynamic and unbalance analysis by 3D FEA and motor design and analysis. An ultra high speed motor prototype for air blower is manufactured cooling fuel cells at the rating of 15 kW, 120,000 rpm. All the performances of the ultra speed motor prototype are verified successfully.

I. INTRODUCTION

This paper introduces design and analysis electrical, structural, rotor dynamic and unbalance analysis to design and manufacture the developed ultra high speed motor. At first step, design and analysis of the electrical machine are performed to develop required high efficiency, power and speed considering core loss and eddy current loss[1]. At the second step, structural analysis and manufacture technique are applied to withstand in ultra high speed condition. It is essential that the method to fix PM of rotor in SPM(Surface Permanent Magnet) motor is selected the proper interference by shrink fit. Also the shrink fitted condition is checked in operating status(120,000 rpm, 210℃, δ:0.087).

At final step, the critical speed and separation margin are proposed by Campbell diagram using rotor dynamic analysis and unbalance analysis[2]. Air foil bearings perform well as supporting bearings for the air blower motor operating at 120,000 rpm. Finally, the ultra high speed motor which is rated at 15 kW, 120,000 rpm for air blower cooling fuel cells is developed well using design, several techniques of analysis and manufacture technique [3-4].

II. DESIGN AND ANALYSIS OF PMSM

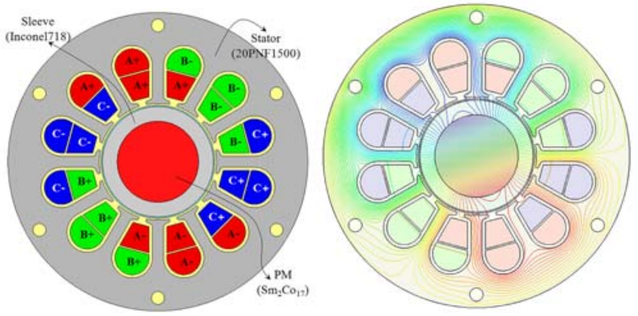
It is well known that the operation characteristics of the SPMSM dominantly depend on the permeance coefficient because it determines an operating point of the permanent magnet on its B-H curve. Assuming that the investigated SPMSM has uniform permeance distribution along the air gap, the permeance coefficient l_m of the SPMSM is expressed by the following equation :

$$p_u = \frac{l_m}{a_m}\frac{a_g}{K_C l_g} = \frac{l_m}{D_m - l_m}\frac{D_m + l_g}{K_C l_g} \tag{1}$$

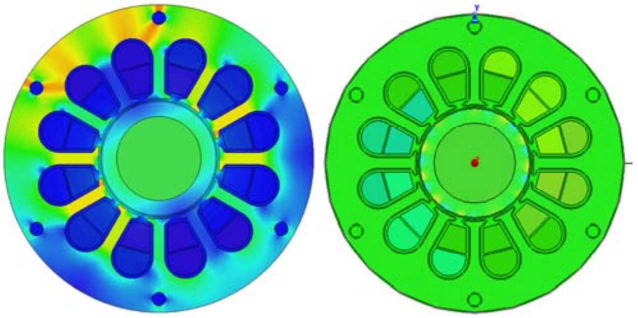
Where l_m is a permanent-magnet thickness, a_m is an averaged cross sectional area of the permanent magnet, a_g is an averaged cross sectional area of the air gap between the rotor and the stator, l_g is an air gap length, D_m is an outer diameter of the permanent magnet, and K_C is a Carter's coefficient. Since K_C normally takes a value of approximately 1.2 to 1.5, a_g can be regarded as almost same as $a_m K_C$; thus, the following approximated expression is obtained:

$$p_u \approx \frac{l_m}{l_g} \tag{2}$$

This equation indicates that the permeance coefficient is determined by the ratio between l_m(magnet thick) and l_g (sleeve thick). The permeance coefficient p_u is basically proportional to the e.m.f. if other physical dimensions of the investigated motor are not changed.



(a) winding (b) flux lines



(c) flux density contour (d) eddy current loss contour

Fig. 1. Winding pattern, flux density contour and flux path

Particular design strategies have to be adopted for ultra high speed applications since motor losses assume a key role in the motor drive performance limit. It has inner rotor type and consists of 2 poles 12 slots. The proposed design parameters for development are considered winding types, number of slots, slot opening width, sleeve thickness. The cross section of the designed PMSM and its flux lines and flux density contour(max. 1.51[T]@ the end of stator teeth) at room temperature are shown in Fig. 1. Eddy current loss is concentrated at sleeve in rotor by 14.5[A/mm^2]. But it not effects on characteristics of system. Fig. 2 shows core loss and eddy current loss.

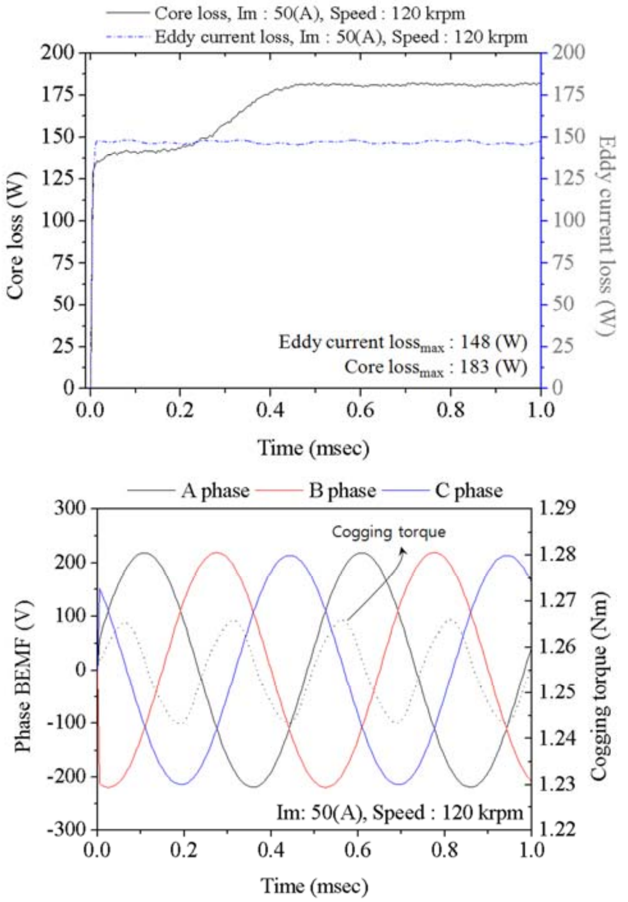


Fig. 2. Core loss and eddy current loss

TABLE I
COMPARISON DESIGN AND TEST RESULT OF THE DEVELOPED PROTOTYPE

Item	Goal	Unit	Value
Vph $_{RMS}$	400	V$_{RMS}$	230
Iph $_{RMS}$	39	A$_{RMS}$	37.5 A
Input power	16,13	W	15.75
Torque	1.19	Nm	1.1902
RPM	120,000	Rpm	120,000
Output Power	15.0	kW	14.96
Efficiency	93	%	95
Core Loss	0.124	kW	-
Eddy Current Loss	0.15	kW	-
Copper Loss	0.52	kW	168
Total Loss	0.794	kW	-

The maximum eddy current loss is about 0.15[kW]. And the maximum core loss is about 0.124[kW]. Copper loss is 0.52[kW]. Fig. 2 shows phase BEMF and cogging torque at input rated current 50[A], speed 120,000 [rpm]. Phase BEMF is max. 213[V] which is allowable at limit 400[Vdc] @120,000[rpm]. Cogging torque is max. 1.22[mNm]. it is only 0.064% of rated power. Cogging torque has not effects on high speed operation.

This paper based on the obtained results analyzes the most critical design parameter in eddy current loss by rotating at the rated speed of 120,000 rpm and researches to reduce eddy current loss. The detailed simulation and experiment result(motor and driver) will be shown in full paper. All the performances of the ultra speed motor prototype are verified successfully in Table I.

III. STRUCTURAL, DYNAMIC CHARACTERISTIC ANALYSIS

The supported bearing stiffness of air foil bearings used 1e6 N/m in simulation. The air foil bearings can be used in high speed. The bending whirling critical speed must be avoided. Fig. 3 shows Campbell diagram. The crossing points are critical speed. The developed model has 62.4[%] separation margin enough. Structural analysis of shrink fit effect and unbalance analysis result will be shown in full paper.

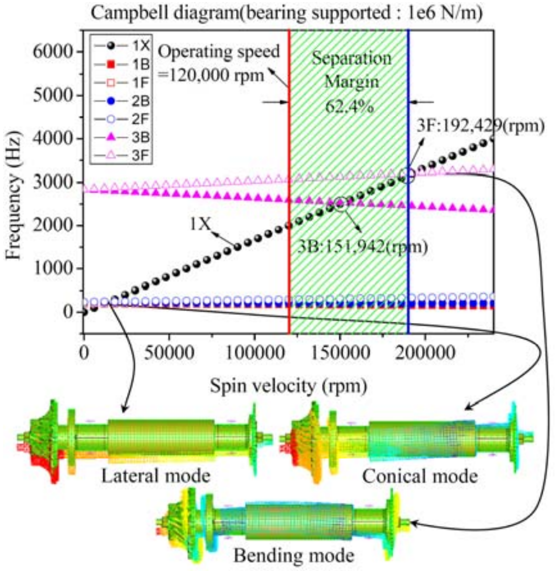


Fig. 3. Campbell diagram

IV. REFERENCES

[1] Miyagi, D., Maeda, N., Ozeki, Y., Miki, K. And Takahashi, N., "Estimation of Iron Loss in Motor Core with Shrink Fitting Using FEM Analysis", *IEEE Trans. Magn.*, Vol. 45., No. 3, pp. 1704-1707, 2009.

[2] D. K. Hong, B. C. Woo and D. H. Koo, "Rotordynamics and Unbalance Response Analysis of 200 kW, 15 krpm, 3 Phase Induction Motor", *PRZEGLĄD ELEKTROTECHNICZNY*, R. 86 NR, pp. 129-132, 2010.

[3] Limei, Zhao, Chan, Ham, Liping, Zheng, Wu, T., Sundaram, K., Kapat, J. and Chow, L., "A Highly Efficient 200 000 RPM Permanent Magnet Motor System", *IEEE Trans. Magn.,* Vol. 43, No. 6, pp. 2528-2530, 2007.

[4] Abe, T., Higuchi, T., Oyama, J. and Shigematsu, K., "The System Simulation for Small Size and Ultra-High Speed Motor Drive System Suing Coupled Analysis", *Power Electronics and Applications, 2007 European Conf.*, pp. 1-8, 2007.