Mechanical Stress Reduction of Rotor Core of Interior Permanent Magnet Synchronous Motor

Jae-Woo Jung[1], Jung-Pyo Hong[1], and Seong-Min Jeon[2]

[1]Department of Automotive Engineering, Hanyang University
17 Haengdang-dong, Seongdong-gu, Seoul, Korea
jjw@hanyang.ac.kr

[2]Motor R&D Center, S&T Daewoo Co., Ltd.
5 Songjeong-ri, Cholma-myon, Kijang-gun, Busan, Korea

Abstract — Mechanical stress of rotor core of interior permanent magnet synchronous motor (IPMSM) is main issue in high speed operation because centrifugal force is appeared in rotating rotor core. Rotor core of IPMSM has very thin area so called rib and this area is mechanically weak point. However, the shape of rib hugely effects on electro-magnetic characteristics of IPMSM. Therefore, rib should be designed by considering both mechanical and electro-magnetic characteristics. Firstly, several model of rotor core is analyzed to find a shape of rib which has low leakage flux and centrifugal force. Next, calculation of centrifugal force and electro-magnetic characteristics are performed. Lastly, core burst test is performed and deformation of rotor core is compared to verify the analysis.

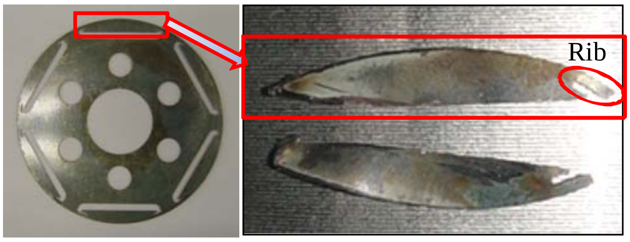
I. INTRODUCTION

According to develop the electric motor for automotive application especially electric vehicle or hybrid electric vehicle, high speed electric motor has been researched by many of expert. Generally, motor volume is determined by output torque and cooling condition. Therefore, increasing a speed of motor is advantageous design strategy to reduce a total size of motor in same output power [1].

Interior permanent magnet synchronous motor (IPMSM) is one of the attractive solutions of high speed electric machine because it produces high torque and wide speed range by mean of current vector control [2]. However, mechanical stress of rotor of IPMSM is main issue in high speed operation because centrifugal force is concentrated locally in rotor core. This local position of rotor core is relatively thin area which is so called rib. The rib of rotor core hugely effects on magnetic characteristics of IPMSM because leakage flux in rotor core is depends on the shape of rib. Therefore, it is important to design of shape of rib.

In this paper, mechanical stress reduction of rotor core of IPMSM is covered with analysis of magnetic characteristics as well as mechanical transient analysis. Design process is shown as following.

1. A study on the cause analysis of mechanical problem of prototype.
2. Selection of candidate model.
3. Analysis of magnetic circuit and centrifugal force. (Steady static condition)
4. Electro-magnetic field analysis and mechanical transient analysis.
5. Experimental verification of designed model.



(a) Rotor core lamination (b) Segment of rotor core

Fig. 1. Rotor core of prototype

II. MECHANICAL STRESS OF ROTOR CORE

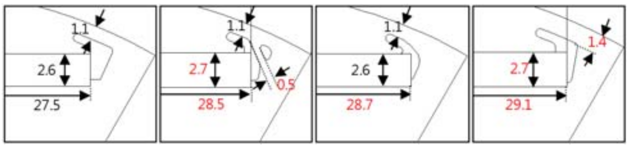
High speed operation of IPMSM effects on mechanical stress which is centrifugal force in the rotor core. Normally, rotor core of IPMSM has very thin area which is named by rib as shown in Fig. 1. Centrifugal force can be concentrated at small area of rib if shape of rib is not robust designed. The centrifugal force is proportional to squire of rotating speed as shown in equation (1).

$$F = \frac{mv^2}{r}. \qquad (1)$$

where, F is centrifugal force, m is mass, v is velocity and r is radius of mass. Therefore, it is important to design the shape of rib to avoid deformation or break of rotor core during high speed operation. Fig. 1 shows single lamination of rotor core and its segment which was broken down by centrifugal force.

III. DESIGN OF RIB

There are many design method to increase the stiffness of rotor core. For example, increasing of thickness of rib, double rib type can be investigated as shown in Fig.2. Model 1 is double rib and centrifugal force of rib can be distributed between two ribs. The rib of Model 2 is slightly differing to prototype except corner of rib. A shape of Model 3 is almost same with prototype except thickness of rib. Thicker rib decreases centrifugal force. Size of permanent magnet (PM) is redesigned to make same of back EMF with prototype because leakage flux of Model 1, 2 and 3 is increased by changing of shape of rib. Table I. shows magnetic characteristics and centrifugal force of each model which is calculated in steady static conditions. Calculation is performed by finite element analysis (FEA). Centrifugal force of prototype is enough to break rotor core because yield strength of rotor core is 390Mpa.



(a) Prototype (b) Model 1 (c) Model 2 (d) Model 3
Fig. 2. Rib shape of prototype and candidate models

TABLE I
Characteristics of prototype and candidate model

	Prototype	Model 1	Model 2	Model 3
Centrifugal force [Mpa]	408.0	259.0	222.9	278.0
Line to line back EMF [Vrms]	23.3	23.4	23.3	23.3
Torque [Nm] (Max. current)	45.9	45.6	45.5	45.0
PM volume [cm^3] (Single pole)	57.5	61.6	59.7	62.9

In spite of most small PM volume among the three models, Model 2 is vest solution for reduction of centrifugal force. Moreover, electro-magnetic characteristics are almost same compared to prototype.

IV. Mechanical and Electro-Magnetic Analysis

A. *Mechanical transient analysis*

Centrifugal force is maximized when mass is rotating with angular acceleration. The application of IPMSM deals with in this paper is integrated starter and generator (ISG) [3]. ISG has wide speed operating range and it is operated with fast speed changing. Therefore, mechanical transient analysis is required to make sure durability. Fig. 3 shows operation profile of durability test of ISG. Mechanical transient analysis is performed both prototype and Model 2.

Mechanical transient analysis is performed by commercial software 'Ansys Workbench'. Fig. 4 is calculated centrifugal force of two models. The maximum value is calculated at 1577sec and its value is larger than result of mechanical static analysis shown in Table I.

Concentrated stress is appeared in corner of rib in case of prototype, whereas the stress of Model 2 is distributed along the corner line of rib. The value is less than yield strength of rotor core, 390Mpa.

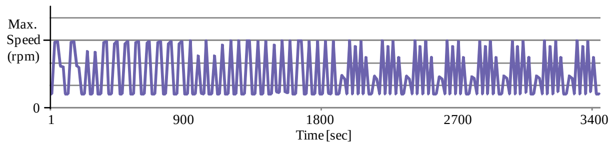


Fig. 3. Test profile of ISG

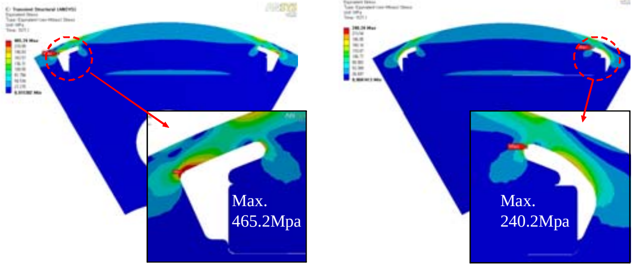
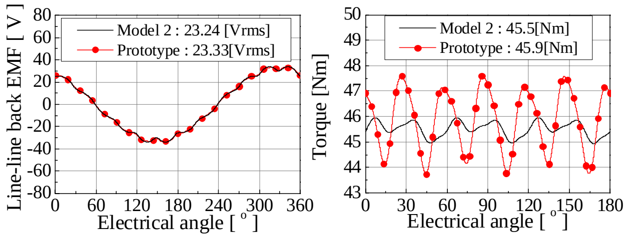


Fig. 4. Results of mechanical transient analysis



(a) Line to line back EMF (b) Torque @ max. current
Fig. 5. Results of electro-magnetic analysis

B. *Electro-magnetic analysis*

Leakage flux in rotor is depending on shape of rib. Therefore, it is necessary to analyze the electro-magnetic characteristics. Fig. 5 shows analysis result of line to line back EMF which is most important parameter of electric machine. The value and waveform is almost same between two models. Maximum torque is also similar and torque ripple is reduced by changing of rib shape.

V. Experimental Result and Conclusion

Because measurement of centrifugal force in rotating rotor core is impossible, measuring the deformation of rotor core is performed instead of measuring the centrifugal force to verify results of mechanical transient analysis. Burst test is measuring the deformation of rotor core after rotor rotating by external servo motor. Fig. 6 shows result of the burst test. Deformation of Model 2 is 65% of prototype which is measured after rotating speed 33000rpm.

It is important to design of rib in IPMSM especially high speed application. Mechanical transient analysis and electro-magnetic analysis is performed at the same time to avoid mechanical problem and degradation of motor performance with least changing of PM volume.

VI. References

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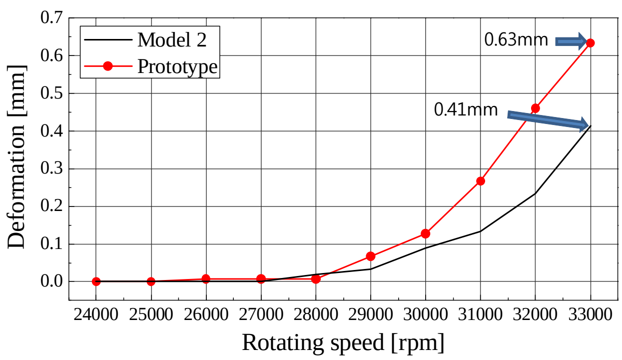

Fig. 6. Burst test result