Design of IPMSM Rotor Shape for Magnet Eddy-Current Loss

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***Abstract*— An interior permanent magnet synchronous motor (IPMSM) with concentrated windings was designed for railway traction applications. The IPMSM was analyzed by a two-dimensional finite-element method (2D FEM). This IPMSM have much permanent magnet eddy current loss. For more accurate calculation, 3D FEM analysis is carried out. Also change the placement of magnets at the rotor. As a result, we reduced the permanent magnet eddy current loss without critical torque reduction. To find cause of this result, the frequency analysis of air-gap magnetic flux density waveforms carried out.**

***Index Terms*— IPMSM, Concentrated Winding, Magnet Eddy Current Loss, Railway, Traction**

I. INTRODUCTION

Recently, interior permanent magnet synchronous motors are widely used in various fields because of its high efficiency and power density. In particular, due to the development of rare earth magnet materials with high energy product, production of IPMSM with high power density is possible. However, these rear-earth magnets have high conductivity. Along with the increasing use of highly conductive magnets, eddy current loss in a magnet is now an important issue. In particular, the IPMSM with concentrated winding has the eddy current loss in the magnets quite a lot. The eddy current generated from the permanent magnets can cause heat demagnetization and loss of motor. Because of these reasons, many studies to reduce eddy current hand have been made permanent magnet. One way to decrease the eddy current loss is to use a divided magnet [1]. One way would change the shape of the rotor core [2]. In this paper, we investigate the influence of magnet eddy current loss due to the placement of the permanent magnet and a permanent magnet split.

II. DESIGN OF TRACTION MOTOR

A. Specifications of Motor

Voltage of overhead line to supply power to a train is DC 750V, and 12 motors must be driven at 100 km/h maximum speed of the train of 108 ton. Table I shows the specifications of the motor to satisfy these conditions. A permanent magnet used in this motor is a Nd-Fe-B magnet that residual magnetic flux density is 1.15T, because of the conductivity of the magnet have a large value 909,090 S/m, critical to get the permanent magnet eddy current loss. In addition, the rated speed of the motor is 2,400rpm and the maximum rotational speed is 6,000 rpm.

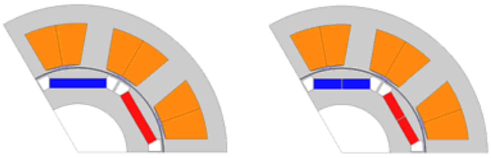
B. Designed Models

We have designed IPMSMs based on the specification of Table I, which have concentrated windings of 6 poles and 9 slots in consideration of manufacturing and power density. Fig. 1 shows 3 designed IPMSM models. All of 3 models have concentrated windings of 6 poles and 9 slots, and Nd-Fe-B permanent magnets with 10mm thickness. Further, one permanent magnet divided 10 in the axial direction to reduce magnet eddy current loss. In other words, 3 IPMSM models were consisted of 10 permanent magnet of 28mm length per one pole.

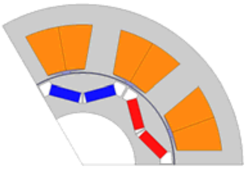
TABLE I
SPECIFICATION OF A IPMSM

Model	Specifications
Phases and poles	3 phases, 6 poles
DC voltage of inverter	750V
Input Current	440A
Maximum output	110kW
Diameter of stator and rotor	318mm, 180mm
Core length	280mm
Thickness of steel plate for core	0.35mm
Magnet type, Magnetization	Nd-Fe-B, 1.15T
Conductivity of magnet	909090 S/m

The Model I of Fig. 1(a) is the basic model that has permanent magnets of 60mm width. The Model II of Fig. 1(b) is that in order to confirm the effect of the circumferentially divided permanent magnet. The model II was divided one 60mm permanent magnet into two 30mm permanent magnets in the model I. The Model III is a model arranged in V-type permanent magnets in the model II.



(a) Model I (b) Model II



(c) Model III

Fig. 1. Designed Models

III. ANALYZED MOTORS

In order to check the characteristics of 3 IPMSM models, two-dimensional (2-D) finite element analysis (FEA) was carried out. The magnetic field equation for the 2-D nonlinear time-stepping analysis is

$$-\nabla\cdot\left(\frac{1}{\mu}\nabla A_z\right)=J_a+\frac{1}{\mu_0}\left(\frac{\partial M_y}{\partial x}-\frac{\partial M_x}{\partial y}\right) \qquad (1)$$

where A_z is the magnetic vector potential, μ is the permeability, J_a is the armature current density, and M is the magnetization of the permanent magnet.

Meanwhile, the loss in the magnet can be calculated from the eddy current distribution by taking into account the effects of eddy currents in magnetic field analysis.

The eddy current density is

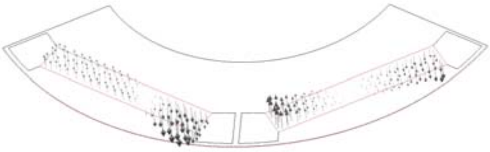
$$J = j\omega\sigma A \qquad (2)$$

The instantaneous eddy current loss is written in terms of the current density as

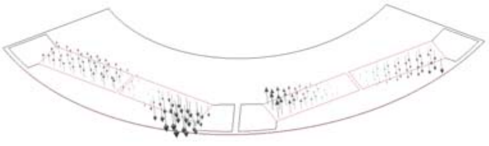
$$P_e=\iint_{\Omega}\frac{1}{\sigma}J^2dxdy \qquad (3)$$

The permanent magnet eddy current loss can be calculated by using equation (3). However, the result of 2-D FEA only has J_z component. Because, the J in the 2-D FEM is calculated by A_z component. Therefore, there is a limit that accurately calculating the eddy current which has a circulating path formed inside the permanent magnet.

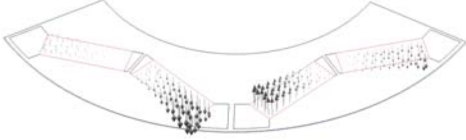
Fig. 2 shows the distribution of eddy current density vector was calculated by the 2-D FEM. Position of the rotor is the same all 3 models. Through the Fig. 2, we can confirm the fact that J vector has only z direction component by characteristics of the 2D FEM. In addition, the distribution of J vectors in the Fig. 2 (b) is displayed substantially the same as Fig. 2 (a), and the magnitude of magnet eddy current loss of the Model I (745.4W) is smaller than the Model II (789.5W). It means that there is no effect of the split magnet. In other word, that is not exact calculation. Therefore, in order to calculate the exact permanent magnet eddy current loss must apply the 3-D FEM. The formulation of the 3-D nonlinear time-stepping finite element analysis is as follows:



(a) Model I



(b) Model II



(c) Model III

Fig. 2. Distribution of eddy current density in the magnets (2D Model).

$$\nabla\times\left(\frac{1}{\mu}\nabla\times\mathbf{A}\right)=J_a-\sigma\left(\frac{\partial\mathbf{A}}{\partial t}+\nabla\phi\right)+\frac{1}{\mu_0}\nabla\times\mathbf{M} \qquad (4)$$

$$\nabla\cdot\left\{\sigma\left(\frac{\partial\mathbf{A}}{\partial t}+\nabla\phi\right)\right\}=0 \qquad (5)$$

where **A** and ϕ are the magnetic vector and electric scalar potentials, respectively, and μ and σ are the permeability and the conductivity, respectively. J_a is the armature current density, **M** is the magnetization of the permanent magnet [3].

IV. CONCLUSION

We have designed an IPMSM with concentrated winding for railway vehicle traction. To calculate the permanent magnet eddy current loss of the IPMSM, 2-D FEM and 3-D FEM are used. And we try to change the placement of the permanent magnet in order to reduce the permanent magnet eddy current loss. As a result, when placed in the V-Type, we have confirmed that the permanent magnet eddy current loss is reduced the most. In order to investigate the cause of this result, we have carried out an analysis of the spatial harmonics for air-gap magnetic flux density waveform. As a result, we have confirmed that the 13th harmonic component is critical. As the amplitude of this 13th harmonic component is reduced, so does the permanent magnet eddy current loss. The arrangement of the permanent magnets is a design variable that greatest affect to the 13th component of spatial harmonics. Thus, many studies on the arrangement of the permanent magnet are needed for performance improvement of the IPMSM with concentrated winding.

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