Analysis on Eddy Current Losses of Permanent Magnet Synchronous Motor with Double Sleeves Rotor using Electromagnetic Field Theory

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Abstract — The rotational loss is one of the most important problems for the practical applications of PM synchronous motor/generator. In this paper deals with the rotor losses minimization techniques combination of two different materials sleeve of high speed PM machines using electromagnetic field theory. This paper presents analytical procedures for calculation of the eddy current losses using Poynting theorem. In order to calculate eddy current losses , this paper derives analytical solutions by the magnetic vector potential, and a two-dimensional (2-d) cylindrical coordinate system, and analytical result with eddy current density obtained from finite element method, and compare results of electromagnetic field theory.

I. INTRODUCTION

Recently more attention is paid to minimizing the eddy current losses for higher efficiency of permanent magnet synchronous machine (PMSM) and many researchers have been continuously developed since they take an interest in the eddy current losses[1]. The rotor of PMSM is usually protected with a nonmagnetic retaining sleeve, but the eddy current losses are induced in the PM and also sleeve due to the time and space harmonics of magnetic field distribution in the air-gap produced by slotting effects. The amount of the eddy current losses is usually considered negligible. However, despite the relatively small amount of the eddy current losses compared with the stator copper and core losses, it may cause significant heating of the PM, due to relatively poor heat dissipation from the rotor, result in partial irreversible demagnetization, and decrease the motor efficiency[2]-[4]. For these reasons, it has been paid attention to reduce the rotor eddy current losses. In particular, the combination of different materials for the sleeve is an interesting method to reduce the eddy current losses.

Therefore, this paper deals with rotor loss minimization techniques using the combination of different materials for the sleeve based on electromagnetic field theory. Since inconel and copper (conductivity being $\sigma = 750{,}000$ s/m $\sigma = 580{,}000{,}000$ s/m, respectively) was used by material of sleeves and PM is SmCo24 (conductivity being $\sigma = 625000$ s/m), and eddy current losses are calculated with 2-d time-stepping finite element (FE) method, and compared trend that calculated results by electromagnetic field theory.

II. ANALYSIS METHOD FOR CALCULATE EDDY CURRENT LOSS

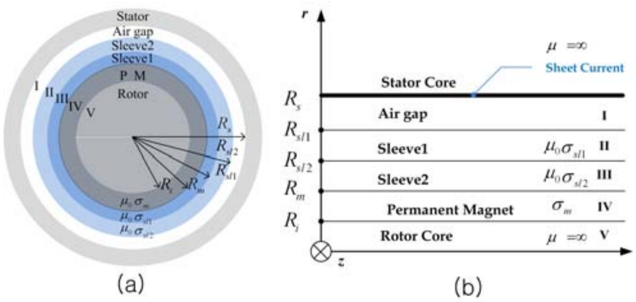

Fig. 1(a) Manufactured model. (b) Multilayer model for calculated eddy current loss

Fig. 1(a) shows the manufactured model with each region, and the model is based on a multilayer developed view model of the motor as shown in Fig. 1(b). I~V are expressed the air-gap, sleeve1, sleeve2, PM and rotor core, respectively, and electromagnetic field theory for calculation the eddy current loss was supposed. First, current of stator is defined sheet current that is distributed at r=Rs, and specific inductive capacity of sleeve1, sleeve2 and PM are 1. Finally, just sleeve1, sleeve2 and PM have conductivity. Sheet current is defined by (1)[5].

$$J_n = \sigma E \tag{1}$$

For the five regions the vector potential equation of each region is expressed by (2).

$$\begin{aligned}
&I \quad Region: \frac{\alpha^2}{\alpha r^2} A_{zn}^{I} + \frac{\alpha}{\alpha r} A_{zn}^{I} - \frac{m^2}{r^2} A_{zn}^{I} = 0 \\
&II \quad Region: \frac{\alpha^2}{\alpha r^2} A_{zn}^{II} + \frac{\alpha}{\alpha r} A_{zn}^{II} - (\frac{m^2}{r^2} + \beta_{sl1}^2) A_{zn}^{II} = 0 \\
&III \; Region: \frac{\alpha^2}{\alpha r^2} A_{zn}^{III} + \frac{\alpha}{\alpha r} A_{zn}^{III} - (\frac{m^2}{r^2} + \beta_{sl2}^2) A_{zn}^{III} = 0 \\
&IV \; Region: \frac{\alpha^2}{\alpha r^2} A_{zn}^{IV} + \frac{\alpha}{\alpha r} A_{zn}^{IV} - (\frac{m^2}{r^2} + \beta_{m}^2) A_{zn}^{IV} = 0 \\
&V \quad Region: \frac{\alpha^2}{\alpha r^2} A_{zn}^{V} + \frac{\alpha}{\alpha r} A_{zn}^{V} - \frac{m^2}{r^2} A_{zn}^{V} = 0
\end{aligned} \tag{2}$$

Boundary conditions substitute to flux density of each region, and it can express by (3), and (4) shown as boundary conditions[6].

$$\nabla \times E = -\nabla \times \frac{dA}{dt} = \int Edl = -\int \frac{dA}{dt} dt \tag{3}$$

$$\begin{array}{lll} a)\ r \to 0 & A_{zn}^{V} = 0 & \\ b)\ r = R_i & B_{\theta n}^{V} = 0 & B_{rn}^{V} = B_{rn}^{IV} \\ c)\ r = R_m & B_{\theta n}^{V} = B_{\theta n}^{IV} & B_{rn}^{V} = B_{rn}^{IV} \\ d)\ r = R_{sl1} & B_{\theta n}^{III} = B_{\theta n}^{II} & B_{rn}^{III} = B_{rn}^{II} \\ e)\ r = R_{sl2} & B_{\theta n}^{II} = B_{\theta n}^{I} & B_{rn}^{II} = B_{rn}^{I} \\ f)\ r = R_s & B_{\theta n}^{I} = -\mu_0 J_n & \end{array} \qquad (4)$$

Eddy current of each region can calculate by (3), and eddy current loss is calculated by using it. Resistance of sleeve and PM is in inverse proportion to conductivity, and resistance is changed by area of conductor. Therefore, it can find rapidly lowest point of rotor loss about materials and thickness because it shows the change pattern of eddy current losses are predicted by conductivity of material and thickness of sleeve and PM. Finally, eddy current losses are calculated by Poynting theorem, and shown as (5)[7].

$$P_{loss} = \frac{1}{2}\int_s \mathrm{Re}(E \times H^*)ds = \frac{1}{2\sigma}\int_{\theta 1}^{\theta 2} \mathrm{Re}(J_Z H_\theta^*) l_a r d\theta \qquad (5)$$

III. RESULT

Fig. 2 is shows the eddy current loss distribution at lowest point, case1 and case2, and Fig. 3 and Fig. 4 show the comparison of analytical and FE results for eddy current losses according to material combinations and according to sleeve thickness for case1 and case2. The analytical method result is different from FE result because of not considered harmonic of current and varying eddy current at each position, and just considered resistance of thickness and materials, skin effect and conductivity. But, the result can be rapidly find lowest point about sleeve thickness and materials for rotor losses minimization. As shown in Fig. 3 and Fig. 4, there is the combination of different materials which makes rotor losses minimum. For each combination, it can be observed from Fig. 3 and Fig. 4 that rotor losses is

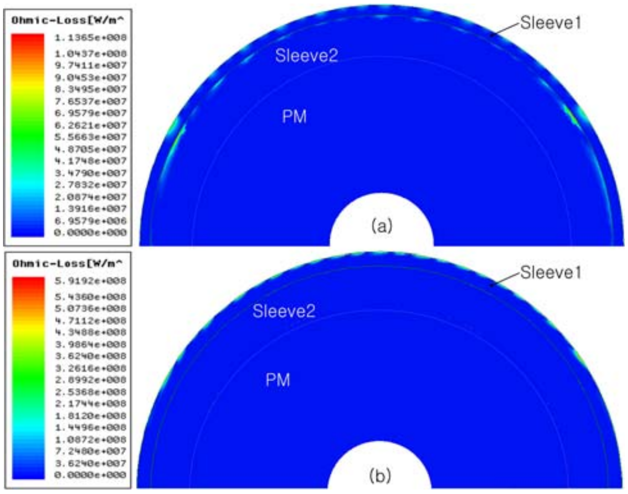

Fig. 2 Distribution of eddy current loss at lowest point, (a) Case1, (b) Case2.

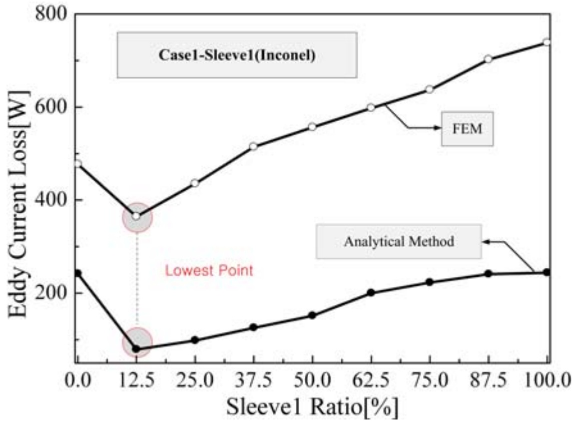

Fig. 3 Comparison of case1 lowest point

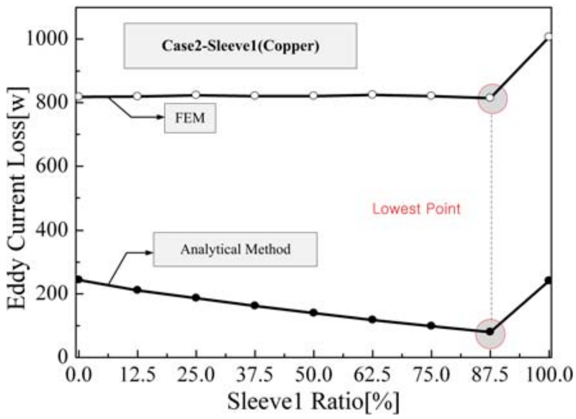

Fig. 4 Comparison of case2 lowest point

affected by sleeve thickness. The more detailed analysis results, discussion and mathematical expressions will be given in final paper.

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