영구자석 사용 효율 향상을 위한 IPM 전동기의 최적 토폴로지

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Topology Optimal Interior Permanent Magnet Machine to Improve the Utilization Ratio of Permanent Magnet

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Abstract - This paper presents an improved estimation procedure for the contribution to no-load flux linkage created by the permanent magnet (PM) in interior permanent magnet synchronous machines. In the proposed method, the saturation effect in stator and rotor cores are taken into account by utilizing the frozen permeability method (FPM). This improved procedure can evaluate the contribution for each local element in the PM to the no-load flux linkage. According to the analysis results, an effective PM topology optimal design can be carried out to achieve high utilization ratio of PM in the machine. In order to determine the threshold of the low contribution of PM for removing, one multi-objective optimization model is proposed. Based on the optimal threshold, the final optimal topology design of PM can be achieved.

1. Introduction

Nowadays, a number of interior permanent magnet synchronous machines (IPMSM) have been considered for application of hybrid electric vehicle and electric vehicle system. The reasons for these applications are high torque density and power density because of PM material[1]. Although IPM machines have smaller size and lower weight than conventional electric machine, the cost of IPM machines are much higher than conventional one because of the cost of PMs. Therefore, it is necessary to improve utilization ratio of PM to decrease the cost of machines.

Usually, the shape of PM in IPM machines is cuboid which is inserted into the rotor core. This shape is not optimized with regard to the generated magnitude of no-load flux linkage per volume of PM material[2]-[4]. It is possible that PM material element in different location has different contribution on no-load flux linkage. In this paper, a systematic topology optimal design procedure of PM is proposed by taking into account the saturation effect of the core by utilizing the FPM method [5].

2. Numerical Method

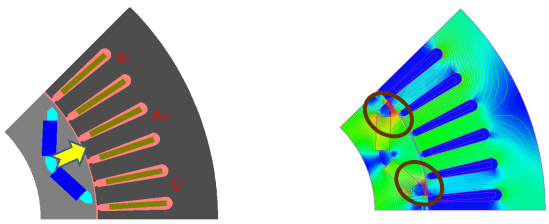
The no-load phase back EMF is proportional to the no-load flux linkage (λ_{PM}). Therefore, in this section, the no-load flux linkage in the stator winding is expressed in terms of a volume integral, which is applied to the volume of PM inside the machine with consideration of saturation effect. Based on the reference[4], the equation is rewritten here firstly.

$$i\lambda = \iiint_{V_{universe}} H \cdot B dv \quad (1)$$

where λ, H, and B are the flux linkage, the magnetic field intensity and the magnetic flux density generated by stator winding and PM of the machine, respectively. The detailed step to obtain this equation can be found in reference[4]. However, actually, the magnetic property of iron is nonlinear. The magnetic saturation effect must be considered in the analysis procedure. The magnetic flux density distribution of an IPMSM is shown in Fig. 1. Therefore, the FPM is adopted to consider the saturation effect in the iron. In order to obtain the two components generated by the stator winding current and the PM, respectively, firstly, the on-load permeability is obtained by performing the nonlinear FEA. Meanwhile, the permeability for each element is stored. Consequently, by utilizing the previous recorded permeability, the linear FEA is applied and the two components of λ, B, and H generated by the coil current and the PM are calculated. Thus, the (1) can be modified as follows:

$$i[\lambda_{froz_a}+\lambda_{froz_{PM}}]= \iiint_{V_{machine}} (B_{froz_a}+B_{froz_{PM}}) \cdot (H_{froz_a}+H_{froz_{PM}}) dv \quad (2)$$

where the subscript ‘froz’ presents that variable is calculated under the FPM. Thus, the superposition principle can be



(a). Analysis model (b). Magnetic flux density

<Fig. 1> One-eighth analysis model of IPMSM.

applied to (1). According to the reference[4], “when the curl of the first vector is zero and the divergence of the second vector is also zero, and then the integral taken over all space of the dot product of these two vectors is also zero”, the equation becomes:

$$i\left[\lambda_{froz\_a}+\lambda_{froz\_PM}\right] = \iiint_{V_{machine}} \left(\boldsymbol{B}_{froz\_a}+\boldsymbol{B}_{froz\_PM}\right)\cdot \boldsymbol{H}_{froz\_a} dv. \quad (3)$$

In order to focus the flux linkage generated from the PM on the coil, only λ_{froz_PM} is applied.

According to the derivation, the integral region is reduced to the PM region and then (3) becomes:

$$i\lambda_{froz\_PM} = \iiint_{V_{PM}} \boldsymbol{H}_{froz\_a} \cdot \boldsymbol{B}_r dv. \quad (4)$$

The mathematical expression given by (4) allows us to calculate flux linkage generated from PM to the coil with consideration of magnetic saturation by injecting an arbitrary current in the coil. By using the 2D FEA, the flux linkage can be calculated from the expression as follows:

$$\lambda_{\text{froz\_PM}} = \frac{l_{\text{Fe}}}{\mu_0 i} \sum_{k=1}^{N} \Delta_{\text{k}} \left(\boldsymbol{B}_{\text{froz\_a}} \cdot \boldsymbol{B}_{\text{r}} \right) \tag{5}$$

where the λ_{froz_PM} is the no-load flux linkage generated by the PM; l_{Fe} is the effective stator core length; μ_0 is the vacuum permeability; i is the current of the phase; B_{froz_a} is the magnetic flux density vector generated by the current with B_r=0 in the magnet region under previous stored permeability; and Δk is the area of the k-th element. Therefore, the contribution for each element in the PM region on the flux linkage can be evaluated by (5).

3. Topology Optimal Design

In the previous section, an improved contribution evaluation algorithm to no-load flux linkage, which is generated by the PM to the stator winding, is improved. However, in order to optimize the utilization ratio of the PM by using the contribution result, a threshold evaluation method should be developed. The threshold means, after the contribution distribution in PM region is calculated, from which level the low contribution element needs to be removed. On one hand, if the level defined by some designers is too low, elements with low contribution in the PM cannot be removed completely. On the other hand, elements with relatively high contribution in PM may be mistakenly removed result in performance deterioration in the machine.

Considering the above discussions, a multi-objective optimal algorithm is developed to find out the optimal contribution threshold to make a balance between the machine performance and utilization ratio of the PM. Here, the utilization ratio is defined as the quotient between the no-load phase back-EMF E0 and effective volume of PM Veff. In the suggested optimal design algorithm, the threshold of contribution ɣ is selected as the design variable. The no-load phase back-EMF and the utilization ratio are selected as two independent objective functions.

Design of the knee point is selected as the optimal design in this stage because it has the shortest distance from the Utopia solution compared with other designs in the design space. From the knee-point design, the optimal threshold level of the contribution is estimated as 3.626%. The corresponding optimal topology shape of the PM in the IPMSM is obtained as shown in Fig. 2

<Fig. 2> The optimal topology shape of PM

4. Conclusions

This paper presents an improved method to evaluate the PM contribution to the no-load flux linkage in IPMSM taking into account of magnetic saturation effect. The result shows that the improved algorithm can give bigger different result than the original one. After calculating PM contribution, a multi-objective optimization algorithm is carried out to determine the optimal threshold of contribution level.

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