Magnetizing Fixture Design for the Ring-type SPM Motor to Reduce the Torque Ripple

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This paper presents a design method to obtain an innovative structural design of a magnetizing fixture that can achieve a target magnetization orientation of a ring-type magnet of a surface-mounted permanent magnet (SPM) motor. The optimization problem is formulated to minimize the integrated value of the difference between the magnetic flux distribution produced by the input current of a magnetizing fixture and the target orientation for improving the torque performance of a SPM motor. Two level set functions are employed to express both the structural boundaries and the material properties of the ferromagnetic material (FM) and coil in a magnetizing fixture. To confirm its effectiveness, the proposed method is applied to the magnetization problem of a 8-pole 12-slot SPM motor designed for a battery cooling system of hybrid electric vehicles.

***Index Terms*—Design optimization, level set method, magnetizing fixture, ring-type magnet, surface-mounted permanent magnet motor**

I. Introduction

The surface-mounted permanent magnet (SPM) motor with a ring-type magnet has been widely used in mass produced applications such as home appliances and automotive electrical devices due to the structural simplicity and easy manufacturability. The high freedom of the magnetization orientation of the ring-type magnet in particular can provide various magnetic performance of the SPM motor to satisfy a design demand [1]-[2]. To improve the magnetic performance of the SPM motor, the key technology is to obtain the optimal orientation for the magnet and to develop a magnetizing fixture for magnetizing the non-magnetized ring-type magnet into the optimal orientation [3]-[4].

In this paper, a new design method to obtain the structural shape of a magnetizing fixture for the ring-type magnet to obtain the optimal magnetization orientation and improve the torque performance of the SPM motor is presented. The optimization problem is formulated to minimize the difference between the target magnetization orientation and the direction of the magnetic flux produced by the input current of a magnetizing fixture. Two level set functions are employed to represent the magnetic properties and the structural boundaries of the coil and ferromagnetic material (FM) in the magnetizing fixture. To confirm the usefulness of the proposed method, the magnetization problem of the 8-pole 12-slot SPM motor for torque ripple reduction is presented.

II. Problem Formulation

A. *Optimal Orientation of the Ring-type Magnet in SPM Motor*

8-pole 12-slot SPM motor designed for the battery cooling system of a hybrid electric vehicle is illustrated in Fig. 1. This model consists of an outer-rotor and a ring-type magnet of which the remanent flux density is 0.5 T. The target output torque is 0.3 Nm and the target torque ripple is set to under 5.0% at maximum speed. Fig. 2 shows the two different types of magnetization of the ring-type magnet. With the simple radial magnetization, as illustrated in Fig. 2 (a), the average torque was 0.28 Nm and the torque ripple 20.5%. The torque ripple can be decreased significantly by applying a 15° skewing angle, as shown in Fig. 3, however, such a skewing magnet also brings a 10.0% decrease of the output power.

On the other hand, using the optimal magnetization orientation ($\mathbf{M}_{opt}$), which has a continuous form of Halbach array [5] as illustrated in Fig. 2 (b), the average torque rose up to 0.3 Nm while maintaining the torque ripple under 5.0%, as shown in Fig. 3. Unfortunately, it is difficult to make such a non-uniform magnetization by using a conventional magnetizing fixture. Therefore, an innovative fixture design for providing the optimal magnetization pattern to the ring-

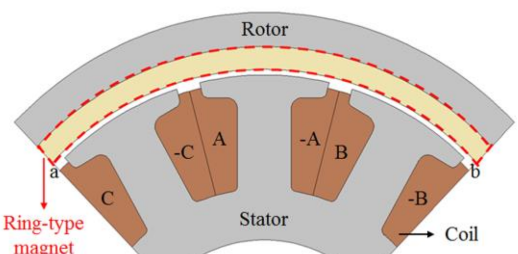

Fig. 1. Configuration of 8-pole 12-slot SPM motor

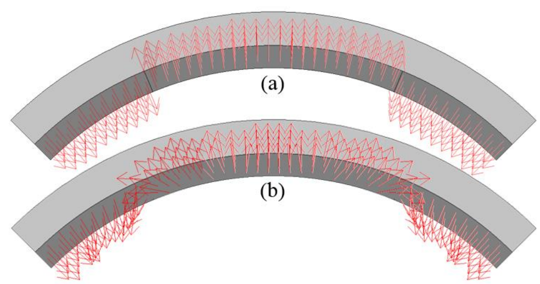

Fig. 2. Magnetization direction of ring-type magnet: (a) radial orientation (b) optimal orientation

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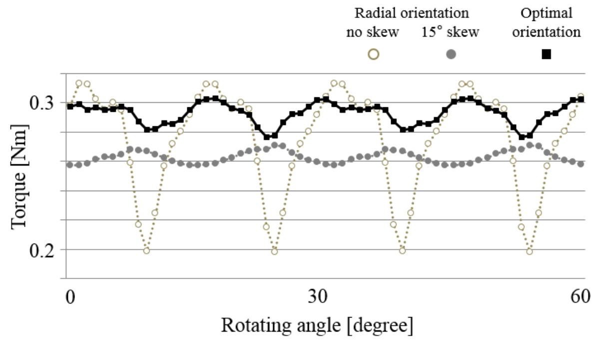

Fig. 3. Torque profiles according to the magnetization orientation

type magnet is needed.

B. Optimization Problem Formulation

The objective function (f) for obtaining the core shape of the fixture can be defined the difference value between the optimal orientation of the ring-type magnet ($\mathbf{M}_{\text{opt}}$) and the direction of the magnetic flux ($\mathbf{B}$) in the magnet region (Ω_{magnet}), which is produced by the input current of a magnetizing fixture. The optimization problem is formulated to minimize the integrated value of f , as follows:

$$\min_{\phi_1,\phi_2} \int_{\Omega_{\text{magnet}}} f\left(\phi_1,\phi_2\right) d\Omega_{\text{magnet}} = \int_{\Omega_{\text{magnet}}} \left(\frac{\mathbf{B}(\phi_1,\phi_2)}{\left|\mathbf{B}(\phi_1,\phi_2)\right|} - \frac{\mathbf{M}_{\text{opt}}}{\left|\mathbf{M}_{\text{opt}}\right|} \right)^2 d\Omega_{\text{magnet}} \quad (1)$$

where ϕ_1 and ϕ_2 are the design variables, which is called level set functions [6], to represent the material distribution of the FM (Ω_{FM}) and the coil (Ω_{coil}) in the fixture, as follows:

$$\begin{cases} \phi_1(\mathbf{x}) \geq 0 & \text{for } \mathbf{x} \in \Omega_{\text{coil}} \\ \phi_1(\mathbf{x}) < 0,\ \phi_2(\mathbf{x}) \geq 0 & \text{for } \mathbf{x} \in \Omega_{\text{FM}} \end{cases} \quad (2)$$

Since the magnetizing fixture uses a high impulse current to magnetize the ring-type magnet, only the direction of the magnetic flux is relevant for the fixture design, not the total amount of the flux density.

III. Optimal Fixture Design

The initial design and the design domain of the fixture are shown in Fig. 4. It is noted that this fixture was designed to magnetize the complete rotor, consists of both magnet and FM, and the rotor plays the part of an armature of the fixture. The boundaries of the FM became a wave shape line to provide the continuous magnetic flux as the optimal orientation, as shown in Fig. 5. Since the shape of the coil is less sensitive to adjust the direction of the magnetic flux than FM, the coil area in the fixture maintained almost the same configuration as the initial design. Using the optimal shape of the fixture, the magnetic flux in the magnet region has almost the same direction as the optimal orientation, as shown in Fig. 5. It is confirmed that the magnetic flux path produced by the optimal fixture design can follow the orientation precisely in comparison with the initial design, as illustrated in Fig. 6.

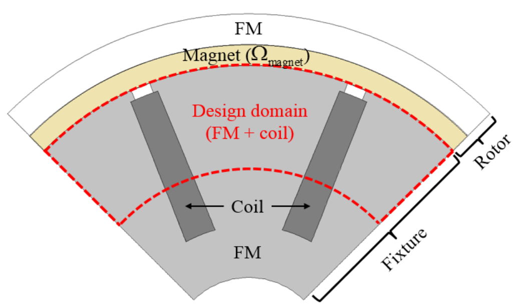

Fig. 4. Initial design and design domain of the magnetizing fixture

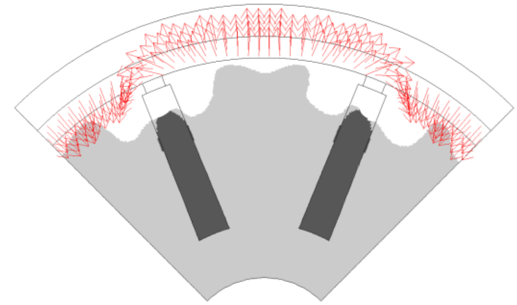
Fig. 5. Optimal fixture design and magnetization orientation

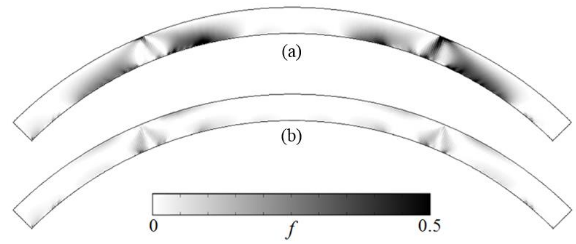

Fig. 6. Surface plot of the objective function: (a) initial fixture design (b) optimal fixture design

IV. Conclusion

A level set-based design optimization method to obtain the structural shape of a magnetizing fixture that can produce the target orientation of a magnet is presented in this paper. The design example of the SPM motor for improving the magnetic performance was provided to verify the effectiveness of the proposed method and it is confirmed that the proposed method can help to control the magnetic flux to the target orientation of the ring-type magnet.

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