

Estimation of Magnetization State of Permanent Magnet with Weak Post-assembly Magnetization Intensity Using Actual Leakage Flux Derived from PMSM Rotor

N. Nakamura¹, K. Takano¹, Y. Okamoto², *Member, IEEE*, N. Tomita³, and M. Hori³

¹Major in Electrical and Electronic Engineering, Graduate School of Science and Engineering, Hosei University, Koganei, Tokyo 184-8584, Japan, narichika.nakamura.3u@gmail.com

²Department of Electrical and Electronic Engineering, Faculty of Science and Engineering, Hosei University, Koganei, Tokyo 184-8584, Japan, okamoto@hosei.ac.jp

³Nihon Denji Sokki Co., Ltd., Tachikawa, Tokyo 190-0031, hori@j-ndk.co.jp

The magnetization performance of the permanent magnets (PMs) using post-assembly magnetization is conventionally evaluated by fluxmeter which is implemented on the magnetizer. Although the surface magnetic flux is measured after its operation, it is not possible to directly estimate the magnetization states inside the PM. Then, the magnetization estimation method using leakage magnetic flux density (MELF) was proposed by some of the authors. The performance of MELF has been verified in the PMs magnetized with saturated magnetization. In this paper, the magnetization estimation of PMs with actual unsaturated magnetization in interior permanent magnet synchronous motor (IPMSM) was carried out.

Index Terms—Leakage flux, magnetization state, permanent magnet, and post-assembly magnetization.

I. INTRODUCTION

EFFICIENT PERMANENT magnet synchronous motors (PMSMs) are extensively designed for EVs to realize the carbon neutral society [1], in which various electric vehicles with PMSMs are driven. Since it is well known that the performance of PMSMs is substantially dependent on the magnetization states of PMs, the estimation of magnetization distribution after the operation of magnetizers is essential.

The PMs implemented on the magnetic core of the PMSM are conventionally magnetized by post-assembly magnetization. Although the magnetization performance is largely evaluated by the surface magnetic flux measured by the fluxmeter which is attached to the magnetizer, the magnetization state inside of PMs cannot be estimated. Then, some of authors proposed the magnetization estimation method using leakage flux derived from the rotor of PMSM [2]. Hereafter, the method is referred to as MELF.

In the reference [2], the magnetization state of PMs with the saturated magnetization intensity was carried out. In this paper, it is investigated that the performance of MELF in the PM magnetization estimation problem which targeting the PMs with unsaturated magnetization.

II. MAGNETIZATION ESTIMATION METHOD USING LEAKAGE FLUX DERIVED FROM PMSM ROTOR

A. Objective Function and Its Gradient Calculation

In the MELF, to estimate the 3D magnetization distribution inside the PMs, the objective function W is formulated as follows:

$$W = \sum_{k=1}^{N_m} (\mathbf{B}^{(k)} - \mathbf{B}_0^{(k)})^2, \quad (1)$$

where N_m is the number of measurement points on the surface of PMSM rotor, $\mathbf{B}^{(k)}$ is the magnetic flux density calculated by

finite element method at k -th measurement point, $\mathbf{B}_0^{(k)}$ is the actual measurement data of leakage flux at k -th measurement point, and N_m denotes the number of measurement points.

To minimize W with respect to the magnetization vector $\mathbf{M}$ inside the PMs, the gradient-based optimization method is applied. Therefore, the gradient is calculated by the adjoint variable method [3]. Firstly, the equation of state discretized by finite element method in the magnetostatic field is formulated as follows:

$$\mathbf{K}(\mathbf{A}) \mathbf{A} = \mathbf{F}, \quad (2)$$

where $\mathbf{K}(\mathbf{A})$ is the stiffness matrix whose argument is the state variables $\mathbf{A}$ which becomes the magnetic vector potential, and $\mathbf{F}$ is the right-hand side vector based on $\mathbf{M}$. By solving the nonlinear equation (2) with respect to $\mathbf{A}$ using Newton-Raphson method, the adjoint equation is obtained as follows:

$$\left\{ \mathbf{K}(\mathbf{A}) + \frac{\partial \mathbf{K}(\mathbf{A})}{\partial \mathbf{A}} \mathbf{A} \right\}^T \boldsymbol{\lambda} = -\frac{\partial W}{\partial \mathbf{A}}, \quad (3)$$

where $\boldsymbol{\lambda}$ is the adjoint vector. By solving (3) with respect to $\boldsymbol{\lambda}$, $\boldsymbol{\lambda}$ is substituted into next equation:

$$\frac{dW}{d\mathbf{M}} = \frac{\partial W}{\partial \mathbf{M}} + \boldsymbol{\lambda}^T \left\{ \frac{\partial \mathbf{K}(\mathbf{A})}{\partial \mathbf{M}} \mathbf{A} - \frac{\partial \mathbf{F}}{\partial \mathbf{M}} \right\}, \quad (4)$$

where the calculation of $\partial \mathbf{F} / \partial \mathbf{M}$ is required because both terms $\partial W / \partial \mathbf{M}$ and $\partial \mathbf{K}(\mathbf{A}) / \partial \mathbf{M}$ are negligible.

B. Optimization Method

The gradient of W is applied to the update formula for steepest descent method (SDM) at n -th iteration as follows:

$$\mathbf{M}_{n+1} = \mathbf{M}_n - \alpha \text{grad } W, \quad (5)$$

where α represents the step-size which is determined by the advanced algorithm of functional minimization which is described in [4]. In the MELF, (5) is iterated until the maximum component of $\text{grad } W$ becomes less than or equal to the specified value.

III. ESTIMATION TARGET

Fig. 1 shows the 2D cross section of the target PMSM which is referred to as IEEJ D-model [5]. In its PMSM, the number of poles is set to four, the material of iron core 35H360 is applied. The specification of 3D finite element mesh is shown in TABLE I. The 1st order edge-based hexahedral edge element is applied, and Non and NoE show the number of nodes and number of elements, respectively. DoF and Nonzero show the degree of freedoms and nonzero entries of $K(A)$. N_{PM} shows the number of elements in the PM region that includes PM1–PM4 in Fig. 1.

The material of PMs is N36Z, and PM are simultaneously magnetized with approximately 45 % intensity of post-assembly magnetization (unsaturated magnetization). Then, the remanence of PM when magnetized with 100 % intensity (saturated magnetization) is approximately 1.18 T. The actual distribution of leakage flux derived from PMSM rotor is shown in Fig. 2. The measurement is carried out using the magnetic field instrumentation: MTX-6R [6]. Because the PMs were simultaneously magnetized with lower energy than usual, the leakage flux distribution is inhomogeneous. The actual measurement value of leakage flux shown in Fig. 2 is used as B_0 shown in (1).

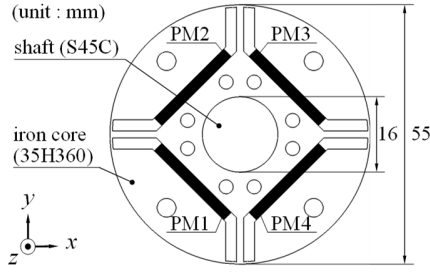


Fig. 1. Cross section of PMSM rotor.

TABLE I
SPECIFICATION OF FINITE ELEMENT MESH

NoN	NoE	DoF	Nonzero	N_{PM}
634,125	618,816	1,826,372	59,489,636	5,760

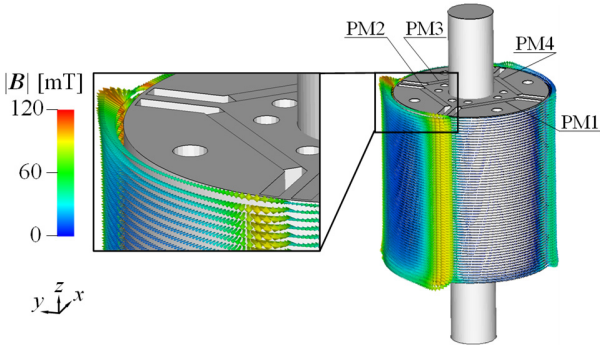


Fig. 2. Actual leakage flux distribution outside of PMSM rotor.

IV. RESULTS OF PM MAGNETIZATION ESTIMATION

By minimizing W , the magnetization distribution inside all PMs is estimated. The initial magnetization distribution M_0 is set as shown in Fig. 3. The intensity of M_0 was set to 0.8 T on the whole PMs region, and the direction of M_0 was determined

by that of the original PMs. Fig. 4 shows the estimated magnetization distribution inside of PMs. Because the magnetization was performed by the saturated magnetization, the magnetization intensity was inhomogeneous for each PM. It can be seen that the magnetization intensity changes based on the intensity of leakage magnetic flux derived from each pole shown in Fig. 2.

The iteration number of SDM was four, and the elapsed time for MELF was 2.5 h.

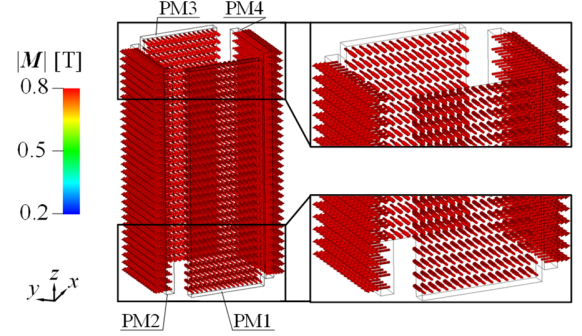


Fig. 3. Initial magnetization distributions M_0 of PMs for MELF.

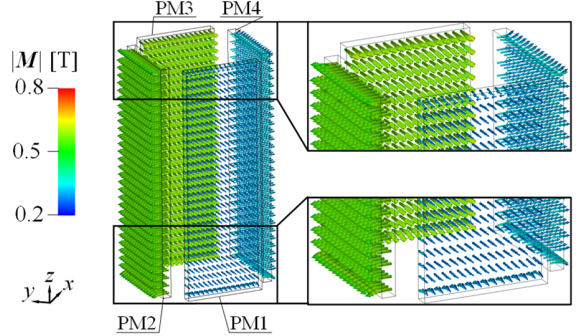


Fig. 4. Estimated magnetization distributions of PMs.

V. CONCLUSION

In this paper, the magnetization estimation method of PM using leakage magnetic flux is applied to the estimation problem in which the magnetization intensity is different among all PMs. In the future, the validity of estimated magnetization distribution will be verified using other numerical and experimental methods.

REFERENCES

- [1] Z. Gao, H. Xie, X. Yang, L. Zhang, H. Yu, W. Wang, Y. Liu, Y. Xu, B. Ma, X. Liu, and S. Chen, "Electric vehicle lifecycle carbon emission reduction: A review," *Carbon Neutralization*, vol. 2, no. 5, pp. 528-550, Sep. 2023.
- [2] N. Nakamura, M. Shioyama, and Y. Okamoto, "Magnetization estimation technique of permanent magnets loaded on rotor of IPMSM using actual measurement value of leakage flux," *IEEE Access*. (to be published)
- [3] I.-H. Park, B.-T. Lee, and S.-Y. Hahn, "Design sensitivity analysis for nonlinear magnetostatic problem using finite element method," *IEEE Trans. Magn.*, vol. 28, no. 2, pp. 1533-1536, Mar. 1992.
- [4] Y. Okamoto, K. Fujiwara, and R. Himeno, "Exact minimization of energy functional for NR method with line-search technique," *IEEE Trans. Magn.*, vol. 45, no. 3, pp. 1288-1291, Mar. 2009.
- [5] IEEJ Technical Report No. 776, *The Institute of Electrical Engineers of Japan* (2000). (in Japanese)
- [6] MTX-6R: <https://ims-jp.com/mtxsp/>