Topology-Parameter Hybrid Optimization of Skewed Permanent Magnet Motor

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In this study, we present a topology-parameter hybrid optimization of a permanent magnet motor with a step-skewed rotor. This optimization simultaneously performed topology optimization of the core shape and parameter optimization of the skew angle. Simultaneous optimization provides optimized motors that are superior to those obtained by parameter, topology, and sequential optimizations. Moreover, the optimized shape was shown to be robust with respect to variations in the skew angle.

***Index Terms*— Parameter optimization, Permanent magnet synchronous motor (PMSM), Robustness, Step-skewed rotor, Topology optimization**

I. Introduction

Permanent magnet synchronous motors (PMSMs) are used in a variety of equipment, including motors for electric vehicles, owing to their high efficiency and power density. Many PMSM applications require a high output performance, minimal torque ripple, and cogging torque to reduce vibration and acoustic noise.

To achieve the required characteristics, we evaluate the performance before fabricating a prototype motor to reduce manufacturing costs and development time using finite element analysis (FEA). The torque ripple and cogging torque can be reduced by designing an appropriate rotor geometry, matching the number of poles and slots, and skewing the rotor or the stator. Many studies have been conducted to reduce the cogging torque and torque ripple in PMSM [1]-[4].

Topology optimization (TO) is effective in reducing torque ripple and increasing torque when designing the flux barrier shapes of an inner permanent magnet (IPM) motor [5]-[8]. Step-skewed rotors in IPM motors shown in Fig. 1, are also widely used to reduce the cogging torque because such structures are easy to manufacture [1][2]. Conventionally, skew angles are determined after the rotor shape is designed. Although one can expect further improvements in motor performance if they are simultaneously optimized, such an approach has never been reported.

In this study, we propose a hybrid optimization method that simultaneously performs TO of the flux barrier and parameter optimization (PO) of the skew angles based on 2D-FEA of magnetic fields. The proposed simultaneous optimization was compared with three conventional approaches: PO, TO, and sequential TO-PO. In the last approach, the skew angles are determined by the PO after TO is applied to the rotor core shape. Moreover, the robustness of the torque performance of the optimized motor against variations in the skew angle was examined considering the manufacturing tolerance.

II. Hybrid Optimization Method

We consider the simultaneous optimization of the flux barrier of the rotor and skew angle of the rotor layers. After formulating the conventional TO method, we present the proposed TO-PO hybrid optimization method.

A. Topology Optimization

It would be difficult to set appropriate geometric parameters for the design of flux barriers that improve the average torque and reduce torque ripple. Therefore, TO is an effective treatment for this purpose. There are various methods for TO, which include sensitivity-based approaches, such as the level set method [9],[10], density method [11], and stochastic approaches based on the NGnet-ON/OFF method [5], [12]. In this study, the NGnet method was adopted because of its high searchability and versatility. In this method, Gaussian basis functions are placed in the design region. The material distribution is determined by the shape function, expressed as

$$\varphi(\boldsymbol{x}, \boldsymbol{w}) = \sum_{i=1}^{N} w_i b_i(\boldsymbol{x}), \tag{1}$$

where w_i is the weighting coefficient, $\boldsymbol{w} = (w_1, w_2, \dots, w_N)^t$, $\boldsymbol{x}$ is the position vector, N is the number of basis functions, and $b_i(\boldsymbol{x})$ is the normalized Gaussian basis function defined by

$$b_i(\boldsymbol{x}) = \frac{G_i(\boldsymbol{x})}{\Sigma_{k=1}^{N} G_k(\boldsymbol{x})} \tag{2}$$

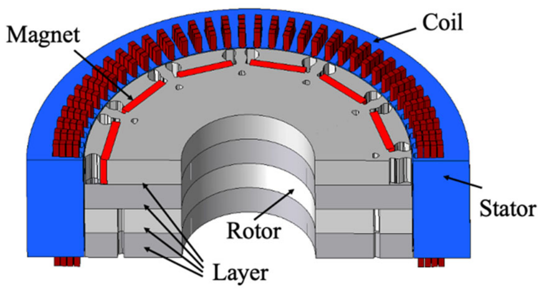


Fig. 1 Structure of the step-skewed PMSM

$$G_k(\boldsymbol{x}) = \frac{1}{2\pi\sigma^2}\exp\left[-\frac{\|\boldsymbol{x}-\boldsymbol{\mu}_k\|^2}{2\sigma^2}\right] \quad (3)$$

In (3), $\boldsymbol{\mu}_k$ and σ^2 are the center of the kth Gaussian basis and variance, respectively. The material attribute v_e of the finite element e is determined from

$$v_e \leftarrow \begin{cases} \text{air}, & \varphi < 0 \\ \text{iron}, & \varphi \geq 0 \end{cases} \quad (4)$$

The material distribution depends on $\boldsymbol{w}$, which is determined to minimize the cost function. This implies that TO is reduced to PO with respect to $\boldsymbol{w}$.

B. Parameter Optimization

The optimal skew angles for reducing the cogging torque in a PMSM were discussed in [2]. However, the skew angle must be carefully tuned because skewing has a side effect by which the average torque is reduced. Here, we perform PO with respect to the skew angles for the torque ripple and average torque. We subdivide the rotor into n layers with skew angles $\boldsymbol{p} = \{\theta_1, \theta_2, \ldots, \theta_n\}$ [deg]. The torque in each layer was analyzed using 2D-FEA to obtain the total torque by adding up them.

C. Proposed method

The optimal rotor geometries and skew angles would depend on one another. TO and PO are suitable for the design of flux barriers and skew angles, respectively. Therefore, we adopt the parameter-topology hybrid optimization method, in which TO for flux barriers and PO for skew angles are simultaneously conducted. Although we can extend the proposed method to also optimize the permanent magnet configuration as in [7] and [8], we consider the above-mentioned problem for simplicity. We determine $\boldsymbol{w}$ and $\boldsymbol{p}$ using CMA-ES [13], a population-based stochastic algorithm in which the number of individuals necessary for the global search increases only in O($\log N$), whereas that for the genetic algorithm increases in O(N), where N represents the number of optimization variables. In CMA-ES, individuals are generated according to the mean vector and covariance matrix, which are adaptively changed during the optimization. A flow diagram of the hybrid optimization, which ends at generation t_{gen}, is shown in Fig. 2. This study focuses on the average torque and torque ripple as indicators of motor performance.

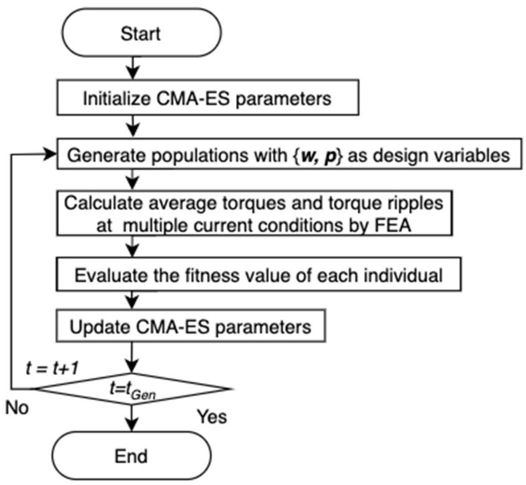


Fig. 2. Flow diagram of the proposed hybrid optimization method

III. Optimization Result

A. Comparison of Hybrid and Conventional Optimizations

The optimization model is shown in Fig. 3, and its specifications are summarized in TABLE I. The hybrid optimization problem is defined as follows:

$$\text{minimize } F(\boldsymbol{p},\boldsymbol{w}) = k_1\frac{T_{rip,1}}{T_{rip,1}^{ref}} + \sum_{i=2}^{3}\left(-(1-k_2)\frac{T_{avg,i}}{T_{avg,i}^{ref}} + k_2\frac{T_{rip,i}}{T_{rip,i}^{ref}}\right) \quad (5)$$

where $T_{rip,i}$ and $T_{avg,i}$ are the torque ripple that is a difference between maximize and minimum torques, and average torque, respectively, under the conditions $i = 1, 2, 3$ for the driving currents summarized in TABLE II. The current phase angle is defined for the no-skew rotor position. The quantities indexed by ref denote those of the reference motor shown in Fig. 4(a). k_1 and k_2 are weighting coefficients, and in this study, we assume $k_1 = k_2 = 0.2$ aiming at the improvement of T_{rip} and T_{avg} in good balance. The optimization settings are summarized in TABLE III.

In addition to the proposed hybrid optimization, PO, TO, and sequential optimization were performed as conventional methods for comparison. In PO, the skew angles of the reference model are optimized, whereas in TO, only the flux barrier is optimized, without a skewed structure. In sequential optimization, TO is performed for the flux barrier without skew, and then PO is performed for the skew angles for the motor shape obtained in the first step.

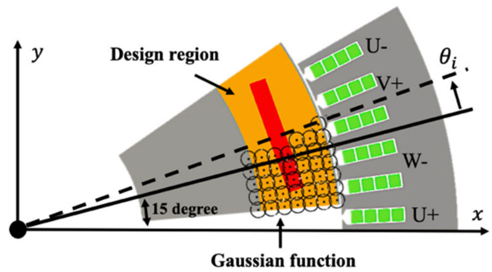


Fig. 3. Optimization model

TABLE I. Motor Specifications

Stator outer diameter [mm]	266.0
Rotor outer diameter [mm]	196.7
Thickness [mm]	65
Phases and poles	3 phases, 12 poles
Coil Turns	4
Number of stator slots	72
Residual flux density	1.1 T
Electromagnetic Steel Sheets	35JN270

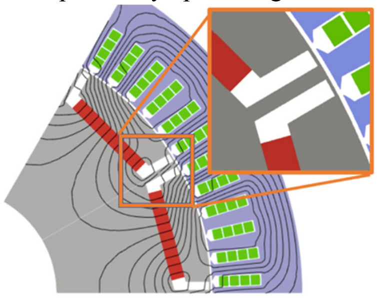
TABLE II. Current Conditions

conditions	1	2	3
amplitude	0.00	100	200
phase angel	0.00	30.0	40.0

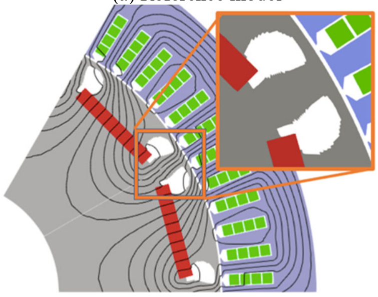
TABLE III. Settings of CMA-ES

Number of generations	100
Number of design variables	43
Size of population	64

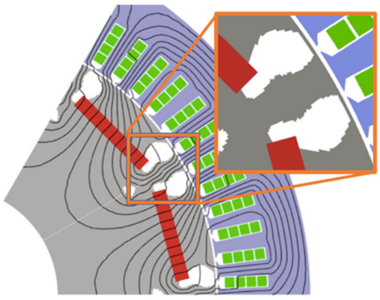
The optimized shapes and skew angles are presented in Fig. 4 and TABLE IV, respectively. TO→PO and PO+TO denote the sequential and proposed hybrid optimizations, respectively. These characteristics are summarized in TABLE V. The motor obtained by the hybrid optimization has a good balance in T_{rip} and T_{avg} and the highest value for T_{avg}. As shown in TABLE V, T_{rip} can be reduced with a step-skewed rotor, whereas T_{avg} is improved by optimizing the flux barrier.



(a) Reference model



(b)TO and TO→PO



(c) PO+TO

Fig. 4. Reference and optimized models

TABLE IV. Skew Angles Of Reference And Optimized Models

	θ_1 [deg]	θ_2 [deg]	θ_3 [deg]	θ_4 [deg]
Ref.	0.00	0.00	0.00	0.00
PO	-0.289	2.05	1.27	-1.33
TO	0.00	0.00	0.00	0.00
TO→PO	1.93	0.423	1.03	-0.659
PO+TO.	1.72	-1.02	0.361	3.27

TABLE V. Characteristics Of Reference And Optimized Motors

Methods (skew Yes/No)	F [-]	$T_{rip,1}$ [Nm]	$T_{rip,2}$ [Nm]	$T_{rip,3}$ [Nm]	$T_{avg,2}$ [Nm]	$T_{avg,3}$ [Nm]
Ref. (N)	-1.00	0.745	35.0	66.7	99.6	206
PO (Y)	-1.47	0.168	6.79	12.1	99.1	204
TO (N)	-1.50	0.0690	11.2	15.1	99.6	212
TO→PO (Y)	-1.52	0.0192	8.31	10.8	98.6	210
TO+PO (Y)	-1.61	0.145	7.21	10.3	108	220

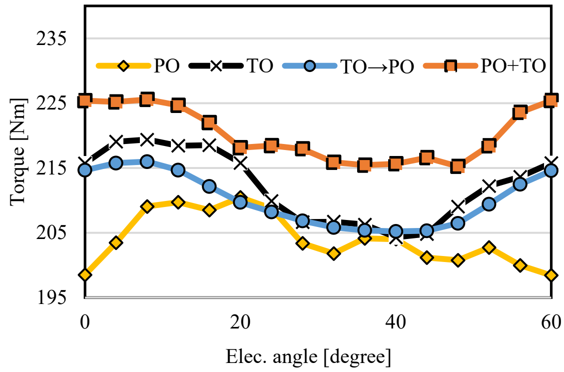
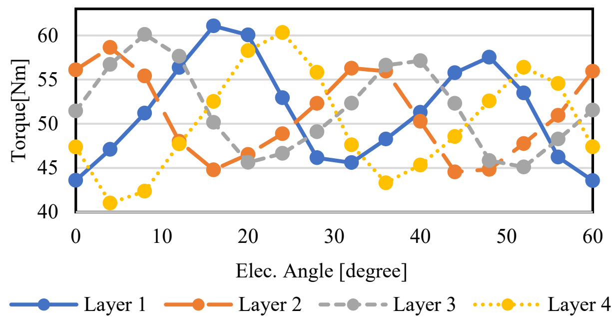
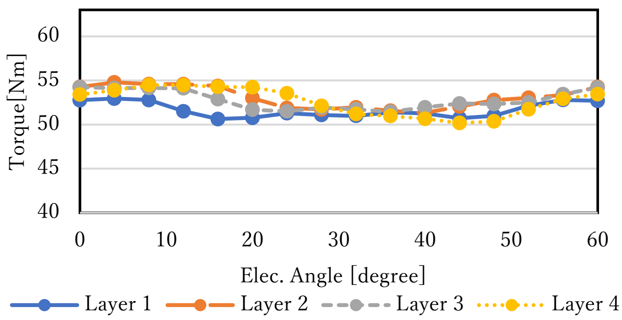


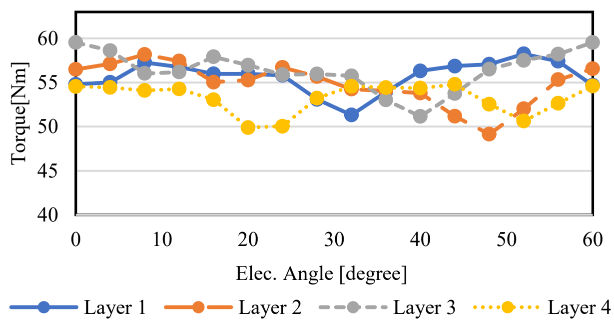
Fig. 5. Torque waveforms of reference and optimized motors



(a) PO



(b)TO→PO



(d) PO+TO

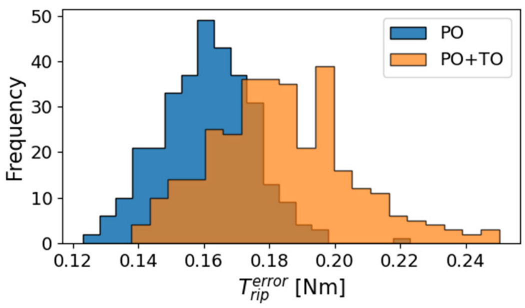
Fig. 6. Torque waveform of each layer

The torque waveforms of the overall layers and each layer of the optimized model under the current condition $i = 3$ are shown in Fig. 5 and 6, respectively. It can be observed that a flat torque was obtained by introducing skewed rotors.

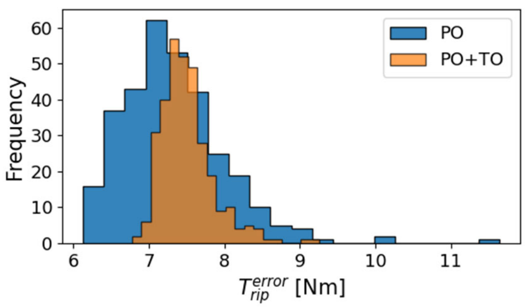
Next, we compare the results of the hybrid optimization with those of the sequential optimization. The rib between the rotor surface and flux barrier in Fig. 4 (b) resulting from the sequential optimization is thinner than that in Fig. 4 (c) resulting from the hybrid optimization. The thin rib suppresses the magnetic flux circulation and, hence makes T_{avg} higher. In sequential optimization, the torque ripple cannot be effectively reduced by introducing skew during the TO phase. Therefore, the rib becomes thicker to reduce the torque ripple. However, this lowered the average torque.

B. Robustness of optimized motor

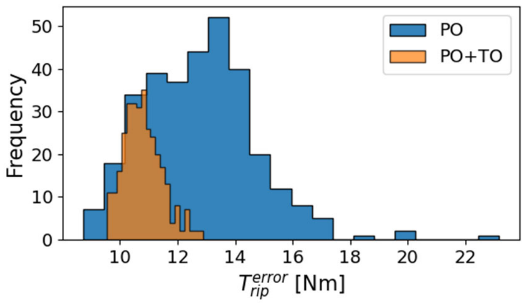
There are errors in the skew angles owing to manufacturing tolerance. Therefore, skewed motors must be robust in their characteristics against variations in skew angles. Therefore, we verify the robustness of the motor obtained by hybrid optimization. Fig. 7 shows the frequency distribution of the torque ripples $T_{rip,1}$, $T_{rip,2}$, and $T_{rip,3}$, where the manufacturing error in the skew angle is assumed to obey the Gaussian noise $N(0, 0.10^2)$. As shown in Fig.7(a), the cogging torques resulting from PO and the proposed hybrid optimization have similar influences on manufacturing errors. However, both cogging torques remained at low levels. Moreover, from Fig.7(b) and (c), we conclude that the optimal solution obtained by the hybrid method is more robust against manufacturing errors than that obtained by PO.



(a) Current condition 1 (0.00A)



(b) Current condition 2 (100A)



(c) Current condition 3 (200A)

Fig. 7. Frequency distribution of torque ripple with noise

IV. Conclusion

In this study, we propose a parameter-topology hybrid optimization method that simultaneously optimizes the skew angle and rotor geometry. The results obtained by hybrid optimization are superior to those of conventional methods, and a shape that achieves a reduction in torque ripple while maintaining high torque is obtained. Because the optimal skew angle and rotor geometry depend on each other, hybrid optimization is effective.

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