

Hybrid Parameter-Topology Optimization of Interior Permanent Magnet Motors Using a Dynamic Gabor Filter

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This paper proposes a hybrid optimization method combining parameter and topology approaches for the design of interior permanent magnet (IPM) motors, utilizing the dynamic Gabor filter. In this hybrid method, magnet shapes are refined through parameter optimization, while the shapes of the magnetic cores are defined via topology optimization with the dynamic Gabor filter. The optimized design features slit-shaped magnetic cores adjacent to the rotor surface, which meet voltage constraints, and incorporate multi-layered magnetic cores and magnet configurations that enhance torque performance.

Index Terms—Design optimization, Gabor filters, permanent magnet motors, torque.

I. INTRODUCTION

IMPROVING the power density and efficiency of traction motors for electric and hybrid vehicles is imperative, as these parameters significantly impact the downsizing of the drive system and extend the maximum cruising range. Interior permanent magnet (IPM) motors utilize both magnet and reluctance torques and are widely utilized to achieve such high performances. As the optimization of magnet configurations and flux barrier geometries within the rotor are essential to improve the torque characteristic of IPM motor, a parameter optimization employing specific shape parameters for the motor has been proposed [1]. However, this method often proves inadequate for developing novel motor shapes, leading to enhanced performance under given constraints. To address these limitations, several topology optimization techniques for rotating machines have been developed over the past decade [2, 3]. These methods enable the unencumbered design of rotor and stator geometries without introducing shape parameters. In particular, the normalized Gaussian network (NGnet) method has been extensively employed in the design of IPM motors for electric and hybrid vehicles due to its capability to produce spatially smooth magnetic cores, satisfying manufacturing constraints effectively [2]. However, the isotropic nature of the normalized Gaussian function constrains the NGnet method's ability to produce slit-shaped magnetic cores, which are essential for decreasing the higher harmonics of electromotive force and improving the rotor's mechanical strength [4]. Therefore, there is a clear necessity for a novel topology optimization method that can effectively produce both smooth and slit-shaped magnetic cores.

This study proposes a novel hybrid optimization strategy that integrates parameter and topology optimization through the implementation of a dynamic Gabor filter, an extension of the Gabor filter technique previously applied to synchronous reluctance motors [3]. In this approach, the shape of the magnetic core is determined using a dynamic Gabor filter, while the magnet configuration is optimized through parameter adjustment. The dynamic Gabor filter's variable spatial distribution, adjustable from isotropic to anisotropic, allows for the creation of both

smooth and slit-shaped magnetic cores. The effectiveness of this method is demonstrated by comparing the optimized geometries and performance metrics of IPM motors configured using both the proposed hybrid method and conventional optimization methods, validating the superiority of the dynamic Gabor filter approach.

II. HYBRID OPTIMIZATION METHOD USING DYNAMIC GABOR FILTER

In the proposed hybrid optimization method, the shape of the magnetic core within the design region is derived from the output of the shape function, defined as:

$$f(\mathbf{x}, \mathbf{w}, \boldsymbol{\theta}, \boldsymbol{\lambda}) = \sum_{i=1}^N w_i g(\mathbf{x}, \theta_i, \lambda_i), \quad (1)$$

where $w_i \in [-1, 1]$ and N denote the weighting coefficient and number of dynamic Gabor filters, respectively. The function $g(\mathbf{x}, \theta_i, \lambda_i)$ in (1) is the dynamic Gabor filter defined as:

$$g(\mathbf{x}, \theta_i, \lambda_i) = b_i(\mathbf{x}) \cos \left[\frac{2\pi}{\lambda_i} (X_i \cos \theta_i + Y_i \sin \theta_i) \right], \quad (2)$$

where λ_i , $(X_i, Y_i) = (x - x_i, y - y_i)$, $\mathbf{x}_i \equiv (x_i, y_i)$, and $\theta_i \in [-\pi/2, \pi/2]$ denote the wavelength, dynamic Gabor filter's position vector, center of the normalized Gaussian function $b_i(\mathbf{x})$, and rotation angle, respectively. The material attribute M_e of finite element e within the design region is determined as:

$$M_e = \begin{cases} \text{iron,} & f(\mathbf{x}, \mathbf{w}, \boldsymbol{\theta}, \boldsymbol{\lambda}) \geq 0 \\ \text{air,} & f(\mathbf{x}, \mathbf{w}, \boldsymbol{\theta}, \boldsymbol{\lambda}) < 0 \end{cases} \quad (3)$$

Due to the anisotropic spatial distribution of the dynamic Gabor filter described in (2), various slit-shaped magnetic cores can be achieved, with their widths dependent on the wavelength λ_i . However, if the wavelength is sufficiently large, the dynamic Gabor filter resembles a normalized Gaussian function, resulting in a spatially isotropic distribution and thus a smoother magnetic core shape. Thus, the proposed topology optimization method effectively extends the NGnet method [2].

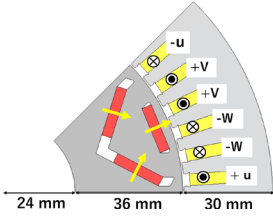


Fig. 1. Reference IPM motor.

Core grade	35A300
Magnetization	1.25 T
Coil turn	10 turn
Rotor radius	60 mm
Stator radius	90 mm

Conversely, the shapes and configurations of the magnets were determined using parameter optimization to enhance manufacturability. In the optimization process, the design variable, $\mathbf{p} = (\mathbf{p}_{\text{mag}}, \mathbf{p}_{\text{Gabor}}, \boldsymbol{\theta}_{\text{ele}})$, is determined using the covariance matrix adaptation evolution strategy (CMA-ES), where $\mathbf{p}_{\text{mag}}$, $\mathbf{p}_{\text{Gabor}}$, and $\boldsymbol{\theta}_{\text{ele}}$ denote the design variables for the magnet shapes, magnetic core topology, and initial electric angles, respectively.

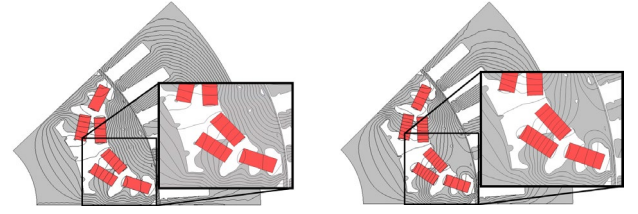
III. OPTIMIZATION RESULTS

Fig. 1 depicts the reference IPM motor featuring a ∇ -type magnet configuration, and Table I provides its specifications. This study addresses the optimization problem aimed at enhancing the torque characteristics of an IPM motor under both low (2,000 r/min, 145 A) and high (10,000 r/min, 90 A) speed conditions, factoring in no-load and load voltage constraints:

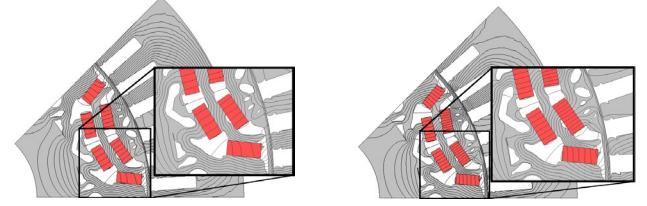
$$\min_{\mathbf{p}} F(\mathbf{p}), \quad F(\mathbf{p}) = \sum_{i=1}^2 \left[-\frac{T_{\text{avg}}^{(i)}(\mathbf{p})}{T_{\text{avg}}^{\text{Ref}(i)}} + 0.2 \frac{T_{\text{rip}}^{(i)}(\mathbf{p})}{T_{\text{rip}}^{\text{Ref}(i)}} \right], \quad (4)$$

sub. to $V_{\text{No_Load}}(\mathbf{p}) \leq 700 \text{ V}$, $V_{\text{Load}}(\mathbf{p}) \leq 650 \text{ V}$,

where $T_{\text{avg}}^{(i)}(\mathbf{p})$, $T_{\text{rip}}^{(i)}(\mathbf{p})$, $T_{\text{avg}}^{\text{Ref}(i)}$, and $T_{\text{rip}}^{\text{Ref}(i)}$ denote the average torque and torque ripple of the optimized and reference IPM motors under each speed condition, respectively. The outcomes of the optimization using the NGnet method [2] and the dynamic Gabor filter are depicted in Figs. 2 and 3, respectively, while the torque components and resultant characteristics are displayed in Fig. 4 and Table II. Both optimized IPM motors demonstrated improved torque performance compared to the reference model. However, under low-speed condition, the average torque of the IPM motor optimized with the dynamic Gabor filter is less than that achieved using the NGnet method. The optimized rotor shown in Fig. 2 incorporates flux barriers aligned with the magnetization direction of the permanent magnets, which reduces the magnetic flux interlinkage at the stator coils, thereby meeting the voltage constraints. However, this rotor configuration poses challenges in meeting manufacturing and mechanical constraints due to the excessively thin magnetic core supporting the permanent magnets. Although it is possible to modify the magnetic core shape depicted in Fig. 2, enhancing the mechanical properties without compromising the magnetic performance remains difficult. Conversely, the rotor depicted in Fig. 3 features a multilayered magnetic core and magnet configuration that approximates a fabricable double-V shape [1]. Notably, the slit-shapes near the rotor surface effectively reduce the spatial harmonics of the magnetic flux across the air gap, thus



(a) Low speed (b) High speed
Fig. 2. IPM motor optimized using the NGnet method.



(a) Low speed (b) High speed
Fig. 3. IPM motor optimized with the dynamic Gabor filter.

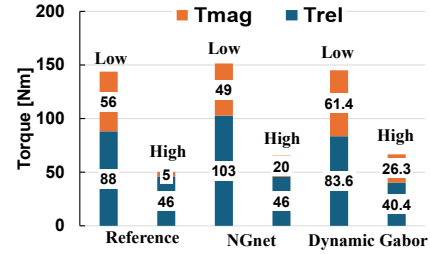


Fig. 4. Torque components of the reference and optimized IPM motors.

	Reference		NGnet		Dynamic Gabor	
Driving point	Low	High	Low	High	Low	High
T_{avg} [Nm]	143.7	50.3	151.3	65.5	145.0	66.7
T_{rip} [%]	14.4	48.7	8.2	11.0	2.6	8.8
V_{Load} [V]	253.1	565.9	252.4	647.2	244.7	647.3
$V_{\text{No_Load}}$ [V]	125.1	623.5	139.4	697.1	139.1	695.5
θ_{ele} [°]	51.0	75.0	47.1	68.7	40.7	65.1
Magnet area [mm ²]	166.8		163.2		163.2	

satisfying the voltage constraints. The effectiveness of the dynamic Gabor filter in representing both slit-shaped and smooth magnetic cores highlights its utility in the proposed hybrid optimization method. Consequently, this approach facilitates the generation of various optimal rotor shapes that conform to the constraints inherent in motor design. Future studies will focus on optimizing the IPM motor within both mechanical and magnetic constraints to determine the advantages of the rotor shapes optimized using the dynamic Gabor filter.

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