Abstract

Integrated Design Optimization Framework for Interior Permanent Magnet Synchronous Motor

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This dissertation proposes a comprehensive and integrated design optimization framework for Interior Permanent Magnet Synchronous Motors (IPMSMs), targeting three major design objectives: torque maximization, manufacturability improvement, and torque ripple reduction under uncertainty. The proposed framework is structured into three sequential phases, each addressing a specific set of design challenges and incorporating tailored modeling and optimization strategies.

In the first phase, a novel topology optimization method is developed to optimize the distribution and magnetization direction of permanent magnets within the rotor. Unlike conventional methods that fix the magnetization direction during optimization, the proposed approach treats the angular magnetization variable as continuous and introduces a discrete set of target angles to which these variables are projected. This is achieved using a multiple Heaviside-based projection scheme that ensures a smooth and differentiable mapping of each angular variable to its nearest target angle. A significant contribution of this phase is the concurrent optimization of the target angle set itself, allowing the optimization process to autonomously determine an effective and manufacturable set of discrete directions. To ensure numerical stability and convergence efficiency, the method incorporates a periodic filtering technique tailored for angular variables and an angular bound relaxation strategy that resolves directional ambiguity at the boundaries of the polar domain. Furthermore, a spatial indicator function is formulated to evaluate angular consistency within individual permanent magnet blocks. This indicator is embedded within a penalization term, encouraging block-wise uniform magnetization and thereby promoting manufacturability in practical motor construction. The proposed method is validated using benchmark and industrial-scale problems, demonstrating its effectiveness in producing discrete magnetization patterns that balance performance and physical realizability.

The second phase focuses on dimensional optimization of the topology-optimized design to refine geometric parameters and ensure robustness across a wider operating range. Although the topology optimization phase yields an optimal material layout, the resulting magnet geometries often include shapes that are difficult or expensive to fabricate. To address this, a CAD-based post-processing step is

performed to adjust the rotor geometry, followed by a parameterized optimization stage to mitigate performance degradation due to these modifications. This phase employs an Equivalent Magnetic Network (EMN) model that captures nonlinear magnetic behavior using an extended Brauer formulation and enables rapid analysis of three-dimensional configurations with significantly reduced computational cost. Analytical sensitivities are derived through an adjoint method and validated against finite-difference results, confirming both the accuracy and efficiency of the proposed sensitivity formulation. The EMN model is used in conjunction with a Sequential Quadratic Programming (SQP) optimizer to perform design updates, and the optimized parameters are further evaluated using high-fidelity FEM simulations. Comparative studies reveal that the EMN-based approach achieves near-identical performance to FEM-based optimization with a fraction of the computational effort, validating its suitability for large-scale motor design problems.

In the third phase, a robust topology optimization (RTO) framework is proposed to minimize torque ripple under current uncertainty, which is a major source of electromagnetic noise and vibration in IPMSMs. Instead of relying on probabilistic modeling or large sample-based simulations, the proposed method employs a non-statistical approach using Chebyshev interval approximation. This enables the approximation of the worst-case torque ripple within a bounded uncertainty region defined by inverter-induced current fluctuations. The current intervals are constructed from actual current profiles generated by Space Vector PWM (SVPWM) in a system-level inverter model, and then transformed into the DQ-axis domain to simplify the uncertainty representation. The robust optimization problem is formulated in a minimax form and solved using a differentiable relaxation of the Chebyshev inclusion function, with sensitivities computed analytically. The RTO framework is validated on a traction motor case study across different inverter switching frequencies, demonstrating that the robust design consistently outperforms deterministic designs by significantly reducing ripple variance while maintaining average torque. In contrast, deterministic designs optimized under ideal current conditions show performance degradation under real operating scenarios, highlighting the necessity and practical value of the proposed robust framework.

In conclusion, the integrated optimization framework developed in this dissertation enables fast, reliable, and manufacturable IPMSM design. By combining advanced topology optimization, analytical modeling, sensitivity-based optimization, and robust design under uncertainty, the framework addresses key limitations of existing methods and demonstrates practical applicability to real-world IPMSM design. The proposed approach contributes to both academic understanding and industrial practice by offering a scalable and flexible solution for next-generation high-performance motor development.