Multi-Objective Optimization of an IPM Machine with Simultaneous Variation of Magnet Geometry and Magnetic Material Properties

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This study presents a multi-objective optimization of an Interior Permanent Magnet (IPM) machine, targeting reduced magnet costs while maintaining or improving output power. The optimization varies magnet geometry and selects from different magnet grades. Machine performance is evaluated by using a Finite Element Method (FEM) model that captures non-linear magnetic behaviour. To reduce computational demands, FEM evaluations are replaced with meta-models during the optimization process. The resulting Pareto front offers a range of cost-effective, high-performance design solutions, with different rotor geometries and permanent magnet grades.

Keywords: Interior Permanent Magnet (IPM) Machine; Meta-modeling; Permanent Magnet Grades

1. Introduction

Interior Permanent Magnet (IPM) machines are widely employed in electric vehicles, mobile applications, and handheld power tools, valued for their efficiency and high power and torque density [1]. Their performance is typically assessed using Key Performance Indicators (KPIs) such as output power, efficiency, cost, and mass [2]. The primary objective of this research was to develop a methodology that integrates material cost (for individual components or the entire machine) as an optimization objective, alongside output power. This study presents an example of reducing magnet cost (specifically focusing on current magnet prices) while simultaneously maintaining or improving output power. Multi-Objective Optimization (MOO) is required to obtain optimal machine designs based on the two specified KPIs. To achieve a significant magnet cost reduction, the optimization search space focused on the permanent magnets. The magnet geometry was varied alongside a discrete selection of different permanent magnet grades. A similar approach is presented in [3] for different optimization objectives.

2. Theoretical Background

The validated reference electrical machine in this study is an IPM machine with six slots, four poles, a Δ-connection, concentrated winding, and tangential-oriented interior magnets. To evaluate the output power of the machine, state-of-the-art Finite Element Method (FEM) models were used. The magnet cost was calculated directly from the parametrized geometry of the IPM machine, where the rotor is presented in Fig. 1.

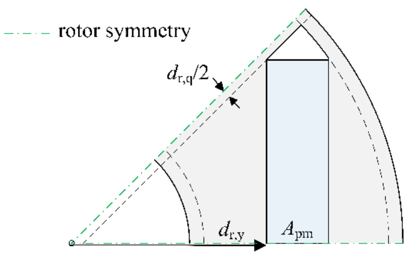

Figure 1: The IPM machine's rotor geometry was parametrized with three design variables to enable variation of the magnet layout.

The geometry variation focused on modifying the magnet layout within a rotor of fixed inner and outer radius, placed inside a stator with fixed geometry. The permanent magnet design was adjusted by using three design variables: the distance of the permanent magnet from the center of the rotor shaft $d_{\mathrm{r,y}}$, q-axis bridge width $d_{\mathrm{r,q}}$ and the permanent magnet cross-section A_{pm}. The MOO considers a range of permanent magnet grades, from high-performance NdFeB to low-cost ferrite magnets. The proposed approach allows for the discrete selection of different magnet materials during optimization. The magnets are modeled in FEM using non-linear $B(H)$ curves, including the knee of the demagnetization curve, at the intended operating temperature.

Since FEM evaluations are time-consuming, an Artificial Neural Network (ANN)-based meta-model was employed in the MOO [2]. This meta-model was trained on a significantly smaller FEM-evaluated dataset than would otherwise be required for the direct FEM-based MOO. This approach enabled a time-efficient MOO.

3. Results and discussion

MOO was performed using the trained ANNs to simultaneously maximize power and minimize magnet cost. The optimization produced a Pareto front of optimal solutions, enabling the selection of a design that meets the specified requirements. The full paper will provide a detailed analysis of which magnet grades and magnet geometries lead to the optimal design.

References

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