Automatic Design Optimization of a Permanent Magnet Assisted Synchronous Reluctance Motor with Field Line Shaped Barriers

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This paper presents an automatic and effective optimization design of a Ferrite permanent magnet (PM) assisted synchronous reluctance motor (PMA-SynRM). To maximize the rotor anisotropy and simplify the design degrees of freedom, the reluctance rotor with field line shaped (FLS) barriers is adopted and a convenient rotor parametric model is also considered. Hereafter, an automatic optimization program coupled with Non-dominated Sorting Genetic Algorithm II (NSGA-II) and computationally efficient finite element analysis (CE-FEA) is developed for improving the optimization efficiency. Based on that, the rotor geometry optimization of a PMA-SynRM with FLS barriers is automatically achieved. And the optimal structure with less PM usage could provide better performance in terms of motor torque output, torque ripple and efficiency, relative to the initial design.

Index Terms—Design optimization, Optimization method, Permanent magnet assisted synchronous reluctance motor, Torque ripple

I. INTRODUCTION

Recently, the permanent magnet (PM) assisted synchronous reluctance motors (PMA-SynRMs) have attracted great attention in many cost-sensitive and high-performance fields (e.g., AC variable speed drives and air compressors), due to the higher efficiency, torque density and power factor (PF) relative to induction motors (IMs) and synchronous reluctance motors (SynRMs) [1]-[2]. In addition, a well-designed PMA-SynRM could obtain a comparable performance with lower cost compared with a PM motor, as shown in [2].

Torque ripple is a crucial issue in the design of SynRMs and PMA-SynRMs. In [3], [5], several hand-designed methods are adopted to reduce the torque ripple of SynRMs. But the final rotor structure is not optimal and may degrade the performance of torque production. In [4], based on the optimization algorithm (OA), the rotor geometry optimization of a SynRM is carried out. As for the PMA-SynRM, the design degrees of freedom and difficulty further increase due to the extra PMs.

In this paper, an automatic multi-objective optimization of a PMA-SynRM is carried out. An optimal rotor structure is automatically achieved by adopting the optimization program coupled with CE-FEA and an advanced OA. And the comprehensive performance of the optimal motor is evaluated and compared with an initial design.

II. PARAMETRIC MODEL OF THE ROTOR GEOMETRY

In this paper, the reluctance rotor with a type of field line shaped (FLS) barrier is adopted. As shown in Fig. 1, the barrier edges are aligned to a family of d-axis field lines, fitted by the N.-E. Joukowski airfoil potential function [5]:

\[
\begin{align*}
  r(\theta, C) &= \sqrt{C^2 + 4 \sin^2(p\theta)} - \frac{D_0}{2} \quad 0 < \frac{\theta}{p} < \frac{\pi}{2} \\
  C &= \sin(p\theta) \frac{(2r)^2 - 1}{(D_0)^2} 
\end{align*}
\]

(1)

Where \( r \) is the polar radius, \( \theta \) is the polar angle from the d-axis in polar coordinates, \( p \) is the rotor pole pair number, \( D_0 \) is the rotor inner diameter and \( C \) determines the position of curves in the polar coordinate plane.

Considering the convenience of modeling, a simple rotor parametric model of the PMA-SynRM with multilayered FLS barriers is adopted and the related parameters are also defined in Fig. 1. As shown, there are only 3 essential degrees of freedom (DOFs) to define the shape and position of the FLS barrier per layer. Relative to the common “U” shaped barrier [1] with 4 DOFs per layer, 4 design DOFs will be abandoned by adopting this FLS structure, when the geometry optimization design of a reluctance rotor with 4-layer barriers is considered.

III. MULTI-OBJECTIVE OPTIMIZATION OF THE PMA-SYNRM WITH FLS BARRIERS

A. Optimization Problem Statement

The automatic design optimization of a PMA-SYNRM with 4-layer FLS barriers and cheap ferrites embedded is considered in this section. The initial motor and basic specifications are reported in Fig. 2 and Table I, respectively.

Motor average torque and torque ripple are selected as the optimization objectives. Then, based on the parametric model in Fig. 1, 16 geometry parameters and current phase angle \( \gamma \) are
selected as the optimization variables and the related variation ranges are listed in Table II.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>22 kW</td>
<td></td>
</tr>
<tr>
<td>Rated speed</td>
<td>3000 rpm</td>
<td></td>
</tr>
<tr>
<td>Slot/pole combination</td>
<td>36/4</td>
<td></td>
</tr>
<tr>
<td>Active stack length</td>
<td>80 mm</td>
<td></td>
</tr>
<tr>
<td>Stator outer diameter</td>
<td>260 mm</td>
<td></td>
</tr>
<tr>
<td>Airgap thickness</td>
<td>0.7 mm</td>
<td></td>
</tr>
<tr>
<td>PM Residual</td>
<td>0.4 T</td>
<td></td>
</tr>
<tr>
<td>flux density @ 20°C</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE II**

<table>
<thead>
<tr>
<th>Item</th>
<th>Variation Range</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrier layer (n_m)</td>
<td>1st 2nd 3rd 4th</td>
<td>--</td>
</tr>
<tr>
<td>Barrier thickness (h_b)</td>
<td>(2, 4)</td>
<td>(3, 7)</td>
</tr>
<tr>
<td>Barrier angle (α_m)</td>
<td>(15, 35)</td>
<td></td>
</tr>
<tr>
<td>Offset coefficient (d_r)</td>
<td>(0, 1)</td>
<td>(0, 1)</td>
</tr>
<tr>
<td>PM width (w_p)</td>
<td>(10, 35)</td>
<td>(30, 65)</td>
</tr>
<tr>
<td>Current angle (γ)</td>
<td>(50, 60)</td>
<td>deg</td>
</tr>
</tbody>
</table>

**B. Optimization Program with NSGA-II and Related Results**

To fix the multi-objective optimization problem mentioned above, an automatic design optimization program coupled with CE-FEA and Non-dominated Sorting Genetic Algorithm II (NSGA-II) [6] is developed and applied. Based on that, a randomly generated initial population with size of 50 is evolved over 60 generations, namely, 3000 candidates are evaluated to search a set of pareto optimal solutions (POSS).

The optimization time only takes about 9 hours. Related results are reported in Fig. 3. The individuals present a good diversity and converge to a bounded region instead of a certain threshold due to the inherent advantage of NSGA-II. And there is a clear conflict between average torque and torque ripple. Hence, a compromise on motor cost and performance is made among the 15 POSSs in Fig. 3(b). Finally, the optimal motor geometry is determined as shown in Fig. 4.

**C. Performance Investigation of the Optimal Motor**

A comparative study of the initial and optimal design is considered for a visualized performance investigation.

In no-load condition, the waveform of the back-EMFs of two designs are similar as shown in Fig. 5. Then, the average torque versus current phase angle curves of two designs are shown in Fig. 6(a). The optimal motor shows a higher torque average and a much lower torque ripple in the maximum torque per ampere (MTPA) condition, as in Fig. 6(b).

The comparison of the detailed performance is shown in Table III. There are significant advantages in PM usage, average torque and torque ripple after optimization. In addition, the PF of the final structure can reach 0.85, which is much higher than conventional IMs.

**IV. CONCLUSION**

In this paper, the design optimization of a PMA-SynRM with 4-layer FLS barriers is carried out by adopting an optimization program coupled with CE-FEA and NSGA-II. The final optimal structure can boost larger torque output with less ferrite PMs, the torque ripple is limited as 2.96% and the PF could reach 0.85 relative to the initial one. Furthermore, it is possible to get a better performance by embedding PMs in both sides of the FLS barriers.

**REFERENCES**


