Automated Design of Rotor Topology for Synchronous Reluctance Machines considering Motor Control Strategies

M. H. Mohammadi, M. Li, R. C. P. Silva and D. A. Lowther

McGill University, Department of Electrical and Computer Engineering, Montreal, QC, Canada

This paper presents an automated method of finding optimal rotor topologies of a synchronous reluctance machine for different objectives. A topology optimization was performed with an evolutionary algorithm coupled with electromagnetic finite element analysis (FEA). The effect of different objectives and a motor control strategy on the final rotor topology is the focus of the work.

***Index Terms*—AC machines, design optimization, finite element analysis, machine vector control, topology.**

I. INTRODUCTION

IN recent years, synchronous reluctance machines (SynRMs) have gained popularity in both fixed speed (e.g. pumps, fans) and variable speed applications (e.g. electric vehicles using cheap permanent magnets) due to their inexpensive iron lamination structure, robustness and smaller frame size when compared to induction machines [1]. A SynRM produces reluctance torque by means of a magnetically-salient rotor structure within a cylindrical stator. The rotor flux barriers play a vital role in the design optimization of SynRMs, since they force the main flux through desired iron paths within a fixed stator geometry [2].

Depending on the desired performance, whether it is high average torque or low torque ripple, different flux barrier geometries, shapes or topologies may be required. For designing an electric motor, there are various topologies from which one of them should be chosen based on the required specification during the conceptual design phase. Next, the relevant geometries are varied and possibly shaped to help improve the final solution in the detailed design stage. Hence, it is initially unknown which flux barrier topology is useful for further improvement of a SynRM design. Thus, solving this problem calls for a topology optimization as described in [3] and [4]. This may not necessarily yield the optimal rotor design, but would provide valuable information about the appropriate flux barrier topology. Previous work in [5] tackled a similar problem by analyzing the barrier shapes and the rotor geometry leading to a high torque-to-volume ratio. Also, the barrier shapes could be impacted by the optimization formulation [3].

For example, Sato et al. found significant changes in the final SynRM rotor designs in [3] for various objectives in their topology optimization problem (i.e. different flux barrier shapes). These conflicting objectives included maximizing average torque, minimizing iron loss with an average torque constraint, and maximizing average torque with an iron loss constraint. Nevertheless, two main issues were neglected. First, the torque ripple needs to be minimized in most applications. Second, the control strategy impacts the typical motoring operation and must be considered in the conceptual design stage as explained later in Section II.

Therefore, this paper proposes an automated method for finding optimal rotor topologies of SynRMs for different objectives while, simultaneously, incorporating a motor control strategy in the problem formulation. The results suggest suitable barrier shapes for the actual rotor optimization.

II. PROBLEM SETUP

To begin with, the Maximum-Torque-Per-Ampere (MTPA) control strategy maximizes the average torque, T_{avg}, (below base speed operation while the current magnitude is fixed) in a quasi-quadratic relationship against the current advance angle, γ, as discussed in [7]. By allowing γ to vary, the peak average torque is found by solving the deterministic optimization problem in (1) as shown in [8]. A fixed γ value for different rotor designs may not yield necessarily accurate results when considering the typical operation of the SynRM.

$$\begin{aligned} &\text{max.} \quad T_{avg}(\gamma) \\ &\text{s.t.} \quad\ \ \gamma_l \le \gamma \le \gamma_u \end{aligned} \tag{1}$$

Hence, a single-objective problem is formulated to observe the effect of each objective on the final rotor topology. In this paper, two objectives are considered as shown below: (2) maximizes the average torque, T_{avg}, and (3) minimizes the torque ripple, T_{rip}. Each objective is a function of γ_{MTPA} and the rotor discretization variable, $\boldsymbol{x}$, which must belong to the set of feasible designs, $\mathcal{F}$. The benefit of using this approach is explored in [8] which accurately emulates the MTPA control strategy. Although the full paper will incorporate the strategy shown in (2) and (3), the value of γ_{MTPA} is fixed to 50° for the digest's feasibility study to obtain the preliminary results.

$$\begin{aligned} &\max_{\boldsymbol{x}} \left(T_{avg}(\boldsymbol{x}, \gamma_{\text{MTPA}})\right) \\ &\text{s.t.} \quad \gamma_{\text{MTPA}} = \operatorname*{argmax}_{\gamma} \left(T_{avg}(\boldsymbol{x}, \gamma)\right) \\ &\qquad\ \ \boldsymbol{x} \in \mathcal{F} \end{aligned} \tag{2}$$

$$\begin{aligned} &\min_{\boldsymbol{x}} \left(T_{rip}(\boldsymbol{x}, \gamma_{\text{MTPA}})\right) \\ &\text{s.t.} \quad \gamma_{\text{MTPA}} = \operatorname*{argmax}_{\gamma} \left(T_{avg}(\boldsymbol{x}, \gamma)\right) \\ &\qquad\ \ T_{avg} \ge 0.6 \text{ Nm} \\ &\qquad\ \ \boldsymbol{x} \in \mathcal{F} \end{aligned} \tag{3}$$

The considered motor model is a SynRM with the fixed parameters shown in Table I. Its cross-section and discretization can be seen later in Fig. 1. For the presented results, a radial mesh of a 6×10 grid is employed since it is compatible with an existing design of the SynRM. To ensure feasibility, the SynRM's flux barriers are both constrained inside the rotor. In short, the sum of all flux carrier and barrier widths are limited to ensure that two adjacent poles do not intersect [2], [7].

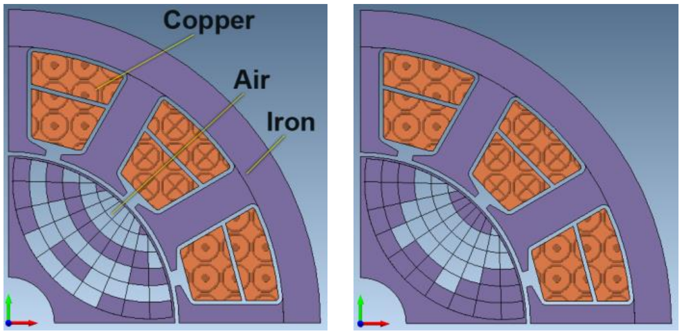
TABLE I
FIXED SYNRM DESIGN PARAMETERS

Fixed Parameters	Value	Fixed Parameters	Value
Number of stator slots	12	Number of poles	4
Stator outer diameter	75 mm	Airgap thickness	0.5 mm
Rotor outer diameter	40 mm	Stack length	34 mm
Rotor inner diameter	11 mm	RMS current density	10 A/mm^2
Core material	M-19 29 Ga	Barrier material	Air

The instantaneous torque waveform, T, is computed for a fixed sinusoidal current excitation using transient 2D FEA simulations, which benefit from 4-pole and 3-phase periodicities to reduce computation time. Then, T_{rip} and T_{avg} are post-processed using an approach like that described in [2].

III. RESULTS & DISCUSSION

Upon solving (2) and (3) using ant colony optimization [6] with 30 ants and 100 cycles for a fixed γ, the final SynRM rotor topologies were found as shown in Fig. 1 (a) and (b) respectively. The iron, air and copper materials are indicated in Fig. 1 (a). Also, Fig. 2 below shows the instantaneous torque waveforms of both solutions.



(a) (b)

Fig. 1. SynRM final cross-sections: (a) max(T_{avg}), (b) min(T_{rip}).

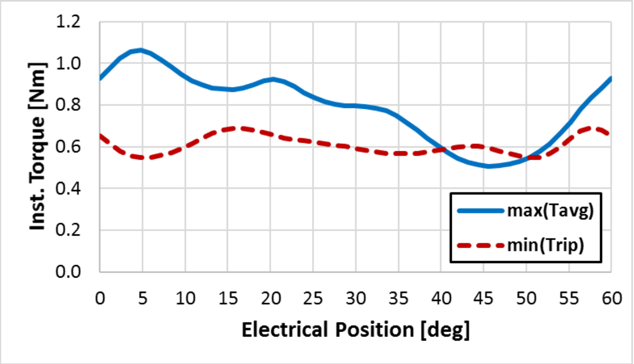


Fig. 2. Instantaneous torque waveforms for the SynRM designs in Fig. 1.

For the T_{avg} maximization problem in (2), the final solution converged to a 2-barrier topology (performance: **0.79 Nm, 68%**). Note that the small 2-cell iron island surrounded by air of the innermost flux carrier may either be due to the absence of a structural constraint in (2) or a tendency towards a 3-barrier design with a higher average torque. Also, this result illustrates the advantage of using 2-barrier topologies with a round-shaped barrier. Mohammadi et al. showed in [7] that for this specific SynRM problem, the peak T_{avg} values possible for the 1, 2 and 3-barrier topologies are roughly 0.72, 0.86 and 0.87 Nm respectively. This result from [7] and the similar topology in [3] indicate the clear advantage of using more flux barriers for high T_{avg} designs.

Furthermore, the T_{rip} minimization problem in (3) resulted in a 1-barrier topology (performance: **0.61 Nm, 23%**) which no longer resembles a clear round shape. Since the minimum T_{rip} attainable in [7] for the 1, 2 and 3-barrier topologies were found to be about 38%, 16% and 13% respectively, this means that the 23% torque ripple in Fig. 2 (b) may have resulted from another topology, e.g. a hybrid of trapezoidal and round-shaped flux barriers. It is important to highlight that incorporating a control strategy, i.e. the inner loop of (2) or (3), in the optimization formulation would most likely impact the final solution found as discussed in [7].

Hence, a further study is needed to validate both solutions by testing other discretizations. Also, this highlights a benefit of using topology optimization which can generate innovative designs without being limited by the initial shape and geometrical parameterization.

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