Effect of Acoustic Noise on Optimal SynRM Design Regions

M. H. Mohammadi\textsuperscript{1}, T. Rahman\textsuperscript{1}, R. C. P. Silva\textsuperscript{1}, B. Wang\textsuperscript{1}, K. Chang\textsuperscript{2} and D. A. Lowther\textsuperscript{1}

\textsuperscript{1} Department of Electrical and Computer Engineering, McGill University, Montreal, Canada
\textsuperscript{2} Infolytica Corporation, Montreal, Canada

This paper investigates the design optimization of synchronous reluctance machines (SynRMs) in a multi-physics scenario. Using electromagnetic and structural finite element analysis (FEA) simulations, the average torque, torque ripple and loudness objectives are computed. In this digest, these three objectives are shown to be in conflict with each other, thereby resulting in a multi-objective problem. While the 33-slot 8-pole stator configuration is fixed, the SynRM’s rotor is geometrically varied for different topologies, i.e. different numbers of flux barriers, for extracting optimal design regions which will be provided in the full paper.

\textbf{Index Terms}— AC machines, acoustic noise, design optimization, finite element analysis, torque.

I. INTRODUCTION

R\textit{ecently}, the design of synchronous reluctance machines (SynRMs) has attracted significant research and development due to their low material cost, robustness and high torque-to-volume ratio for fixed speed applications. However, an important point of concern for SynRMs remains, since their rotor design is not a simple task. Selecting the right topology and geometry (i.e. barrier configuration and dimensions) has a major influence on a motor’s performance, whether it is electromagnetic, acoustic or thermal.

In previous works [1], [2], [3], optimal design regions were extracted using the electromagnetic performance of two SynRM models: a 33-slot 8-pole and a 12-slot 4-pole. It was demonstrated in [2] and [3] that different topologies for a round-shaped barrier are interrelated based on the optimal values of average torque, $T_{\text{avg}}$, and torque ripple, $T_{\text{rip}}$. Nevertheless, these findings do not account for multi-physics aspects. For instance, would adding an extra objective, e.g. loudness, $L_w$, significantly impact the SynRM’s optimization’s outcome, such as the location and size of the optimal design region?

Therefore, this paper extends the design optimization of SynRMs by solving the multi-objective problem in (1) using three objectives, $T_{\text{avg}}$, $T_{\text{rip}}$ and $L_w$. Both electromagnetic and structural finite element analysis (FEA) simulations are used for the objective computations of a 33-slot 8-pole SynRM as in [2] and [4]. Only the SynRM’s rotor is geometrically varied for different topologies, i.e. different number of flux barriers, $n_b$, to extract optimal design regions which will be provided in the full paper. Here, $x$ corresponds to a design variable vector and $\mathcal{F}_x$ denotes the feasibility triangle or design space.

\begin{equation}
\min_x (-T_{\text{avg}}, T_{\text{rip}}, L_w), \quad \text{s.t. } x \in \mathcal{F}_x
\end{equation}

II. LOUDNESS CALCULATION AND SYNRM ROTOR GEOMETRY

Following [5], [6], the loudness of an electric machine is calculated using the amplitude of its stator vibrations. The stator is displaced by forces arising from the air gap pressure waves. The normal pressure wave component, $P_n$, at any angle, $\theta$, along the air gap is calculated from the Maxwell stress tensor [5] and is given by (2). Here, $F_n$ is the normal force on the stator tooth, $L_{\text{stk}}$ is the stack length, $w_s$ is the tooth width, $B_n$ is the normal air gap flux density and $\mu_0$ is the permeability of free space.

\begin{equation}
P_n(\theta) \approx \frac{F_n(\theta)}{w_s L_{\text{stk}}} = \frac{B_n^2(\theta)}{2\mu_0} \quad (2)
\end{equation}

Note that tangential forces do not contribute significantly to the acoustic noise, since the teeth are constrained sideways. Due to the force’s $i^{th}$ harmonic on the $m^{th}$ vibration mode, the stator’s displacement, $A_{mr}$ is given by (3) as in [6]. Here, $F_{mr}$ is the $i^{th}$ force amplitude, $f_m$ is the $i^{th}$ harmonic frequency, $f_m$ is the $m^{th}$ mode of natural vibration, $M$ is the stator mass (core and winding) and $\zeta_m$ is the $m^{th}$ harmonic of the damping factor.

\begin{equation}
A_{mr} = \frac{F_{mr}/[(2\pi f_m)^2 M]}{\sqrt{[1 - (f_m/f_r)^2]^2 + [2\zeta_m (f_m/f_r)]^2}} \quad (3)
\end{equation}

The sound pressure level, $SPL$, on the surrounding air is computed using (4), where $\rho_0$ is the air density, $c_0$ is the speed of sound, and $n_p$ is the number of poles. Then, the loudness value in dB, $L_w$, is calculated in (5) using $SPL$ and $SPL_{\text{ref}} \approx 10^{-5}$ Pa.

\begin{equation}
SPL = 2\pi \rho_0 c_0 n_p \sum A_{mr} \quad (4)
\end{equation}

\begin{equation}
L_w = 10 \log_{10} \left(\frac{SPL}{SPL_{\text{ref}}} \right) \quad (5)
\end{equation}

Fig. 1 (a) illustrates an example of a single-barrier SynRM’s cross-section with the labelled rotor variable widths: the flux carrier’s, $W_c$, and the flux barrier’s, $W_b$. The rotor barrier dimensions and the number of barriers, $n_b$, were varied to generate datasets of SynRM models for which $T_{\text{avg}}$, $T_{\text{rip}}$ and $L_w$ were calculated. For example, using a full factorial sampling for 90 designs across the single-barrier design space, $(W_c, W_b)$, the response surfaces of $T_{\text{avg}}$, $T_{\text{rip}}$ and $L_w$ are then plotted in Fig. 1 (b), (c) and (d) respectively. It can be seen that $L_w$ conflicts with both the $T_{\text{avg}}$ and $T_{\text{rip}}$ objectives. That is, the location of maximum $T_{\text{avg}}$ in the $(W_c, W_b)$ design space does not correspond to the minimum $L_w$ location. Therefore, the suggestions proposed in [2] for restricting the design space do not hold when dealing with multi-physics problems including acoustic noise.
that for all combinations, the conflict levels are generally high and more than 50%. Only the \((L_w, T_{rip})\) pair’s conflict decreases for higher \(n_b\) values. Nevertheless, these results indicate that the multi-objective problem in (1) is meaningful and it will be solved and analyzed in the paper’s full version. This also means that the optimal design region using only \((T_{avg}, T_{rip})\) described in [2] and [3] will be impacted.

**TABLE I**

<table>
<thead>
<tr>
<th>(n_b)</th>
<th>(T_{avg, T_{rip}})</th>
<th>(T_{avg, L_w})</th>
<th>(T_{rip, L_w})</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>52.4%</td>
<td>65.6%</td>
<td>67.8%</td>
</tr>
<tr>
<td>2</td>
<td>65.6%</td>
<td>62.8%</td>
<td>46.0%</td>
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<tr>
<td>3</td>
<td>68.7%</td>
<td>65.6%</td>
<td>34.2%</td>
</tr>
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**REFERENCES**


