Multi-objective Optimization for a Dual-Flux-Modulator Coaxial Magnetic Gear with Double-Layer Permanent Magnet Inner Rotor

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In order to improve the torque capability and permanent magnets (PMs) utilization efficiency of the dual-flux-modulator coaxial magnetic gear (DFM-CMG), a double-layer PMs (DLPM) layout on the inner rotor (IR) is proposed. In this paper, the torque performance of the DFM-CMG is investigated by 3-D finite element analysis and validated by corresponding experiment. According to parametric analysis results, it is found that six dimensional design parameters can significantly affect the stall torque (ST) and ST per PM volume (STPPV) of the DFM-CMG. To achieve multi-objective optimization (MOO) of the DFM-CMG given that the ST and STPPV normally conflict with each other, a metamodel-based MOO method is employed under the premise of the constant active region volume. The optimized DFM-CMG with DLPM IR shows a 19.7% and 2.2% growth in the STPPV than the initial design and the optimized counterpart with single-layer PMs IR under the same constraint of the ST. Furthermore, the optimized DFM-CMG with DLPM IR possesses excellent PMs utilization efficiency compared to other typical CMGs.

Index Terms—Dual-flux-modulator coaxial magnetic gear (DFM-CMG), double-layer permanent magnets (PMs) layout, metamodel-based multi-objective optimization (MOO), PMs utilization efficiency, torque capability.

I. INTRODUCTION

Coaxial magnetic gears (CMGs) are promising candidates for power transmission, which could realize non-contact torque and speed operation with the help of flux modulation effect [1]. The CMGs have attracted great attentions in recent years due to the excellent transmission properties of minimum friction loss, low acoustic noise and overloads self-protection. A dual-flux-modulator coaxial magnetic gear (DFM-CMG) was proposed and studied in [2], which showed better torque characteristics comparing to other types of CMG. However, it is still possible to further improve the torque performance of the DFM-CMG by optimization. Besides, it has been proven that the multilayer permanent magnets (PMs) rotor layout has the advantages of lower flux leakage, higher rotor saliency and specific reluctance torque production, comparing to the single-layer PMs (SLPM) rotor [3]. In this paper, a double-layer PMs (DLPM) layout is adopted in the inner rotor (IR) of a DFM-CMG for suppressing the flux leakages and improving the torque performance. In addition, the torque capability of PMs devices exhibits a strong correlation with the consumption of PMs [4]. The PMs usage ratio should be paid more attention for the CMGs, due to the massive consumption of PMs. Therefore, it is very essential to perform the multi-objective optimization (MOO) design for DFM-CMG with DLPM IR aiming to maximize the ST and ST per PM volume (STPPV) simultaneously.

In this study, the 3D finite element (FE) model of the DFM-CMG is developed and validated by corresponding experiment. Furthermore, the effects of the design parameters of PMs and auxiliary flux modulator (AFM) on the ST and STPPV are investigated. Finally, MOO design of DFM-CMG with DLPM IR is implemented by applying a multi-objective method with polynomial regression (PR) metamodels and multi-objective particle swarm optimization (MOPSO) algorithm [7].
would couple the modulated magnetic fields in the two air-gaps, when the corresponding relationship is satisfied [1]
\[ p_{IR} + p_{OR} = N_{m} \]  
A stationary AFM is placed on the outermost layer. In order to achieve the magnetic-gearing effect as the MMR, the following relationship needs to be obeyed,
\[ N_{AFM} = N_{m} \]  
In addition, to enhance the magnetic gearing effect, the pitch angle of the pole-pieces on MMR \( \theta_1 \) and angle difference between the axis of pole piece on AFM and neighboring pole piece on MMR \( \theta_2 \) satisfy [2]
\[ \theta_1 = 2\theta_2 \]  
Then, a FE model of the DFM-CMG is developed and solved by using 3-D Maxwell software.

III. PARAMETRIC ANALYSIS

It has been proved that the torque performance of CMGs may exhibit a strong correlation with several parameters [5]. Eight dimensional parameters, \( t_R, a_p, d_R, \omega_{OR}, L_R, I_t, I_y \) and \( \theta_1 \) are considered as the design parameters to be investigated, as shown in Fig. 3. \( t_1 \) and \( t_2 \) are the outer and inner layer PMs thickness on the IR, respectively, with no gap between the above two layers PMs. \( \alpha_1 \) and \( \alpha_2 \) are the pole arc lengths of the outer and inner layer PMs on the IR, respectively. \( d_{pole} \) is the polar distance of IR. The other unstudied design parameters are kept as the initial design.

A. Effect of the IR PMs Dimensions

In addition, to enhance the magnetic gearing effect, the pitch angle of the pole-pieces on MMR \( \theta_1 \) and angle difference between the axis of pole piece on AFM and neighboring pole piece on MMR \( \theta_2 \) satisfy [2]
\[ \theta_1 = 2\theta_2 \]  
Then, a FE model of the DFM-CMG is developed and solved by using 3-D Maxwell software.

B. Validation of the FE Model

A test rig for the torque performance measurement of the existing conventional DFM-CMG is shown in Fig. 2. The OR of measured DFM-CMG is loaded by a magnetic powder brake, while the IR is rotated by a driving motor. Two torque-speed meters are used to measure the torques and speeds of the two rotors, and the torque-speed signals are collected by a NI data acquisition card USB-6343. Because the accuracy of the FEM simulation results may affect the accuracy of the metamodels directly and further affect reliability of the optimization, it is more reasonable to use the 3D FEM at the expense of calculation time. In order to validate the 3-D FE simulation models of DFM-CMG, the simulation results are compared with the experimental data under the static load. The tested ST on the OR is 190.0 Nm, which is very close to the 3-D FE simulation result of 194.2 Nm. As the relative error between the simulation and experimental results is only 2.21%, the accuracy of the 3D FE model is validated. The trade-off made on the manufacturing and assembling of the DFM-CMG accounts for the tiny discrepancies probably. The same FE modeling method is adopted for the proposed DLPM DFM-CMG in the later sections, and the FE simulation models and results are feasible to be used for further study.
generally first increases, and then decreases with the raise of \( \text{lt}, \alpha_p \) and \( \alpha_R \) due to the magnetic saturation of PMs and steel laminations.

**B. Effect of the OR PMs Dimensions**

The evolution of the ST and STPPV as a function of \( \text{lor} \) and \( \text{wor} \) changing within 12-15 mm and 4-7 mm respectively are shown in Fig. 7, while fixing the other parameters. It can be found from Fig. 7 (a) that ST first rapidly raises and then slightly decreases with the increase of \( \text{wor} \). It is interesting to note from Fig. 7 (b) that as \( \text{wor} \) increases, the STPPV does not monotonously change. It is also found that the STPPV decreases with the growth of \( \text{lor} \). It is because the ST is not very sensitive to the change of \( \text{lor} \), but the usage of PMs obviously rises with the growth of \( \text{lor} \). Hence, it could be concluded that the OR PMs dimensions have an important and complex effect on the STPPV.

**C. Effect of the AFM Dimensions**

Due to the high dimensionality and complexity of the DFM-CMG with two rotors and two flux modulators, it is difficult to optimize the DFM-CMG by using conventional analytical optimization method. The mathematical procedures assisted with metamodels have been widely used in the design of the modern electrical machines [4], in which the coupling of several design parameters would be taken into the account. A metamodel-based MOO method is employed in this study, and the flow chart of the method is shown in Fig. 9. The full factorial design method, which is one of typical design of experiments (DOEs), is adopted to generate 324 sampling points totally due to the advantage of its uniformity.

**IV. MOO DESIGN OF THE DFM-CMGs**

**A. Optimization Method**

The impact of the design parameters of PMs and AFM on torque performance has been explored in section III. However, parametric analysis could not find the global optimal designs. In order to simultaneously maximize the ST and STPPV, the MOO designs for the DFM-CMG with DLPM IR are carried out. Typically, the MOO problem could be formulated as (4), while the unstudied parameters are kept as the initial design.

\[
\begin{align*}
\min & \quad -\text{ST}, -\text{STPPV} \\
\text{s.t.} & \quad 5 \text{ mm} \leq \text{lt} \leq 8 \text{ mm} \\
& \quad 0.8 \leq \alpha_p \leq 1.0 \\
& \quad 0.8 \leq \alpha_R \leq 1.0 \\
& \quad 4 \text{ mm} \leq \text{wor} \leq 7 \text{ mm} \\
& \quad 12 \text{ mm} \leq \text{lor} \leq 15 \text{ mm} \\
& \quad 3^\circ \leq \theta_R \leq 6^\circ
\end{align*}
\]

TABLE II

<table>
<thead>
<tr>
<th>ACCURACIES ASSESSMENT OF THE METAMODELS</th>
<th>RMSE</th>
<th>( R^2 )</th>
<th>MEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST</td>
<td>0.0163</td>
<td>0.9964</td>
<td>0.0318</td>
</tr>
<tr>
<td>STPPV</td>
<td>0.0172</td>
<td>0.9959</td>
<td>0.0339</td>
</tr>
</tbody>
</table>
accurate enough to predict the responses of ST and STPPV. Thus, the metamodels above would be adopted in the following MOO. Finally, the MOPSO is employed to simultaneously maximize the ST and STPPV while keeping the active region volume constant.

B. Optimization Results

The MOO for both conventional and novel DFM-CMGs are implemented. Fig. 10 compares the Pareto fronts for the DFM-CMGs with SLPM and DLPM layout. The STPPV of the optimized point O₂ has a 2.2% growth than that of optimized point O₁ under the same constraint of ST. Compared with the initial design point I, the optimal design O₂ has a 19.7% growth in STPPV on condition of the same ST level. The optimums at right side of point O₁ and O₂, in the black-dotted area as shown in Fig. 10, could simultaneously increase the ST and STPPV comparing to the initial design. The optimization results of dimensional design parameters at the point O₁ and O₂ are listed in Table III. Consequently, the ST and STPPV of the above optimum designs are calculated by FEM. As shown in Table III, it could be found that these errors between the FE simulation results and the optimization results obtained by metamodels are lower than 0.05%, indicating the effectiveness of the metamodel-based MOO method. According to various design requirements, a set of optimal designs could be picked up from Pareto fronts shown in Fig. 10 (a). Furthermore, it is also found that the green Pareto fronts as shown in Fig. 10(a) all locate to the top right of those red solutions, indicating that the DLPM IR layout could present better Pareto fronts than the SLPM counterparts. Therefore, it is proved that the DFM-CMG with DLPM layout on the IR could improve the ST and STPPV simultaneously.

In addition, according to the study in [6], Fig. 10 (b) compares the STPPV calculated by FEM of the DFM-CMGs and that of other typical CMGs. It could be seen that the DFM-CMGs are superior in terms of the STPPV as well as torque capability among four types of typical CMGs. Moreover, it is worth noting that the DFM-CMG with DLPM IR studied in this paper has the highest STPPV, up to 608 Nm/L, which is much higher compared with that of other typical CMGs. As a result, the DFM-CMG with DLPM IR layout is believed to be a promising power transmission device in future industrial applications as it possesses the best PMs usage ratio and torque capability.

V. CONCLUSIONS

In this paper, a DFM-CMG with DLPM IR is proposed, and the torque performance of the DFM-CMG is investigated by FEM. According to the parametric analysis, six dimensional parameters of the DFM-CMG are found to have significant effects on the ST and STPPV. The metamodel-based MOO method is employed to maximize the ST and STPPV simultaneously. The optimized DFM-CMG with DLPM IR shows a 19.7% and 2.2% growth in the STPPV than the existing initial design and the optimized counterpart with SLPM IR under the same constraint of the ST, which demonstrates that the proposed optimization approach can significantly improve the torque performance of DFM-CMGs. Furthermore, it could be found that the PMs usage ratio of novel DFM-CMG with DLPM IR is much higher than other typical CMGs. As a result, the DFM-CMG with DLPM IR would be a potential power transmission device in future industrial applications.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China (Grant No. 51877074) and the Natural Science Foundation of Hunan Province, China (Grant No. 2020JJ2005).

REFERENCES