Derivation of Optimal Rotor Topologies for Consequent-Pole PMSM by ON/OFF Method

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Abstract—Consequent-pole permanent magnet synchronous machines (CP-PMSMs) have attracted considerable interest as a means of reducing manufacturing costs through a marked reduction in the volume of permanent magnet required to meet a particular torque specification. In this paper, novel rotor topologies for a CP-PMSM are derived to unlock the full design space potential. The ON/OFF method is introduced to manage the laminated steel material distribution over the rotor region, high average torque and low torque ripple are the objects of rotor design, and the immune algorithm is used to search for the optimal material distribution for the formulated problem. More than 9000 different rotor topologies are created and evaluated within 12 hours by this methodology. The optimal topologies under different design strategy are presented, and performance of these topologies are analyzed. The analysis results show that the proposed methodology can deliver novel rotor topologies for the CP-PMSM with surprising torque quality since the torque ripple is suppressed to a low level with no average torque sacrifice.

Index Terms—Consequent-pole, Immune algorithm, Permanent magnet synchronous machines, Topology optimization.

I. INTRODUCTION

In order to meet the on-going demand of energy saving and emission reduction across several related sectors, electrical machines, especially permanent magnet (PM) machines, have been applied to myriad industrial applications because they can combine competitive torque density with high efficiency. However, due to the processing of rare earth PMs will produce a large amount of greenhouse gases and the supply of rare earth in some countries is limited, the conventional topologies, e.g., surface mounted PM (SPM) machines and interior PM (IPM) machines, rely on comparatively large quantities of PM material is becoming an issue. Therefore, many less or no PM machines have been developed in the past several years. Although the developed PM-saving machines such as hybrid excitation PM machines, switched reluctance machines and synchronous reluctance machines can reduce the consumption of PMs, they still suffer from poor torque density or efficiency.

Introducing the consequent-pole (CP) structure to PM machines is an attractive option. The CP structure is firstly proposed to improve the flux adjusted capability of the hybrid-excited machines [1]-[3], and to enhance the suspension force of the bearing less PM machine [4]-[6]. The CP structure has been reported in the transverse flux machine [7], flux reversal machine [8], flux switching machine [9], vernier machine [10], spoke-array PM machine [11], coaxial magnetic gear [12], and so on. Among the wide category of CP machines, the surface-mounted consequent-pole permanent magnet synchronous machines (CP-PMSMs) have been extensively studied to reduce the PM consumption [13]-[26]. It has been demonstrated in [13] that approximately 33% reducing in the volume of PM can be realized for CP-PMSM while maintaining similar output torque as its conventional SPM machine counterpart. [14] pointed out that although the output torque of a representative CP-PMSM is decreased by 8% compared to a SPM counterpart, the torque per unit PM volume is improved by 38%. Given their promise and in particular the scope for marked reductions in the volume of PM required to meet a given torque specification, CP-PMSMs have been used, inter-alia, in traction applications [19], electric vehicles [20]-[21]. However, CP-PMSMs tend to result in large torque ripple caused by the unbalanced flux distributions in the air-gap, which in turn can give rise to problems with noise and vibration. To cope with this issue, many methods have been investigated to enhance CP-PMSM’s torque property, such as nonuniform air-gap [20], dovetailed rotor [22], staggered rotors [23], four-layer winding [24], and modular rotors with same number of north and south PMs [25]-[26].

Despite these previous investigations into CP-PMSM’s torque property enhancement, the fundamentally different natures of PM and laminated steel are not meaningfully taken into account. The flux density under the PM pole is governed largely by the magnetic potential of PMs, while under the salient iron pole it is mainly governed by the topology of the rotor core. Predictably, the rotor core can be processed into different topologies for considerable performance dividends. Therefore, design the rotor core in the CP-PMSM by topology optimization-based approach seems to be very promising. According to the knowledge of authors, the relevant studies have not up to now been reported.
This paper aims to explore optimal rotor topologies in a CP-PMSM by topology optimization-based approach. The machine is modelled by finite element (FE) method and Delaunay triangulation, ON/OFF method is used to manage the distribution of laminated steel material over the rotor region. High average torque and low torque ripple are the optimization objects, and the immune algorithm (IA) is used to search for the optimal material distribution for the formulated problem. This paper is more application-oriented to discover the undeveloped design potential of the CP-PMSM by the topology optimization approach. Nevertheless, different from the published topology optimization studies, which adopt rectangle cells to constitute the optimization model. In this paper, the Delaunay algorithm-based FE meshes are directly used as the cells to present the optimization model, this makes the proposed methodology a general technique for the optimal material distribution design and can be directly integrated into commercial FE analysis software.

This paper is organized as follows. In section II, the configuration and working principle of CP-PMSM are explained by simplified flux paths. In section III, the numerical methodology used for topological evolution and simulation are elaborated, focusing on how the ON/OFF method and IA coupling work to deliver the optimal rotors. In section IV, the design region is presented and clearly identified, the settings in modeling and simulation are also encompassed. In section V, the optimal rotor searching is performed, optimal CP-PMSMs under two different design strategies are presented. In section VI, the electromagnetic performances of the two CP-PMSMs with the optimal rotor core, including open-circuit flux distribution, cogging torque, average torque, and torque ripple are investigated and compared to that of the conventional CP-PMSM and SPM-PMSM. Finally, section VII gives the main conclusions.

II. STRUCTURE AND OPERATION PRINCIPLE OF CP-PMSMS

Fig.1 depicts the cross-sections of the SPM-PMSM and the counterpart CP-PMSM with conventional rotor topology. Specification of the CP-PMSM is based on a benchmark machine from IEEJ [27]. Detailed specification can be found in Table I. Compared with the SPM-PMSM, all the S poles in the in the CP-PMSM are replaced by laminated steel poles.

To explain the working principle of CP machines, simplified flux paths under one pole pair of SPM and CP machines are employed. The analytical models are derived based on the following assumptions:

1) The saturation of the stator and rotor core is neglected.
2) Flux lines are perpendicular to stator and rotor surfaces.
3) The relative recoil permeability of PM is the same as that of the air gap.
4) The flux leakage and the end effect are neglected.
5) The slotting effects are ignored.

Based on the flux paths shown in Fig.2, the flux produced by the PMs in SPM-PMSM $\theta_{SPM}$ and CP-PMSM $\theta_{CP}$ can be expressed as:

$$\theta_{SPM} = \frac{2F_{PM}}{2R_{PM} + 2R_{ag} + R_s + R_r} \quad (1)$$

$$\theta_{CP} = \frac{F_{PM}}{R_{PM} + 2R_{ag}} \quad (2)$$

where $F_{PM}$ denotes magnetomotive force of a PM pole, $R_{PM}$, $R_{ag}$, $R_s$, $R_r$, $R_{ss}$ denote magnetic resistance of PM, air gap, stator laminated steel, rotor laminated steel, steel pole, respectively.

In fact, $R_s$, $R_r$, and $R_{ss}$ can be neglected because the magnetic resistance of air and PMs is much larger than that of laminated steel. Then, (1) (2) can be further simplified as:

$$\theta_{SPM} = \frac{2F_{PM}}{2R_{PM} + 2R_{ag}} \quad (3)$$

$$\theta_{CP} = \frac{F_{PM}}{R_{PM} + 2R_{ag}} \quad (4)$$

By comparing the two expressions, it can be found although magnetomotive force in the magnetic circuit of CP-PMSM is half that of SPM-PMSM due to the missing of half PM pole, magnetic resistance of CP-PMSM is much lower than that of SPM-PMSM because of the missing of PM. Consequently, the flux produced by the PMs will not reduce proportionally with the reduction of PM volume, which means that the PMs will have higher utilization ratio in CP-PMSM. Torque waveforms of the two machines are simulated. As shown in Fig.3, the average torque of SPM machine and CP machine are 3.18 Nm and 2.45 Nm, respectively. The CP machine has higher PM utilization ratio, which is consistent with the previous flux path analysis.

This section gives the basic working principle of CP-PMSMs. The flux paths show that CP-PMSMs can maintain attractive torque density with reduced PM usage. However, for a CP machine, its rotor can guide the flux distribution and influence the performance, which should be investigated and optimized.

It is worth mentioning that the CP machine in Fig.1 (b) is a baseline model without any torque density enhancement design, e.g., extend PM arc [14], adopt dovetail consequent-pole [22]. Considering the aim of this study is the rotor core topology, this machine is directly used as the study object in the later sections.
### TABLE 1

<table>
<thead>
<tr>
<th>Specification of the CP-PMSM for Topology Optimization</th>
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</thead>
<tbody>
<tr>
<td>Number of poles</td>
</tr>
<tr>
<td>Number of slots</td>
</tr>
<tr>
<td>Coils (per teeth)</td>
</tr>
<tr>
<td>Current (R.M.S.)</td>
</tr>
<tr>
<td>Resistance of one phase</td>
</tr>
<tr>
<td>PM remanence</td>
</tr>
<tr>
<td>PM relative permeability</td>
</tr>
<tr>
<td>Split ratio</td>
</tr>
<tr>
<td>Core material</td>
</tr>
<tr>
<td>Laminated length</td>
</tr>
<tr>
<td>Teeth width</td>
</tr>
<tr>
<td>Air-gap length</td>
</tr>
<tr>
<td>Teeth height</td>
</tr>
<tr>
<td>Slot opening width</td>
</tr>
<tr>
<td>Stator diameter</td>
</tr>
<tr>
<td>Slot opening height</td>
</tr>
<tr>
<td>Rotor diameter</td>
</tr>
<tr>
<td>Shaft diameter</td>
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</table>

#### III. NUMERICAL METHODOLOGY

In this section, the numerical methodologies used for searching the optimal rotor topologies of the CP-PMSM are elaborated. The coupling workflow of FE calculation and ON/OFF method is also encompassed.

**A. ON/OFF Method**

Topology optimization (TO) is an inverse problem. In contrast with the forward problem (“Given the structure, find the properties”) it pursues a new paradigm (“Given the desired property, find the structure”). To allows creative and radical design compared to parameter optimization because the shape is free deformed without constraint. TO can be used to find the optimal shape of a device for a certain purpose with little dependence on engineer’s knowledge and experience. In the past few years, growing interest in TO techniques has been shown in the computational electromagnetic community for the design of modern electric devices [28]-[31].

The broad category of TO methods can be generally divided into ON/OFF Method [31]-[36], Density Method [37], Homogenization Method [38], and Level-Set Method [39] - [42]. The underlying modelling method adopted for the former three is generally the FE method, while the latter one is principally performed to model the design region to be optimized. The ON/OFF method is a stochastic algorithm-based TO method. Compared to other TO methods, the ON/OFF method can find clear material boundaries, allows global searching, and can be easily combined with FE method. The ON/OFF has been widely applied thanks to its conceptual and practical simplicity [31]-[36], [43]-[45].

Fig. 4 depicts the basic principle of the ON/OFF method. The ON/OFF uses numerous cells to discretize the design region.

The materials in the cells are optimization variables, a binary state “ON (material)” and “OFF (no material)” is used to represent the material existence in each cell. By using stochastic algorithms to search a greater variety of “ON”/“OFF” binary combinations, the material shape in the design region gradually approaches the optimum in terms of the design targets. For ease of illustration, the “ON”/“OFF” map shown in Fig.4 containing only 56 cells, and all the cells are structured with the same shape. In fact, it should be the design region in Fig.10, which contains 1335 unstructured cells.

**B. Filtering algorithm**

Checkerboard structures are often generated when the ON/OFF method is combined with stochastic algorithms. Fig.5 shows a checkerboard structure. Even the checkerboard structures can meet the established optimization targets, they are non-feasibility topologies from the aspect of engineering realization because of the existence of jagged boundaries and isolated material blocks.

To cope with the checkerboard structures, a filtering algorithm for unstructured cells is proposed, which checks for checkerboard patches throughout the whole TO process. As shown in Fig.5, a surface smoothing process and a floating material removing process are included in the proposed filtering algorithm.

The surface smoothing process performs the following steps to ensure the smoothness of material’s surface:

1. Search and check the neighborhood of each cell.
2. If two or three sides of a cell face toward another state, the state of this cell will be converted to fill the jagged material boundary.
3. Back to Step 1 until no cell can be converted.
The floating material removing process is used to manage the detached material to make sure the topology is manufactural. For example, the rotor core should be a continuum. The floating material removing process is performed after finishing the surface smoothing process, it has the following steps:

1) Check the material connection status of each cell, the connected material cells are considered as a material block.

2) Calculate the area of each material block, list them up from large to small.

3) Keep the biggest material block, convert the others to no material state.

4) Back to Step 1 until only the biggest material block left.

C. **Immune Algorithm**

An algorithm is necessary to search the optimal material distribution presented by the ON/OFF method. The IA is inspired by the clonal selection principle in the mammalian immune system. Compared with the genetic algorithm, a well-known and well-used evolutionary algorithm, IA has the local search capability realized by the affinity maturation. The IA has shown its excellent ability in the TO of electric devices thanks to the satisfactory exploration capability [43]-[45].

In this section, we elaborate how to combine the ON/OFF method with IA for TO. Fig.6 depicts a flowchart of this method. The procedures of ON/OFF method with IA can also be briefly summarized as the following steps.

1) Generate $N$ initial antibodies (topologies).

2) Filtering process: Smoothen surface and eliminate floating material blocks for each antibody (topology) to ensure it can be easily processed.

3) Evaluation and selection: Evaluate the objective function of each antibody (topology), list them up from strong to weak, then weed out $W$ weak antibodies (inferior topologies).

4) Cloning: Generate clones for each antibody (topology). Strong antibodies will be cloned more times to ensure they have more chance for affinity maturation.

5) Affinity maturation: Apply small modifications on each clone.

6) Filtering process: Perform the same process as step 2, so as to ensure the offspring (similar topologies) can be easily processed.

7) Selection: If the strongest offspring (similar topologies) has higher objective function value than its parent, this offspring will take place of its parent for evolution.

8) Add antibodies: Add randomly generated antibodies (shapes) to keep the antibody size $N$ constant.

9) Start next generation: End the evolution of this generation, back to step 2 to start the next generation.

In step 1, the “ON (material)” and “OFF (no material)” binary combinations are randomly generated to obtain an optimal solution that is independent of the initial shape. In step 5, small modifications will be applied to topologies. This operation is called affinity maturation and plays a role of local exploitation. Fig.7 depicts the process of affinity maturation, this node-based evolution operator can gradually find the optimal material distribution by the following steps:

1) Randomly select $C$ nodes from the material boundary.

2) Find the surrounding cells of each selected node.

3) Randomly change the state of the cells surrounding the selected nodes.

In the step 8, the additional randomly generated antibodies play a role of global exploration.

D. **Governing Equation in FE Simulation**

When end effect is not considered, the field distribution in the 2-D model of field weakening of PM motor is governed by:

$$\nabla \times (\nabla \times A) = J + \nabla \times (\nu M)$$

where $A$, $\nu$, $M$, $J$ are magnetic vector potential, reluctivity of material, remanent flux density of PM, and, and current density in three phase single tooth windings, respectively.

For the design regions, the field distribution is governed by:

$$\begin{align*}
\nabla \times (\nu_{\text{air}} \nabla \times A) &= 0 & \text{if the state is "OFF(air)"} \\
\nabla \times (\nu_{\text{iron}} \nabla \times A) &= 0 & \text{if the state is "ON(iron)"}
\end{align*}$$

The iron material is modelled by laminated steel JIS 50A350 (JIS: Japanese Industrial Standard). In the FE calculation, the non-linear reluctivity of laminated steel material is considered, the reluctivity of silicon iron is updated gradually to correct...
magnetic flux density by using Newton-Raphson method. Incomplete Cholesky decomposition conjugate gradient is used as the solver in the Newton-Raphson iterations. The B-H data is graphically shown in Fig.8.

E. Topology Optimization Workflow

The machine is meshed by commercial software an Delaunay triangulation algorithm. The maximum length of the finite element meshes in the rotor domain is 0.6mm. 32608 unstructured first-order meshes, of which 10680 are rotor meshes, are generated to discretize the machine. The node information (including the coordinate and connectivity of each node) is exported from the software in Nastran format. The exported node information is read by an in-house FE program for 2-D non-linear magnetostatic field calculation and TO.

The workflow of ON/OFF method combined with IA for TO can be briefly summarized as follows. The IA creates topologies and gives corresponding material distribution over the design region to the in-house FE analysis program, the FE program solves magnetostatic field, and output the torque waveform of each topology. Then the IA program ranks each topology, creates offspring topologies to start next generation. The looping finish when meeting the finish criterion. Fig.9 depicts the working loop of the TO process.

IV. SETTINGS IN MODELING AND SIMULATION

Rotor topology of the CP-PMSM will be re-designed by the aforementioned numerical techniques. Fig.10 shows the model created by FE method for optimization.

The rotor is the design region, 10680 Delaunay algorithm-based triangular FE meshes in the rotor are directly used as the cells in ON/OFF method. These meshes can freely take the material property of “ON (laminated steel)” or “OFF (air)” during the optimization process. Since the symmetry, a total of 1335 meshes, which belonged to the design region 0-45 degrees and colored by orange, will be managed by the ON/OFF method. The shape of laminated steel over 0-45 degrees will be copied to structure the entire rotor core.

Since the contribution to the overall torque from the reluctance torque is very modest, the torque is simulated by three-phase sinusoidal current whose amplitude is 3 Arms and current advanced angle is 0°. The nodal force method is adopted to calculate the torque. Under this setting, the computational time for evaluating one topology is about 5 seconds using a server with Linux, C++ compiler, and Intel Xeon Gold 6134 CPU.

V. OPTIMIZATION RESULTS

The two optimal design targets, average torque and torque ripple, are normalized to form the objective function:

\[
F = (1 - w) \frac{T_{\text{ave}}}{T_{\text{ave}}^{\text{conv}}} - w \frac{T_{\text{rip}}}{T_{\text{rip}}^{\text{conv}}}
\]

where \(T_{\text{ave}}\) and \(T_{\text{rip}}\) are the average torque and torque ripple (peak-peak value) of the conventional CP-PMSM shown in Fig.2(b). \(T_{\text{ave}}^{\text{conv}}, T_{\text{rip}}^{\text{conv}}\) and \(w\) are average torque, torque ripple, and weighting factor, respectively. A penalty function for average
torque is not used in the objective function since we consider that a little torque sacrifice is acceptable if the ripple can be suppressed to a low level.

The TO is performed considering two optimization strategies (OS) by setting the weighting factors $w$ equals 0.5 and 0.8, respectively. Note that, in the two cases, the algorithm places importance on improving average torque and suppressing torque ripple, respectively. The settings in optimization are summarized in Table II, and the TO is performed over 200 generations as the stop condition. In this setting, the program evaluates more than 9000 topologies and takes about 12 hours.

Transition of the objective function is shown in Fig.11, it seems that 200 generations are enough for this problem because the value of objective function raised fast in the beginning generations and gradually saturated. All the evaluated topologies during the evolution process are graphically summarized in Fig.12 and Fig.13, from which we can observe the IA keeps a good balance between global and local search.

Fig.14 and Fig.15 briefly show the topological evolution under the two OS, from which we can clearly see the affinity mutation operator gradually modifies the topologies, forms better flux paths, and finally delivers the optimal topologies.

The average torque and torque ripple of the optimal CP-PMSM under optimization strategy 1 (CP-PMSM-OS1) and the optimal CP-PMSM under optimization strategy 2 (CP-PMSM-OS2) are 2.47Nm, 0.17Nm, 2.37Nm, 0.12Nm, respectively. Compared with the CP-PMSM with conventional rotor, whose average torque and torque ripple are 2.45 Nm and 1.81 Nm, the average torque of the optimized machines is at the same level because of the equal PM strength, but the torque ripple is significantly suppressed to a surprisingly low level.

Compared with CP-PMSM-OS1, there are larger magnetic barriers on the iron poles in CP-PMSM-OS2. These barriers increase the equivalent air-gap length, reduce the average torque marginally, but seem effectively suppress torque ripple.

The iron pole with multi-tooth structure is obtained under both two strategies. It seems that iron poles with this geometrical feature can improve the torque property of the CPM-PMSM, which will be analyzed in the next section.
VI. ANALYSIS OF THE OPTIMIZED CP-PMSMs

The ON/OFF method with IA shows excellent design capability for the formulated problem because it delivers creative topologies with better torque performance.

In order to investigate the reasons for the improved torque property, the magnetostatic field of the optimal machines under no-load conditions is solved. We post-process the solving results to visualize the magnetic field. The flux lines are visualized by extracting the z-direction component of the magnetic potential of each node in the FE model, the magnetic flux density is obtained by calculating its absolute value in the gravity center of each element.

As shown in Fig. 16, the magnetic flux density distribution under no-load condition of CP-PMSM-OS1 and CP-PMSM-OS2 is draw based on post-processing results. For comparison, the magnetic flux density distribution of the conventional CP-PMSM and the SPM-PMSM is also simulated. By comparing the flux density distribution, we can observe the flux over rotor region and air gap region is re-guided by the

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**TABLE III**

COMPREHENSIVE COMPARISON OF THE OPTIMIZED CP-PMSMs AND THE CONVENTIONAL CP-PMSM

<table>
<thead>
<tr>
<th>Machines</th>
<th>Average torque Value (N·m)</th>
<th>Torque ripple Value (N·m)</th>
<th>Cogging torque Value (N·m)</th>
<th>Rotor mass Variation</th>
<th>Rotary inertia Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Variation</td>
<td>Variation</td>
<td>Variation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional CP-PMSM</td>
<td>2.45 standard</td>
<td>1.81 standard</td>
<td>1.5 standard</td>
<td>standard</td>
<td>standard</td>
</tr>
<tr>
<td>CP-PMSM-OS1</td>
<td>2.47 [+]0.8%</td>
<td>0.17 [-]90.6%</td>
<td>0.12 [-]92%</td>
<td>[-]16%</td>
<td>[-]12%</td>
</tr>
<tr>
<td>CP-PMSM-OS2</td>
<td>2.37 [-]3.3%</td>
<td>0.12 [-]93.4%</td>
<td>0.08 [-]94.7%</td>
<td>[-]28%</td>
<td>[-]24%</td>
</tr>
</tbody>
</table>

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optimized rotors. In addition, more flux lines gather toward the teeth facing the iron pole in the optimized CP-PMSMs. The airgap flux density of CP-PMSM-OS1, CP-PMSM-OS2, conventional CP-PMSM and SPM-PMSM is plotted in Fig.17, from which we can observe how the optimized iron poles modulate the flux.

The cogging torque waveform of CP-PMSM-OS1, CP-PMSM-OS2, and the conventional CP-PMSM is calculated for comparison. The cogging torque of the conventional CP-PMSM is 1.5 Nm, while that of CP-PMSM-OS1 and CP-PMSM-OS2 is 0.12 Nm and 0.08 Nm, respectively. After optimization, the cogging torque is significantly reduced by 92% and 94.7%.

The output torque waveform of CP-PMSM-OS1, CP-PMSM-OS2, and conventional CP-PMSM is summarized in Fig.19. The reluctance torque was simulated and compared in Fig.20, from which we can observe that the contribution from reluctance torque is small.

Structure strength is important for motor design. Since the diameter of the rotor is only 53.5mm, the centrifugal force is very modest in rated speed. Consequently, the stress and displacement will be very small. To discover the structure strength of the optimized rotors, we simulated the Von Mises stress of the optimized rotors at a harsh rotation speed. As shown in Fig.21, when the rotation speed is 30000RPM, the maximum stress on two rotors is 101Mpa and 197Mpa, respectively, which is much smaller than the yield strength of the core material (330Mpa). Considering the actual operating speed, the rotors meet the strength requirement.

A comprehensive comparison of these machines is given in Table III. After optimization, the torque ripple is suppressed by 90.6% with no average torque sacrifice. It can be indicated that the optimized CP-PMSMs can provide smoother torque in all operating conditions since the cogging torque is suppressed to a surprising low level. Meanwhile, the rotor mass of the optimized CP-PMSMs is much lower than that of SPM-PMSM and the conventional CP-PMSM, which can enhance the dynamic response characteristic and improve torque density.
VII. CONCLUSION

This paper has derived optimal rotor topologies and unlocked the full design space potential for the CP-PMSM. The ON/OFF method is introduced to manage the laminated steel material over the rotor region, IA is then used for searching the optimal laminated steel material distribution. Thereby we demonstrated how to combine the ON/OFF method with IA and how to apply this technique efficiently for deriving optimal topologies of this machine. The derived novel rotor topologies with multi-tooth-shaped iron poles can surprisingly suppress the torque ripple to a low level with no average torque sacrifice. In addition, the power density and rotary inertia are also improved.

As the first study that investigates CP-PMSM’s rotor core topology, the aiming of discovering the undeveloped design potential for the CP-PMSM has been completely fulfilled, the most obvious finding to emerge from this study is that the CP-PMSM can provide high-quality torque by adopting carefully designed multi-tooth-shaped iron poles. It has been demonstrated that the proposed method can provide instructions in the initial design phase for the CP-PMSM.

Moreover, the proposed optimal topology derivation methodology is general for the optimal material distribution design in other electric machines and can be directly integrated into commercial FE analysis software, because the Delaunay triangular FE elements are directly used as the cells in ON/OFF method to constitute the optimization model.

Future work can aim at topology optimization considering processability, efficiency, and machine drive.

REFERENCES

Zhen Sun (Student Member, IEEE) was born in Xinyang, China, in 1995. He received the B.E. and M.E. degrees in Electrical Engineering from the Henan Polytechnic University, Jiaozuo, in 2017, and 2020, respectively. From April to October 2019, he had been studied as a visiting student at Muroran Institute of Technology, Muroran, Japan, where he is currently pursuing the Ph.D. degree in Engineering.

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