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Topology Optimization for Skew of SPMSM by using Multi-Step Parallel GA

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Abstract—In this paper, it was proposed to the optimization of skew of SPMSM with 3-dimensional finite element method (3D-FEM). The optimization technique was used multi-step parallel Genetic Algorithm (GA) and the allocation of material assignment method. As a result, in useful computation time, it was able to obtain an optimal skew special shape. And, it was able to reduce the cogging torque of more than 97%.

Keywords—IPMSM, 3D-FEM, Optimization, Skew

I. INTRODUCTION

Skew is one of the effective technique for reducing cogging torque. However, it is not able to correctly analyze by the 2-dimensional finite element method, because the skew has 3-dimensional structure. Furthermore, optimization of 3-dimensional model was hard to practical due to limit of computational time and coding. In this paper, it is proposed to the optimization of skew of SPMSM. The optimization technique is used multi-step parallel GA and the allocation of material assignment method.

II. PROPOSED METHOD

The proposed method process is shown in Fig.1. First, material is assigned to the prepared mesh [1]. Analysis region is divided in the grid pattern. In this method is divided by 10th for permanent magnet region of rotor surface to axial direction, and divided by 16th to radial direction. Thus, it have 2 dimensional matrix of 10 × 16. Because the position of the grid points are not changed, the design variable is not necessary remesh the model. And, for a combination optimization problem 0, 1 bit string 160, it is possible to use GA [2-4]. It is possible to change the shape without remeshing, the proposed method is suitable for shape optimization of three-dimensional model. However, it must be finely divided search area in order to obtain a more detailed solution. To solve this problem, using the multi-step method. It is shown multi-step method in Fig.2. First step is to divide the rough searching region. Then, according to the results obtained, Second step is subdivided.

Moreover, to reduce the calculation time, it is used the parallel computing for GA. It is shown parallel GA flowchart in Fig.3. GA is a probabilistic search algorithm. Therefore, so as not to evaluate the same individual, it is checked whether the evaluated individual. In addition, considering the parallel efficiency of the slave, the master distributes the evaluation individuals to slave [5].
The “Evaluation check” block in Fig. 3 is to prevent re-evaluation. In the population, there are some individuals that are already evaluated in the previous generations because of elitist strategy or result of genetic operations. In order to shortening computing time for main-process, these individuals are skipped the evaluation block.

The “Self mutation” block is one of the genetic operations. In this GA, chromosome coded decimal number can take a value 0-9. Therefore, the initial convergence and falling into local solution is easier to occur than SGA (Simple GA). To maintain the diversity of the population, “Self mutation” is added as new genetic operation. As shown Fig 4, in the self mutation, 1-chromosome is selected at random and calculated the value +1 or -1. This operation uses the characteristic of integer such as decimal number. Its behavior is similar to the local search rather than mutation.

GA has to evaluate and compare two or more mutually independent individuals. Therefore, the “Evaluation” block can be parallelized by distribute individuals to two or more servers, and the computing time is expected to be shortened.

We use the master/slave type GA for parallelization. As shown Fig. 4, there are two scripts: master and slave. The master performs genetic operations and controls the slave as task manager. The slave performs the evaluation of individuals by the 3-D FEM in several remote servers. The master sends the genetic information
of the individual to each slave, and the slave replies the fitness of the individual to the master. Master/slave type GA is simple algorithm, but it is effective method when the computing time becomes long in order to adopt the 3-D FEM for the evaluation.

However, there is a problem in the master/slave type GA when the number of individuals evaluated in a generation is less than the number of slaves. Some slaves don’t work in the parallel processing because the evaluation of 1-individual can be performed by only 1-slave. Therefore, it is necessary for effective parallel processing that to be able to share the evaluation of 1-individual with some slaves. If the evaluate target is not transient such as cogging torque or steady torque, the evaluation target can divide in the time domain. In Fig.5 for example, slave #1 need to evaluate only the range of T1. Thus, the computing time for evaluation of 1-individual can be expected to be shortened to 1/n by evaluating with n-slaves at the same time.

\[ \text{maximize } F_i = \frac{100}{W_i} \]

\[ W_i = W_C \cdot \text{RATE}_C + W_B \cdot (100 - \text{RATE}_B) \] (1)

Where, \( W_C \) and \( W_B \) are weighting function. \( \text{RATE}_C \) and \( \text{RATE}_B \) are following equation.

\[ \text{RATE}_C = \frac{T_{ci}}{T_{ci}}, \quad \text{RATE}_B = \frac{B_i}{B_0} \] (2)

Where, \( T_{ci} \) is peak to peak value of cogging torque of \( i \)-th individual, \( T_{ci} \) is peak to peak value of cogging torque of initial model, \( B_i \) is average value of magnetic flux density of gap of \( i \)-th individual and \( B_0 \) is average value of magnetic flux density of gap of initial model. Equation (1), to explore the individual while maintaining the flux density in the gap in the initial shape, the cogging torque is reduced. Relationship of this trade-off can be adjusted by a weighting function, it is set as \( W_C = 1, W_B = 3 \) in this case.

### III. PARAMETER DESIGN

The objective function is used cogging torque which is obtained by 3 dimensional analysis and magnetic flux density of the gap [6-7]. Cogging torque reduction effect can be expected when it is implemented large skew angle in the skew. However, there is a problem flux linkage that the number decreases. Therefore, it is set as a constraint condition flux density in the gap.

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### IV. ANALYSIS MODEL

The analysis model was using a 3-dimensional model of SPM 3-phase 4-pole 24 slot (Surface Permanent Magnetic) motor. SPM motor has a structure in which pasted a permanent magnet in the rotor surface by Fig.6 (a). The optimization of the 3-dimensional model, was not much practical that from coding limit and the length of the computation time. In this paper, is subjected to a skew in the permanent magnet, to determine such an arrangement to minimize the cogging torque. The motor has a periodic structure. Therefore, it can be analyze as 1/8 model (radial direction 1/4 and axial direction 1/2). Mesh model is shown in Fig.6 (b). Analysis model parameter is shown in Table I.

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V. ANALYSIS RESULTS

The results of optimization shape and cogging torque of 1\textsuperscript{st} step GA is shown in Fig. 6 (a) and (b). As the results, skew shape has been created the 2-stage rotor in the vicinity of 40-60 degrees. Cogging torque was reduced by 94%. And, Steady torque waveform and magnetic flux density of gap of 1\textsuperscript{st} step are shown in Fig. 7 (a) and (b). The results of optimization shape and cogging torque of 2\textsuperscript{nd} step GA is shown in Fig. 8 (a) and (b). There is a difference in the vertical skew angle of the 2\textsuperscript{nd} step than the 1\textsuperscript{st} step model. By skew angle spread, the cogging torque is further reduced. Cogging torque is reduced by about 97% compare to initial model. And, Steady torque waveform and magnetic flux density of gap of 1\textsuperscript{st} step are shown in Fig. 9 (a) and (b). Computation time is about 11 hours in each step.

![Analysis model (SPMSM)](image1)

![Mesh of analysis model](image2)

![1st step optimal shape](image3)

![Cogging torque waveform](image4)

TABLE I
PARAMETER OF ANALYSIS MODEL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of element</td>
<td>133680</td>
</tr>
<tr>
<td>Radius of stator [mm]</td>
<td>50</td>
</tr>
<tr>
<td>Number of node</td>
<td>25058</td>
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<tr>
<td>Radius of rotor [mm]</td>
<td>22</td>
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<tr>
<td>Number of edge</td>
<td>164173</td>
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<tr>
<td>Gap [mm]</td>
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<tr>
<td>Unknown value</td>
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</tr>
<tr>
<td>Thickness [mm]</td>
<td>30</td>
</tr>
<tr>
<td>*Computing time [sec/step]</td>
<td>30.1</td>
</tr>
<tr>
<td>Magnetization [T]</td>
<td>1.0</td>
</tr>
<tr>
<td>Turn of coil [turn/phase]</td>
<td>140</td>
</tr>
<tr>
<td>Magnetization direction</td>
<td>Parallel</td>
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<tr>
<td>Frequency of power source [Hz]</td>
<td>50</td>
</tr>
<tr>
<td>Core material (Rotor and Stator)</td>
<td>M-19 (50H250)</td>
</tr>
<tr>
<td>Current (rms) [A]</td>
<td>3.0</td>
</tr>
</tbody>
</table>

*CPU: Intel Core-i7 (2.93GHz), Memory: 8GB, Compiler: Intel Compiler ver11.1
VI. CONCLUSION

In this paper, it was proposed to the optimization of skew of SPMSM. The optimization technique is used multi-step parallel GA and the allocation of material assignment method. As the results, skew shape had been created the 2-stage rotor in the vicinity of 40-60 degrees. Cogging torque was reduced by 94%. And, there was a difference in the vertical skew angle of the 2nd step than the 1st step model. By skew angle spread, the cogging torque was further reduced. Cogging torque was reduced by about 97% compare to initial model. Computation time was about 11 hours in each step.

REFERENCES

