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Paper

Effect of Cleaning Level on Topology Optimization of Permanent Magnet Synchronous Generator

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We propose a topology optimization method that incorporates the concept of the cluster and cleaning method in a genetic algorithm. This method can be used to design a rotor structure with high output power and low permanent magnet volume from an empty space. In this study, the effect of the level of the cleaning method on the obtained rotor structure is investigated. A permanent magnet synchronous generator is designed using the optimal level of the cleaning method. This generator has higher output power characteristic with low permanent magnet volume than a generator used in Prius, which is a general hybrid vehicle.

Keywords: interior permanent magnet machine, genetic algorithm, topology optimization

1. Introduction

Many optimization methods have been proposed and used in electrical machine design, but many of them start from an initial structure, which is assumed by a designer. We think that it is very important to carry out the topology design from empty state without depending on an existing shape. Several types of topology optimization methods have been proposed, because they have a possibility to obtain an initial conceptual structure. Some of the topology optimization methods were proposed approximately twenty years ago [(1)(2)]. Since then, several papers have been published in this field, for example, Takahashi et al. proposed a topology optimization using ON/OFF method [(3)], Okamoto et al. proposed a genetic algorithm (GA) and design space reduction [(4)], and Sato et al. proposed topology optimization using normalized network [(5)]. The authors also proposed a topology optimization method to optimize the material distribution of electrical machines using the GA [(6)–(8)]. In the method, the concept of the cluster of material and cleaning procedure has been proposed, which can remove small pieces of iron scattered in the air and in the permanent magnet (PM), and remove small structural spots in the iron and in the PM. Therefore, this method is different from normal parameter optimization methods using GA, which design the best shape by changing the parameters from an initial shape.

This paper investigates the effect of the level of cleaning procedure on the obtained rotor structure and its performance. A permanent magnet synchronous generator (PMSG) is designed using the optimal level of the cleaning method. This generator has higher output power characteristic with low permanent magnet volume. The output power and the magnet volume are compared with those of Prius generator.

2. Proposed Topology Optimization

2.1 Design Region and GA Design object is the rotor of a generator used in Prius. The generator characteristics are as follows [(9)]; stator outer diameter is 246 mm, stator inner diameter is 152.7 mm, stator stack length 27 mm, rotor outer diameter is 151.3 mm, inner diameter of rotor lamination is 90 mm, lamination thickness is 0.305 mm, rotor mass is 3.93 kg, stator mass is 8.58 kg, and number of stator slots is 12. The design region is not one 16th but one eighth of the rotor region as shown in Fig. 1(a) because we assume that the rotor shape is asymmetric in one pole region. At the first iteration we will design the distribution of material in 90 cells, which is composed of 10 by 9 parts shown in Fig. 1(b).

In the rotor topology optimization, several materials such as air, iron and PM are set to each cell and the material distribution is optimized, and a cleaning method using the concept of the clusters is used. The GA is one of the optimization process, which simulates the biological evolutionary process. It is possible to optimize the design region from an empty state, and to optimize for various demands according to the fitness function. Therefore, we can optimize not depending on an existing rotor structure. Moreover, the GA has the advantage that consists of a simple algorithm for easier programming. The GA process is shown by the flowchart of Fig. 2, where the portions surrounded by a thick frame are our original optimization process.

The information to be optimized is generally encoded in GA. This code is called chromosome that has a number of genes. In this paper, the number of genes is same as the number of cells, whose content represents the materials in the cell. The materials used for the rotor topology design are air, iron, and permanent magnet magnetized in x-direction, 45 deg.-direction, and r-direction as shown in Fig. 3. These materials are represented as 0, 1, 2, 3, and 4. An example of

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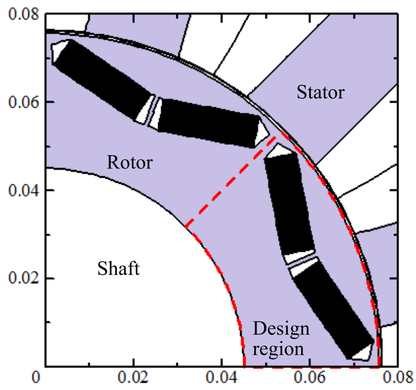
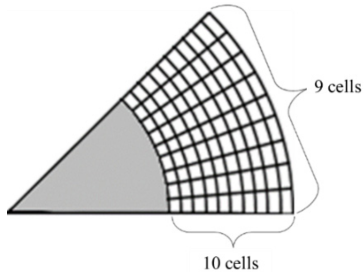


(a) Design region



(b) Design region divided by cell

Fig. 1. Design region and cell

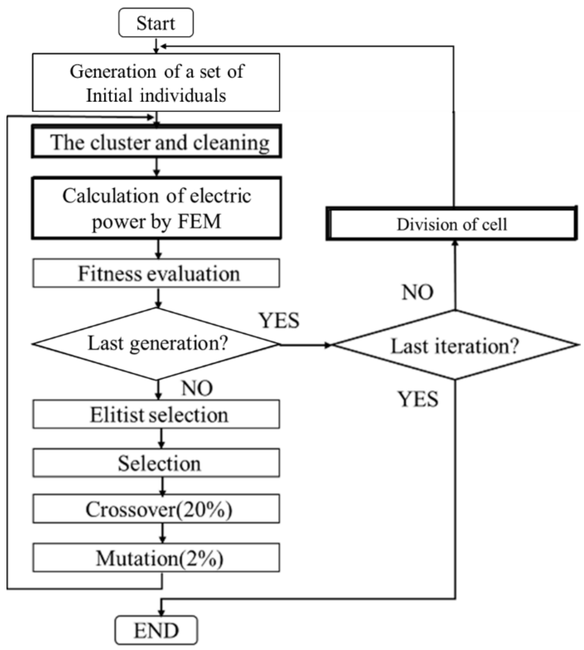
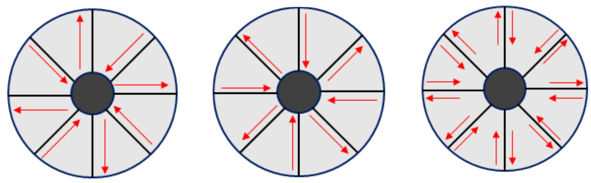


Fig. 2. Flowchart in GA



(a) Magnetization in *x*-direction (b) Magnetization in 45°-direction (c) Magnetization in *r*-direction

Fig. 3. Magnetized direction of PMs

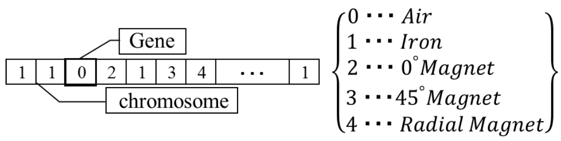


Fig. 4. Image of chromosome

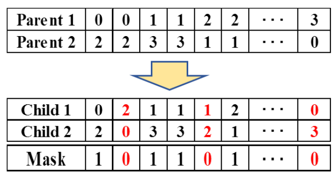


Fig. 5. Uniform crossover

chromosome in this case is represented in Fig. 4.

At first in the optimization process, 40 units as initial population are generated using random numbers. They have a variety of possibilities, and therefore have a low fitness function. Individuals are growing up by “crossover” and “mutation”. Two indivisuals are selected as parents, and then “uniform crossover” is performed as shown in Fig. 5. The ratios of crossover and mutation are set to 20% and 2%, respectively. In addition the elitist selection is adopted so as to inherit an indivisual, which has the maximum fitness function, to the next generation. The number of generations is set to 300 at the first iteration and 600 at the second iteration.

2.2 Cluster and Cleaning Method In this section, we will explain the cluster and cleaning method. The cluster is the mass of cells within the design region, which have the same material and are adjacent to each other. The size of the cluster is the number of cells. If the cluster of cells is in contact to the periodic boundary, a special treatment is necessary. The number of cells in the cluster of iron and air is doubled at both sides of the periodic boundary. Figure 6(a) shows an example to demonstrate three materials of air, iron and PM, which are scattered in the rotor. In this figure, Air1 and Air6 are the cluster that consists alone and the number of their cells are two and one, respectively. Air2 and Air3 are regarded as one cluster because they connect to each other at the corner, and the number of cells is four. Air4 and Air5 are regarded as one cluster, because they connect to each other by the periodic boundary. Therefore the number of cells in Air4 and Air5 is three. The concept of the cluster and its size are utilized in performing the cleaning process.

Next, we will explain the cleaning method and the cleaning level *Nmin* we have proposed. The cleaning method changes the material of a small cluster to the surrounding material, when the number of cells in the cluster is less than a positive number *Nmin*, that is, the cleaning level. Figure 6(b)~(f) show the material distribution after the cleaning process, where *Nmin* is set to 2 ~ 6. In the case of *Nmin* = 2 as shown Fig. 6(b), Air6 is removed and changed to iron, which is the material surrounding Air6. The cleaning process is executed for each *Nmin* as shown in Fig. 6(c)~(f). It is found that the larger *Nmin*, the larger effect of cleaning process. When *Nmin* = 6 as shown in Fig. 6(f), all clusters expect the largest permanent magnet cluster are changed to the iron. The performing this cleaning process is possible to eliminate micro region from design region. In other words, the proposed method is possible to design the topology by removing micro magnet regions and iron regions in the air, and

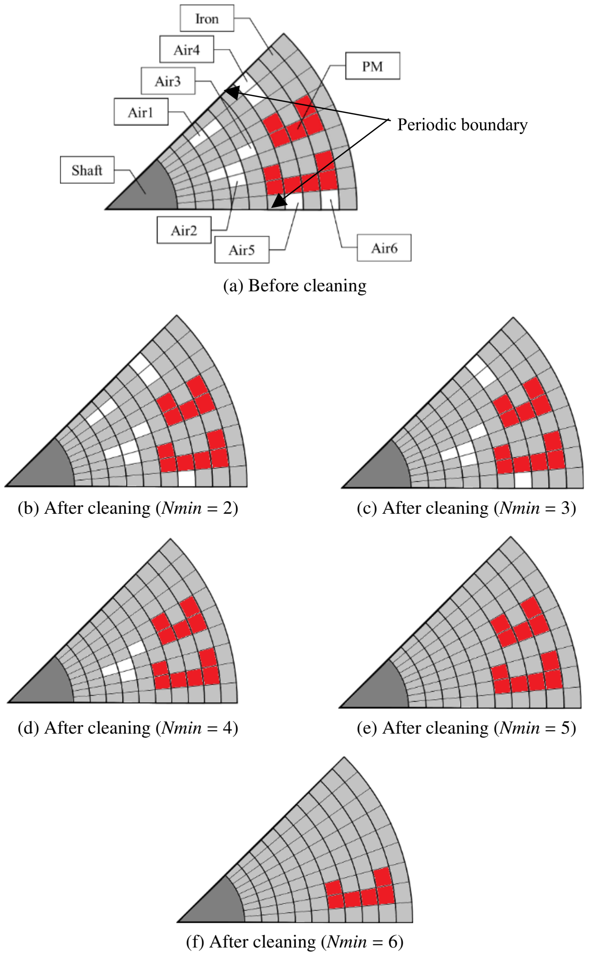


Fig. 6. Execution examples of the cleaning method

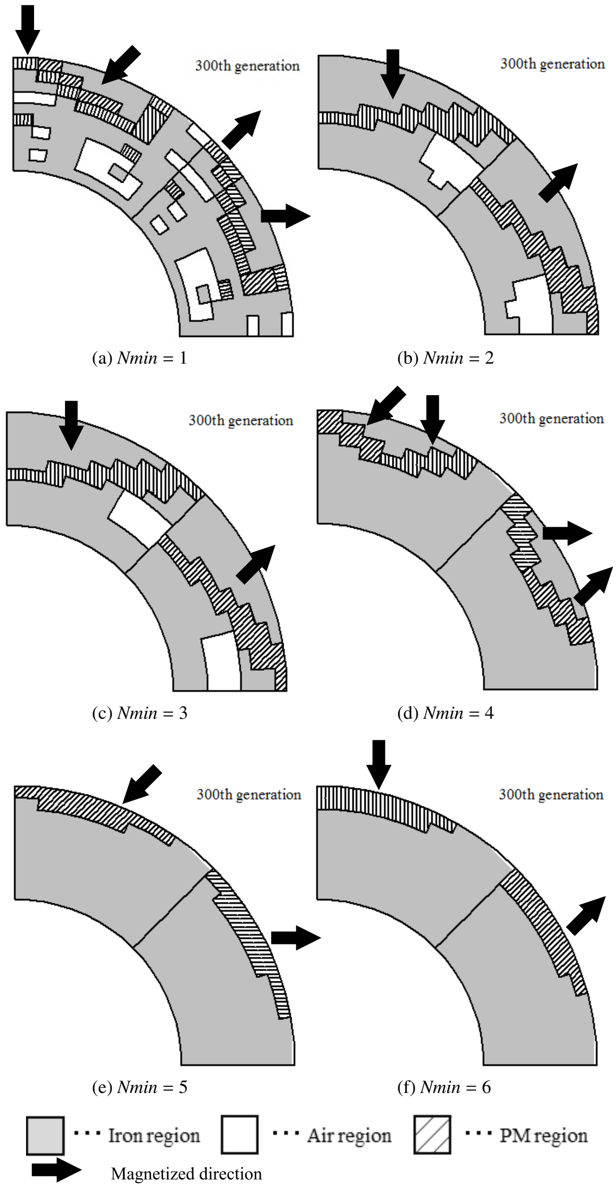


Fig. 7. Obtained results (1st iteration)

magnet regions in the iron. In this paper, *Nmin* is set to the same value for all design materials. However, it is possible to set different *Nmin* to each material.

2.3 Fitness Function In this section, the fitness function used for the evaluation in the GA is described. In order to design the rotor with a large electric power while reducing the volume of PMs, a fitness function below is used.

$$Fitness = \frac{P_{ave}}{1 + kV_{pm}/V_{rotor}} \quad (1)$$

where, P_{ave} is average electric power, V_{rotor} is the volume of the rotor except for shaft, V_{pm} is the volume of PMs in the rotor, and k is a positive number. The fitness function is proportional to P_{ave} and becomes small when V_{pm} is large. When a constant k is large, V_{pm} strongly influences the fitness function, and then a small amount of PMs is obtained. We investigated the obtained results for k = 1, 2 and 4. The PM volume of rotor obtained for k = 2 at the first iteration was approximately similar to that of PMSG used in Prius. Therefore, this paper designs the rotor topology by setting k = 2.

3. Design Results by the Topology Optimization

3.1 Design Results at the First Iteration The purpose of this paper is to clarify the effect of the cleaning level *Nimin* on the obtained rotor structure and the performance of PMSG. This paper optimizes the rotor topology by setting *Nmin* = 1∼6. Since this method uses random numbers, the obtained results depend on them. We have performed the optimization using four different random numbers, that is, the seed of them was set to *Randseed* = 1∼4. This paper shows the results when *Randseed* = 1. In addition, the CPU time for 300 generations is about 35 hours on a 2.9 GHz Intel Core i5- 3470S.

Figure 7(a)∼(f) shows the rotor topologies obtained by setting the number of cells and generations to 9*10 = 90 and 300, respectively. Figure 8 shows the convergence characteristic of the fitness function with each *Nmin* at the first iteration. If *Nmin* = 2∼4, the fitness function converges to the optimum solution at about 300th generation, and it achieves significantly higher value than the case of *Nmin* = 1, 5 and 6. The rotor has a shape of the interior permanent magnet type. In the case that *Nmin* = 5 or 6, the fitness function converges a lower value at a smaller generation than those of *Nmin* = 1∼4, and the material distribution is strongly limited. The rotor becomes a shape of the surface magnet type. By setting

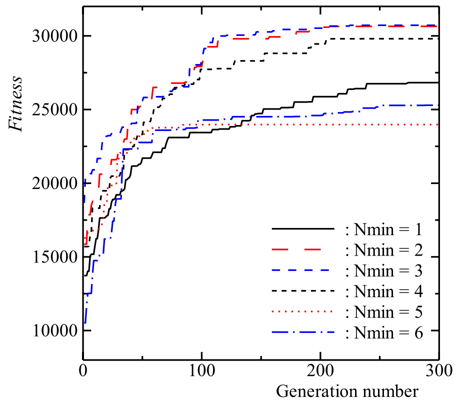


Fig. 8. Convergence characteristic of fitness function with each *Nmin* (1st iteration)

Table 1. Obtained PM volume, output power and fitness (1st iteration)

	V_{pm} [cm^3]	P_{ave} [kW]	*Fitness*
Nmin = 1	7.83	37.6	26831
Nmin = 2	7.59	42.5	30648
Nmin = 3	7.59	42.6	30722
Nmin = 4	6.49	39.7	29805
Nmin = 5	5.80	31.1	23981
Nmin = 6	5.78	32.7	25292
Prius	8.55	38.7	26971

Nmin to 1, lots of small regions remain because the cleaning procedure does not perform. Note that approximately similar shapes were obtained in the case of the different random number whose *Randseed* = 2~4, but different shapes were sometimes obtained. Therefore, we think that the results shown in Fig. 7 are due to not only the cleaning level *Nmin* but also the material distribution of individuals at 1st generation.

Table 1 shows the comparison of the output power and the magnet volume of obtained PMSG with those of Prius generator.

It is found that the fitness functions are higher than that of Prius model in the case of *Nmin* = 2 and 3. They generate the similar amount of electric power with low permanent magnet volume. Therefore, it is confirmed that proper *Nmin* in the proposed method gives an excellent design result.

3.2 Design Result at the Second Iteration In the previous section, the design region is divided by 10 × 9 = 90 cells and therefore the designed results are rough shape. In order to get more detailed design results, the design region is divided by 30 × 27 = 810 cells; 30 cells in the radial direction and 27 cells in the circumferential direction. Therefore, the computational cost can be reduced, compared with the method using a large number of design variables at the first iteration. At the second iteration, a set of initial individuals is generated by using the individual that has the best fitness at the first iteration. The initial material in a cell is generated by the probability of 1/5 from materials in five cells; the existing cell and four surrounding cells. The number of generations is set to 600 at the second iteration. The design results are shown in Fig. 9(a)~(f), and Fig. 10 shows the convergence characteristic of the fitness function with each *Nmin* at the second iteration. The CPU time for 600 generations is about 76.5 hours on a 2.9 GHz Intel Core i5-3470S. When generation number = 1500th, the fitness function is almost

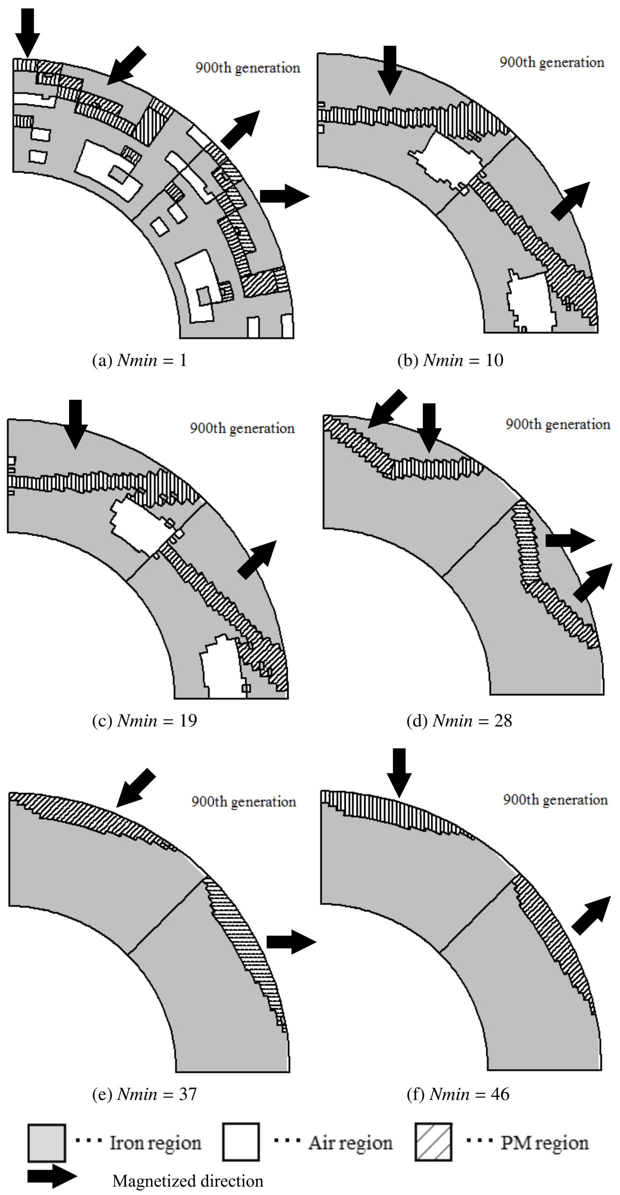


Fig. 9. Obtained results (2nd iteration)

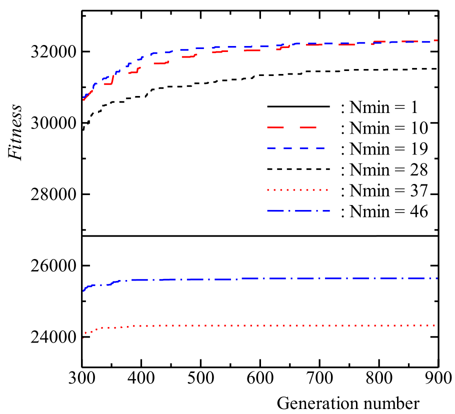


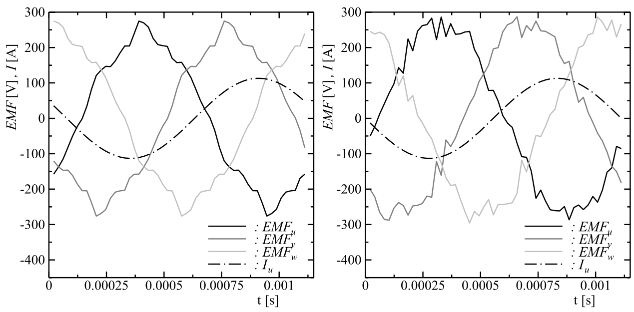
Fig. 10. Convergence characteristic of fitness function with each *Nmin* (2nd iteration)

the same as 900th. Therefore, the fitness function converges to the optimum solution at about 900th generation.

It is found from Fig. 9 that the obtained rotor shapes are

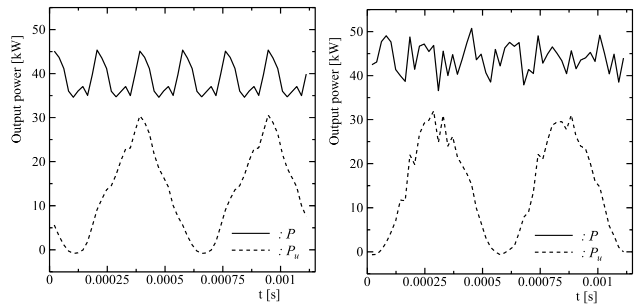
Table 2. Obtained PM volume, output power and fitness (2nd iteration)

	V_{pm} [cm^3]	P_{ave} [kW]	*Fitness*
Nmin = 1	7.73	37.3	26831
Nmin = 10	7.11	43.9	32188
Nmin = 19	6.69	43.2	32225
Nmin = 28	5.60	40.9	31820
Nmin = 37	5.63	31.7	24641
Nmin = 46	5.33	32.6	25620
Prius	8.55	38.7	26971



(a) Prius model (b) Designed model

Fig. 11. Comparison of electromotive force when *I*e = 80 A



(a) Prius model (b) Designed model

Fig. 12. Comparison of output power when *Ie* = 80 A

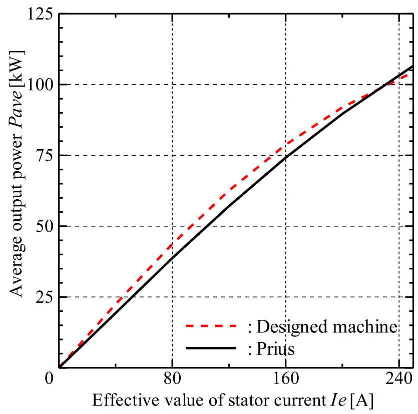


Fig. 13. Comparison of output power characteristics

similar to those shown in Fig. 7, and are a little bit smooth except for *Nmin* = 1. Table 2 shows the PM volume, average output power and the fitness of the rotor designed at the second iteration. It is found that the shape of PMs shown in Fig. 9(d) is very similar to that of generator used in Prius, but the fitness function is not the best. Comparison of Table 1 and Table 2 shows that the fitness is improved. However, the improvement of average output power is very small, that is, less than ((43.9 − 42.5)/42.5 =) 3.3%, and there is sometimes no improvement. From this fact, the average output power is affected mainly by the rough topology shape obtained at the first iteration. The detailed shape design at the second iteration does not affect the output power very much. However, relatively large improvement is seen for PM volume. In case of *Nmin* = 4 at the first iteration and 25 at the second iteration, for example, the PM volume is reduced by ((5.60−6.49)/6.49 =) 13.7% at the second iteration, and the output power is improved by ((40.9 − 39.7)/39.7 =) 3.0%. We think that the detailed shape design at the second iteration can remove a magnet region that does not contribute to the output power by making a smoother shape. In case of *Nmin* = 1 at the first and second iterations, that is, the GA without using the cleaning procedure, a lot of small pieces of magnet are remains and the fitness function is low. Therefore, it is found that the GA without using the cleaning procedure cannot give good results.

Next, we compare the generator characteristic of Prius model with that of the rotor obtained by setting *Nmin* = 19 at the 2nd iteration. Figures 11 and 12 show the comparison of electromotive force and output power, where *Pu* is the output electric power of one phase and *P* is that of three phases. For the Prius model, the phase angle of stator current is chosen to 25 deg. so as to generate the maximum P_{ave}. In contrast, the phase angle of the designed machine that generates the maximum output power is approximately 0 deg. Here, the phase angle is not measured from the *d*-axis, but measured from the initial position shown in Fig. 9. The maximum output power is developed when this current phase angle is almost 0 de.g., which means that this shift of PMs from the initial position corresponds to the phase angle of the stator current. Figure 12 confirms that the average output power of the designed machine is higher than that of Prius model. However, the ripple of output power of the designed machine is a little higher than that of Prius model. There is distortion in the EMF waveforms. As the fifth and seventh components are 2.8% and 3.0%, respectively, this distortion is not so large. This paper does not discuss the influences of the distortion in the EMF waveform and the ripple in the output power. They will be discussed in the future when a simple shape of PMs is designed by considering ease of manufacturing.

Figure 13 shows the comparison of the output power characteristics. The designed machine has a larger (output power)/(stator current) than the Prius model, when the stator current is less than about 200 A.

4. Conclusions

This paper has clarified the effect of the cleaning procedure level of the proposed topology optimization method on the designed rotor structure and its performance. An interior permanent magnet type generator is obtained for a low level of the cleaning procedure, and a surface type is obtained for a high level. A new generator has been designed, when the cleaning level *Nmin* = 3 at the first iteration and is 19 at the second iteration. The output power is improved by 11.6% and PM volume is reduced by 21.8% comparing with those of the generator used in Prius. The authors think this improvement is mainly given by the fact that the rotor shown in Fig. 9(c) does not have iron part between PM and the rotor surface.

When *Nmin* = 4 and 28 at the first and second iteration, the shape of PMs which is very similar to that of the generator used in Prius is obtained.

Since the designed rotor has a complicated and weak structure and therefore is difficult to manufacture, the design of a simple shape of PMs considering ease of manufacturing is a future work [8].

References

(1) Z.Q. Zhu, D. Howe, and Z.P. Xia: "Prediction of open-circuit air gap field distribution in brushless machines having an inset permanent magnet rotor topology", *IEEE Trans. on Magnetics*, Vol.30, No.1, pp.98–107 (1994)

(2) D.N. Dyck and D.A. Lowther: "Automated design of magnetic devices by optimizing material distribution", *IEEE Trans. on Magnetics*, Vol.32, No.3, pp.1188–1193 (1996)

(3) N. Takahashi, T. Yamada, and D. Miyagi: "Examination of optimal design of IPM motor using ON/OFF method", *IEEE Trans. on Magnetics*, Vol.46, No.8, pp.3149–3152 (2010)

(4) Y. Okamoto, Y. Tominaga, and S. Sato: "Topological Design for 3-D Optimization Using the Combination of Multistep Genetic Algorithm with Design Space Reduction and Nonconforming Mesh Connection", *IEEE Trans. on Magnetics*, Vol.48, No.2, pp.515–518 (2012)

(5) T. Sato, H. Igarashi, S. Takahashi, S. Uchiyama, K. Matsuo, and D. Matsuhashi: "Shape Optimization of Rotor in Interior Permanent Magnet Motor Based on Topology", *IEEJ Trans. on Industry Applications*, Vol.135, No.3, pp.291–298 (2015) (in Japanese)

(6) T. Ishikawa and K. Nakayama: "Topology Optimization of Rotor Structure in Brushless DC Motor with Concentrated Windings Using Genetic Algorithm Combined with Cluster of Material", *IEEE Trans. on Magnetics*, Vol.48, No.2, pp.899–902 (2012)

(7) T. Ishikawa, K. Nakayama, N. Kurita, and F.P. Dawson: "Optimization of Rotor Topology in PM Synchronous Motors by Genetic Algorithm Considering Cluster of Materials and Cleaning Procedure", *IEEE Trans. on Magnetics*, Vol.50, No.2, p.7015704 (2014)

(8) T. Ishikawa, P. Xie, and N. Kurita: "Topology Optimization of Rotor Structure in Permanent Magnet Synchronous Motors Considering Ease of Manufacturing", *IEE Japan, Journal of Industry Applications*, Vol.4, No.4, pp.469–474 (2015)

(9) M. Olszewski: Evaluation of the 2010 Toyota Prius Hybrid Synergy Drive System, 1-79, Mrach (2011)

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