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Research paper

Optimal Design of Surface-Permanent-Magnet-Type BLDC Motor for Radiator Fan to Reduce Cogging Torque using Genetic Algorithm

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Abstract

Background/Objectives: This paper proposes an optimal design method to reduce the cogging torque of a surface permanent magnet (SPM)-type BLDC motor widely used for automotive radiator fan by changing the shape of permanent magnet attached to rotor.
Methods/Statistical analysis: To reduce the cogging torque, we designed the shape of the permanent magnet and used a genetic algorithm (GA), which is a type of optimization method. Three design variables, i.e., the width of the permanent magnet, radius of the outer diameter, and thickness of the permanent magnet, were set when the optimization method was applied.
Findings: In recent years, there has been an increasing demand for a vehicle electric system that uses a motor to improve the fuel efficiency and output of a vehicle. Among them, the development of a BLDC motor using a DC power source is actively being carried out. BLDC motors use permanent magnets in the rotor to enable miniaturization for vehicle mounting. However, a BLDC motor having a permanent magnet structure necessarily generates a cogging torque owing to a difference in reluctance, which causes noise and vibration. The cogging torque varies depending on the shape of the permanent magnet and core of the rotor, and it can be reduced by changing the magnet's shape. Using the proposed optimal design algorithm, BLDC motors for four pole and 24 slot radiator fans with rated 100W were designed. To verify the design results, the cogging torque and torque ripple characteristics were calculated by finite element analysis. As a result of the finite element analysis, the cogging torque and torque ripple of the optimal model have been reduced compared to the initial model. Finally, it has been confirmed that it is appropriate to reduce the cogging torque characteristics of a BLDC motor for a radiator fan by implementing the proposed optimal design algorithm.
Improvements/Applications: The proposed optimal design procedure is suitable for improving the performance of the SPM type BLDC motor that drives the automotive radiator fan, as it reduces the motor's cogging torque. The proposed optimal design procedure is able to stabilize the operation of the vehicle radiator fan by reducing the cogging torque and torque ripple of the BLDC motor.

Keywords: *Brushless DC, Motor, SPM, Optimal design, Radiator, Automobile.*

1. Introduction

To improve the fuel efficiency of automobiles and the convenience of the driver, there is a growing need for the development of various electric field systems, and studies on automobile motor systems are being actively conducted all over the world. As automotive motor systems use battery power, systems with 12 V input power have been used [1,2]. However, as the capacity of the system increases, the level of the voltage increases to 24 V or 48 V. The motor used in such an automotive system needs to be small and light to help improve the fuel economy of the vehicle [3,4]. Brushless direct current (BLDC) motors have the advantage of having a simple and miniaturized structure because they do not need field winding and field current[5,6]. In addition, because a permanent magnet is used in the rotor, a brushless structure exists and there is less loss; thus, BLDC motors have excellent mechanical life. Furthermore, such motors have a high torque density as compared to a direct current (DC) motor, which is advantageous for high torque low speed operation[7]. Owing to the small harmonic effect, such motors are mainly used in precision-type applications that require cogging torque and torque ripple reduction, and are widely applied to automotive systems where reliability and reliability are important [8]. In general, BLDC motors are divided into interior permanent magnet (IPM) types and surface permanent magnet synchronous motor surface permanent magnet (SPM) types, depending on the position of the permanent magnet of the rotor. In the case of the IPM type, the permanent magnet is embedded in the rotor and is structurally stable and strong. However, as the gap is not constant, the torque ripple is large, and control and design are difficult [9]. On the other hand, the SPM type is applicable to a system in which the magnet is attached to the rotor surface, the gap is constant, the torque ripple is small, the motor operates at a constant speed condition, and precision is required [10]. Therefore, in this study, an SPM-type BLDC motor with a small torque ripple is designed. The biggest problem in BLDC motors using permanent magnets is the starting torque, as it hinders the smooth starting of the motor. The starting torque of the BLDC motor makes up the cogging torque, a bearing loss, such as mechanical friction including the torque and the cogging torque, is needed for the biggest proportion of them. The characteristics of the cogging torque and torque ripple also have a great influence on the noise and vibration of the fan of the automobile radiator. Therefore, a design method is needed to minimize the cogging torque and torque ripple when designing a BLDC motor. In this study, we investigate the optimal design for reducing cogging torque and torque ripple of an SPM-type BLDC motor. A basic design of an SPM type BLDC motor was developed. The proposed optimal design method based on the genetic algorithm (GA) was developed to minimize the cogging torque by selecting three parameters, namely, the width, radius of the outer diameter, and thickness of the permanent magnet. As a result of the optimal design, the output level is designed to be the same by changing the specifications of the windings to prevent the output of the motor from decreasing due to the change of the rotor shape. Cogging torque characteristics were analyzed using two-dimensional finite element analysis. The optimal model cogging torque and torque ripple were lower than the initial model. The proposed design method of SPM type BLDC motor for radiator fan is effective to reduce cogging torque.

2. Design of the SPM type BLDC Motor

The design of the BLDC motors in this study was performed in three phases. First, an initial design was developed using the load distribution method. Then, a detailed design was created a using numerical analysis program (ANSYS Electromagnetics Suite 18.0). Finally, the optimized design was achieved using an optimization algorithm (GA).

2.1. Initial Design of the SPM Type BLDC Motor

In the load distribution method, the capacity of a motor is expressed as a product of an electric load and a magnetic load, and an electric motor is designed based on the distribution of a proper load [11]. To design a motor using the load distribution method, the pole and slot of the motor must first be determined. Usually, the number of poles is set to an even number. Depending on the cogging torque and the output of the motor, there is a suitable number of poles and slots. Therefore, it is necessary to set the proper number of poles and slots according to the capacity and purpose of the motor [12,13]. Figure 1 shows the structure of the SPM type BLDC motor. The pole/ slot combination of 24 slots-4 poles was selected considering the cogging torque, and the stator was designed by the load distribution method. The permanent magnet used in the initial model of the BLDC motor is an N42UH (Br: 1.26T, Hc: -875kA/m) grade magnet with excellent characteristics at high temperature and a working temperature of 180 °C.The core material of the stator and rotor was S18 (35PN360). The BLDC motor designed in this study has a 100 W power output and the total outer diameter and stacking length of the stator were selected through a basic calculation. Detailed design specifications for the initial model are shown in Table. 1.

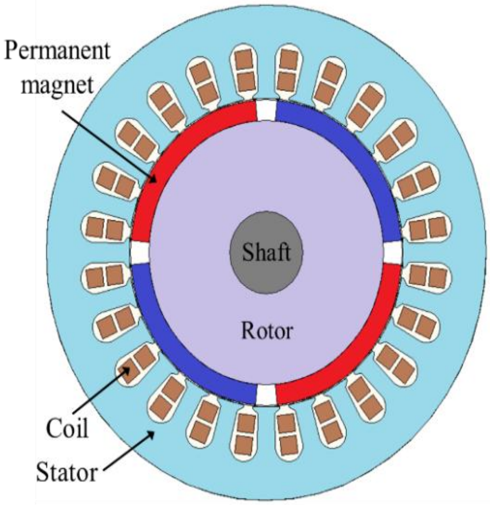


Figure 1: Structure of the SPM type BLDC motor

Table 1: Specifications of the initial model

Items	Value	Unit
Outer dimension of stator	60	mm
Outer dimension of rotor	32	mm
Outer dimension of rotor	10	mm
Length of air gap	1	mm
Stack length	50	mm
Number of slots	24	Slots
Number of coil turns per slot	30	Turns
Number of poles	4	Pole
Core material of stator and rotor	S18 (35PN360)	-
Material of permanent magnet	N42UH (Br : 1.28T)	-

The arrangement of the three-phase stator winding of the BLDC motor is shown in Figure 2; each phase is defined as A, B, and C. The coils of the slots were wound in two layers in a distributed winding. When the starting point of the current was A, the current flowed in the -A direction; each equivalent coil had 30 turns, and a total of 90 coils were wound. Figure 3 shows the driving circuit for operation of the BLDC motor. The coil of each phase was connected by a Y-connection method and was designed to be driven by a three-phase 120-degree six-step driving method.

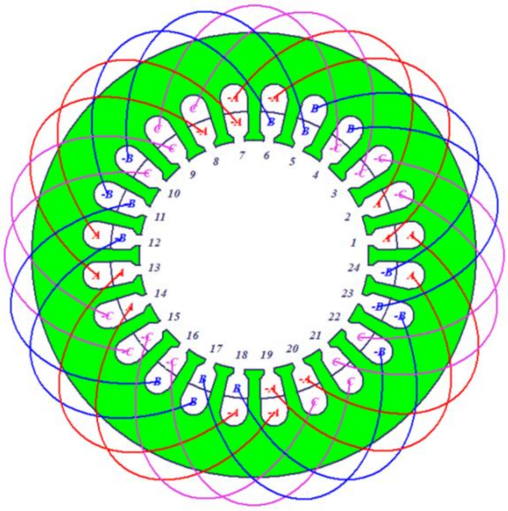


Figure 2: Arrangement of the three-phase stator winding of the BLDC motor

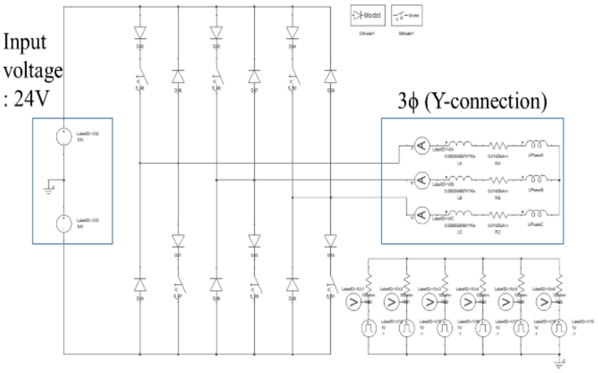


Figure 3: Driving circuit for operation of the BLDC motor

3. Cogging Torque Reduction of BLDC Motor

Common methods for reducing the cogging torque include skewing a stator or rotor, changing the stator tooth and slot structure, changing the shape of the slot, and increasing the length of the gap. In this study, an optimization design method for reducing the cogging torque by changing the shape of the permanent magnet was investigated. The finite element (FE) analysis and GA were used to analyze the cogging torque according to the shape of the permanent magnet and to derive the magnet's optimal shape.

3.1 Optimal Design Method

The optimization algorithm used the GA, and Figure 4 shows the flowchart of the GA procedure. This algorithm sets the initial shape of the motor and compares it to the shape of the next randomly generated generation. When the target design value is reached, the program is terminated, and the parent generation value is determined as the final shape of the optimal model.

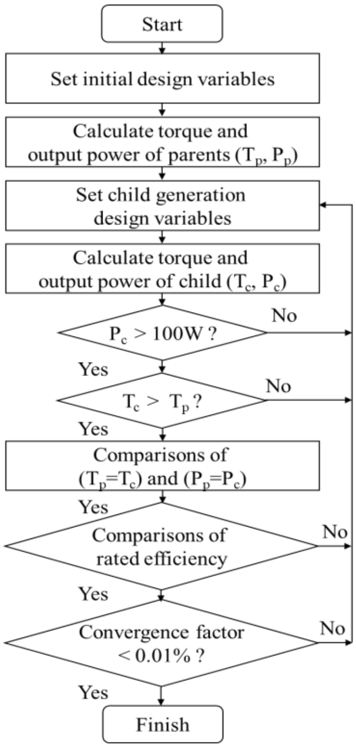


Figure 4: GA procedure

By applying the optimal design technique using such a GA, an algorithm that requires an optimal shape minimizing the cogging torque while changing the shape of the permanent magnet is executed. In the BLDC motor, the magnetic flux distribution changes with the change of the shape of the permanent magnet. Further, a change in the magnetic flux distribution due to the shape change of the permanent magnet changes the cogging torque of the BLDC motor. The design of the permanent magnet is optimized so that the characteristic of the cogging torque changes and the cogging torque is reduced. To randomly change the shape of the rotor during the optimum design process, design parameters that determine the shape of the permanent magnet need to be changed. The design parameters of the permanent magnet applied to the optimization design method were set as the angle of the permanent magnet width θ, radius that changes the outer diameter R, and thickness of the permanent magnet T. Figure 5 shows θ, R, and T defined by design variables.

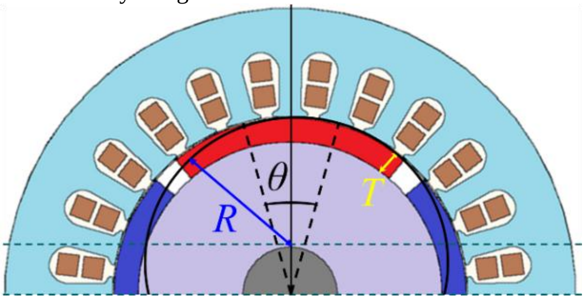


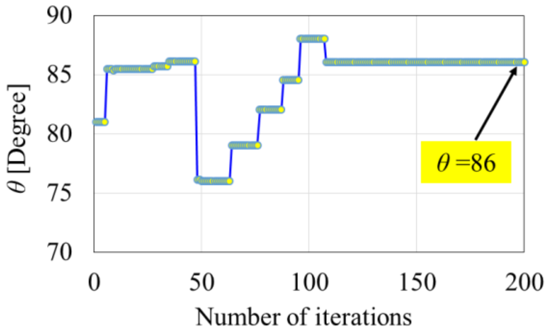
Figure 5: Design variables

3.2 Comparisons of Characteristics

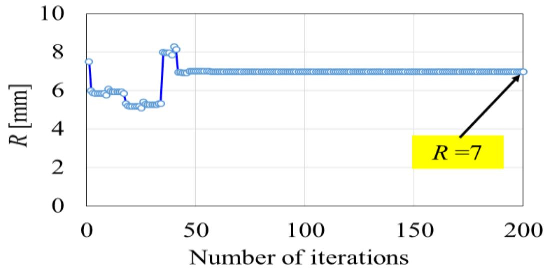
The determination of the permanent magnet shape of the optimal model is performed using FE analysis and GA. The objective function to minimize the cogging torque is selected, and the objective function and its constraint are defined as shown in Table 2. The rated output of the motor should exceed 100 W and the peak-to-peak of the cogging torque shall be less than 0.0785 Nm of the initial model. Figure 6 shows each of the 200 design iterative convergence profiles for three design variables and cogging torque. To reduce the cogging torque, the values of the design variables were adjusted through the convergence process. Optimization is complete when the optimal design result converges to the desired target value. Otherwise, the optimal design variable is iteratively adjusted until convergence for a given design result is achieved within the constraints. Table 3 presents a comparison of design variables of the initial model and the optimal model. Figure 7 compares the changes in shape of the permanent magnet of the initial model and the optimal model. Figure 8 shows a comparison of residual magnetic flux density distributions with residual magnetic flux densities of approximately 1.2T at the air gap between the stator and the rotor, approximately 1.6T at the center of the teeth, and approximately 1.9T at the saturation of the teeth.

Table 2: The objective functions and constraints

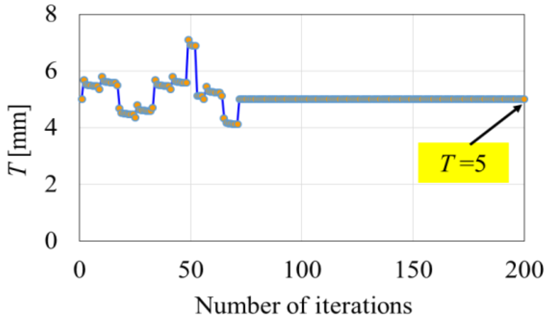
Items	Descriptions
Objective function	Minimize cogging torque
Constraint	Output power > 100 W
	Cogging torque < 0.0785 Nm (peak to peak)



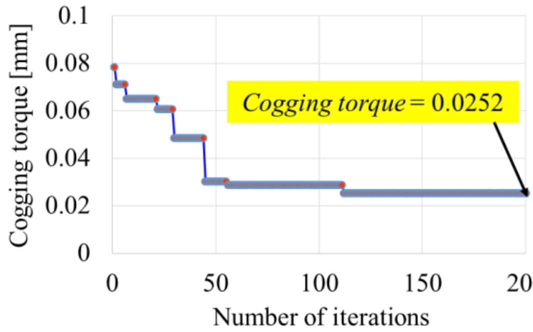
(a) θ



(b) R



(c) T



(d) Cogging torque

Figure 6: Convergence profile of design variables and cogging torque: (a) θ, (b) R, (c) T, and (d) cogging torque

Table 3: Comparison of design variables

Items	Initial	Optimal	Unit
θ	81	86	Degree
R	7.5	7	mm
T	5	5	mm

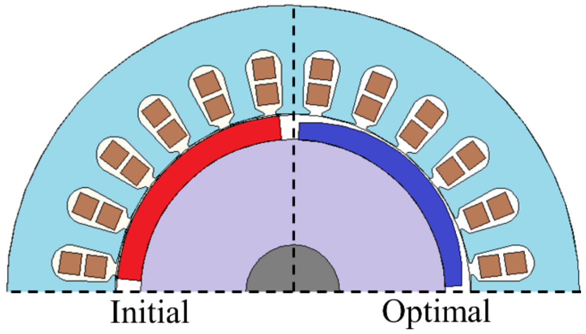


Figure 7: Comparison of shape

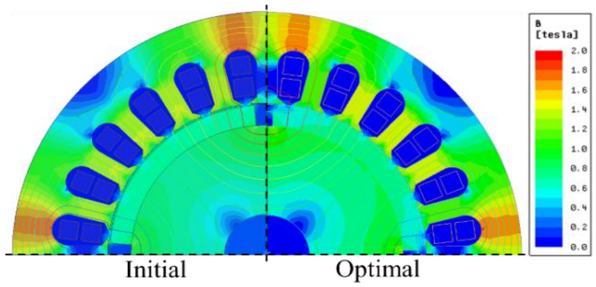


Figure 8: Comparison of residual magnetic flux density distribution

Figure 9 shows a comparison of the back-electromagnetic force (EMF) characteristics. Decreasing the back-EMF degraded the output and efficiency characteristics of the BLDC motor. Therefore, we needed to confirm whether the proposed back-EMF characteristics of the optimal model were comparable with those of the initial model. The root mean square value of the back-EMF was confirmed to be similar to those of the initial model and the optimal model, which were 18.0 V and 17.9 V, respectively.

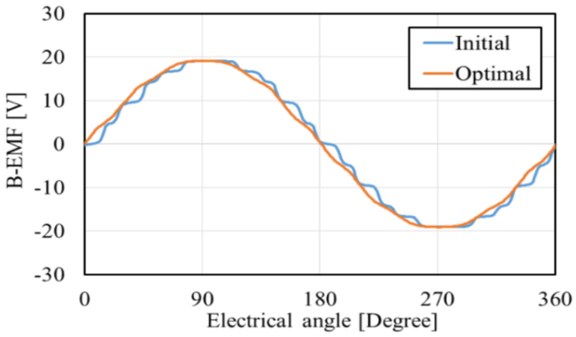


Figure 9: Comparison of the back-EMF characteristics

Figure 10 compares cogging torque characteristics. The peak-to-peak characteristics of the initial and optimal model cogging torque are 0.0785 and 0.0252 Nm, respectively. Therefore, the cogging torque of the optimal model was reduced to 32.1% compared with the initial model due to the shape change of the permanent magnet.

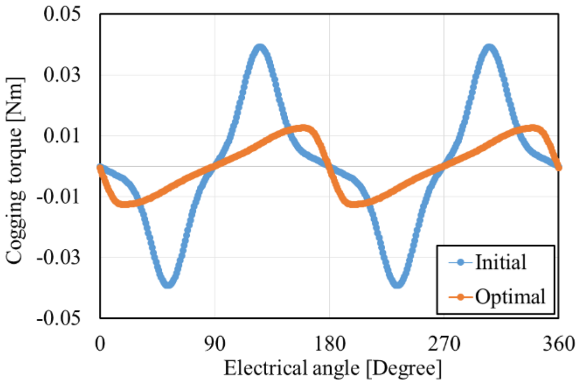


Figure 10: Comparison of the cogging torque characteristics (no-load condition)

Figure 11 shows a comparison of the torque characteristics; it is a torque waveform operating at rated conditions (2500 rpm and 100 W). In general, the torque ripple tended to decrease as the cogging torque reduced. Therefore, the peak-to-peak characteristic of the torque ripple of the optimal model was confirmed to be 6.9% lower than the initial model. Finally, Table 4 compares performance and specifications. The optimal design method proposed in this study reduces the cogging torque characteristics, which will improve the stable operation and noise performance of the SPM type BLDC motor for automobile radiator fan.

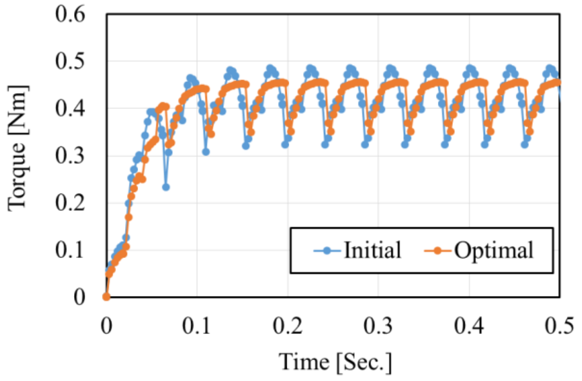


Figure 11: Comparison of the torque characteristics

Table 4: Comparison of the performance and specifications

Items	Value		Unit
	Initial	Optimal	
Input voltage	24		V
Rated output	100		W
Rated speed	2500		rpm
Rated current	4.90	4.88	Arms
Rated efficiency	85.0	84.8	%
Cogging torque	0.0785	0.0252	Nm
Torque ripple	0.13229	0.12322	Nm

4. Conclusion

The cogging torque is a disadvantage of a BLDC motor using a permanent magnet structurally, as it comprises most of the starting torque required for the motor to start and has a great influence on noise and vibration. In this study, an optimal design method to reduce the cogging torque of an SPM type BLDC motor used in an automotive radiator fan was developed by using finite element analysis and the genetic algorithm. By using the proposed optimal design method, the optimal shape of the reduced permanent magnet of cogging torque of 100 W class BLDC motor with 24 slot 4 pole combination was obtained. The magnetic flux density distribution, back EMF, and torque characteristics were calculated through finite element analysis, and the characteristics of the initial and optimal models were analyzed. The optimal design of the SPM type BLDC motor exhibited a significant decrease in the cogging torque compared to the initial model, and the torque ripple during the rated operation was also reduced.

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