Fundamental Analysis of a Ferrite Permanent Magnet Axial Gap Motor with Coreless Rotor Structure

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Rare earth permanent magnets (PMs) with a large energy product are generally used in the traction motors of hybrid electric vehicles. However, developing rare-earth-free motors is necessary because of problems with rare earth materials, such as increasing prices and difficulty in their supply. This paper introduces such a rare-earth-free motor: a ferrite PM axial gap motor with a coreless rotor structure. The motor structure and the results of three-dimensional finite element analysis are described in detail.

Keywords: axial gap motor, coreless rotor structure, rare-earth-free motors, hybrid electric vehicles

1. Introduction

Interest in environmental problems such as global warming is increasing every year. Hybrid electric vehicles (HEVs) are expected to reduce carbon dioxide emissions—one of the causes of environmental problems. In HEVs, permanent magnet synchronous motors (PMSMs) are generally used because of their small size, high power, and high efficiency. Rare earth permanent magnets (PMs) with a large energy product are generally used for PMSMs^{(1)–(4)}. However, it is necessary to develop rare-earth-free motors for HEV traction motors because of several problems such as increasing prices and the uncertain supply of the required rare earth materials—neodymium and dysprosium.

The Toyota Prius is a well-known HEV. The total axial length of the traction motor of the third-generation Prius is only 69% of that of the second-generation model. Traction motors with flatter shapes will be required in future generations; hence, it is important to develop appropriately shaped rare-earth-free motors. This paper sets the 60 kW traction motor in the third-generation Toyota Prius as its development target.

Radial gap motors are generally used as HEV traction motors. In radial gap motors, the ratio of the coil end to the motor volume increases as the motor shape flattens, thereby decreasing torque density because the coil end generates no torque. However, the dead space at the coil end resulting from the motor flattening is small in axial gap motors, and hence, high torque densities can be expected^{(1)–(14)}. Therefore, we propose a motor that takes the structure of an axial gap motor and replaces the rare earth PMs with ferrite PMs.

We had proposed a ferrite PM axial gap motor with a segmented rotor structure in a previous paper⁽¹⁾. In this motor,

soft magnetic composite (SMC) cores are installed inside a rotor to utilize reluctance torque. In contrast, the rotor in the motor proposed in this paper is made up of ferrite PMs and a non-magnetic rotor support component without the SMC cores. Hence, the proposed motor has a coreless rotor structure that attains high efficiency by reducing iron loss owing to its decreased magnetic flux density.

This paper introduces a ferrite PM axial gap motor with a coreless rotor structure as an example of a rare-earth-free motor suitable for flat shapes. Three-dimensional finite element analysis (3D-FEA) confirms that the proposed motor can achieve a maximum torque of 207 Nm, a constant output of 60 kW, and a maximum efficiency of 97%. This performance is equivalent to that of the 60 kW traction motor in the third-generation Toyota Prius.

2. Structure of a Ferrite Axial Gap Motor with a Coreless Rotor Structure

Table 1 lists the specifications of our target motor: the 60 kW traction motor that employs rare earth magnets and is used in the third-generation Toyota Prius. The motor volume including the coil end, as measured in our laboratory, is 5.91 L, the maximum torque is 207 Nm, the constant output power is 60 kW, and the maximum efficiency is 97%. Here, the efficiency of the traction motor in the third-generation Toyota Prius was calculated using two-dimensional finite element analysis (2D-FEA). We intend to develop a motor that has similar performance specifications but does not use rare earth materials.

Figure 1 shows an outline of the proposed motor: an axial gap motor with an internal rotor and an external stator structure, in which a single rotor is sandwiched by two stators. The volume of the proposed motor is the same as that of the target motor.

Figure 2 shows the rotor configuration of the proposed motor with 10 poles. The rotor is constructed by installing only ferrite magnets on a rotor support component with non-magnetic steel. The coreless rotor structure does not use

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Table 1. Target value of a ferrite PM axial gap motor with coreless rotor structure

	Target value
Max. power	60 kW
Volume (including the coil end)	5.91 L
Max. torque	207 Nm
Max. torque density	35.01 Nm/L
Base rotational speed	2768 r/min
Max. rotational speed	13900 r/min
Max. efficiency	97%
Max. current density	20 Arms/mm ² (surmised value)

Fig. 1. Outline of a ferrite PM axial gap motor with coreless rotor structure

Fig. 2. Rotor configuration of a coreless rotor structure

magnetic materials such as the SMC core. The ferrite magnets are magnetized parallel to the axial direction and the direction of magnetization alternates at each magnet segment. The proposed motor is a non-salient pole machine in which the self-inductance of the d-axis and q-axis are equal because the rotor is a surface PM with a coreless rotor structure. Hence, the magnetic torque can be utilized exclusively and efficiency improvements can be expected from the reduced iron loss because the coreless rotor structure can

Table 2. Specification of a ferrite PM axial gap motor with coreless rotor structure

Number of poles	10
Number of slots	15
Outer diameter of stator	264 mm
Inner diameter of stator	74 mm
Stator height	42.25 mm
Outer diameter of rotor	264 mm
Rotor thickness	21 mm
Total motor axial length	108 mm
Diameter of shaft	66 mm
Air gap	1.25 mm
Volume (including the coil end)	5.91 L
Max. current density	18.4 Arms/mm ²
Rotor support component	Japan Steel Works, Ltd. 18% Mn steel
Ferrite permanent magnet	Hitachi Metals, Ltd. NMF-12G+
Iron core	Kobe Steel, Ltd. SMC core

reduce magnetic flux density.

This rotor structure resists irreversible demagnetization, which is a problem with ferrite magnets, because it is possible to maximize the thickness of the ferrite magnet within the limited rotor dimensions⁽¹⁾.

A stator with 15 slots is constructed using SMC cores and windings. Specifically, three-phase 10-pole concentrated windings are wound around the 15 stator teeth.

Table 2 lists the specifications of the proposed motor. The outer diameter of the stator is 264 mm, and the total axial length between the backs of the two stators is 108 mm. Accordingly, the volume (including the coil end) of the proposed motor is 5.91 L, which is equivalent to that of the target motor. The gap length on one side of the proposed motor is 1.25 mm. The exact form of each part is determined such that the magnetic torque is maximized for the restricted motor size. The rotor support component uses 18% Mn steel (Japan Steel Works, Ltd.), which is a non-magnetic material, and the ferrite magnet uses NMF-12G+ (Hitachi Metals, Ltd.). The stator uses an SMC core (Kobe Steel, Ltd.). The tensile strength and yield strength of the 18% Mn steel depend on the nitrogen content⁽¹⁵⁾. We use 18% Mn steel with a yield strength of 415 MPa. In addition, the conductivity of 18% Mn steel is 1320000 S/m, and this value is used for the eddy current loss calculation. The rare earth material, lanthanum, is used in the ferrite magnet NMF-12G+. Because the problems arising from the use of neodymium and dysprosium, which are used in rare earth PMs, do not arise in the case of lanthanum, the use of lanthanum is preferred in this study. Figure 3 and Fig. 4 show the magnetic properties of NMF-12G+ and the SMC core, respectively. These magnetic properties are used for 3D-FEA.

Additionally, the copper fill factor of the proposed motor is 57.55%, whereas that of the target motor is 56.40%. The copper fill factor of the proposed motor approximately corresponds to that of the target motor. The thickness of an insulation sheet used for the slots is not considered while calculating the copper fill factor of both motors.

Fig. 3. Magnetic property of NMF-12G+

Fig. 4. Magnetic property of SMC core

3. Characteristics of the Proposed Motor

3.1 Torque Characteristics 3D-FEA was carried out to confirm the validity of the proposed motor. The analysis conditions were as follows. The base rotational speed was 2800 r/min, which is almost equal to the base rotational speed of 2768 r/min of the target motor. The magnet temperature was constant at 75°C. The current phase angle was 0° because the proposed motor generates only magnetic torque. To evaluate the proposed motor, 2D-FEA was also performed for the target motor. For the analysis, the rotational speed was adjusted to 2800 r/min to match that of the proposed motor, the magnet temperature was constant at 75°C, and the current phase angle was 50°—conditions at which the target motor generated the maximum torque.

Figure 5 shows the instantaneous torque waveform under the maximum current density of 18.4 Arms/mm² and the above analysis conditions. The maximum average torque of the proposed motor is 207.65 Nm, the same as that of the target motor. Hence, the output power is 60.89 kW at the base rotational speed, and the proposed motor can provide an equal output power at the same volume as the target motor with rare earth magnets.

Figure 6 compares the torque ripple ratio between the proposed and target motors. In Fig. 6, the maximum average torque of each motor is standardized as 1 p.u. for simplicity of comparison. The torque ripple ratios of the proposed motor and the target motor are 10.73% and 12.45%, respectively.

Figure 7 shows the cogging torque waveform of both

Fig. 5. Relation of instantaneous torque and rotational angle at maximum current density

Fig. 6. Comparison of torque ripple ratio between the proposed motor and the target motor at maximum current density

Fig. 7. Comparison of cogging torque between the proposed motor and the target motor

motors under zero torque load. The cogging torques of the proposed motor and the target motor are ± 7.03 Nm and ± 0.53 Nm, respectively. The cogging torque of the proposed motor is greater than that of the target motor. Although the cogging torque of the proposed motor is only 3.4% of the maximum average torque, in future research, we hope to suppress the cogging torque by optimizing the motor shape.

3.2 Comparison of the Flux Density Distribution

The proposed motor uses a coreless rotor structure to reduce the magnetic flux density. Here, the flux density distribution of both motors is compared to validate the concept of

Fig. 8. Comparison of magnetic flux density distribution between the proposed motor and the target motor at maximum current density

the coreless rotor structure.

Figure 8 shows the flux density distribution of both motors. The proposed motor is shown using a 1/5 cut model of only the stator by hiding the rotor, and the target motor is shown with a 1/4 cut model. The magnetic flux densities on the main flux path of the proposed motor and the target motor are 1.35 T and 1.75 T, respectively. Figure 8 shows that the magnetic flux density of the proposed motor is low compared to that of the target motor.

3.3 Irreversible Demagnetization We performed demagnetization analysis for the proposed motor to evaluate the irreversible demagnetization of the ferrite magnets. Demagnetization of rare earth magnets tends to occur at high temperatures, but it can also happen at low temperatures in ferrite magnets. Therefore, the analysis conditions were set as follows. The temperature was -40°C and 75°C for ferrite magnets and 150°C for rare earth magnets. The current phase angle was constant at 90° , and the rotational angle was fixed at 0° .

Figure 9 shows the appearance of irreversible demagnetization in the ferrite magnets in the proposed motor for the maximum current density. In Fig. 9, the temperature of the ferrite magnets is -40°C . In spite of this worst-case analysis condition, irreversible demagnetization does not increase drastically in the ferrite magnets of the proposed motor. Hence, irreversible demagnetization is not considered to be a significant problem at the maximum current density in the proposed motor.

The reduction ratio of the U-phase flux linkage is used as an index to assess the irreversible demagnetization of the magnet quantitatively. The reduction ratio of the U-phase flux linkage is derived from Ψ_{mA} and Ψ_{mB} , the U-phase flux linkages generated by the ferrite PMs before and after conduction, respectively. Thus, the reduction ratio δ of the U-phase flux linkage is as follows:

$$\delta = \frac{\Psi_{mA} - \Psi_{mB}}{\Psi_{mA}} \times 100 [\%], \dots \dots \dots (1)$$

Figure 10 shows the reduction ratio of the U-phase flux linkage in both motors at each current density, derived from Eq (1). Here, the reduction ratio of the U-phase flux linkage in the proposed motor is shown for magnet temperatures of -40°C and 75°C , and the reduction ratio of the U-phase flux

Fig. 9. Analysis results about the irreversible demagnetization of ferrite permanent magnets in the proposed motor

Fig. 10. Comparison of the transitions of the reduction ratio of U-phase flux linkage in both motors

linkage in the target motor is shown for a magnet temperature of 150°C . At the maximum current density, the reduction ratio of the U-phase flux linkage is less than 0.5% in each curve. Although irreversible demagnetization is more likely in the proposed motor at -40°C than in the target motor at 150°C , the U-phase flux linkage reduction of the proposed motor at 75°C is almost equal to that of the target motor at 150°C . In fact, the operating time of HEVs under -40°C conditions is quite short because the motor temperature, including that of the magnet, increases immediately. Hence, in terms of irreversible demagnetization, the performance of the proposed motor is almost the same as that of the target motor.

3.4 Von Mises Stress Another important investigation is the endurance of the proposed motor against von Mises stress. Figure 11 shows the maximum von Mises stress in the rotor support component at each rotational speed. The yield strength of the 18% Mn steel used in the rotor support component is 415 MPa. At 7500 r/min, the maximum von Mises stress is 280.1 MPa. At this point, the safety ratio with respect to the yield strength of 18% Mn steel is 1.48. Accordingly, 7500 r/min is set as the maximum rotational speed of the proposed motor as a margin against stress.

Figure 12 shows the distribution of the von Mises stress

Fig. 11. Relation of rotational speeds and von Mises stress

Fig. 12. Analysis results about the von Mises stress in the proposed motor at 7500 r/min

at the maximum rotational speed of 7500 r/min. The von Mises stress in the rotor support component is concentrated at the boundary between the pillars extending radially from the center and the outer circular ring. As designed, the proposed motor's rotational speed cannot be increased to the target motor's maximum speed of 13900 r/min. Therefore, the proposed motor is suitable for use as a traction motor in a parallel hybrid system that rotates at the same speed as the engine because the engine rotational speed is generally 7500 r/min or less.

3.5 Efficiency This section compares and discusses the efficiencies of the proposed and target motors. The efficiency of the proposed motor is derived from the following equation:

$$\eta = \frac{P_{OUT}}{P_{OUT} + W_C + W_{IR} + W_{IS}} \times 100 [\%], \dots \dots (2)$$

where P_{OUT} is the output power, W_C is the copper loss, W_{IR} is the eddy current loss that is generated in the rotor support component, and W_{IS} is the iron loss that is generated in the SMC cores.

In (2), the eddy current loss of the ferrite magnets is negligible, and therefore, it is not considered.

Fig. 13. Relation of average torque and efficiency at base rotational speed

Fig. 14. Relation of average torque and total loss at base rotational speed

Figure 13 shows the comparison of the efficiencies of the proposed and target motors at the base rotational speed. The maximum efficiencies of the proposed and target motors are 96.27% and 97.07%, respectively. The maximum efficiency of the target motor is only 0.8% higher than that of the proposed motor, and the efficiencies at the maximum average torque are 90.27% and 90.41%, respectively, making the efficiencies of both motors almost equal.

Figure 14 shows the total loss in both motors at the base rotational speed. The total loss in the proposed motor is slightly higher than that in the target motor, resulting in the efficiency gap shown in Fig. 13.

Figure 15 shows the copper and iron losses in both motors at the base rotational speed to show the small difference in the total loss in both motors. While the copper loss in the proposed motor is slightly lower than that in the target motor owing to its concentrated winding structure, the iron loss in the proposed motor is higher than that in the target motor. However, the total loss in both motors is almost the same because the copper loss dominates the total loss.

We investigate the iron loss in the proposed motor more closely because it is much greater than that in the target motor.

Fig. 15. Relation of copper loss and iron loss at base rotational speed

Fig. 16. Relation of total iron loss and eddy current loss in the rotor support component at base rotational speed

Fig. 17. Comparison of iron loss density versus magnetic flux density between the SMC core and the silicon steel sheet at 200 Hz

Fig. 18. Efficiency map of the proposed motor

Figure 16 shows the iron loss factors in both motors. In the proposed motor, the eddy current loss in the rotor support component is 12.79% of the total loss and the iron loss in the stator SMC core is 87.21%. While the iron loss in the SMC core of the proposed motor is 0.97 kW when it is generating the maximum torque, the iron loss in the target motor's silicon steel sheet is 0.35 kW. Figure 17 shows the comparison of the data on the iron loss in the SMC core and the silicon steel sheet at the base frequency vicinity of 200 Hz. This iron loss data is used for the iron loss calculation. Eddy current loss and hysteresis loss are included in the data on the iron loss in the SMC core. The density of the iron loss in the SMC core is much greater than that in the silicon steel sheet. In addition, at other frequencies, the iron loss density in the SMC core is greater than that in the silicon steel sheet. Thus, the result shown in Fig. 16 is due to the material performance differences between the SMC core and the silicon steel sheet. The iron loss reduction in the coreless rotor structure is higher as compared to that in the conventional rotor structure, causing high magnetic flux density. However, the reduction of iron loss in the proposed motor is insufficient in comparison with that in the silicon steel sheet of the target motor. Hence, improving the motor shape to reduce the eddy current loss in the

rotor support component and the iron loss in the stator SMC core is required to increase efficiency.

Figure 18 shows an efficiency map, obtained through 3D-FEA, for the complete operating range of the proposed motor. The thick line in Fig. 18 shows the torque curve, which can achieve a constant 60 kW output. In spite of the surface PM and coreless rotor structure, 60 kW of constant output power is achievable in the driving range, from the base rotational speed of 2800 r/min to the maximum rotational speed of 7500 r/min. In addition, the efficiency exceeds 90% over a very wide range. The maximum efficiency of the proposed motor is 97.18% for an average torque of 51.42 Nm at 7500 r/min. The maximum efficiency of the proposed motor is equal to that of the target motor. Particularly remarkable is the high efficiency at rotational speeds higher than the base rotational speed. Figure 19 shows the transition of the iron loss, copper loss, and total loss in the proposed motor, at a constant output power of 60 kW, in the driving range between 2800 r/min and 7500 r/min. In spite of the constant output power, the iron loss, copper loss, and total loss decrease with an increase in the rotational speed. In particular, the decrease in the amount of copper loss is large and the motor current decreases significantly. In the proposed motor,

Fig. 19. Transition of total loss, copper loss, and iron loss of the proposed motor at constant power of 60 kW in region from 2800 r/min to 7500 r/min

the magnetic flux generated by the motor current is dominant because the magnetic flux that the ferrite magnets generate is small. The motor current required for the flux-weakening operation is also small. Thus, the magnetic flux density of the proposed motor decreases with an increase in the rotational speed. Even if the rotational speed is increased, the iron loss does not increase. Hence, the point of maximum efficiency is reached at 7500 r/min. At points of high efficiency where the rotational speeds are higher than the base rotational speed, the performance of the proposed motor exceeds that of the target motor using rare earth magnets.

4. Conclusions

This study introduced a 60 kW ferrite PM axial gap motor with a coreless rotor structure and investigated the detailed motor characteristics using 3D-FEA. It was found that the proposed motor achieved a maximum torque, maximum output power, maximum efficiency, and motor volume equal to those of the 60 kW motor in the third-generation Toyota Prius, which uses rare earth PMs. These outstanding attributes are the result of the axial gap configuration, the proposed coreless rotor structure, and the concentrated winding structure.

The areas of further improvement include the large cogging torque and the inability to accelerate up to the maximum rotational speed of the target motor. Future research should include methods for utilizing this motor's advantages, as well as improvements in design. In addition, we would like to conduct load and no-load experiments, and evaluate the proposed motor based on the experimental results.

References

- (1) S. Chino, T. Miura, M. Takemoto, S. Ogasawara, A. Chiba, and N. Hoshi: "Fundamental Characteristics of a Ferrite Permanent Magnet Axial gap Motor with Segmented Rotor Structure for the Hybrid Electric Vehicle", in Proc. 2011 IEEE Energy Conversion Congress and Exposition (ECCE 2011), pp.2805–2811 (2011)
- (2) M. Aydin, S. Huang, and T.A. Lipo: "Design, Analysis, and Control of a Hybrid Field-Controlled Axial-Flux Permanent-Magnet Motor", *IEEE Trans. Ind. Electronics*, Vol.57, No.1, pp.78–87 (2010)
- (3) C. Versele, Z. De Greve, F. Vallee, R. Hanuise, O. Deblecker, M. Delhaye, and J. Lobry: "Analytical Design of an Axial Flux Permanent Magnet In-Wheel Synchronous Motor for Electric Vehicle", in Proc. 2009 IEEE Int. EPE'09, pp.1–9 (2009)

- (4) Z. Wang, R. Masaki, S. Morinaga, Y. Enomoto, H. Itabashi, M. Ito, and S. Tanigawa: "Development of an Axial Gap Motor With Amorphous Metal Cores", *IEEE Trans. Ind. Appl.*, Vol.47, No.3, pp.1293–1299 (2011)
- (5) K.M. Rahman, N.R. Patel, T.G. Ward, J.M. Nagashima, F. Caricchi, and F. Crescimbeni: "Application of Direct-Drive Wheel Motor for Fuel Cell Electric and Hybrid Electric Vehicle Propulsion System", *IEEE Trans. Ind. Appl.*, Vol.42, No.5, pp.1185–1192 (2006)
- (6) T.J. Woolmer and M.D. McCulloch: "Analysis of the yokeless and segmented armature machine", in Proc. 2007 IEEE Int. Electric Machines and Drives Conf. (IEMDC'07), pp.704–708 (2007)
- (7) P. Zheng, J. Zhao, R. Liu, C. Tong, and Q. Wu: "Magnetic Characteristics Investigation of an Axial-Axial Flux Compound-Structure PMSM Used for HEVs", *IEEE Trans. Ind. Appl.*, Vol.46, No.6, pp.2191–2194 (2010)
- (8) M. Aydin, S. Huang, and T.A. Lipo: "A New Axial Flux Surface Mounted Permanent Magnet Machine Capable of Field Control," in Conf. Rec. 37th IEEE IAS Annu. Meeting, pp.1250–1257 (2002)
- (9) M. Aydin, S. Huang, and T.A. Lipo: "Torque Quality and Comparison of Internal and External Rotor Axial Flux Surface-Magnet Disc Machines", *IEEE Trans. Ind. Electron.*, Vol.53, No.3, pp.822–830 (2006)
- (10) C. Zhang, K.J. Tseng, and T.D. Nguyen: "Analysis and comparison of axial flux PM synchronous motor and induction motor", in Proc.2010 IEEE Int. IPEC2010, pp.572–577 (2010)
- (11) S.L. Ho, S. Niu, and W.N. Fu: "Design and Analysis of a Novel Axial-Flux Electric Machine", *IEEE Trans. Magnetics*, Vol.47, No.10, pp.4368–4371 (2011)
- (12) T.S. Kwon, S.K. Sul, L. Alberti, and N. Bianchi: "Design and Control of an Axial-Flux Machine for a Wide Flux-Weakening Operation Region", *IEEE Trans. Ind. Appl.*, Vol.45, No.4, pp.1258–1266 (2009)
- (13) R. Al Zaher, S. de Groot, H. Polinder, and P. Wieringa: "Comparison of an axial flux and a radial flux permanent magnet motor for solar race cars", in Conf. IECM2010, pp.1–6 (2010)
- (14) A. Mahmoudi, H.W. Ping, and N.A. Rahim: "A Comparison between the TORUS and AFIR Axial-Flux Permanent-Magnet Machine Using Finite Element Analysis", in Conf. IEMDC2011, pp.242–247 (2011)
- (15) Y. Ikeda, I. Iwata, T. Hatano, and J. Ishizaka: "Development and Manufacturing of High Strength and Toughness 18%Mn-18%Cr Retaining Ring Materials", Technical Report of Japan Steel Works, Ltd, No.46, pp.67–70 (1992) (in Japanese)

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