NUMERICAL CONSIDERATION OF INTEGRATED RADIAL AND DUAL AXIAL-FLUX FERRITE MAGNET MACHINE

Takatoshi Sunaga*, Shoji Shimomura

(Graduate School of Engineering and Science, Shibaura Institute of Technology)

E-mail Address : simomura@shibaura-it.ac.jp

ABSTRACT Recently, significant attention has been paid to the use of ferrite magnets in the main traction machines of electric vehicles/hybrid electric vehicles (EVs/HEVs). However, while ferrite magnets are advantageous in terms of cost, they provide poor magnetic performance in comparison to the neodymium (NdFeB) magnets used in high-performance, high-efficiency machines with high torque densities. To overcome this issue, the application of axial-flux structures (AFSs) to ferrite magnets has been proposed, and it is anticipated that the extended air gap area created when an AFS is used could compensate for their poor magnetic properties. As an additional countermeasure, we propose an integrated radial and dual axial-flux (IRDAF) structure that has one radial-flux gap and two axial-flux gaps. Evaluations performed using finite element analysis show that a machine designed with our proposed IRDAF structure would provide good performance in terms of output torque, efficiency.

1. INTRODUCTION

In order to facilitate the realization of a low-carbon and sustainable society, numerous researchers have tackled the development of highly efficient main traction machines for electric vehicles/hybrid electric vehicles (EVs/HEVs). One of the more attractive solutions pursued in those efforts is the use of an interior permanent magnet synchronous machine (IPMSM) that uses high-performance magnets made of the rare-earth materials neodymium (Nd) and dysprosium (Dy) [1]. However, since these rare-earth materials are in scarce supply and are expensive, interest is currently turning to EV traction machine designs that do not require rare-earth permanent magnets.

One magnet-free machine type, the switched reluctance machine (SRM) discussed in Refs. [2] and [3], can provide the required performance levels in terms of torque, output power, and efficiency. However, SRMs need dedicated power convertors instead of conventional voltage source inverters (VSIs).

Of the available rare-earth-free magnets, ferrite magnets appear to be a potentially better choice at present, but it is difficult to find ferrite magnet machines that satisfy the performance required for EVs/HEVs from the machines proposed to date if the design scope is limited to radial flux structures. Accordingly, attention is now being paid to axial flux structures as a strategy for improving efficiency by increasing torque [4,5,6].

With this point in mind, we herein propose an integrated radial and dual axial-flux (IRDAF) permanent synchronous machine (PMSM) design with a structure that has one radial-flux and two axial-flux air gaps. Since the torque produced by the rotating rotor is proportional to the change in the stored magnetic energy in the air gap, the extended air gap area produced by the IRDAF design has the potential to compensate for the poor magnetic properties of ferrite magnets.

Note that while the PM machine discussed in Ref. [7] has a structure that is similar to our design proposal, the authors of that study did not perform practical evaluations to determine its suitability for EV use. Therefore, in this paper, we will evaluates the performance of our proposed machine and make a comparative study with the IPMSM discussed in Ref. [1] using the finite element method (FEM) on the JMAG software suite (JSOL Corp., Tokyo, Japan).

2. PROPOSED MACHINE

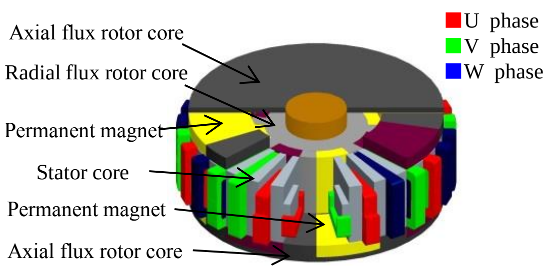
2.1 Topology

Figure 1 describes the topology of our proposed IRDAF-PMSM machine, which consists of one stator and one rotor that integrates one radial-flux rotor and two axial-flux rotors. Figures 1(a) and 1(b) show the general view and rotor respectively. The radial-flux rotor core and the axial-flux rotors are made of stacked magnetic sheet steel and soft magnetic composite (SMC), respectively.

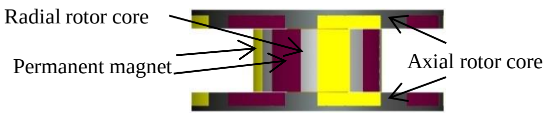
The rotor is an inset type, a design in which the permanent magnets are embedded in the core surface. Ferrite magnets are used. In the radial-flux rotor, one magnet is oblong shaped and has an arced cross-section similar to conventional radial-flux rotors. The width of the arc is 120° in electrical angle. In the axial-flux rotors, a flabellate magnet with an angle of 120° is used. Since the proposed machine has eight poles, the radial-flux and each axial-flux rotor each have eight magnets. Thus, the total number of magnets is 24.

The stator is a toroidal core made of SMC to which 30 teeth have been fixed. These teeth face the three air gaps. In this stator, two coils are wound on the toroidal yoke for each slot, which is a technique referred to as double layer toroidal winding in this paper. The 60 coils compose the armature winding of the eight poles. This winding configuration has been chosen for its ability to reduce the harmonic contents in the back electromotive force (BEMF).

The main specifications of the proposed machine are shown in Table I. The machine volume is almost the same as the target machine, including its coil ends.



(a) General view



(b) Integrated rotor

Fig. 1 Proposed IRDAF-PMSM machine.

2.2 Torque Characteristics

In this subsection, the torque characteristic calculated by FEM will be shown. Figure 2 shows the static torque characteristics. The broken line is its waveform, which shows the dependence of the torque on the current vector phase. The current vector phase is given as (1).

$$\varphi = \tan^{-1}(i_\beta / i_\alpha) \tag{1}$$

when the rotor is locked at a reference position, where i_α and i_β are α- and β-axis current of the stationary reference frame on the stator, respectively. The effective value (RMS) of current is given as (2) and the result is 235 A.

Table I: Specifications of the Designed Machine

Pole number of armature	8
Slots number of armature	30
Outer diameter (mm)	274.4
Stator outer diameter (mm)	249.6
Stator inner diameter (mm)	128.8
Radial rotor diameter (mm)	127.2
Shaft diameter (mm)	60
Air gap (mm)	0.8
Magnet thickness (mm)	12.8
Axial length (mm)	100
Resistance of the armature winding (Ω/phase)	0.04981
Magnet material	NMF-12G
Core material	MBS318 35H210
Winding space factor (%)	60
Number of turns (turn/phase)	100

$$I_{rms} = \sqrt{i_\alpha^2 + i_\beta^2} / \sqrt{3} \tag{2}$$

The brown curve is the fundamental component of the broken curve and shows the magnet torque change yielded by the PM flux. The green curve is the second component of the broken curve and shows the reluctance torque. The blue curve is the combined brown and green curves, that is, the total torque. The ratio of the magnet and reluctance torque peak values is approximately 10:9. Thus, it can be seen that the proposed machine yields a sufficient amount of reluctance torque in addition to magnet torque.

The dependence of the torque on current is shown in Fig. 3. Here it can be seen that the torque increases monotonically and reaches 192 Nm at 235 A (current density, 23.1 A/mm^2). The torque waveform for steady state running has a ripple, as can be seen from Fig. 4, but the pulsation ratio is 12.6%.

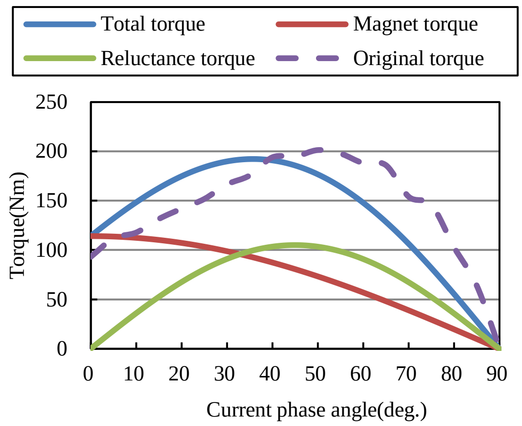


Fig. 2 Relationship between average torque and phase angle for a current density of 23.1 A_{rms}/mm^2

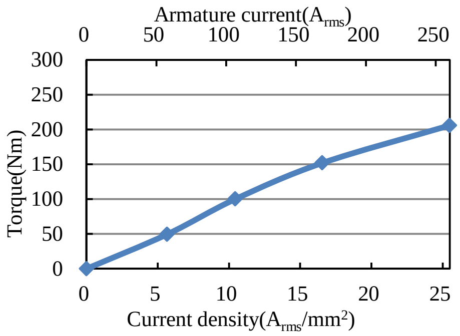


Fig. 3 Torque vs. current density

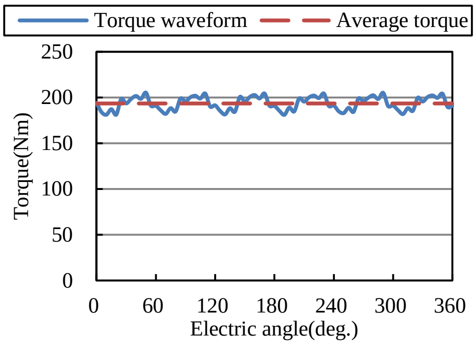


Fig. 4 Torque waveform of IRDAF-PMSM with a current density of 23.1 A_{rms}/mm^2

2.3 Operation Characteristics

The machine must be controllable under limited voltage conditions, and the operation characteristics, which are the speed-torque and speed-output, must satisfy the requirements. The method used to examine those characteristics, which is described in Ref. [8], evaluates the operation range by drawing a circle showing the limiting current value and two locus types at the current vector tip. One type is the current vector tip locus when generating a constant torque, while the other is the current vector tip locus at which the voltage maintains a limiting value.

The required operation characteristics, which have been taken so as to agree with that of the target machine shown rater, are shown in Fig. 5. The limiting values of the voltage and current are 495 V and 450 A in d-q reference frame voltage and current, respectively.

The hyperbola-like curves are the current vector tip locus at a constant torque. The ellipse-like curves are the current vector tip locus at the limiting voltage. Each hyperbola-like and ellipse-like curve pair has at least one intersection point inside the circle of the limiting current. This indicates that this machine can be operated at the three operation points under limited voltage and current conditions.

In this section, the operation characteristics have been examined at three speeds of 3000, 6000 and 13900 min^{-1}. These speeds were chosen as representative values for the low-, middle-, and high-speed range. Consequently, it can be concluded that the proposed machine will satisfy the required characteristics over the entire speed range.

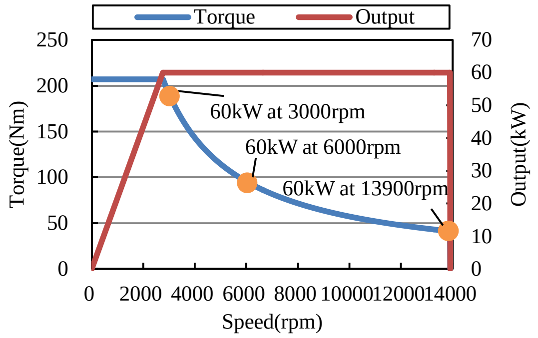


Fig. 5 Required speed – torque and speed – output characteristics

3. COMPARATIVE EFFICIENCY STUDY

3.1 Target Machine

The efficiency of our proposed machine was evaluated in comparison with a target machine, which is the IPMSM mounted on the third generation Toyota Prius. The outer diameter of stator is 264mm and the axial length is 108mm. Other dimensional data and specifications were obtained from Ref. [1]. The efficiency of the IPMSM to be compared with our proposed machine was calculated using FEM based on the Ref. [1] design data.

3.2 Efficiency Comparison

The calculated efficiency results in Figs. 6 and 7 show the proposed machine and the target machine, respectively. Since the output is the product of angular velocity, ω, and torque, T, and the input is obtained by the sum of the copper loss, iron loss, and ωT, the efficiency was given by the ratio of the input to the output. These characteristic values were calculated under the temperature environment condition of 150°C in the proposed machine and 140°C in the target machine. While these temperature conditions were slightly different, the effect on the results is considered to be negligible.

In terms of copper loss, the propose machine showed smaller losses than the target machine, excluding Operation Point A, which was caused by the smaller resistance of the toroidal winding. On the other hand, the iron losses for the proposed machine were bigger than those for the target machine. As a result, it can be concluded that the efficiency of the proposed machine at each operation point was very nearly equal to the target machine.

4. CONCLUSION

This paper described an evaluation of the torque, efficiency of our proposed IRDAF-PMSM machine, which uses a ferrite magnet. The obtained results are summarized as follows:

· By adopting an integrated radial and dual axial-flux structure with the inset PM rotors, even when a ferrite

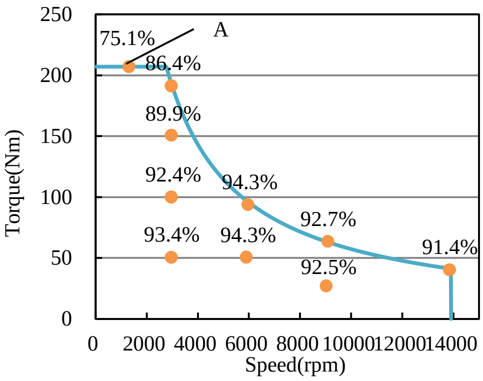


Fig. 6 Efficiency for proposed machine

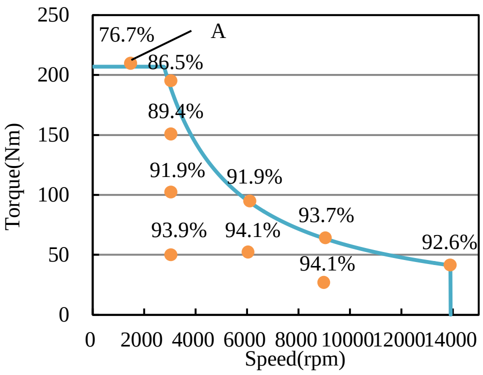


Fig. 7 Efficiency for target machine

PM is used, the proposed machine yielded a maximum torque equal to that of a target machine using an NdFeB sinter magnet, in the same volume of space as the target machine.

・ The proposed machine attained the targeted operation characteristics, speed-torque, and speed-output, under limited voltage conditions.

・ In terms of efficiency, the proposed machine was found to be very nearly equal to the target machine over the entire speed range of the operational characteristics.

In our future study, we intend to consider problems related to the creation of an actual machine, such as a method for supporting the stator.

REFERENCES

[1] Burress, Timothy A., et al. Evaluation of the 2010 Toyota Prius hybrid synergy drive system. No. ORNL/TM-2010/253. Oak Ridge National Laboratory (ORNL); Power Electronics and Electric Machinery Research Facility, 2011.

[2] K. Kiyota and A. Chiba, “Design of switched reluctance motor competitive to 60-kW IPMSM in third-generation hybrid electric vehicle,” IEEE Trans. Ind. Appl., vol. 48, no. 6, pp. 2303‐2309, Nov./Dec. 2012.

[3] Sulaiman, E.; Kosaka, T., "Parameter sensitivity study for optimization of field-excitation flux switching synchronous machine for hybrid electric vehicles," in Industrial Electronics and Applications (ICIEA), 2012 7th IEEE Conference on , vol., no., pp.52-57, 18-20 July 2012

[4] Murakami, S.; Goto, H.; Ichinokura, O., "A study about optimum stator pole design of Axial-gap switched reluctance motor," in Electrical Machines (ICEM), 2014 International Conference on , vol., no., pp.975-980, 2-5 Sept. 2014

[5] Madhavan, R.; Fernandes, B.G., "Performance Improvement in the Axial Flux-Segmented Rotor-Switched Reluctance Motor," in Energy Conversion, IEEE Transactions on , vol.29, no.3, pp.641-651, Sept. 2014

[6] Sone, K.; Takemoto, M.; Ogasawara, S.; Takezaki, K.; Hino, W., "Consideration of 10kW in-wheel type axial-gap motor using ferrite permanent magnets," in Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE-ASIA), 2014 International , vol., no., pp.3525-3531, 18-21 May 2014

[7] Xubiao Wei; Kai Yang; Zhicheng Pan; Hongqin Xie; Cheng Zhu; Yingli Zhang, "Design of a novel axial-radial flux permanent magnet motor," in Electrical Machines and Systems (ICEMS), 2014 17th International Conference on , vol., no., pp.80-84, 22-25 Oct. 2014

[8] Morimoto, S.; Takeda, Y.; Hirasa, T.; Taniguchi, K., "Expansion of operating limits for permanent magnet motor by current vector control considering inverter capacity," in Industry Applications, IEEE Transactions on , vol.26, no.5, pp.866-871, Sep/Oct 1990.

Takatoshi Sunaga received the B.E. (2014) degrees in electrical engineering from Shibaura Institute of Technology. He is a Student, Department of Electrical Engineering, Shibaura Institute of Technology. His Current interests include machines for electric vehicles.

Shoji Shimomura received his Dr. Eng. from Okayama University, in 1999. From 1984 to 1992, he worked for Fuji Electric Co., Ltd. From 1993 to 1999, he was an assistant and then a lecturer at the Polytechnic University of Japan. In 2000, he was an Associate Professor at Shibaura Institute of Technology and has been a professor since 2007. His research interests are electric machinery and its drives. He is a member of IEEE and IEEJ.