Optimal Design of Magnetic Planetary Gear Permanent Magnet Machines

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Abstract—This article investigates the optimal design of a magnetic-planetary-gear permanent magnet (MPG-PM) machine. The key is to develop a design method for the pole shoe thickness, stator outer diameter, and coil turns of the MPG-PM machine in such a way that the torque waveform is sinusoidal. The magnetic field distributions are solved by the finite element analysis according to the optimization results. A prototype of MPG-PM machine is used for exemplification in terms of the experiment performance requirement. Both the predicted and measured results are given to illustrate the proposed machine. The theory analysis and experimental results show that the magnetic circuit of the MPG-PM machine is correct, and the torque satisfies design requirements. It provides reference and application value for developing high performance and low-cost MPG-PM machine.

1. INTRODUCTION

The integrated design of the motor and magnetic gear mechanism is still an emerging research field. For the past years, magnetic gears have been proposed and designed, such as magnetic worm gear [1], externally meshed parallel shaft magnetic gear [2], magnetic bevel gear [3], coaxial magnetic gear [4–6], planetary magnetic gear [7, 8], linear magnetic gear [9, 10], anti-rotating magnetic gear [11], axial magnetic flux magnetic gear [12, 13], and transverse flux magnetic gear [14]. Recently, a class of magnetic gear (PG) machines, namely, magnetic-planetary-gear permanent magnet (MPG-PM) machine has been introduced. MPG-PM machines have attracted increasing concern and interest, due to the dramatic improvements of power (torque) density, efficiency, high durability, high gear ratio, and thermal dissipation ability, and are widely used in high driving torque and/or low rotational speed applications [15, 16]. Most of the traditional PG machine parameter design methods only consider the case where the magnetic pole shape is relatively regular, and the magnetic pole does not have a pole shoe, but the optimal size problem existing in the practical application of the magnetic bearing is not considered. Therefore, the designed MPG-PM machines have many shortcomings in practical application. For example, the stator core material and coil turns are not fully utilized [17, 18].

This paper designs and optimizes the parameters of an MPG-PM machine in terms of design requirements and existing key problems, and gradually refines the design and optimization methods of its key parameters. Finally, the prototype machine is tested and verified to provide reference for the development of high performance and low cost MPG-PM machines.

2. TEST PROTOTYPE PARAMETER DESIGN

The whole MPG-PM machine is divided into a motor drive part and a PG transmission part. The two parts are magnetically isolated by the rotor core of the motor, and the two parts can be operated
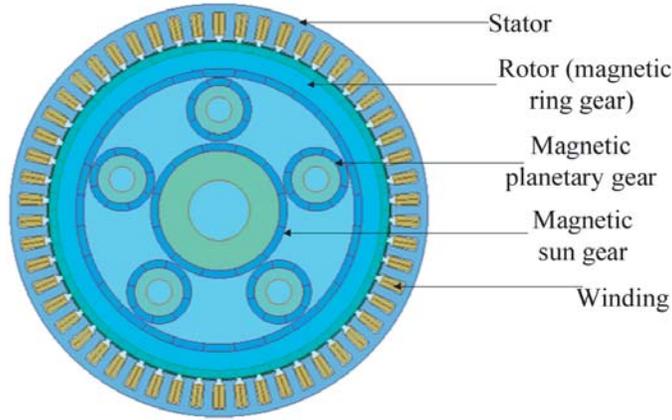
Figure 1. Topologies of MPG-PM machine.

independently. Therefore, two modules are calculated in the subsequent simulation analysis, and the effects of parameters on motor performance and transmission performance are analyzed respectively. Fig. 1 shows the topology of the MPG-PM machine, which consists of four main components, namely the stator, rotor (magnetic ring gear), magnetic sun gear, and magnetic planet gear.

In this section, the electromagnetic performances of MPG-PM machines are calculated and compared using 2-D FEA, including the magnetic saturation, torque, pole shoe thickness, stator outer diameter, and coil turns. The design data of the proposed MPG-PM machine are shown in Table 1.

Table 1. Key specifications and dimensions of MPG-PM machine.

Quantity	MPG-PM
Based speed nb (rpm)	1000
magnetic planet gear center diameter (mm)	38.5
Inner Diameter of Stator (mm)	70.6
Outer Diameter of Stator (mm)	100
PM material	NeFe35
Number of turns per coil	50
Gear ratio	$1 : 4 : -2$
stator punching material	DW310-35
Airgap of machine (mm)	1
Pole-pairs of magnetic sun gear	6
Pole-pairs of magnetic planet gear	3
Pole-pairs of magnetic outer rotor	24
Pole-pairs of Inner tooth magnetic steel	12
PM height of magnetic sun gear (mm)	2.5
PM height of magnetic ring gear (mm)	2.5
PM height of magnetic planet gear (mm)	2.5

2.1. Optimal Stator Pole Shoe Thickness

The stator pole shoe thickness must be designed to meet the magnetic circuit requirements. When the pole shoe thickness is properly designed, the air gap density under the pole shoe is equal. Stator
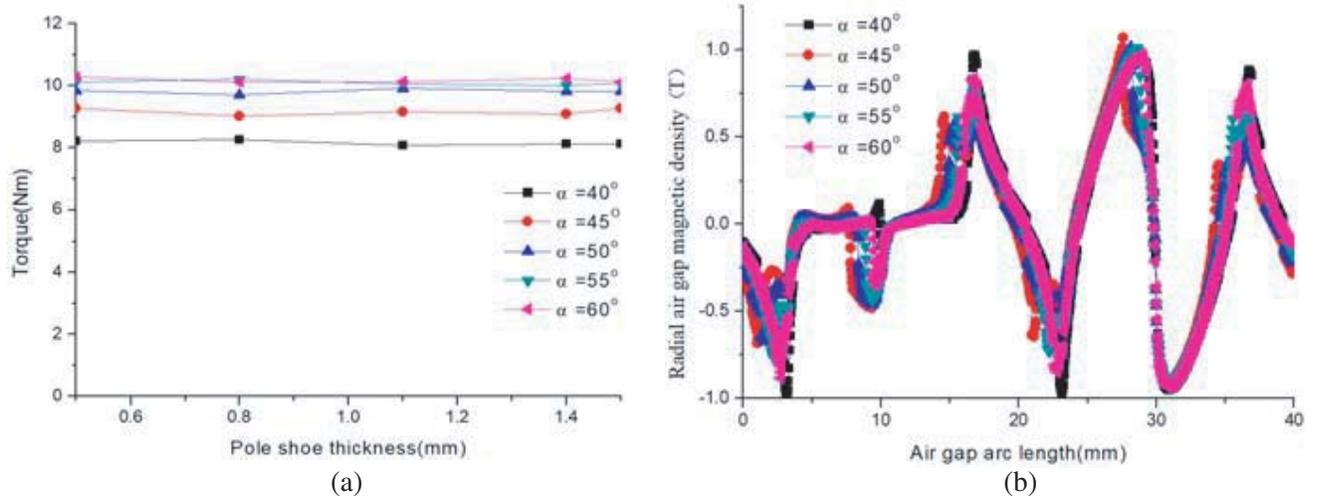
Figure 2. Optimal stator pole shoe thickness. (a) Pole shoe thickness vs torque. (b) Air gap arc length vs radial air gap magnetic density.

pole shoe thickness is analyzed and optimized by FE analysis, and pole shoe thickness d_m varies from 0.5 mm to 1.5 mm. The magnetic pole angle α changes evenly in the range of $40° \sim 60°$. The relationship between the transmitted torque F and pole shoe thickness d_m and magnetic pole angle α is studied. The corresponding relationship curve is shown in Fig. 2. We can see from Fig. 2(a) that when the pole shoe thickness d_m is 1.30 mm, and the magnetic pole angle α is 60°, the transmission torque F reaches the maximum value. When pole shoe thickness $d_m = 1.30$ mm and magnetic pole angle α changes uniformly in the range of $40° \sim 60°$, the influence of the change of the magnetic pole angle on the air-gap magnetic flux density is studied. The corresponding relationship curve is shown in Fig. 2(b). It can be seen from Fig. 2(b) that the air-gap magnetic flux densities under the pole shoe corresponding to different magnetic pole angles are basically equal, and the pole shoe thickness is relatively reasonable.

2.2. Optimal Stator Outer Diameter

Take the opening groove slot width $b_n = 5$ mm and the outer diameter d_s to change uniformly in the direction of the arrow in the range of $95 \sim 105$ mm. Study the relationship between the magnetic flux
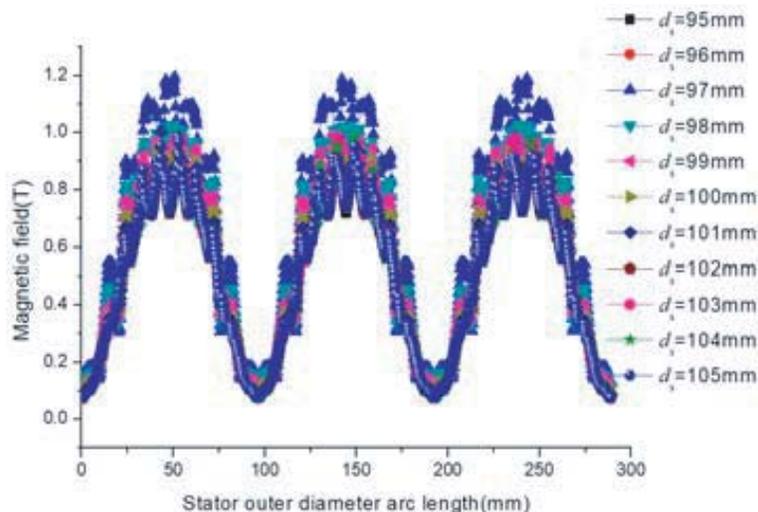

Figure 3. Magnetic field vs stator outer diameter.

density in the stator core yoke and the yoke width. The corresponding relationship curve is shown in Fig. 3. As can be seen from Fig. 3, when $b_n = 5\,\text{mm}$, the larger the outer diameter of the stator d_s is, the smaller the magnetic flux density is in the yoke. In order to make reasonable use of the stator core and obtain a large transmission torque, the stator outer diameter is $d_s = 98\,\text{mm}$, and the width of the open slot is $b_n = 5\,\text{mm}$.

2.3. Transfer Torque

The transmitted torque is related to the current and position angle. According to the design parameters of the prototype, the range of the current is $5 \sim 20\,\text{A}$. The position angles of the magnet sun gear, magnet planetary gear, and magnet ring gear are in the range of $0 \sim 30\,\text{deg}$. The transmission torque varies with current and position angle. The corresponding relationship is shown in Fig. 4. It can be seen from Fig. 4(a) and Fig. 4(b) that the current of magnet sun gear and magnetic planet gear has almost no effect on torque. It can be seen from Fig. 4(c) that the current of rotor (magnet ring gear) has a great influence on the torque. Due to the limitation of the maximum ampere-turns number of this machine, the torque linearity can be improved by reducing the current and increasing the number of the coil turns. Considering the need for heat dissipation and transmitted torque of this machine, the number of selected coil turns is 130.
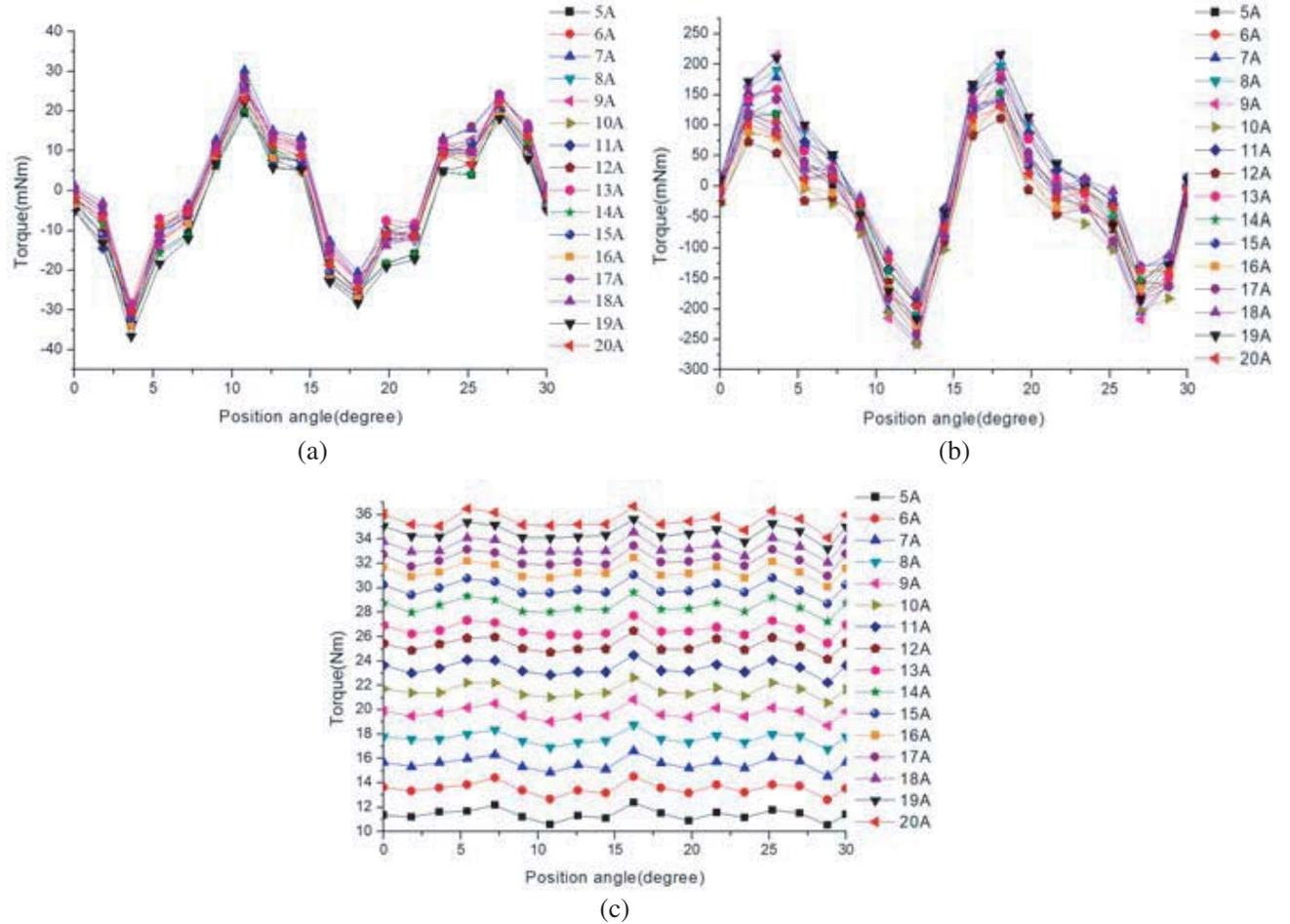

(a)

(b)

(c)

Figure 4. Torque-angle characteristics. (a) Torque-angle characteristics of magnetic planet gear. (b) Torque-angle characteristics of magnetic sun gear. (c) Torque-angle characteristics of rotor (magnetic ring gear).

2.4. Finite Element Analysis

By optimizing stator pole shoe thickness, the number of stator coil turns, and stator outer diameter, a new magnetic gear transmission mechanism is obtained, and the theoretical design results are simulated to analyze the distribution of magnetic flux and magnetic flux density. Fig. 5 is magnetic flux lines and magnetic flux density distribution diagrams of the magnetic gear motor. The magnetic fields between the magnetic sun gear part and magnetic planetary gear part are relatively independent. Their specific values are all around 1.1 T in Fig. 6, which contributes to achieving the desirable transmitting torque in the proposed new machine. It indicates that the magnetic coupling between the two parts is low, which lays the foundation for achieving the high torque operation of the machine.
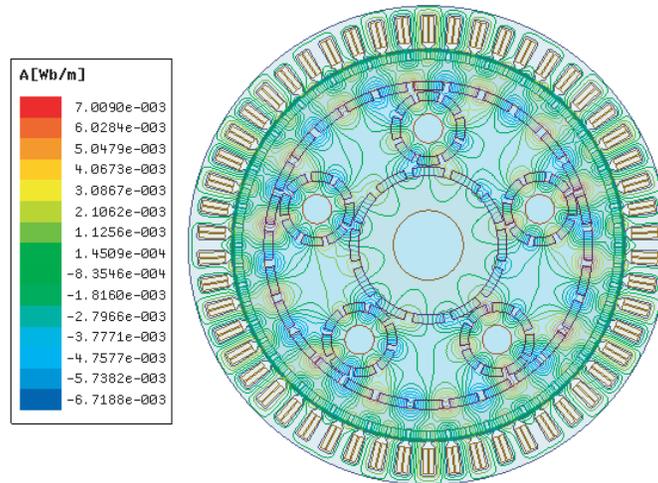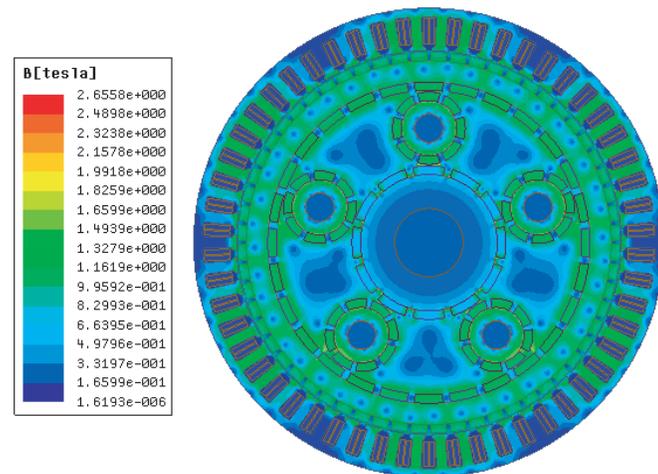

Figure 5. Magnetic flux lines.

Figure 6. Magnetic flux density distribution.

3. EXPERIMENTAL VALIDATION

To further verify the theoretical analysis, we process MPG-PM machine, as shown in Fig. 7. The test results on this prototype can be used as verification for finite element analysis. The measured and predicted transmitting torques are compared in Fig. 8 with satisfied agreement.
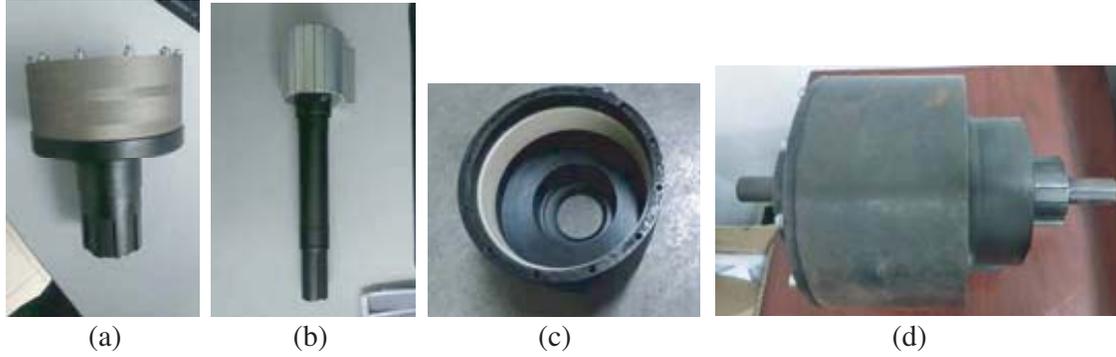
Figure 7. Prototyped MPG-PM machine. (a) Magnetic planetary gear. (b) Magnetic sun gear. (c) Outer ring gear. (d) MPG-PM machine.
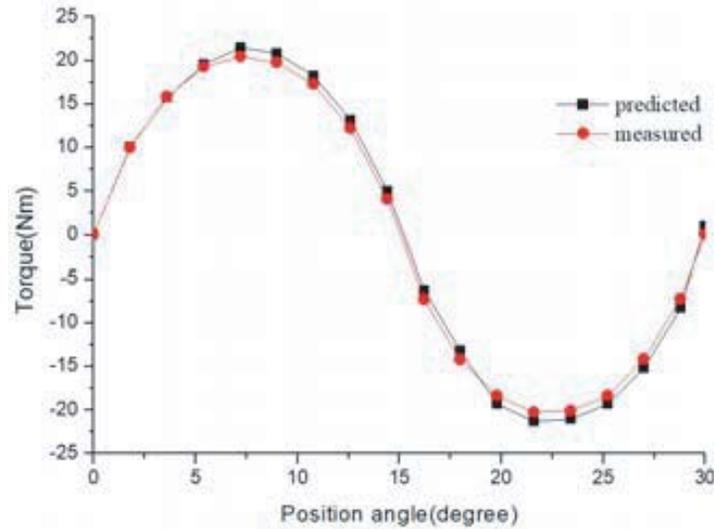

Figure 8. Torque-angle characteristics between the predicted and measured designs.

A prototype MPG-PM machine has been fabricated to validate theoretical analysis results. Experimental results on the prototype show that the measured two transmitted torques are in good agreement with the predicted torque.

4. CONCLUSION

The mechanical structure and magnetic circuit design of MPG-PM machines are reasonable, and the small volume and low power consumption are easy to realize digital control. Prototype MPG-PM machines have been fabricated to validate theoretical analysis results. Experimental results on the prototype show that the measured transmitted torque waveform fits well with the predicted waveform. The prototype of the optimized MPG-PM machine is under construction and will soon be reported for experiments on the MPG-PM prototype machine.

REFERENCES

1. Kikuchi, S. and K. Tsurumoto, "Design and characteristics of a new magnetic worm gear using permanent magnet," *IEEE Transactions on Magnetics*, Vol. 29, No. 6, 2923–2925, 1993.

2. Cirimele, V., L. Dimauro, M. Repetto, et al., "Multi-objective optimisation of a magnetic gear for powertrain applications," *International Journal of Applied Electromagnetics and Mechanics*, Vol. 60, No. 5, 1–10, 2019.

3. Muruganandam, G., S. Padma, and P. Selvakumar, "Design and implementation of a novel magnetic bevel gear," *Control Engineering & Applied Informatics*, Vol. 15, No. 2, 30–37, 2013.

4. Shin, H. and J. Chang, "Comparison of radial force at modulating pieces in coaxial magnetic gear and magnetic geared machine," *IEEE Transactions on Magnetics*, Vol. 54, No. 3, 1–4, 2018.

5. Lee, J. and J. Chang, "Analysis of the vibration characteristics of coaxial magnetic gear," *IEEE Transactions on Magnetics*, Vol. 53, No. 6, 1–4, 2016.

6. Shin, H. M. and J. H. Chang, "Analytical magnetic field calculation of coaxial magnetic gear with flux concentrating rotor," *IEEE Transactions on Magnetics*, Vol. 52, No. 7, 1–4, 2016.

7. Oleg, M., D. Pavel, O. Sergey, et al., "A novel double-rotor planetary magnetic gear," *IEEE Transactions on Magnetics*, Vol. 54, No. 11, 1–5, 2018.

8. Zhang, X., X. Liu, and Z. Chen, "A novel coaxial magnetic gear and its integration with permanent-magnet brushless motor," *IEEE Transactions on Magnetics*, Vol. 52, No. 7, 1–7, 2016.

9. Li, W., K. T. Chau, et al., "A new linear magnetic gear with adjustable gear ratios and its application for direct-drive wave energy extraction," *Renewable Energy*, Vol. 105, 199–208, 2017.

10. Yang, Q., G. Bao, and H. Zhang, "Design and analysis of a cylindrical linear magnetic-geared generator," *Ferroelectrics*, Vol. 504, No. 1, 180–188, 2016.

11. Pakdelian, S., Y. B. Deshpande, and H. A. Toliyat, "Design of an electric machine integrated with trans-rotary magnetic gear," *IEEE Transactions on Energy Conversion*, Vol. 30, No. 3, 1180–1191, 2015.

12. Morimoto, E., K. Hirata, and N. Niguchi, "Performance evaluation of an axial-type magnetic-geared motor," *Electrical Engineering in Japan*, Vol. 194, No. 1, 48–59, 2016.

13. Wang, R. J., S. Gerber, et al., "An axial flux magnetically geared permanent magnet wind generator," *IEEJ Transactions on Electrical and Electronic Engineering*, Vol. 10, S123–S132, 2015.

14. Chen, M., K. T. Chau, W. Li, et al., "Cost-effectiveness comparison of coaxial magnetic gears with different magnet materials," *IEEE Transactions on Magnetics*, Vol. 50, No. 2, 821–824, 2014.

15. Shin, H. M. and J. H. Chang, "Analytical magnetic field calculation of coaxial magnetic gear with flux concentrating rotor," *IEEE Transactions on Magnetics*, Vol. 52, No. 7, 1–4, 2016.

16. Bomela, W., J. Z. Bird, and V. M. Acharya, "The performance of a transverse flux magnetic gear," *IEEE Transactions on Magnetics*, Vol. 50, No. 1, 1–4, 2014.

17. Zhu, X., Z. Xiang, L. Quan, et al., "Multi-mode optimization research on a multi-port magnetic planetary gear permanent magnet machine for hybrid electric vehicles," *IEEE Transactions on Industrial Electronics*, 1–10, 2018.

18. Ho, S., Q. Wang, S. Niu, et al., "A novel magnetic-geared tubular linear machine with Halbach permanent-magnet arrays for tidal energy conversion," *IEEE Transactions on Magnetics*, Vol. 51, No. 11, 11–17, 2015.