EVTeC 2025
7th International Electric Vehicle Technology Conference 2025
20259023

Development of Powertrain System Integrated of Magnetic Gear and Multiple High-Speed motors

Kohei Aiso [1)] Kan Akatsu [2)]

1) Shibaura Institute of Technology, Department of electrical engineering, Tokyo, Japan

E-mail: E-mail: K-aiso@shibaura-it.ac.jp

2) Yokohama National University, Department of Faculty of Engineering, Division of Intelligent Systems Engineering, Yokohama, Japan

E-mail: akatsu-kan-py@ynu.ac.jp

ABSTRACT: A technical innovation for the downsizing of motor system is necessary to realize the saving energy, and roomy and comfortable car interior space in Electric Vehicles (EVs). In this research, a novel powertrain system of multiple high speed motors and Magnetic Multiple Spur Gear (MMSG) for the electric vehicle is proposed. The MMSG can achieve the high transmitted efficiency by magnetically transmission using permanent magnets. Moreover, the drive system realizes the drastic downsizing by using multiple high speed motors which rotate in the speed region of 50000 min^{-1}. In this paper, the motor system is designed for a powertrain of EVs, the optimal configuration of the gear ratio, number of motors, and motor shape from the perspective of downsizing and improving efficiency is clarified.

KEY WORDS: Magnetic gear, high-speed motors, Electric vehicles

1. INTRODUCTION

The downsizing of motor drive system is required to realize the saving energy and the roomy and comfortable car interior space for EVs. As one of methods for downsizing, the volume and weight of a motor can be reduced by the high speed drive and the lower output torque under a constant output power. Then, mechanical gears are used to transform a demand torque and speed according to the load. However, mechanical gears have problems that gear teeth are worn by contacting and require the lubrication and the maintenance. Moreover, the gear volume becomes larger and the transmitted efficiency is decreased by increasing the gear ratio as the rotational speed is higher. In order to take advantage of higher motor speeds, the technical innovation of gears is necessary. Therefore, this research focuses on magnetic gears. Magnetic gears can convert the torque and rotational speed through magnetic force of permanent magnets in non-contact, that can solve problems of mechanical gears and realize the motor system with maintenance-free, low acoustic noise and low vibration characteristics. By taking advantage of the non-contact power transmission, the motor system can be made smaller and lighter by further increasing the motor speed.

Most of conventional magnetic gears are based on the principle of magnetic flux modulation using pole pieces as shown in Fig. 1(a). These magnetic gears transmit power by the flux modulation technique using stationary pole pieces, that can obtain high torque density of more than 100 kNm/m^3 [(1)-(3)]. Additionally, the magnetic geared motor integrated with a motor and a magnetic gear enable compact system size [(4)(5)]. However, there are no magnetic gears that can be used for applications exceeding 10000 min^{-1} such as automobiles because it decreases the transmitted efficiency because the eddy current loss and core loss due to harmonic flux generate in the flux modulation process. Moreover, the mechanical strength of input rotor is low because large rotor diameter makes it susceptible to centrifugal force at high-speed rotation. Although the rotor can be reinforced by using retaining sleeves[(6)(7)], it is difficult to suppress the mises stress because the magnetic gear needs to ensure the large diameter of input rotor for the high transmitted torque.

To overcome problems, a novel magnetic gear has been proposed in this research [(8)-(11)]. It called as Magnetic Multiple Spur Gear (MMSG). In Fig. 1(b), MMSG consists of one output rotor, and several input rotors which are input by small-sized high speed motors. It can easily drive in high speed of more than 50,000 min^{-1} by separating into multiple input rotors with small diameter. Additionally, the flux transmission method without the pole pieces can decrease the harmonic flux in the air gap and reduce the eddy current loss and core loss, that realizes high transmitted efficiency in the high speed rotation. The MMSG is input by multiple small-sized motors. These multiple motors are driven in a maximum rotational speed of exceeding 50,000 min^{-1} to achieve high power

(a) Conventional magnetic gear (b) Proposed MMSG system
Fig. 1 Magnetic gear structure.

density, the total output powers are efficiently converted by using MMSG, that can realize the downsizing and high efficiency of the drive system. In previous study, it has been shown that the prototype of MMSG system can achieve the high torque density and high efficiency in the high-speed range(10)(11). However, the optimal configuration of magnetic gears and multiple motors for the actual EV powertrain to achieve compactness, lightness and high efficiency has not been clarified.

This study clarifies the optimal configuration of types of magnetic gear, the gear ratio, number of input motors, and motor shape in proposed system from the perspective of downsizing and improving efficiency for EV powertrain.

2. MOTOR SYSTEM INTEGRATED OF MMSG AND MULTIPLE MOTORS

As described in Section I, the motivation of this research is to take advantage of the non-contact power transmission of magnetic gear, the motor system can be made smaller and lighter by further increasing the motor speed. In this section, the proposed motor system is described.

2.1. Magnetic Multiple Spur Gear (MMSG)

Fig. 1(b) shows the structure of the proposed MMSG. It consists of one output rotor and several input rotors which are rotated by the multiple high speed motors. The magnetomotive force of each input rotor is directly transformed to the output rotor. Then, the gear ratio G between the input rotor and the output rotor is given by:

$$G = Z_l / Z_h \tag{1}$$

where Z_h, Z_l, and G are the pole pairs of the input rotor and the output rotor, and the gear ratio, respectively. The output torque T_l is defined as follow:

$$T_l = GT_{nh} \times N \tag{2}$$

where T_{nh}, N are the torque of the n_{th} input rotor, number of input rotors, respectively. That is, the output torque is obtained by the product of the torque of one motor, gear ratio, and number of motors. From the operation principle, there are some advantages in MMSG as follows. (i) The mechanical strength of input rotor is high because the mises stress generating at the input rotor can be reduced in high speed rotation by separating into multiple small-sized input rotors. (ii) High efficiency is realized in the high speed region because the eddy current loss in the magnet and core loss can be much reduced by decreasing the harmonic flux due to pole piece less construction. Moreover, (iii) it can achieve high torque density because the fundamental component of flux density

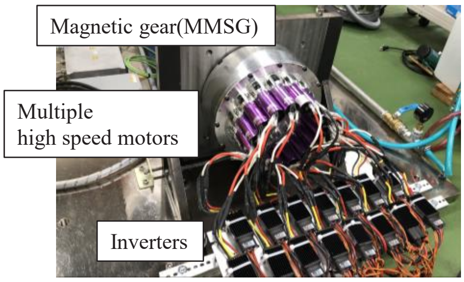


Fig. 2 Prototype motor system.

2.2 Performances of MMSG

The performances of MMSG system have been evaluated by the experiment(11). The prototype machine is shown in Fig. 2. The prototype system was designed to satisfy 25 kW and the gear ratio 1:10, the dimension of the gear is φ220 mm×L26.5 mm. The MMSG is driven by 15 motors and 15 inverters, a commercial brushless motor of maximum power 1.7 kW is used as the input motor. Fig. 3, Fig. 4, and Fig. 5 show the measured gear efficiency, motor efficiency, and system efficiency including motor and gear. As shown in Fig. 3, the prototype gear achieves the high efficiency of more than 95 % even if the rotational speed increases up to 21,000 min^{-1}. As shown in Fig. 4 and Fig. 5, the system efficiency of about 80 % is achieved in the high-speed and low load area. However, the system efficiency is low in the low speed and the high load area, that depends strongly on the efficiency distribution of the brushless motor. Fig. 6 shows the gear efficiency and system efficiency at maximum power 25 kW and in the input speed up to 42,000 min^{-1}. The gear efficiency of more than 95%, the system efficiency of more than 85% can be obtained because the motor efficiency increases in the range of high speed and high output power.

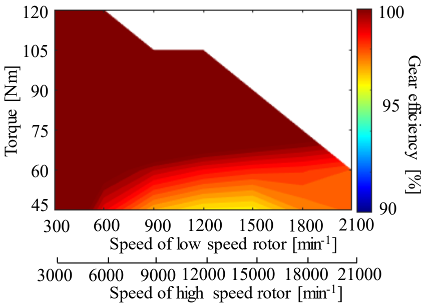


Fig. 3 Measured gear efficiency.

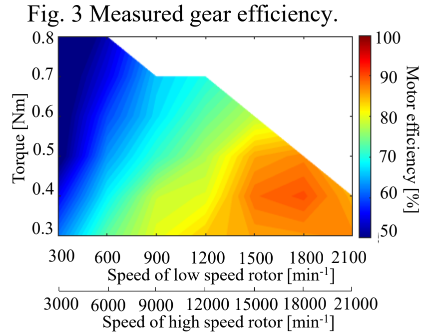


Fig. 4 Measured motor efficiency.

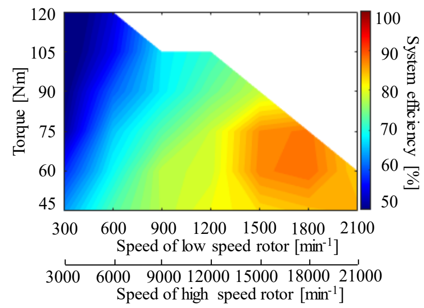


Fig. 5 Measured system efficiency including motor and gear.

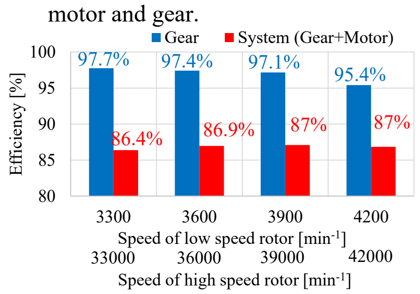


Fig. 6 Measured system efficiency and gear efficiency at maximum output power 25 kW.

3. DESIGN OF MMSG SYSTEM FOR EV

3.1. Specifications for powertrain system

In this section, the proposed motor system is designed as the powertrain system for EVs. The configuration of powertrain system is shown in Fig. 7. The system of MMSG and multiple motors is integrated with the mechanical gear, the output power is added to the output power of another motor by mechanical gears. The Model 1 and Model 2 are configured by the parallel shaft mechanical gear and the coaxial mechanical gear. The total system achieves the output power 150 kW and the output torque 3090 Nm.

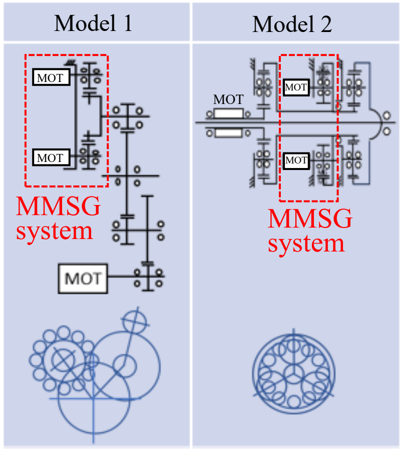
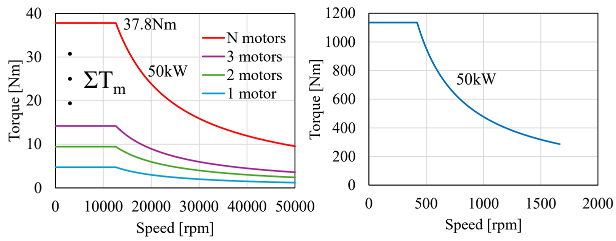


Fig. 7 Configuration of powertrain system.

Table. 1 Specifications of MMSG system and mechanical gear.

Output power of system [kW]	50
Maximum torque of system [Nm]	1135
Maximum torque of total motors [Nm]	37.8
Maximum rotational speed of tire [min^{-1}]	1,167
Maximum rotational speed of input motor [min^{-1}]	50,000
Gear ratio (Mechanical gear + Magnetic gear)	1:30



(a) Input motors (b) Mechanical gear

Fig. 8 Output characteristics of multiple motors and mechanical gear.

The specifications of MMSG system and mechanical gear are shown in Table. 1. The drive system satisfies the maximum power 50 kW and the maximum torque 1135 Nm to drive WLTC mode. The output characteristics of multiple motors and the mechanical gear show Fig. 8. The system gear ratio of magnetic gear and mechanical gear is 1:30, the maximum rotational speeds of the tire and the input motor are 1,667 min^{-1} and 50,000 min^{-1}, respectively. The system diameter is designed to less than 260 mm.

3.2. Design of MMSG

In this design, two types of MMSG are considered. The structures of MMSG are shown in Fig. 9. The outer type MMSG has an output rotor outside of input rotors. The inner type MMSG has an output rotor inside of input rotors. As characteristics of the outer type MMSG, the high torque density of magnetic gear can be easily obtained because the diameter of output rotor is larger. On the other hand, in the inner type MMSG, the diameter of motor can be ensured because the distance between the input rotor is large, that makes easier to reduce the size of the motor. Additionally, the small bearing of output rotor can be used.

Fig. 10 shows the shape of MMSG. In the MMSG, the following geometrical condition is satisfied to prevent torque reduction and pulsation in the flux transmission between the input and output rotors.

$$R_l \theta_l = R_h \theta_h \tag{3}$$

where R_l, R_h, θ_l, and θ_h are the inner radius of output rotor, the radius of input rotor, magnetic pole arc degree of output rotor, and magnetic pole arc degree of input rotor, respectively. Substituting the relation of $Z_l\theta_l = \pi$ and $Z_h\theta_h = \pi$ into equation (3), the relation between the rotor radius and gear ratio is expressed as follows.

$$\frac{R_l}{Z_l} = \frac{R_h}{Z_h} \leftrightarrow R_h = \frac{1}{G} R_l \tag{4}$$

That is, the radius of the input rotor is determined by the radius of the output rotor and the gear ratio. If the condition in equation (3) is considered, the following equation is applied to limit the number of input rotors not to contact between neighboring input rotors in outer type MMSG.

$$N_0 < \frac{\pi}{sin^{-1}(\frac{R_h}{R_l - R_h - l_g})} \tag{5}$$

Where N_o, l_g are number of input rotor in outer type MMSG, and the air-gap length between input rotor and output rotor, respectively. Additionally, the radius of motor needs to satisfy the following equation so that motors do not contact each other.

$$r_{mo} \leq (R_l - R_h - l_g) sin\left(\frac{\pi}{N_o}\right) \tag{6}$$

where r_{mo} is the radius of motor in the outer type MMSG.

In the case of an inner type MMSG, the number of rotors is limited by the following formula.

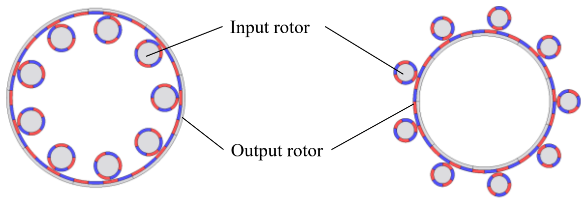
$$N_i < \frac{\pi}{\sin^{-1}(\frac{R_h}{R_l + R_h + l_g})} \tag{7}$$

where N_i, is number of input rotor in the inner type MMSG. The radius of motor is determined to satisfy the following equation.

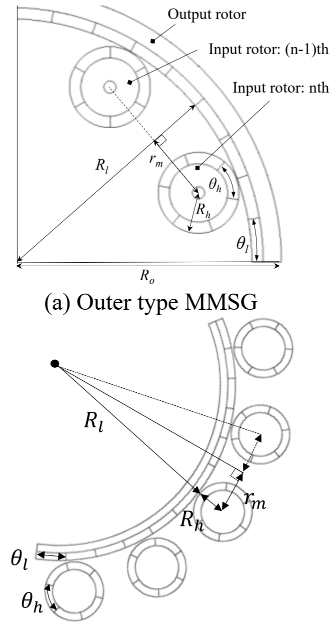
$$r_{mi} \leq (R_l + R_h + l_g) \sin(\frac{\pi}{N_i}) \tag{8}$$

where r_{mi} is the radius of motor in the inner type MMSG. From Eq. (5), (6), (7), and (8), in the inner type MSMG, more input rotors can be arranged and the motor diameter can be increased compared with the outer type MMSG.

The torque density of MMSG for number of input rotors shows Fig. 11. As shown in Fig. 11, the torque density of MMSG can be increased by increasing the number of input rotor. Additionally, the MMSG of high gear ratio needs to increase the number of input rotor to achieve high torque density compared with the MMSG of low gear ratio. On the other hand, the increasing number of input rotor results in decreasing the diameter of motor by Eq. (6) and (8), that causes to become large motor size due to increasing the motor stack length. Therefore, the gear ratio of magnetic gear is set at 1:6, which allows the highest torque density to be achieved under a small number of input rotors. The gear ratio of mechanical gear is set at 1:5.



(a) Outer type MMSG (b) Inner type MMSG
Fig. 9 Structure of two types MMSG.



(a) Inner type MMSG

Fig. 10 Shape of MMSG.

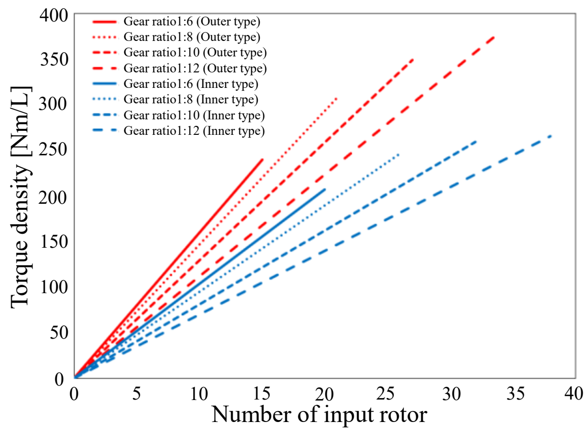


Fig. 11 Torque density of MMSG.

3.3. Design of Motors

Fig. 12 shows a standard model of PMSM. The structure is 4 pole and 6 slots, Surface Permanent Magnet Synchronous Motor (SPMSM). Fig. 13 shows the design flow of motor. Once the number of input rotors is decided, the required torque and output power of one motor are determined, and the motor diameter is determined by Eq. (6), and (8). Next, based on the standard model in Fig. 12, the dimensions of each part of the rotor and stator are determined by the ratio of diameter to the standard model. The magnetomotive force and motor stack length are determined so that the current density and the required torque are achieved.

3.4. Evaluation of size and weight for number of input rotors

The designed models of each type are shown in Table 2. The models with different numbers of input rotors are designed for outer type and inner type of magnetic gear. As the number of input rotor increases, the diameter of motor is decreased, the stack length of motor is increased to achieve the required torque.

The size and weight of designed models are shown in Fig. 14 and Fig. 15. The size and weight of motors include total volume and weight of multiple motors. As shown in Fig. 14 and Fig. 15, as the number of input rotor increases, the size and weight of magnetic gear decrease due to increasing high torque density of magnetic gear, however, the size and weight of motors increases because the torque density of one motor is decreased due to becoming large stack length. That is, there is a trade-off relationship in size and weight between magnetic gear and motors for the number of input rotors. Comparing the outer type MMSG and the inner type MMSG, the system size of outer type MMSG

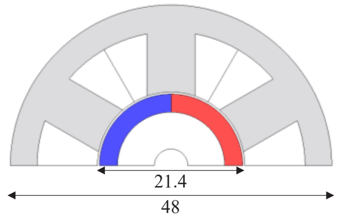


Fig. 12 Standard structure of PMSM (1/2 model).

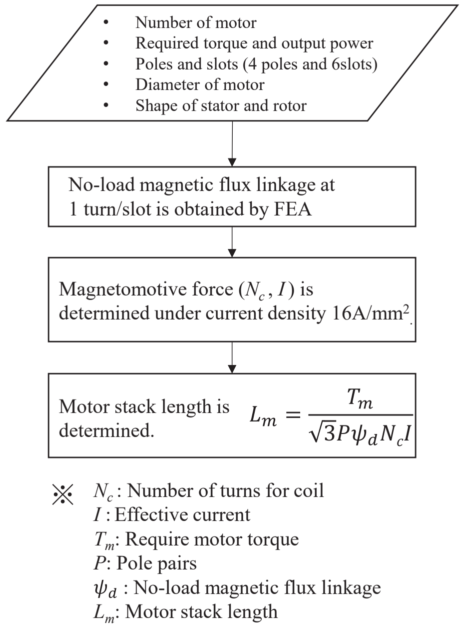
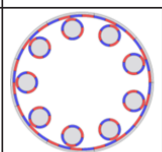
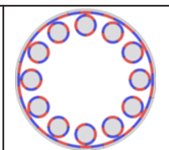
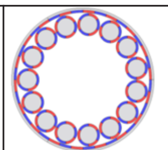
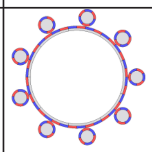
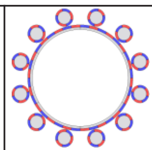
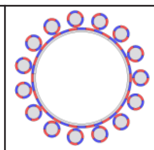
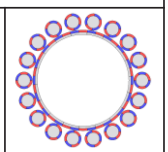
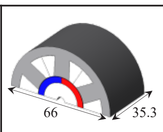
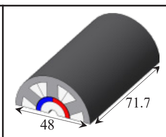
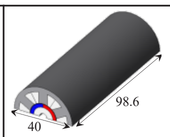
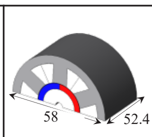
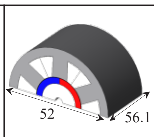
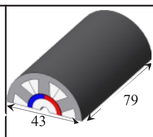
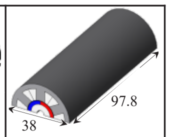
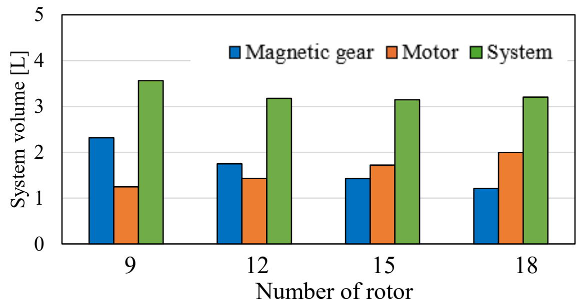


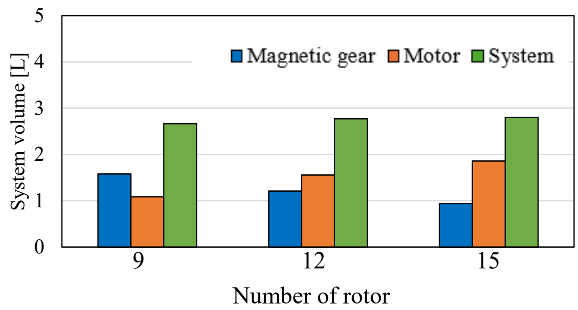
Fig. 13 Design flow of motor.

Table 2. Designed models of outer type MMSG and inner type MMSG.

	Outer type MMSG			Inner type MMSG			
Magnetic gear models							
Number of rotor	9	12	15	9	12	15	18
Gear ratio	1:6			1:6			
Pole pairs of input rotor	3			3			
Pole pairs of output rotor	18			18			
Diameter of gear [mm]	250			230	230	240	250
Motor models							
Output power [kW]	5.6	4.2	3.3	5.6	4.2	3.3	2.8
Torque [Nm]	4.2	3.2	2.5	4.2	3.2	2.5	2.1
Diameter of motor[mm]	66	48	40	58	52	43	38
Stack length[mm]	35.3	71.7	98.6	52.4	56.1	79	97.8

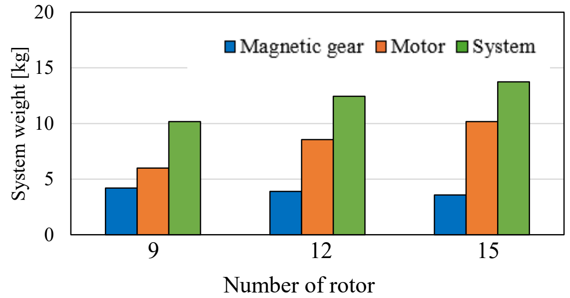


(a) Outer type MMSG

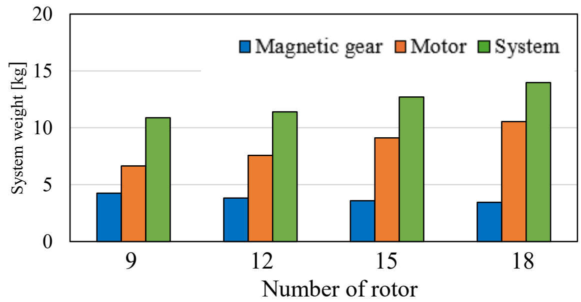


(b) Inner type MMSG

Fig. 14 System size.



(a) Outer type MMSG



(b) Inner type MMSG

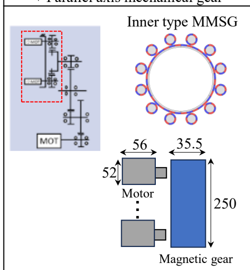
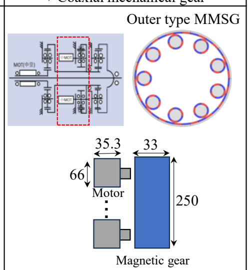
Fig. 15 System weight.

can be reduced compared with that of the inner type because the volume of magnetic gear is smaller, the system weights are almost same in both types. Although the inner type MMSG has a larger system volume, the system weight does not increase so much because the diameter of the output rotor in magnetic gear is small, and the weight of motors can be reduced compared with that of outer type MMSG. From these results, considering the size and wight, the numbers of input rotor (number of motor) in outer type and inner type are set to 9, and 12, respectively.

3.5. Configuration of designed models

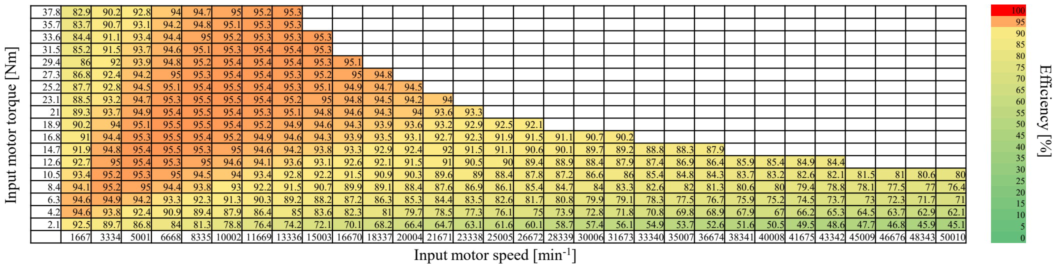
The configuration of designed models shows Table. 3. As shown in Table 3, the Model 1 is configured with the inner type MMSG system and the parallel axis mechanical gear, the Model 2 is configured with the outer type MMSG and the coaxial mechanical gear. The power density of outer type MMSG system is 18.8 kW/L and 4.9 kW/kg, that of inner type MMSG system is 15.7 kW/L and 4.4 kW/kg. The power density is calculated by considering only magnetic gear (MMSG) and multiple motors, does not consider mechanical gear, a housing of motor and gear, inverter.

Table 3. Configuration of designed models.

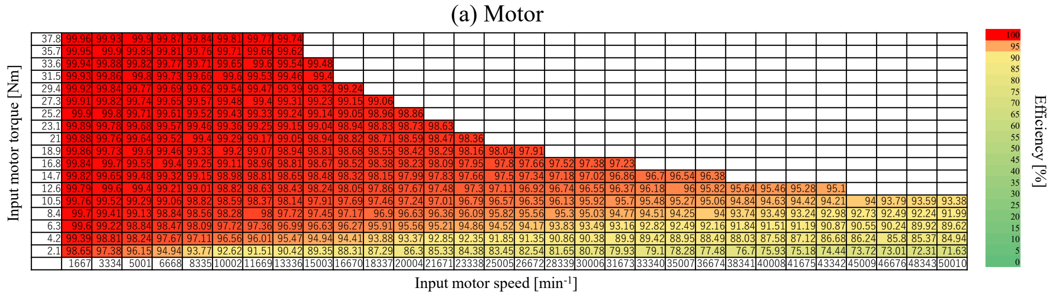
	Model 1	Model 2
	Inner type MMSG + Parallel axis mechanical gear	Outer type MMSG + Coaxial mechanical gear
Model		
Gear ratio	6	6
Number of rotor	12	9
Power density [kW/L]	15.7	18.8
Power density [kW//kg]	4.4	4.9

4. EVALUATION OF SYSTEM EFFICIENCY

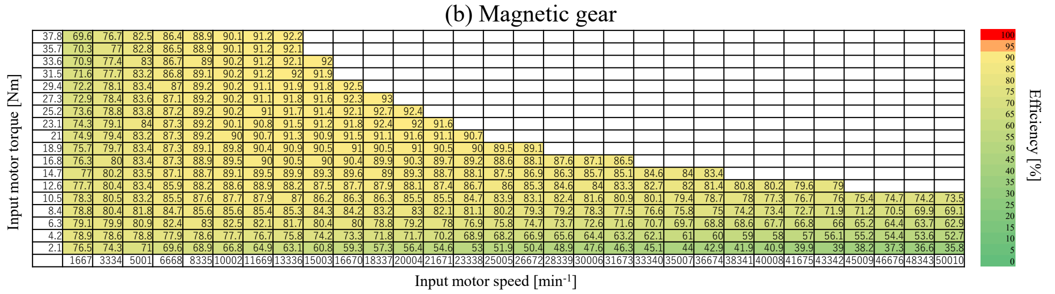
The efficiency map of magnetic gear, motor, and system (magnetic gear + motors + inverter) are evaluated in the input speed range up to 50,000 min^{-1}. The efficiency maps of the Model 1 and Model 2 are shown in Fig. 16 and Fig. 17. As shown in Fig. 16 and Fig. 17, the efficiency maps show almost the same distribution for these types. The magnetic gear achieves high efficiency of more than 95 % in wide speed range. However, the efficiency is reduced due to the eddy current loss in magnets in the range of low torque and high speed. The motor achieves the efficiency of more than 90 % in the input speed up to 25,000 min^{-1}. However, the core loss and eddy current loss in magnet increase in the input speed range of more than 25,000 min^{-1}, the motor efficiency are decreased. The losses of motors and magnetic gear in high-speed range need to be reduced.



(a) Motor

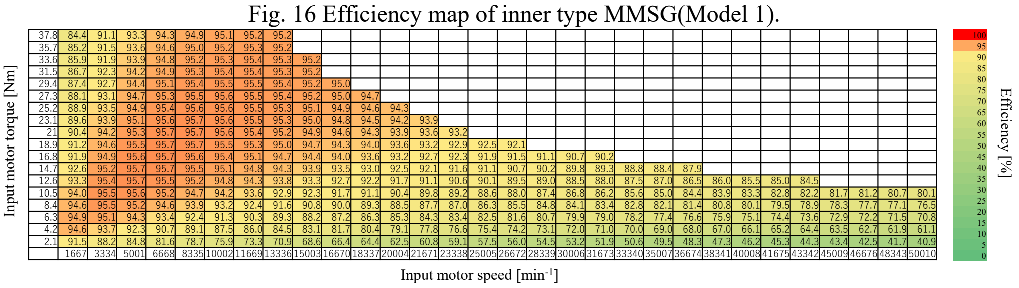


(b) Magnetic gear

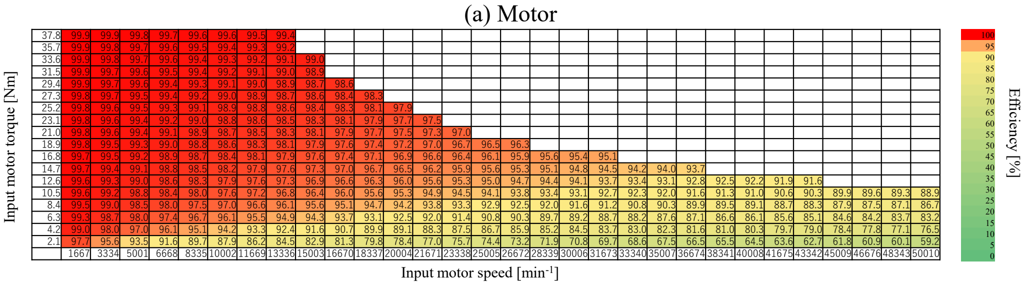


(c) System

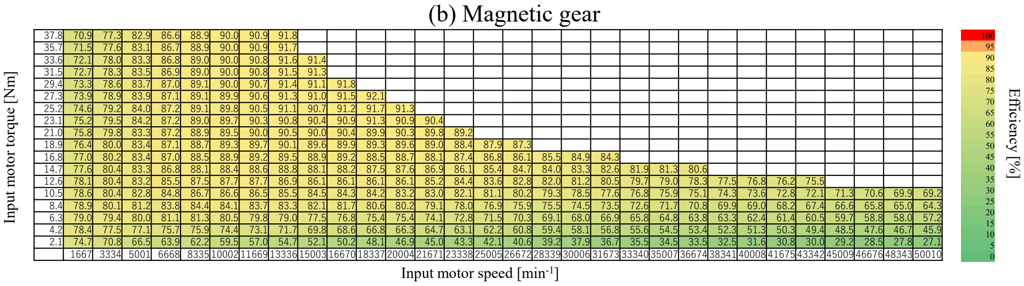
Fig. 16 Efficiency map of inner type MMSG(Model 1).



(a) Motor



(b) Magnetic gear



(c) System

Fig. 17 Efficiency map of outer type MMSG (Model 2).

5. CONCLUSION

In this paper, a novel motor drive system of multiple high-speed motors and Magnetic Multiple Spur Gear (MMSG) for the electric vehicle was proposed. The proposed system was designed as a powertrain of EV, the relationship between gear ratio and number of input rotor was clarified in terms of volume, mass, and power density for two models of the outer type MMSG and the inner type MMSG. The outer type MMSG had an advantage in terms of system size, however, the difference in system weight was almost the same in both types. Additionally, the efficiency distribution of the magnetic gear and motor was almost the same for each model, but there is a need to reduce losses of the magnetic gear and motor during high-speed rotation. In the future, the system efficiency will be improved by reducing losses of magnetic gear and motors in the high speed range.

REFERENCES

(1) K. Atallah, D. Howe, “A novel high-performance magnetic gear”, *IEEE Transactions on Magnetics*, Vol.37, No.4, pp.2844-2846, Jul 2001.

(2) M. C. Gardner, M. Johnson, H. A. Toliyat, “Analysis of High Gear Ratio Capabilities for Single-Stage, Series Multistage, and Compound Differential Coaxial Magnetic Gears,” IEEE Transaction on Energy Conversion, pp. 1-8, Sept. 2018.

(3) B. Dai, K. Nakamura, Y. Suzuki, Y. Tachiya, K. Kuritani, “Comparison of Two Different Interior Permanent Magnet Type Low-speed Rotor Structures of Axial-Flux Magnetic Gear,” IEEJ Journal of Industry Applications, Vol.10, No.6, pp.632-637, Aug 2021.

(4) M. Johnson, M. C. Gardner, H. A. Toliyat, S. Englebretson, W. Ouyang, and C. Tschida, ”Design, Construction, and Analysis of a Large-Scale Inner Stator Radial Flux Magnetically Geared Generator for Wave Energy Conversion”, *IEEE Transactions on Industry Applications*, Vol. 54, No. 4, pp. 3305-3314, 2018.

(5) R. S. Dragan, R. Clark, E. K. Hussain, K. Atallah, M. Odavic, ”Magnetically Geared Pseudo Direct Drive for Safety Critical Applications,” *IEEE Transactions on Industry Applications*, Vol. 55, No. 2, pp. 1239-1249, Mar 2019.

(6) F. Zhang, G. Du, T. Wang, G. Liu, W. Cao, “Rotor Retaining Sleeve Design for a 1.12-MW High-Speed PM Machine”, *IEEE Transaction on Industry Applications*, Vol. 51, No. 5, pp. 3675-3685, April. 2015.

(7) H. Fang, D. Li, R. Qu, J. Li, C. Wang, B. Song, “Rotor Design and Eddy-Current Loss Suppression for High-Speed Machines With a Solid-PM Rotor,” *IEEE Transaction on Industry Applications*, Vol. 55, No. 1, pp. 448-457, Jan-Feb 2019.

(8) K. Aiso, K. Akatsu, Y. Aoyama: “Motor System Integrated Magnetic Multiple Spur Gear and High Speed Motors for Electric Vehicle”, *2020 IEEE Energy Conversion Congress and Exposition (ECCE),* (2020)

(9) K. Aiso, K. Akatsu, Y. Aoyama: “Characteristics Evaluation of Magnetic Multiple Spur Gear for High Speed Motor Drive System”, *2021 IEEE Energy Conversion Congress and Exposition (ECCE),* (2020)

(10) K. Aiso, K. Akatsu, Y. Aoyama: “A Novel In-Wheel Motor Drive System of Multiple High-Speed Motors Integrated with Magnetic Gear for Electric Vehicle”, *2022 International Power Electronics Conference (IPEC-Himeji 2022- ECCE Asia),* (2022)

(11) K. Aiso, K. Akatsu, Y. Aoyama: “Development of A Novel In-Wheel Motor System Integrated of Magnetic Gear and Multiple High-Speed Motors”, *EVTeC 2023*, (2023)