Motor Length Reduction of Outer Rotor Type SPM Motor by Magnet Overhang Structure with Three-dimensional Flux Recovery

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***Abstract*— This paper presents a novel stator structure for outer rotor type surface permanent magnet (SPM) motors. The magnet overhang structure is a technique to increase the magnet flux by utilizing the space at the coil end, and has been widely used in SPM motors. However, because leakage flux is generated in the overhung area, which is longer than the stator core in the axial direction, the effect of torque improvement was limited. In the proposed stator, the magnet flux in the overhang area was picked using the flux recovery structure. Owing to the proposed stator, the leakage flux was reduced, resulting in a reduction in the motor length compared to conventional motors. In this study, numerical verification was conducted using numerical analysis to clarify the superiority of the proposed structure. From the numerical verification, the motor length reduction effect of the magnet overhung was 1.4 times higher than that of the conventional structure.**

Keywords—Magnet overhang structure, three-dimensional flux recovery structure, Leakage flux, outer rotor, SPM motor.

I. INTRODUCTION

PMSMs are widely used in various applications because they can achieve high-torque characteristics by actively utilizing the magnetic flux of the magnet [1]. Depending on their structural characteristics, they are divided into two types: interior permanent magnet synchronous motors (IPMSMs) [2-3] and surface permanent magnet synchronous motors (SPMSMs) [4-5], with different oriented applications. IPMSMs have the advantage of high torque density and efficiency because reluctance torque can be used in addition to magnet torque. However, permeance distribution occurs in the rotor core in front of the magnet, and torque pulsation is an issue in applications where controllability is required, such as robots, servo motors, and automatic guide vehicles (AGVs). Therefore, SPMSMs are widely used in such applications [6-8]. In this study, a novel motor structure is proposed to achieve high-performance SPMSMs, particularly for AGVs.

For AGVs, motors are mounted inside the wheels to prioritize the space for cargo loading. This configuration is called an in-wheel motor, and there are two types: one is the power supply system via gears [9-10] and the other is the direct drive system that connects directly to the tires [11-12]. In particular, the direct-drive system is considered an effective in-wheel power system because it has fewer parts and is more space-efficient. For SPMSMs used in direct-drive systems, outer-rotor-type SPMSMs [13-14] are effective. In outer rotor-type SPMSMs, magnets are affixed to the thin motor frame, and a rotating magnetic field is supplied from the stator on the inner diameter side. Because the rotor is located on the outer diameter side, the circumference is longer, making it easier to make multiple poles. This feature is also an advantage in the axial thinning required for in-wheel motors of AGVs. However, because the torque density of SPMSMs depends on the number of magnets, the thickness of the outer rotor system is limited.

Structures with overhung magnets have also been proposed [15-16]. In this motor, the magnet is longer than the stator core in terms of the axial length. The stator has a longer axial length than the rotor, because the coil ends protrude from the stator core. The overhung structure is a torque improvement method that utilizes the space on the coil ends. However, the overhung area does not face the stator core and generates a large leakage flux. Consequently, the effect of the overhung structure on motor length reduction is limited, and reducing the leakage flux is an important design issue. This study aims to improve the motor length reduction effect of an overhung structure. Orthodox outer-rotor-type SPMSMs are called reference motors [13], and those with overhung magnets are called conventional motors [15].

In the proposed motor, a novel stator structure is proposed to reduce the leakage flux, which is an issue in the conventional overhung structure. Specifically, the stator core is divided into the tips of the teeth and other parts, and both parts are connected by an adhesion material. The tip of the teeth was manufactured to be longer in the axial direction than the main stator core and had the same length as the overhung magnet. The magnet flux in the overhang area passes through the extended tip and is linked to the stator coil. In this study, this structure is called as the three-dimensional flux recovery structure. Using the proposed structure, the magnet flux in the overhang area can be effectively utilized, and a higher motor length reduction effect can be achieved compared to conventional motors. The purpose of this study is to obtain the magnetic performance of the proposed motor using numerical analysis and to clarify the effectiveness of the proposed novel stator structure.

In Section II, the motor structures of conventional and proposed motors are described. In Section III, the magnetic properties are obtained using a numerical analysis to clarify the effectiveness of the proposed motor. The obtained results were compared to those of conventional motors to clarify their superiority. The magnetic field analysis software JMAG-Designer was used for the numerical verification.

II. Motor Structure and Basic Verification

A. Length definition

In this paper, three different axial lengths were defined to clear the advantages of the proposed structure: core length, magnet length, and motor length. These definitions were shown in Fig. 1. The subsequent evaluation was conducted based on this definition. The supplementary explanations of the three-axis length definitions are provided below.

- Core Length: laminated stator core
- Magnet Length: rotor magnet
- Motor Length: Total length including coil end

B. Reference motor

Table 1 lists the specifications of the reference motor, and Fig. 2 shows the structure of the reference motor. The reference motor is a 14-pole, 12-slot outer rotor type SPM motor. The permanent magnets have chamfered corners on the stator-side surface to reduce the torque ripple. The frame was made of non-magnetic stainless steel and had grooves to determine the position of the magnet. The core and magnet lengths were aligned, and no overhang structure was used. The performance of this motor was set to target spec, and the motor lengths required to achieve the same performance for the conventional and proposed structures were compared. The structure of the coil ends is unified for all motors, and the axial height is evaluated to be the same. In other words, there is a difference in the structure of the core length and magnet length between the conventional and proposed motors.

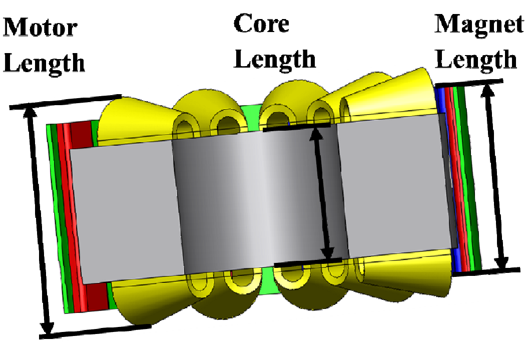


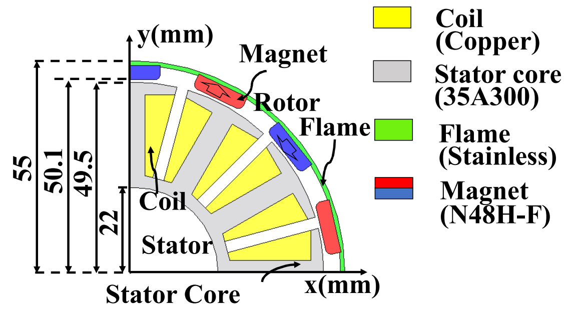
Fig. 1. Length definition.

Table. I. Reference motor specifications.

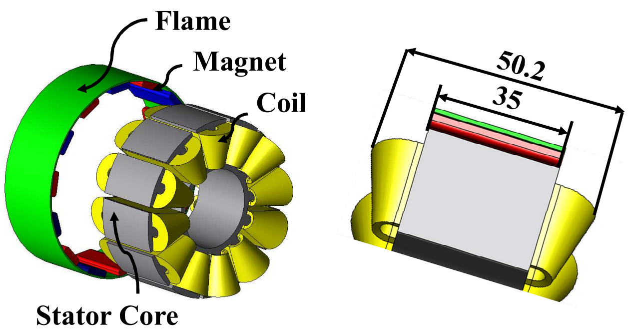
Pole number		14
Root mean squared of maximum phase current (A)		1.90
Motor length (mm)		50.2
Stator	Outer / inner diameter (mm)	99 / 44
	Core length (mm)	35.0
	Number of slots	12
	Turn number of Coil	98
Rotor	Outer / inner diameter (mm)	110 / 99.6
	Magnet length (mm)	35.0
	Magnet grades	N48

C. Conventional motor

The conventional motor is illustrated in Fig. 3. The 2D cross-section of the conventional motor is the same as that of the reference motor. However, the magnet structure differed from that of the reference motor. Specifically, the axial length of the magnet was greater than that of the stator core, and an overhang structure was applied. Although the rotor magnetic flux can be increased by overhanging the magnets, significant leakage flux is generated from the magnets in the overhung portions that do not face the stator core. Therefore, the effect of shortening the motor length is limited. Fig. 4 shows the three-dimensional magnetic flux diagram of a conventional motor. In the magnet region protruding in the axial length direction from the stator core, many magnetic fluxes that do not chain with the stator coil and become leakage fluxes are observed.

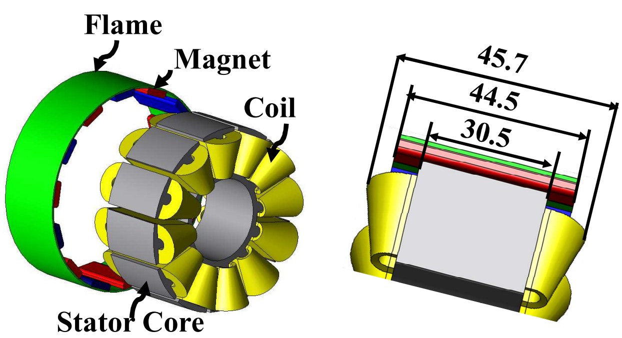


(a): 2D.



(b): 3D.

Fig. 2. Reference motor.



(a): 3D.

Fig. 3. Conventional motor.

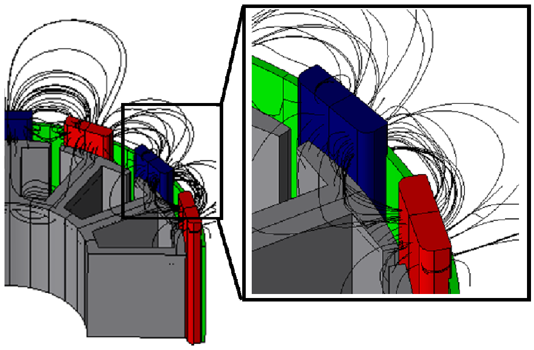
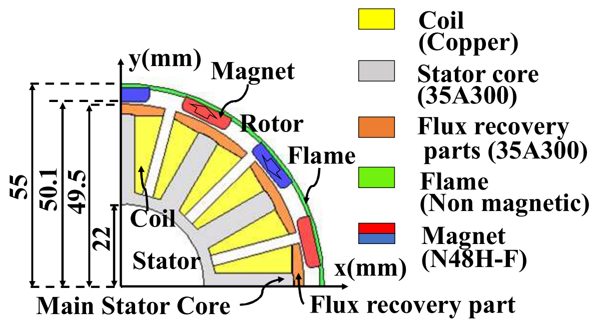
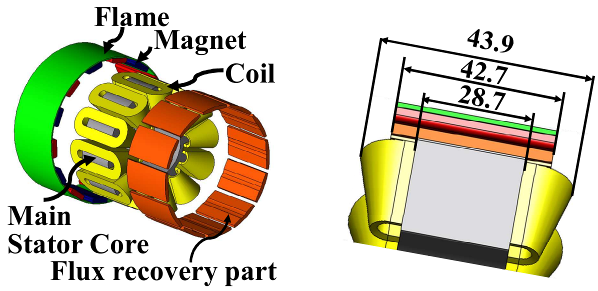


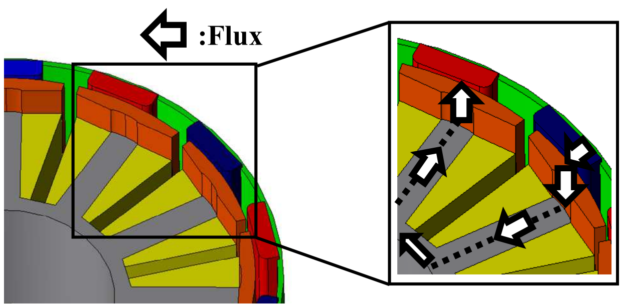
Fig. 4. Leakage magnetic flux.



(a): 2D.



(b): 3D.



(c): Flux path.

Fig. 5. Proposed motor.

D. Proposed motor

The two-dimensional cross-section of the proposed motor is shown in Figure 5(a), and the three-dimensional cross-section is shown in Figure 5(b). In the proposed motor, the stator core is divided into two parts: the main stator core and the magnetic flux recovery section. The material of the flux recovery section is the same as that of the main stator core. The aim of the proposed structure is illustrated in Figure 5(c). The flux leakage flux generated in a conventional motor can be picked up by the flux recovery section to increase the induced voltage. Therefore, a higher torque density can be achieved than that in a reference or conventional motor.

Table 2 presents a comparison of the shaft lengths of the reference, conventional, and proposed motors. The motor length of the conventional motor is 4.5 mm shorter than that of the reference motor, while the proposed motor is 6.3 mm shorter. This means that the effect of the motor length reduction owing to the overhang of the comparative structure can be increased by 1.4 times. The proposed motor can actively utilize the magnetic flux of the overhang magnet and reduce the leakage flux by installing a magnetic-flux recovery section. Note that the number of magnets tends to increase in the conventional and proposed motors, because the torque density is improved by overhanging the magnets.

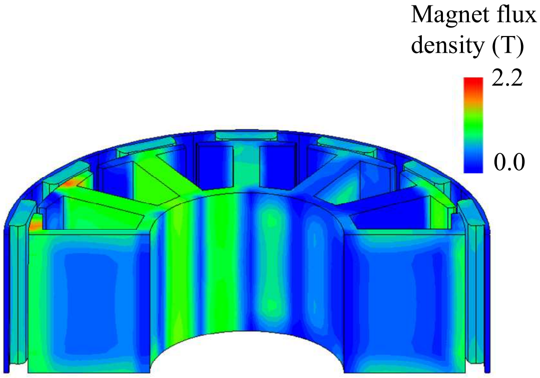
E. Analysis results on no-load conditions

Figure 6 shows the magnetic flux density distribution of the reference motor, conventional motor, and proposed motor under no-load conditions. In the reference motor shown in Figure 6(a), the magnetic flux density at the stator teeth is not high, and no magnetic saturation is observed. In contrast, the magnetic flux density was higher in the conventional and proposed motors, and magnetic saturation was most pronounced in the proposed motor. This is because the magnetic flux in the conventional motor is increased by the overhang structure, and the proposed motor picks up the leakage flux of the conventional motor. In other words, because more magnetic flux can be utilized, a higher back EMF can be achieved even with a smaller motor length, and this effect was confirmed by the degree of magnetic saturation. Fig. 7 shows the induced voltage waveforms. As shown in Table II, the motor length of the conventional motor is lower than that of the reference motor, and the proposed motor is even lower than both motors, that is, the proposed motor can achieve characteristics equivalent to those of the conventional motor with lower motor length.

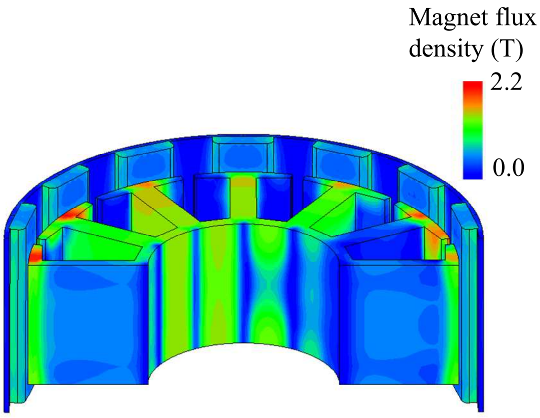
In the next section, magnetic properties are compared to confirm the superiority of the proposed motor.

Table. II. Comparison of axial length and Magnet volume.

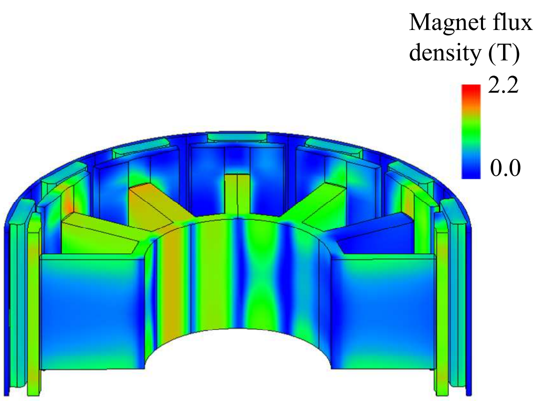
	Reference	Conventional	Proposed
Core Length(mm)	35	30.5	28.7
Magnet Length(mm)	35	44.5	42.7
Motor Length(mm)	50.2	45.7	43.9
Magnet Volume (mm^3/pole)	1826	2322	2228



(a): Reference motor.



(b): Conventional.



(c): Proposed.

Fig. 6. Magnetic flux density on no-load condition.

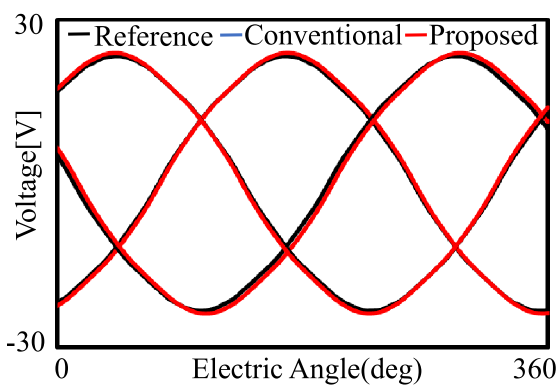


Fig. 7. Induced voltage

III. Numerical Verification

A. Maximum torque characteristics

Fig. 8 shows the maximum torque characteristics. In this verification, root mean squared value of the phase current was set to 1.9 A and the current phase was varied from -90 to 90 deg. From Fig. 8, the performance was equivalent for all the motors. In other words, the proposed structure can achieve the same maximum torque with a smaller motor length than the reference and conventional motors. For all motors, the current phase of the maximum torque was 0 deg. This indicates that the proposed motor mainly use magnet torque, and the fact that the same torque can be achieved with a smaller motor length can be attributed to the proposed flux recovery modification.

B. Current versus Torque

Fig. 9 shows the current versus torque characteristic. In this verification, root mean squared value of the phase current was varied up to 1.9 A, and the current phase was adjusted to obtain the maximum torque under each current condition. From Fig. 9, it can be confirmed that all motors have the equivalent characteristics under the maximum torque condition, whereas the proposed motor is superior under the low-current condition. This result confirms that the effect of the proposed motor on reducing the motor axial length is effective both on the linear and saturated regions. The proposed motor reduced the leakage flux by collecting the flux at the overhang area by the teeth tip. This area tends to be magnetic saturated with axial magnetic flux, and the effect of picking up is considered to be small under higher torque conditions. Therefore, this effect was more pronounced in the linear region.

C. Speed versus Torque

Fig. 10 shows the speed versus torque characteristic. In this verification, the root mean squared value of the phase current was fixed at 1.9 A and the rotation speed was varied from 50 to 600 r/min. The maximum line voltage was set at 48V, and the current phase was adjusted to be below the upper voltage limit in the high-speed region. The proposed motor showed a decrease in power output near the base rpm, but it was superior under many rpm conditions. The proposed motor has the shortest stator core length and the smallest inductance. In addition, because the torque in the low-speed range is the same, the amount of magnetic flux is

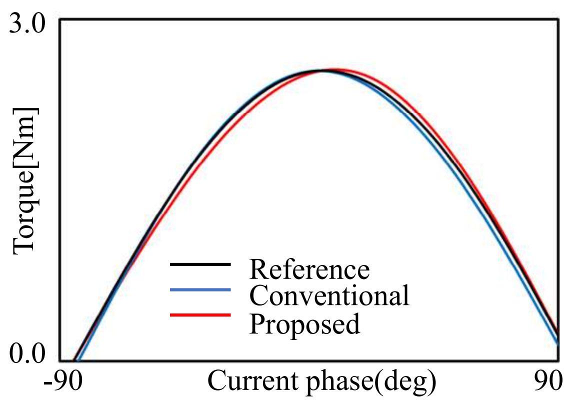


Fig. 8. Maximum torque.

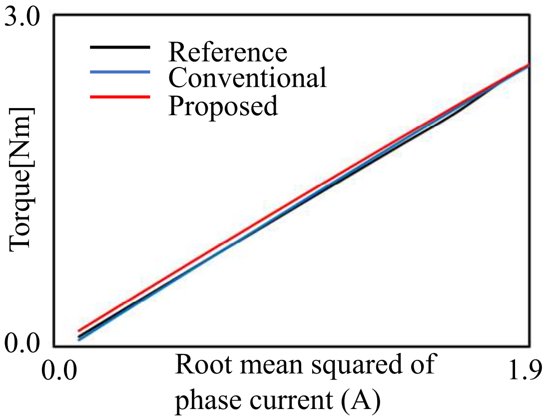


Fig. 9. Current versus torque.

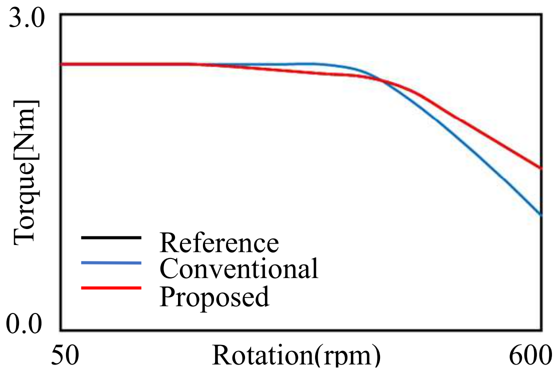


Fig. 10. Speed versus torque.

considered to be the same. In other words, the proposed motor can energize the largest amount of phase current within the voltage limit; therefore, the output power is considered superior in the high-speed range.

The results of these numerical verifications confirm that the torque improvement of the proposed motor does not adversely affect the magnetic properties.

IV. Conclusion

This study proposes a novel stator structure for a outer rotor type SPM motor with overhang magnet structures. In the proposed structure, the stator core is divided into the tips of the teeth and other parts, and only the tips of the teeth are extended to the same axial length as the overhang magnet. By using this structure, leakage flux, which is generated on overhang area in conventional motors, can be picked using the axial flux path. This allows the rotor flux of the outer rotor type SPM motor to be increased compared to conventional motors, and further motor length reduction can be achieved. To verify this effect, the magnetic properties of the proposed motor were calculated using the finite element method. The obtained results were compared with those of the conventional motor to confirm the superiority of the proposed motor. The numerical verification results show that the motor length reduction effect of the proposed motor can be improved to 1.4 times that of the conventional motor.

Although this study numerically demonstrated the superiority of the proposed motor, its effectiveness in experiment should be verified. The experimental verification using prototypes will be conducted in the future.

References

[1] K. Yamazaki and Y. Seki, "Zeroization of Cogging Torque of Permanent Magnet Machines by Optimizing Rotor Surface Shape: Comparison Between Surface and Interior Types," *IEEE Transactions on Magnetics*, vol. 59, no. 5, pp. 1-4, May 2023

[2] W. Wu et al., "Design and Analysis of a New Permeability-Modulated Interior Permanent-Magnet Synchronous Machine," *IEEE Transactions on Magnetics*, vol. 57, no. 2, pp. 1-5, Feb. 2021

[3] F. Mahmouditabar, A. Vahedi and N. Takorabet, "Design and Analysis of Interior Permanent Magnet Motor for Electric Vehicle Application Considering Irreversible Demagnetization," *IEEE Transactions on Industry Applications*, vol. 58, no. 1, pp. 284-293, Jan.-Feb. 2022

[4] W. Zhao, Z. Yang, Y. Liu and X. Wang, "Analysis of a Novel Surface-Mounted Permanent Magnet Motor With Hybrid Magnets for Low Cost and Low Torque Pulsation," *IEEE Transactions on Magnetics*, vol. 57, no. 6, pp. 1-4, June 2021

[5] S. -Y. Im, S. -G. Lee, D. -M. Kim, G. Xu, S. -Y. Shin and M. -S. Lim, "Kriging Surrogate Model-Based Design of an Ultra-High-Speed Surface-Mounted Permanent-Magnet Synchronous Motor Considering Stator Iron Loss and Rotor Eddy Current Loss," *IEEE Transactions on Magnetics*, vol. 58, no. 2, pp. 1-5, Feb. 2022

[6] S. -W. Hwang, J. -W. Chin and M. -S. Lim, "Design Process and Verification of SPMSM for a Wearable Robot Considering Thermal Characteristics Through LPTN," *IEEE/ASME Transactions on Mechatronics*, vol. 26, no. 2, pp. 1033-1042, April 2021

[7] Y. Gao, Z. Yin, Y. Zhang, Y. Zhang, D. Yuan and J. Liu, "Surface-Mounted Permanent Magnet Synchronous Motor Servo System Speed Control Using Antidisturbance Enhanced Finite-Time Composite Control," *IEEE Transactions on Power Electronics*, vol. 39, no. 8, pp. 9996-10008, Aug. 2024

[8] C. H. Bae and S. G. Min, "Data-Driven Electromagnetic–Thermal Coupling Optimization of Permanent Magnet Machines for UAVs," *IEEE Transactions on Transportation Electrification*, vol. 10, no. 3, pp. 6473-6487, Sept. 2024

[9] K. T. Chau, D. Zhang, J. Z. Jiang, C. Liu and Y. Zhang, "Design of a Magnetic-Geared Outer-Rotor Permanent-Magnet Brushless Motor for Electric Vehicles," *IEEE Transactions on Magnetics*, vol. 43, no. 6, pp. 2504-2506, June 2007

[10] Juan C. Tejada , Alejandro Toro-Ossaba , Santiago Muñoz Montoya , 1and Santiago R ´ua, "A Systems Engineering Approach for the Design of anOmnidirectional Autonomous Guided Vehicle (AGV)Testing Prototype," *HindawiJournal of Robotics volume 2022*, Article ID 7712312, pp. 13, March 2022

[11] H. Vansompel, A. Rasekh, A. Hemeida, J. Vierendeels and P. Sergeant, "Coupled Electromagnetic and Thermal Analysis of an Axial Flux PM Machine," *IEEE Transactions on Magnetics*, vol. 51, no. 11, pp. 1-4, Nov. 2015

[12] Y. Huang, F. Wang, A. Li, Y. Shi and Y. Chen, "Development and Performance Enhancement of an Overactuated Autonomous Ground Vehicle," *IEEE/ASME Transactions on Mechatronics*, vol. 26, no. 1, pp. 33-44, Feb. 2021

[13] D. Savitski et al., "Wheel Slip Control for the Electric Vehicle With In-Wheel Motors: Variable Structure and Sliding Mode Methods," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 10, pp. 8535-8544, Oct. 2020

[14] Xie, S," Design, analysis, and application of field-modulated machine s withdirect-drive features for automated ground vehicles," *Doctoral t hesis, Nanyang Technological University*, Singapore, 2023

[15] C. H. Kang, K. J. Kang, J. Y. Song, Y. J. Cho and G. H. Jang, "Axial Unbalanced Magnetic Force in a Permanent Magnet Motor Due to a Skewed Magnet and Rotor Eccentricities," *IEEE Transactions on Magnetics*, vol. 53, no. 11, pp. 1-5, Nov. 2017

[16] Dong Yu , Xiaoyan Huang , Lijian Wu and Youtong Fang, " Design and Analysis of Outer Rotor Permanent-Magnet Vernier Machines with Overhang Structure for In-Wheel Direct-Drive Application, "*Energies 12*, no. 7: 1238. , Feb. 2019