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ABSTRACT

Unlike the conventional railway traction motor, the concept of the dual-rotor in a dual-rotor permanent magnet synchronous motor (DR-PMSM) is that two rotors are mounted on the same rotation axis, and the outer rotor and the inner rotor rotate at different speeds. The DR-PMSM can transmit the power to the wheels in a structure that can cope with various problems of the reducer systems using mechanical gear mechanisms. In this research, the design study of the inner rotor including the permanent magnet is carried out in the application of the DR-PMSM. In designing the DR-PMSM models, surface permanent magnet (SPM) type and interior permanent magnet (IPM) type are considered according to the permanent magnet type of rotor, and IPM type is designed by dividing into bar type and V type. A comparative analysis of the three 1kW-class DR-PMSM models, in terms of electromagnetic properties, is performed to assess their general performance. The overall electromagnetic properties of the three designed models are similarly derived. But, the cogging torque and the rated torque characteristics of the IPM (V) type model are the best in comparison with the other models. In addition, the 1kW-class DR-PMSM prototype with V type magnet is fabricated to verify the validity of the analytical model and performance verification is performed.

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I. INTRODUCTION

In recent, as research on the weight reduction and low-floor of railway vehicles has been actively conducted, designs for the miniaturization of the driving devices for railway vehicle are required. In addition, the conventional driving devices have large maintenance cost problem due to transmission oil leakage and tooth wear of the mechanical reduction gears. Therefore, it is necessary to develop a new topology that can decrease the size and increase the maintainability of the conventional driving devices. Dual-rotor permanent magnet synchronous motor (DR-PMSM) can be a good alternative to the conventional driving devices. Unlike the conventional railway traction motor (PMSM), the concept of the dual-rotor in a DR-PMSM is that two rotors are mounted on the same rotation axis, and the outer rotor and the inner rotor rotate at different speeds. The DR-PMSM can transmit the power to the wheels in a structure that can cope with various problems of the reducer systems using mechanical gear mechanisms. DR-PMSM is structurally integrated with magnetic gear and PMSM, and it has high efficiency characteristics similar to PMSM. The research on magnetic gears to replace mechanical reduction gears is currently being carried out variously all over the world.1–3 However, the researches of DR-PMSM as a driving system for rail vehicle traction is now the beginning.1 Fig. 1 shows the major global applicants in the field of the magnetic gear system technology. As shown in Fig. 1, the major applicants are Magnomatics® (UK) and Genesis Robotics and Motion Technologies (Canada), and all of the major applicants are characterized by their filing activities around the US market.

In this research, the design study of the inner rotor including the permanent magnet is carried out in the application of the DR-PMSM. In designing the DR-PMSM models, surface permanent magnet (SPM) type and interior permanent magnet (IPM) type are considered according to the permanent magnet type of rotor, and...
IPM type is designed by dividing into bar type and V type. A comparative analysis of the three 1kW-class DR-PMSM models, in terms of electromagnetic properties, is performed to assess their general performance. The overall electromagnetic properties of the three designed models are similarly derived. But, the cogging torque and the rated torque characteristics of the IPM (V) type model are the best in comparison with the other models. In addition, the 1kW-class DR-PMSM prototype with V type magnet is fabricated to verify the validity of the analytical model and performance verification is performed.

II. DESIGN AND ANALYSIS

A. Derivation of design model of 1kW-class DR-PMSM

The DR-PMSM in this study has a dual rotor structure unlike conventional traction motors in which the outer and inner rotors...
rotate at different speeds. Generally, the inner rotor of the DR-PMSM has a high-speed rotation, low-torque characteristic, while the outer rotor has a low-speed rotation, high-torque characteristic. Therefore, when the DR-PMSM is applied in a driving system for railway vehicles, in the case of an inner rotor type, the wheel should be directly connected to the outer rotor having low speed and high torque characteristics. Fig. 2 shows the structure of a conventional driving system and a new direct driving system composed of DR-PMSM.

In this paper, the basic model of the small-scaled 1kW-class DR-PMSM (4 poles, 7 pole-pieces and 48 slots) is designed, and inner rotor models with 3 different magnet structures are derived to examine the applicability of DR-PMSM to railway vehicle. Table I shows the required design criteria for the small-scaled 1kW-class DR-PMSM. The dimensions of the stator and the outer rotor (pole pieces) are basically the same in the three designed models. However, in the process of deriving the structure that satisfies the required torque, the size of permanent magnets used in each model was designed differently. Based on the criteria in Table I, the surface-mounted permanent magnet (SPM) type rotor and the interior permanent magnet (IPM) type rotor are designed respectively according to the structure of the permanent magnet, and the bar-shape and V-shape are designed as the IPM type rotors respectively. In general, the interior permanent magnet synchronous motor (IPMSM) has many advantages in terms of manufacturing and performance as compared with the surface-mounted permanent magnet synchronous motor (SPMSM). Especially, when the SPM type is applied to the DR-PMSM, a structure for preventing the scattering of the permanent magnet during high-speed rotation is additionally required. In this case, there is a problem that the air-gap between the inner rotor and the outer rotor of the DR-PMSM becomes larger. Therefore, the IPM type rotor is more advantageous than the SPM type rotor in terms of securing the structural rigidity of the high-speed rotor of DR-PMSM. Fig. 3 shows the design procedure of the 1kW-class DR-PMSM for railway vehicle as presented in this research. Fig. 4 shows three different rotor models of 1kW-class DR-PMSM derived using the design procedure in Fig. 3.

B. Analysis of electromagnetic characteristics

The small-scaled 1kW-class DR-PMSM design models are analyzed using a 2D-electromagnetic FEA (Finite Element Analysis). The back EMF (electromotive force) waveforms, the magnetic flux density distributions and torque characteristics of the DR-PMSM models are calculated using the design procedure in Fig. 3.
models are analyzed in the no-load and rated load conditions. Fig. 5 shows the cogging torque characteristics of the three 1kW-class DR-PMSM models. As shown in Fig. 5, the cogging torque of the inner rotor of the IPM (V) type model is 0.348 and the cogging torque of the outer rotor is 0.841, which is superior to the cogging torque of the other two models. In particular, the cogging torque characteristic of IPM models are better than that of SPM model in this research. Table II show the magnetic flux density distribution

**FIG. 6.** Back EMF characteristics of the 1kW-class DR-PMSM models at the no-load and rated load conditions ((a) SPM(No-load), (b) IPM-Bar(No-load), (c) IPM-V(No-load), (d) SPM(Rated load), (e) IPM-Bar(Rated load), (f) IPM-V(Rated load)).

**FIG. 7.** Harmonic analysis results of the back EMF waveforms of the 1kW-class DR-PMSM models ((a) No-load condition, (b) Rated load condition).
characteristics of the designed three 1kW-class DR-PMSM models under the rated load condition. In particular, in the case of the IPM (V) type model, the magnetic flux density in the stator yoke is lower than the other two models. Since core loss is generally proportional to the square of the magnetic flux density, core loss in the stator yoke will occur least in the IPM (V) type. This means that the IPM (V) type model is advantageous in the temperature rise problem compared with the other two models. Fig. 6 show the back EMF characteristics of the designed three 1kW-class DR-PMSM models at the no-load and rated load conditions. When the SVPWM control method is selected, the back EMF limit value is 69 V peak at the rated speed, and it is confirmed in Fig. 6 that all three models meet the voltage limit value. Fig. 7 shows the harmonic analysis results of the back EMF waveforms of the three 1kW-class DR-PMSM models. It is found in Figure 6 that all three models contain similar types of harmonics. Fig. 8 shows the torque characteristics of the IPM (V) type model are the best in comparison with the other models similar to the cogging torque characteristic in Fig. 4. In particular, since the torque ripple characteristic of the IPM (V) type model is the best compared to the other two models, the noise & vibration characteristics are expected to be the best when driving. Table III shows the analysis results of the electromagnetic parameters of the three 1kW-class DR-PMSM models. As shown in Table III, the torque characteristics (cogging torque & torque ripple) of the IPM (V) type model are the best of the three models designed. As a result, IPM (V) type model is selected as the 1kW-class DR-PMSM prototype model for design verification in this research.

### III. VERIFICATION OF DESIGN MODEL USING PROTOTYPE

The 1kW-class MG-PMSM prototype with IPM (V) model is manufactured for verification of the MG-PMSM design method in...
In this study, verifications of design method and parameters are completed through the no-load and load performance test. Fig. 12 shows the experimental wave and the calculated wave of no-load line-to-line back-emf of the 1kW-class MG-PMSM prototype. In the no-load state of the MG-PMSM, the low-speed rotor composed of a pole piece made of a magnetic material is forcibly aligned with the high-speed rotor at which a permanent magnet is inserted at a position where the magneto-resistance is minimum. Under this no-load condition, the line to line back-emf is measured while rotating the high-speed rotor at 1,000 rpm using the performance tester. Table IV shows the comparison results between the experimental value and the simulation value of no-load line-to-line back-emf of 1kW-class MG-PMSM prototype. Experimental value is 152 V$_{rms}$ at 1000 rpm by the high-speed rotor. Under the same condition, calculated value is 168 V$_{rms}$ and difference ratio is about 9%. Fig. 13 shows the comparison between the experimental and calculated half-load torques of 1kW-class MG-PMSM prototype (low speed rotor @ 89–800rpm). The load test is conducted under half load conditions in consideration of the load performance margin of the tester. First, the load torque of the low speed rotor is fixed at 6Nm, and the input current of the MG-PMSM is measured while increasing the speed of the low speed rotor to 800rpm. Next, the FEM analysis is performed under the same conditions as the test conditions based on the measured input current, and the test value and the calculated value are compared. As shown in Fig. 13, there is an average of 6.4% difference between the experimental and calculated values. The reason why the experimental value is small compared with the analytical value is that since the pole piece is made of a solid structure using a steel material in manufacturing the prototype, it seems to be due to the fluctuation of magnetic flux linkages by eddy currents in the pole piece part during high-speed rotor rotation of the MG-PMSM. Therefore, further analysis using 3D-FEM analysis method considering the solid structure of the pole piece of the MG-PMSM is required for the analysis of the difference with the experimental data. The controller for MG-PMSM will be prepared in the future, and the control performance test will be further conducted under the load condition.
TABLE IV. Comparison between experimental and simulation values for no-load line to line back-emf.

| Item                | Experimental Value | Calculated Value |
|---------------------|--------------------|------------------|
| Bemf₈, peak, noload | 215 V              | 237 V            |
| Bemf₈, rms, noload  | 152 V              | 168 V            |
| Difference Ratio    | 91 %               | 100 %            |

FIG. 13. Analysis and comparison of half-load torque test of 1kW-class MG-PMSM prototype (low speed rotor @ 89–800rpm).

IV. CONCLUSIONS

In this research, the shape design of the inner rotor including the permanent magnet is carried out in the application of the DR-PMSM. In designing the DR-PMSM models, SPM and IPM types are considered according to the structure that the permanent magnet is mounted on the rotor, and IPM type is designed by dividing into bar and V shapes. A comparative analysis of the three designed 1kW-class DR-PMSM models, in terms of electromagnetic characteristics, is performed to assess their general performance. The overall electromagnetic characteristics of the three designed 1kW-class DR-PMSM models are similarly derived. But, the cogging torque and the rated torque characteristics of the IPM (V) type model are the best in comparison with the other models. In addition, the 1kW-class DR-PMSM prototype model with V shape magnet is made to verify the validity of the design procedure and analytical model, and its performance verification is performed. The verification of the back EMF and load torque parameters are completed through the no-load and half-load test. The difference between the experimental value and simulated value is about 10 % or less. Further analysis using 3D-FEA considering the solid structure of the pole-piece in the outer rotor of the 1kW-class DR-PMSM will be conducted for the difference analysis with the experimental data. The controller for the 1kW-class DR-PMSM will be prepared in the future research, and the performance test will be further conducted under the load condition.

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