J Electr Eng Technol.2016; 11(5): 1311-1315
http://dx.doi.org/10.5370/JEET.2016.11.5.1311

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Study of New PMSM Design for Leakage Magnetic Flux Reduction

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Abstract – This paper suggests the new PMSM design that can reduce leakage magnetic flux. Through adapting non-magnetic frame structure, it decreases leakage magnetic flux on the rotor's rib and web structure. And with this, it increases power density of the motor. To verify the effectiveness of the new design of rotor compared to the common type, through small sized real model's test was conducted. To obtain final model, structural FEM analysis was also used for structural stability. Additional loss generation problem that can occur in the new frame structure was checked with the 3D FEM analysis.

Keywords: PMSM, Power density, Leakage flux, Eddy current loss

1. Introduction

When designing the traction motor of railway vehicles, to decrease size of driving module and to improve high efficiency, PMSM type of motor is widely used in such application. In PMSM design, various designs can be applied like IPMSM, SPMSM, Spoke type and Inset type. In those types of motors, especially IPMSM is widely used because of its superior points in power density and efficiency. And IPMSM type motor doesn't need rotor sleeve structure in SPMSM for high speed rotation. The absence of sleeve structure on the rotor surface increases its permeance than SPMSM motor which using same amount of permanent magnet, because its air-gap width was decreased in electromagnetic view. Higher permeance makes higher magnetic flux density in permanent magnet's operating point. Furthermore, IPMSM type motor using reluctance torque as well as magnetic torque. It makes higher torque density then other type of motors. [1] IPMSM type motor can be considered that having advantages on efficiency and output density. Because of those strong point, IPMSM type motor could widely use in rail car's traction motor.

However, in common structure of IPMSM, rotor's rib and web structure becomes magnetic leakage flux's path, so in commonly, design those parts as minimal as possible to decrease leakage amount. But there is limit because those parts are concerned with structural stability of the rotor structure. Still, the existence of those magnetic parts produces leakage flux that is relevant to the output power reduction. [2]

In this paper, new design of PMSM model was suggested that can be decrease leakage magnetic flux around the rotor's surface. Output characteristic was predicted with FEM(Finite Element Method) analysis and small sized real model was made to prove it. The reason of conducting real model test is verification of FEM result. Because of that, small sized model test was supposed that it is enough to demonstrate the new model's advantage compared to the common type of IPMSM with respect to the output density.

2. New PMSM Structure to Reduce Leakage Flux

In this study, rotor's rib and web structure in common IPMSM shape was removed to minimize leakage magnetic fluxes. After that, there is magnet and pole piece part on the rotor surface only and they are fixed with adhesive.

Instead of those removed parts, structural reliability was improved by non-magnetic frame structure to support the rotor assembly in high speed rotation. In addition to electromagnetic FEM analysis, structural FEM analysis was needed to evaluate structural reliability in high speed rotating. The new design should satisfy demanded output characteristics and design restriction, and sufficient structure stability. For this, electromagnetic analysis and structural analysis was performed together in preliminary design stage. The rotor's safety standard coefficient is based on the core material's tensile strength. Through electromagnetic analysis, structure that gains maximum torque by obtaining sufficient reluctance torque as well as magnetic torque was derived. With common type of IPMSM model, suggested new model's output characteristics were evaluated in the equal level of current.

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Received: March 7, 2016; Accepted: May 5, 2016

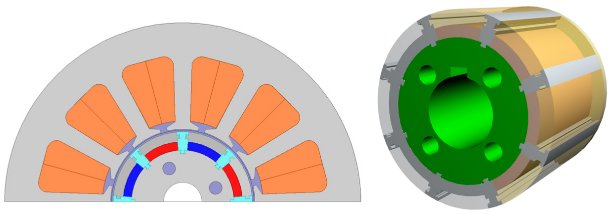


Fig. 1. 2D cross section shape and rotor assembly shape of suggested PMSM model

2.1 Design and concept of new design of PMSM

In this suggested new IPMSM model, in order to leakage flux in rib structure which occurs from common type of IPMSM, barrier and rib structure of rotor is removed and non-magnetic rotor supporting structure is inserted. This structure supports permanent magnet and pole piece structure. Below Fig. 2 shows the structure of rotor supporting structure and assembly method of pole piece. The permanent magnet and pole piece are firmly assembled with rotor supporting structure and protruding structure to prevent rotor from damaging in high-speed driving condition. Rotor supporting structure is produced in non-magnetic materials to prevent generation of leakage flux from permanent magnet. Through this structure, the flow of leakage flux by rib structure is fundamentally blocked and thus, it is possible to use magnetic flux from permanent magnet efficiently. Also, power density will be enhanced due to the increase in size of magnetic torque. Along with this, by remaining the pole piece structure, generation of additional reluctance torque can be achieved.

Fig. 2 shows the magnetic flux line around the rotor rib structure based on the FEM analysis result of general IPMSM model and suggested model. It can be found that the flow of leakage flux in (a), passing through the rotor rib structure, has considerably reduced in suggest model in (b).

The characteristics of improved model are summarized in below table using parametric study on rotor shape variables in equal stator of IPMSM model.

2.2 Predict characteristics of new PMSM model using FEM analysis

Below table is the comparison of characteristics between IPMSM model shown in Fig. 2 and suggested model using FEM analysis when it powers equal current ($20A_{peak}$) on

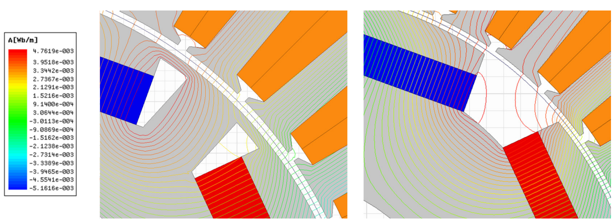


Fig. 2. Magnetic flux comparison of compared common type PMSM and suggested PMSM model

Table 1. Suggested PMSM model's basic design parameter

	Design parameter	Value (Unit)
Stator design parameter	Diameter	70 mm
	Slot number	12
	Air-gap width	1 mm
	Stack length	45 mm
Rotor design parameter	Diameter	27.3 mm
	Pole number	8
	Magnet thickness	3 mm
	Pole arc	0.8
	Stack length	45 mm
Characteristics	Resistance (@75℃)	0.054 Ω
	Rated speed	4,000 rpm
	Rated current	20 A_{max}
	Output	1.15 kW

Table 2. Characteristic prediction of initial type of PMSM model through FEM analysis

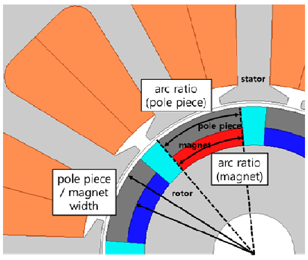
	Unit	Common type IPMSM	Proposed PMSM (initial model)
Beta degree	degE	15	10
Net. torque	Nm	2.34	2.77
Reluctance torque (ratio in total torque)	Nm	0.23 (9.8%)	0.13 (4.7%)
Magnetic torque (ratio in total torque)	Nm	2.10 (90.2%)	2.65 (95.3%)
Ld	mH	1.71	0.82
Lq	mH	2.10	1.05

rated speed. The voltage value is limited to $50V_{peak}$. And for the current, $20A_{peak}$ is applied equally on both models. The common type of IPMSM model, the comparison target, was set in condition where it has equal permanent magnet condition(amount of permanent magnet usage, magnetic force, arc ratio) and electrical design condition(number of turn and input current) of suggested PMSM model. For comparing two models, the same base design was applied on both two models. When comparing two models, reluctance torque accounts for about 9.8% in total torque and magnetic torque occupies 90.2% with total torque of 234Nm for common IPMSM model. Suggested model, however, 4.7% of reluctance torque and 95.3% of magnetic torque are the composition of torques with total torque of 2.77Nm, which is about 18.4% increase compared to original IPMSM model. This is contributed to the increase of magnetic torque due to minimizing leakage flux despite slight decreasing portion of total reluctance torque. From this, suggested model (though the reluctance torque has decreased) has showed the possibility of high output design compared to common model by expanding the increase range of magnetic torque.

Based on the above early model, design improvement was processed using parametric study of design variables such as arc ratio of permanent magnet and pole piece, the position of permanent magnet from surface of rotor, and those variables.

Final model has derived at the point where the total sum of magnetic torque and reluctance torque is maximized.

Table 3. Rotor design parameters of initial model



Parameter	Range	level
Arc degree (magnet) [deg]	16-20	3
Arc degree (pole piece) [deg]	16-20	3
Magnet width [mm]	2-4	3

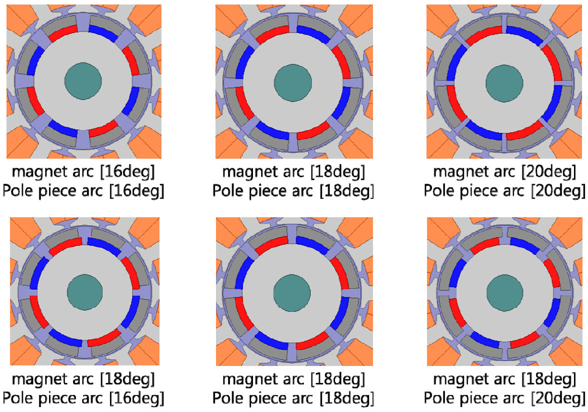


Fig. 3. Example of rotor shapes according to the design parameter combination

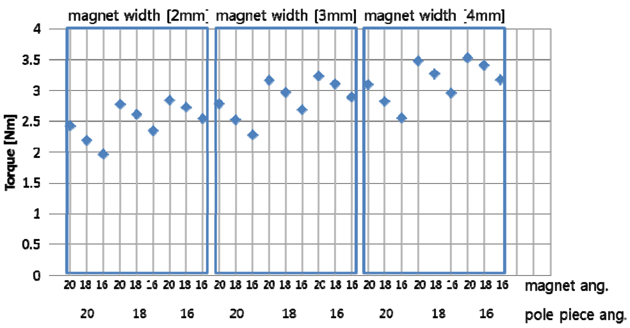


Fig. 4. Change of output characteristic according to the design parameter combination

Comparing the output characteristics according to the above combinations of rotor design variables, properties are found as in Fig. 4 Most influential variable affecting the characteristics is magnet angle and it shows the importance of ensuring arc ratio as much as possible to improve output. As in Fig. 4, it can be found that at the same magnet angle, if pole piece angle extends more than certain angle, the output rapidly drops. This indicates that rather than enlarging the width of pole piece to have advantageous form in generating reluctance torque, reducing leakage flux by ensuring optimal distance between pieces increase the total output as it extends magnetic torque. When the thickness of permanent magnet increases, the output increases only within the examined range. However, when the thickness of permanent magnet increases above

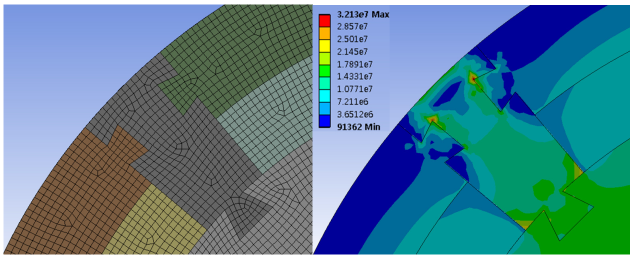


Fig. 5. Structural analysis result of rotor part

the range, the thickness of pole piece will be thinner that causing manufacturability problem.

2.3 Confirming structural stability through FEM analysis

In combining real rotor assembly, slot shape structure is added so that it firmly supports at the high speed rotation via combination between pole piece and stainless steel structure. To manufacture the slot shape, some extent of thickness of pole piece is required and this causes constraints on thickness of permanent magnet. Considering the manufacturing problem of stainless steel material structure and the ruggedness problem of the structure, slot shape is applied to the structure by manufacturing as magnet angle 18deg, pole piece angle 18deg.

3. Manufacturing and Characteristic Analysis of the Suggested PMSM

3.1 Manufacturing and test results

Final model's design was obtained through reviewing process of structural stability with FEM structural analysis. In Fig. 6, produced model's cross section and rotor assembly is shown. In the frame, protruding frame structure shape is shown and it's combining way. In the Fig. 7, no-load BEMF FEM analysis result of the common type of IPMSM and suggested PMSM model were compared with each other and suggested model's BEMF test result was shown. In FEM analysis result, common type of IPMSM shows 20.92V_{rms} in line voltage, and suggested model shows 23.46 V_{rms} which is 12.14% increased value than common type. No-load BEMF is due to rotation speed and air gap magnetic flux density, so it means this result comes from suggested model's leakage flux reduction, and it means in same current, suggested model generates higher output in same ratio of BEMF.

3.2 Loss analysis in the frame structure through 3D FEM analysis

The frame structure which is for the rotor parts assembles, is made with stainless steel. The stainless steel

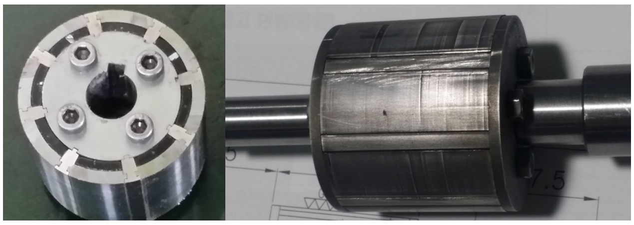
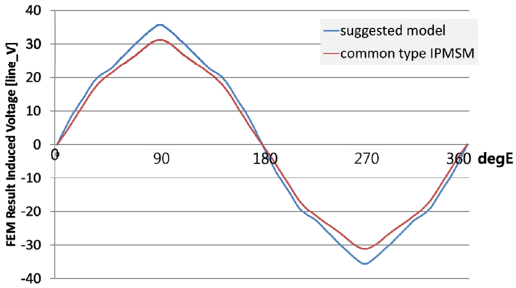
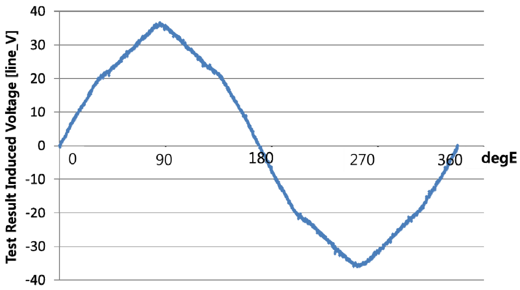


Fig. 6. 2D section of the rotor core and shape of rotor assembly



(a) FEM analysis result (no-load BEMF)



(b) Test result (no-load BEMF)

Fig. 7. No-load BEMF waveform comparison of common type IPMSM and suggested PMSM model and suggested model's BEMF test result

material is the non-conductive material (304 sts : $1.4{\cdot}10^6$ S/m), which has much lower conductivity than core material (electrical steel 50PN1300 : $5.9{\cdot}10^6$ S/m).[3] But the frame structure locates close to the air-gap, it affect significant effect on the air-gap's space harmonics when rotating, and it inducing eddy current on the frame structure that generating additional ohm loss.[4]

In this study, effect of the induced eddy current on the motor's efficiency was confirmed with 3D electromagnetic FEM analysis. When driving the motor, parts causing eddy current loss are permanent magnet and frame structure. In the 3D FEM analysis result of table 4, most of eddy current loss is occurring in stainless frame. 3D FEM result and suggested model's real model test result were compared to compare its efficiency in rated speed operation. Slightly more current was supplied in real model's test to generate same amount of output, and it is assumed that it is due to the leakage magnetic flux or stray loss in the core. In Fig. 8, eddy current's vector plot through 3D FEM analysis is

Table 4. Comparison of final model's FEM and test result

	3D-FEM	Test result	Unit
Torque	2.69	2.77	Nm
Input current	20	21.35	A_{peak}
Copper loss	22.62	25.79	W
Core loss	29.94	-	W
Eddy current loss	6.08 (frame loss : 5.81)	-	W
Efficiency	95.53	95.36	%

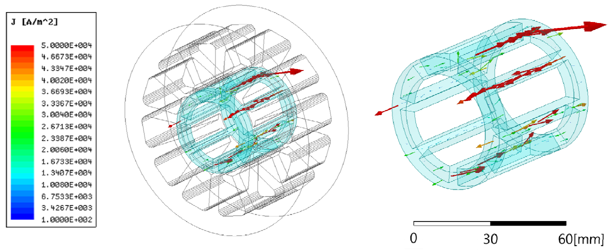


Fig. 8. Eddy current flow in the frame in 3D FEM analysis

shown, eddy current flow like this makes ohm loss. To achieve additional higher efficiency, material with lower conductivity is preferable for frame material. [5]

4. Conclusion

This paper suggests new type of PMSM design that could be applied to railway vehicle's traction motor due to its high power density. It removes rotor's rib and web parts that occurring magnetic flux leakage. Non-magnetic material frame was adapted to support the rotor structure in high speed rotation. And real model was made to confirm the characteristic. Like common type of IPMSM, to obtain reluctance torque, pole piece structure was applied to the new design of PMSM. Through the basic model, potential of higher torque density than that of common type of IPMSM was demonstrated, and improved design was obtained through parametric study. Existence of eddy current flow on frame structure was demonstrated through 3D FEM analysis, and emphasized the importance of selection of the proper frame material in magnetic point of view. In further research, using the suggested PMSM structure, improved design can be obtained through the design optimization study.

Acknowledgements

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy (No.20132010101870)

This work was supported by the Human Resources Program in Energy Technology of the Korea Institute of Energy Technology Evaluation and Planning(KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (No. 2015 4030200900)

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