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Research paper

Electromagnetic Characteristics Analysis of the Interior Permanent Magnet Synchronous Motor considering Temperature Change

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Abstract

Background/Objectives: Becauseofthe environmental pollution problem and the development of A rare earth magnet, research on IPMSM forElectric Vehicle(EV)s, which are eco-friendly automobiles, is actively under way.
Methods/Statistical analysis: Inthis paper,the changes of electromagnetic field characteristics according to the temperature change of 20℃, 80℃, and 140℃ are compared and analyzed through Finite Element Method(FEM). Also, for the high efficiency design of the motor, through FEM we propose the ventilation hole design which reduces the temperature while keeping the output of the motor almost.
Findings: As the result of FEM simulation, it was confirmed that the residual flux density increase and the winding resistance decrease due to the temperature decrease. Because of that, d-axis and q-axis inductance, and magnetic flux linkage are changed. In particular, it was confirmed that phase current and angle of phase current, which are the control parameters of IPMSM, is not accurately controlled unless temperature is taken into account. Also, at MTPA driving point the efficiency was improved according to temperature decrease, and at the field weakening point, the efficiency decreased as the temperature decreased. Finally, it was confirmed that the output can crease by drilling the ventilation hole considering the path of the magnetic flux through FEM simulation.
Improvements/Applications: The study is most suitable for motors that require high power density. We plan to the study considering thermal analysis and electromagnetic field analysis at the same time.

Keywords: angle of phase current, high efficiency, phase current, residual flux density, temperature, and winding resistance.

1. Introduction

Recently, because of the reinforced regulation on the environmental pollution problem and the development of A rare earth magnet, the automobile market is moving from internal combustion engines to hydrogen cars or EVs, which are eco-friendly automobiles[1]. Among them, the recent interest of EV is to increase the efficiency of its system or components. In this sense, Interior Permanent Magnet Synchronous Motor (IPMSM) is used for EV. The characteristics of IPMSM are high output by utilizing both reluctance torque using saliency and magnetic torque using the property of arranging polarity, and it is possible to perform a wide range of operation through weak field control[2]-[4]. The high efficiency means that the output density is high. The high output density enables the weight reduction and miniaturization of IPMSM. The weight reduction can improve the fuel efficiency of EV and the miniaturization can increase the freedom of the system configuration and the convenience of the user by securing the free space of EV. There are many papers on the high output density of IPMSM. Most papers assume a constant temperature according to the load condition. However, the temperature varies by more than 140 ℃ depending on the load conditions. This temperature change affects the residual magnetism of the permanent magnets in the rotor and the winding resistance in the stator, thus changing the electromagnetic field characteristics such as inductance, and saliency etc. IPMSM is controlled by a vector converter by inputting the phase current and angle of phase current for maximum efficiency operation within a wide operating range. Since the current characteristics due to the temperature change are changed, the current control considering the temperature change is required[5]-[10].
In this paper, the changes of electromagnetic field characteristics according to the temperature change of 20 ℃, 80 ℃, and 140 ℃ are compared and analyzed through FEM. Also, for the high efficiency design of the motor, through FEM we propose the ventilation hole design which reduces the temperature while keeping the output of the motor almost.

2. Analysis Model

2.1. 2dfemsimulationmodel

Figure 1 shows 2D FEM simulation model. As shown in Figure 1, the permanent magnet of the reverse triangle shape is inserted in the rotor. IPMSM consists of 8 poles and 48 slots. Ventilation hole are formed in the rotor and the stator to increase the cooling efficiency. Table 1 shows the specification of 2D FEM simulation model.

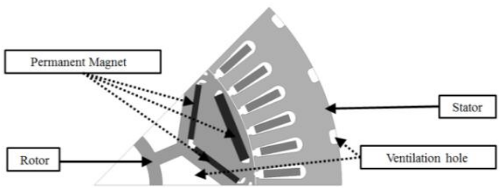

Figure 1: 2D FEM simulation model

Table 1: The specification of 2D FEM simulation model

Parameter	Value	Unit
Stator diameter(Inner / Outer)	131/200	mm
Rotor diameter(Inner / Outer)	45/130	mm
Air gap	1	mm
Stack	140	mm
Magnet material	N42UZ-GR	-
Parallel branches	4	-
Num. of Reels per slot	11	-
Num. of Turns per slot	**9**	-

2.2. IPMSM Analysis Considering Temperature Change

Since IPMSM for EV applies a high current, the most heat is generated in the winding portion as the copper loss. The winding temperature also is directly measured using a temperature sensor. However, the temperature of permanent magnets of the rotating rotor is difficult to measure and the heat of winding is transmitted to the permanent magnet through the air gap. For the above reasons, the temperature of permanent magnets is assumed to be 80 % of the winding temperature as shown in Table 2.

Table 2: Temperature of winding and permanent magnet

Winding temperature	Permanent magnet temperature	Unit
25	20	℃
100	80	℃
175	140	℃

Figure 2 shows Characteristics of material according to temperature change. The same coil is used and the winding resistance changes according to the change of the specific resistance. Specific resistance can be calculated by equation (1).

$$\rho = \rho_0[1 + a_0(T - T_0)] \quad (1)$$

ρ, ρ_0, a_0, and T_0 are specific resistance, specific resistance at reference temperature, reference temperature, and a temperature coefficient of resistance respectively. For the above reasons, the winding resistance increases linearly according to equation (1). Fig. 2(b) shows characteristics of permanent magnets according to temperature change. As shown is Fig. 2(b) residual flux density of permanent magnets due to temperature rise decreases from 1.3 T to 1.1 T.

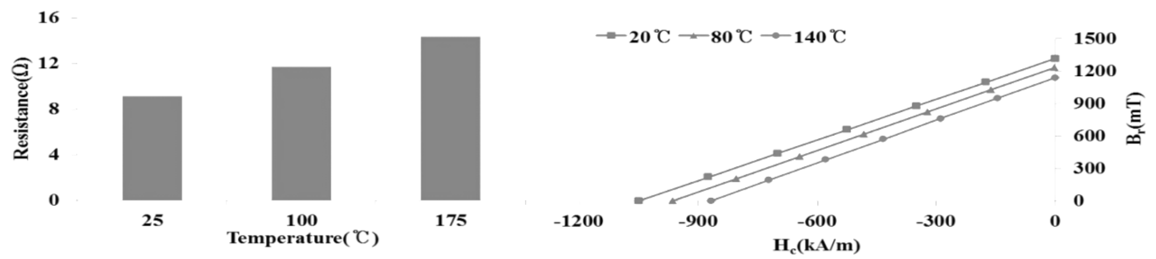

Figure 2:.Characteristics of material according to temperature change (a)The winding resistance according to temperature change (b)Characteristics of N42UZ-GR according to temperature change

Fig. 3 and Table 3 shows Torque-phase current angle curve at 298A according to temperature change and the current information at Maximum Torque Per Ampere (MTPA). Torque can be calculated by equation (2).

$$T = P_n[\Psi_a i_q + (L_q - L_d) i_d i_q] \quad (2)$$

T, P_n, and Ψ_a are respectively torque, pole pair, and magnets flux linkage. i_d and i_q are d-axis and q-axis current. L_d and L_q are d-axis and q-axis inductance. The first term on the right side is magnetic torque and the second term on the right side is reluctance torque. Torque creases from 245.4409 A to 262.75 A at the same current and Phase current decrease from 310 A to 289 A at the same torque according to the increase in magnets flux linkage as shown in Fig. 3 and Table 3. Because the maximum torque of magnetic torque and reluctance torque are generated from 0 ° and 45 ° of current angle respectively, Angle of phase current decrease from 46 ° to 44 °at the same current and from 46.5 ° to 43.6 ° at the same torque according to the increase in magnets flux linkage as shown in Fig. 3 and Table 3.

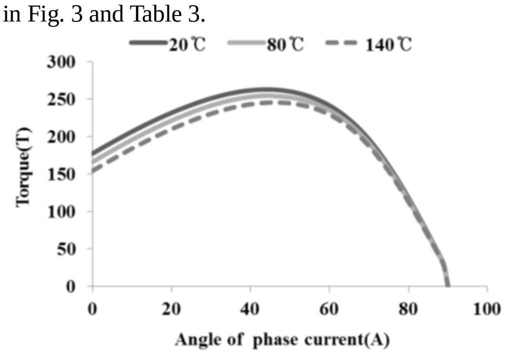

Figure 3:. Torque-phase current angle curve at 298 A

Table 3::Phase current and angle at MTPA

Permanent magnet temperature	Phase current(A)	Angle of phase current(°)
20	289	43.6
80	298	45.1
140	**310**	**46.5**

Table 4 shows current information of field weakening. For the high-speed operation of IPMSM, d-axis armature reaction magnetic flux is used. The EMF is proportional to the speed and magnet flux linkage. Therefore, it is necessary to reduce magnet flux linkage by utilizing d-axis armature reaction magnetic flux. In this research, since the magnet flux linkage increases with temperature decreases it is necessary to raise d-axis armature reaction magnetic flux. How to increase in d-axis armature reaction magnetic flux is to increase phase current and angle of phase. For the above reasons, the results of table 4 are obtained.

Table 4::phase current and angle at field weakening

Permanent magnet temperature	Phase current(A)	Angle of phase current(°)
20	265	82.8
80	240	81.2
140	**222**	**79.5**

Table 5 shows efficiency at MTPA and field weakening according to temperature change. Since MTPA driving point does not limit the battery voltage, the same torque is generated with less current increasing residual flux due to the temperature decrease. Also, due to the current and winding resistance decrease the copper loss was significantly reduced and the efficiency increase from 94.61 % to 96. 78 %. In the field weakening region (high speed region), because it is necessary to consider the limitation of the battery voltage, the bigger residual magnetic flux density, the bigger current required should is. Therefore, despite the decrease of winding resistance the efficiency decreases from 95.73 % to 94.98 %.

Table 5: efficiency at MTPA and field weakening according to temperature change

Permanent magnet temperature	Efficiency at MTPA(%)	Efficiency at field weakening(%)
20	96.78	94.98
80	95.66	95.66
140	**94.61**	95.73

2.3.Design of Ventilation Hole

Fig. 4 shows 2D FEM simulation base model andflux line distribution of base model. A selected model don't have ventilation hole as base model for desigh of ventilation hole. Except for the ventilation hole, it has the same dimensions as the IPMSM model describe before. When examining flux line distribution shown in Fig. 4(b), making ventilation hole between the shaft and permanent magnet and on the outermost side of the stator doesn't affect the path of magnetic flux.

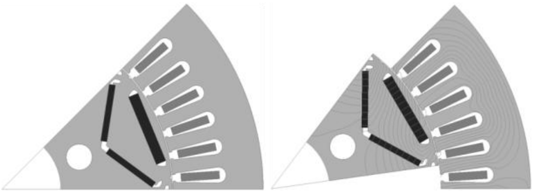

Figure 4:.2D FEM simulation model (a)base model (b)flux line distribution of base model

Fig. 5 shows 2D FEM simulation proposed model. The proposed model are designed considering the path of magnetic flxu and 3-phase voltage imbalance. As shown in Fig. 5, the ventilation hole are arranged according to the number of coils because of 3-phase voltage imbalance.

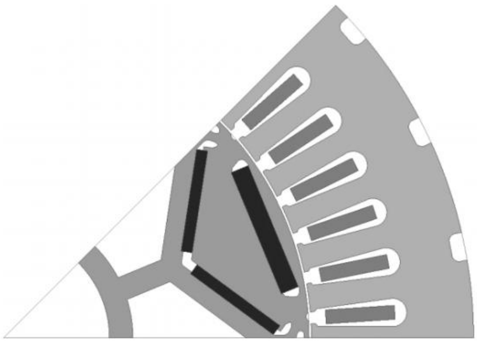

Figure 5:.2D FEM simulation proposed model

Table6 shows torque, phase current, and angle at base model and proposed model. Analysis of Table 6 was done at the same temperature and same current to find ventilation hole doesn't affect torque. As show in table6, the torque decrease by 1.56 % even though the ventilation hole is pierced.

Table 6: Torque, phase current, and angle at base model and proposed model

	Base model **P**	**Proposed model**	**Unit**
Phase current	298	298	A
Angle of phase current	44.5	44.5	.°
Torque	**256**	**252**	**Nm**

Table 7 shows torque phase current, and angle at base model and proposed model. The base model and proposed model was analyzed as difference of 20 ° considering cooling efficiency. Results of 2D FEM simulation analysis show that the efficiency of the proposed model is 0.28 % higher than that of the base model at the same torque.

Table 7: Efficiency at MTPA of base model and proposed model

	Base model **P**	**Proposed model**	**Unit**
Phase current	298.5	298	A
Angle of phase current	43.7	45.1	.°
Efficiency	**95.49**	**95.76**	**%**

3. Conclusion

In this paper, because of temperature change it was confirmed that d-axis and q-axis inductance, and magnetic flux linkage are changed. In particular, it was confirmed that phase current and angle of phase current, which are the control parameters of IPMSM, is not accurately controlled unless temperature is taken into account. Also, at MTPA driving point the efficiency was improved according to temperature decrease, and at the field weakening point, the efficiency decreased as the temperature decreased. Finally, How to drill the ventilation hole considering the path of the magnetic flux through FEM simulation was proposed. Through this method, Efficiency of proposed model is 0.28 % higher than that of the base model and the fuel efficiency of EV has been increased by reducing the weight of IPMSM. In addition, efficiency will be better given the core characteristics according to temperature.

Acknowledgment

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