

Design of IPMSM for EV Propulsion to Improve Torque and Efficiency Characteristics Considering Temperature Variation

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This article derives the rotor shape of interior permanent magnet synchronous motor (IPMSM) to reduce performance deviation under temperature variation. The overall characteristics of IPMSM in response to temperature variation, such as constant torque curve and maximum torque per ampere trajectories, are analyzed. Moreover, the effects of temperature on efficiency of IPMSM are investigated. As a result, for reducing average torque and efficiency deviation caused by temperature changes, the proportion of reluctance torque needs to be increased. In this article, the improvement design considering temperature variation are conducted by positioning the magnets more vertically compared to the original model. Finally, to validate the theoretical analysis and numerical simulations, a prototype is fabricated and tested.

Index Terms—Design methodology, efficiency, electric vehicles, permanent magnet motors, temperature.

I. INTRODUCTION

WITH the increase in demand for electric vehicles (EVs), interior permanent magnet synchronous motors (IPMSMs) are widely used for EV propulsion due to their high efficiency, high power density and wide operating range [1]-[2]. The high performance of IPMSMs is attributed to the high magnetic energy density of rare-earth PM materials. Meanwhile, the EVs operate in wide temperature range, which affects the PM remanence and PM flux linkage (λ_f). Moreover, performance, such as average torque and efficiency, deviation of the IPMSMs arises in response to temperature variation. This deteriorates the control accuracy of the IPMSMs and fluctuates the driving range per charge of EVs [2]. Therefore, reducing performance deviation due to temperature is essential.

In [2], the influence of temperature variation on motor characteristics including constant torque curves, maximum torque per ampere (MTPA) trajectories, and voltage limit ellipses were investigated. However, a detailed reason for the changes in above mentioned characteristics has not been analyzed, and the effects of temperature on efficiency have not been identified. Moreover, few studies have conducted the design to mitigate the effects of temperature on average torque and efficiency, simultaneously.

In this article, the overall operating characteristics and efficiency from 20 °C to 150 °C of IPMSM are analyzed in detail, and rotor design to improve average torque and efficiency characteristics considering temperature variation is conducted. First, the changes in the constant torque curves and MTPA trajectories as the temperature increases are analyzed, and detailed reason for the changes are identified. Furthermore, the effects of temperature on efficiency on IPMSM at main operating point are investigated. Additionally, the design to reduce the influence of temperature on average torque and efficiency is conducted. Finally, experimental tests are carried out to verify the theoretical analysis and numerical simulations.

II. EFFECTS OF TEMPERATURE ON CONSTANT TORQUE CURVES AND MTPA TRAJECTORIES

In this section, to investigate the operating characteristics of IPMSM in response to temperature, the changes in the constant torque curves and MTPA trajectories are analyzed. The torque of IPMSM can be expressed as follows [1].

$$T_e = \frac{3}{2} \frac{P}{2} (\lambda_d i_q - \lambda_q i_d) = \frac{3}{2} \frac{P}{2} [\lambda_f i_q + (L_d - L_q) i_d i_q] \quad (1)$$

where P denotes the number of poles, λ_d and λ_q are d - and q -axis flux linkage, respectively. Also, i_d and i_q are d - and q -axis current, respectively. Fig. 1 illustrates the constant torque curves and MTPA trajectories at 20°C and 150°C. As the temperature increases, the constant torque curves rotate counterclockwise. This is because the magnetic torque generated by λ_f is highly sensitive to temperature variations. Therefore, as indicated by the intersection points of the MTPA trajectories and the constant torque curves in Fig. 1, i_d increase with rising temperature to enhance the contribution of reluctance torque.

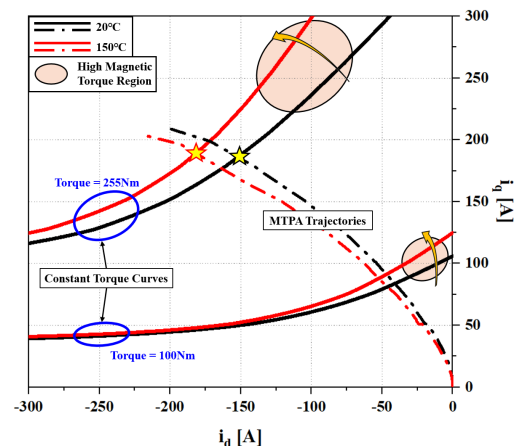


Fig. 1. Constant torque curves and MTPA trajectories according to temperature.

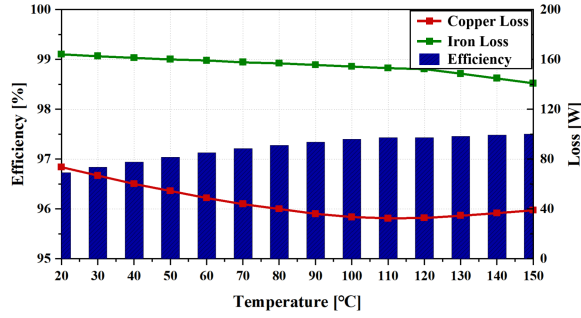


Fig. 2. Loss and efficiency of the original model.

Consequently, to reduce effects of temperature on the average torque of IPMSM, the proportion of reluctance torque needs to be increased.

III. EFFECTS OF TEMPERATURE ON EFFICIENCY

To investigate the efficiency of IPMSM for EV propulsion, this article selected a main operating point (14Nm@4,800rpm) with a high energy consumption ratio. The specifications of the target motor are summarized in Table I.

Fig. 2 shows the loss and efficiency at main operating point of original model. Since the main operating point is at low load, iron loss is the major component to total losses. However, the efficiency drop with decreasing temperature is caused by an increase in copper losses. When the temperature decreases relative to 110°C, the copper loss increases due to the rise in λ_f , which subsequently leads to an increase in voltage. In order to satisfy the voltage limit, field weakening operation is conducted, resulting in an increase in the d-axis current. Therefore, to enhance efficiency at low temperature and reduce the variation in the driving range per charge of EVs, it is necessary to decrease λ_f .

IV. IMPROVEMENT DESIGN OF IPMSM

From the previous theoretical analyses, this article proposes a rotor shape of IPMSM to reduce the influence of temperature on average torque and efficiency. Fig. 3 shows the configuration of original and proposed model, and the stator of two models are same. In this article, the magnets in second layer are positioned more vertically compared to the original model. This rotor shape can reduce λ_f . Additionally, due to the larger space between the first and second layer magnets, the reluctance torque increases as q -axis inductance increases.

Table II shows the torque characteristics of two models. Also, the loss and efficiency according to temperature of two models are illustrated in Fig. 4. By applying the proposed rotor shape, the average torque reduction due to temperature was decreased by 22.8%. As shown in Fig. 4(a), the copper loss and iron loss decreases when the temperature is lower than 110°C. Consequently, due to the increase in efficiency at low temperature, the variation in efficiency according to temperature decreased, as shown in Fig. 4(b).

V. EXPERIMENTAL VERIFICATION

As shown in Fig. 5(a), a prototype of the proposed model was fabricated and tested to verify the reliability of the numerical simulations. Fig. 5(b) shows the measured and simulated torques of the prototype, and they exhibited a high accuracy.

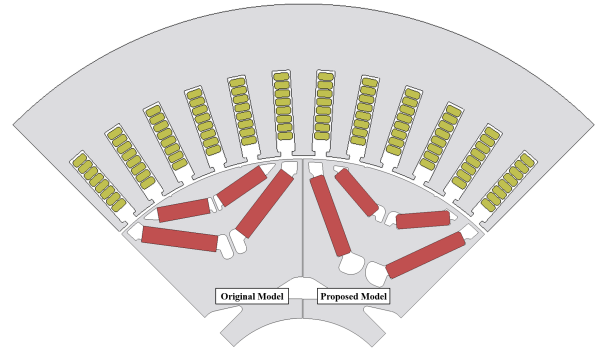


Fig. 3. Configuration of original and proposed model.

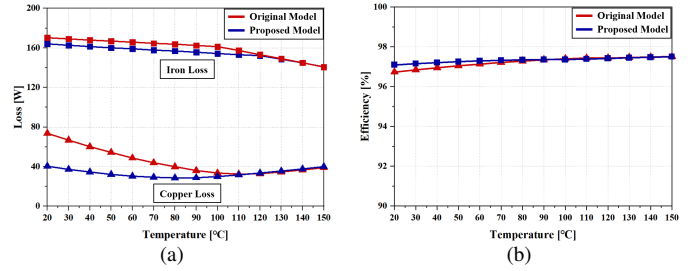


Fig. 4. Loss and efficiency of two models. (a) Loss. (b) Efficiency.

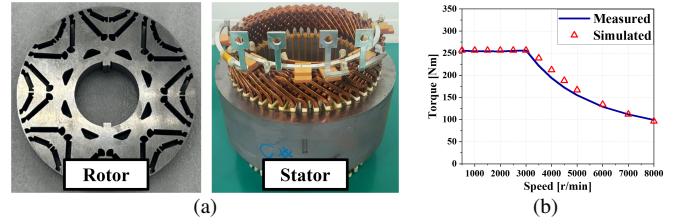


Fig. 5. Fabricated motor and test results. (a) Prototype. (b) Torques.

TABLE I. Target Specifications

Item	Value	Unit
Maximum power	80	kW
Maximum torque (at 50°C)	255	Nm
DC link voltage	650	V_{dc}
Input current limit	250	A_{pk}
Main operating point	14Nm@4,800rpm	-

TABLE II. Torque Characteristics of Two Models

Item	Original	Proposed	Unit
Magnetic torque at 50°C	176.4	153.3	Nm
Reluctance torque at 50°C	78.6	101.7	Nm
Total torque at 50°C	255		Nm
Total torque at 20°C / 150°C	267 / 246	264 / 249	Nm
Δ Torque/ Δ Temperature	-0.150	-0.116	Nm/°C

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