

Fast Computation of Iron Loss in EV Propulsion Motors for Optimal Design with Maximum Efficiency Per Ampere Control

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Recently, achieving high efficiency in propulsion motors is a crucial factor for improving the mileage of electric vehicles. While designing motor geometry for high efficiency is important, incorporating control strategies for high efficiency operation also plays a critical role in the design stage. Subsequently, the importance of maximum efficiency per ampere (MEPA) control, which considers not only copper loss but also iron loss, is increasing. However, implementing MEPA control requires the iron loss data set, which increases computational cost. Therefore, this paper proposes a calculation method using polynomial regression of d - q parameters and interpolation of the frequency-dependent saturation factor to derive the data required for MEPA control. The efficiency map derived from the proposed method was validated by comparing the result with FEA-based, with a maximum error of 0.8%.

Index Terms—Electric vehicles, efficiency, finite element analysis, interior permanent magnet synchronous motors, iron loss.

I. INTRODUCTION

PERMANENT magnet synchronous motors (PMSMs) are widely utilized in various industries due to advantages such as high power density and efficiency enabled by the use of rare-earth PMs. These advantages make them well-suited for improving the mileage of electric vehicles (EVs) [1].

Since motor characteristics vary depending on the control method, achieving high efficiency requires not only geometry design but also design that takes control method into account. Typically, most of electromagnetic losses in motors are copper losses. As copper loss can be minimized for the same torque generation, the application of maximum torque per current (MTPA) control in PMSMs can be regarded as a control method to achieve high efficiency operation. In the case of interior PMSMs (IPMSMs), the maximum torque generation requires a control that considers the q -axis current, i_q , as well as the d -axis current, i_d . Depending on the i_d and i_q , there are some operating points where iron loss becomes the dominant factor in electromagnetic losses. Therefore, MTPA control cannot be regarded as a definitive control for high efficiency operation. The motor design based solely on MTPA control may face limitations in achieving high efficiency. As a result, research on maximum efficiency per ampere (MEPA) control that considers copper loss as well as iron loss is being conducted for the high efficiency operation [2].

To consider MEPA control, it is essential to consider iron loss. When calculating iron loss in PMSMs, finite element analysis (FEA) is commonly applied to account for non-linearity; however, this method has the drawback of increasing computational cost. Consequently, research is being conducted to address this issue. In [3], according to the polynomial regression, iron loss was evaluated by calculating it at a reference frequency and applying a scaling based on frequency variations. This method offers the advantage of simplifying the analysis. However, it has the drawback of increased errors that occur at field-weakening operating points. In [4], iron loss

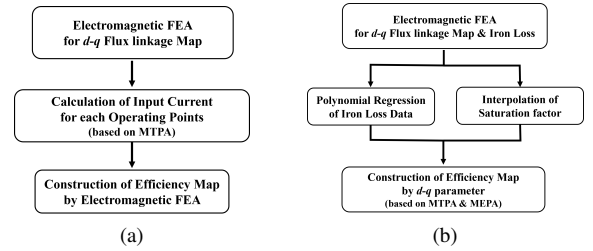


Fig. 1. The flow charts of efficiency map construction. (a) the conventional. (b) the proposed.

estimation was performed by fitting loss data for both with- and without-load variations across the operating range. This method is applicable to both surface mounted PMSMs (SPMSMs) and IPMSMs. However, an error exceeding 1.0% at the maximum efficiency point was observed in IPMSMs.

Therefore, this study aims to propose an analysis method for iron loss data set that reduces computational cost and improves accuracy. To achieve these, the calculation method based on polynomial regression of iron loss data and saturation factor induced by d - q parameters was applied. To alleviate the error in the field-weakening operating region, interpolation of the frequency-dependent iron loss curve considering magnetic saturation is conducted. The proposed method was validated by comparing the efficiency map with that obtained by FEA. Finally, the effectiveness of the proposed method in the design stage was demonstrated by optimizing the IPMSM considering the driving cycles with the MEPA control.

II. IRON LOSS MODELING BY POLYNOMIAL REGRESSION

Typically, performance analysis of the EV propulsion motor is conducted by searching for the i_d and i_q that satisfy the input constraints at each operating point, based on the flux linkage map, as depicted in Fig. 1 (a). Not only is the flux linkage map constructed, but the efficiency calculation is also performed by the FEA. Therefore, to reduce the computational

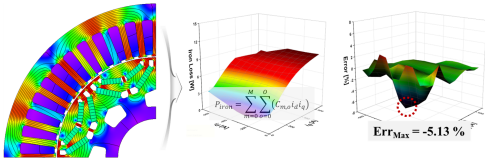


Fig. 2. Polynomial regression of iron loss and error at f_{ref} .

cost, the calculation method for the analysis of iron loss and efficiency map is proposed, as shown in Fig. 1 (b).

Among the iron loss analysis methods by the FEA, the calculation in the frequency domain is performed by post-processing the magnetic flux density within the elements, as expressed by the following equation [5].

$$P_{iron} = \int_V \sum_n D(K_e(nf)^2 + K_h nf) \cdot (B_{r,n}^2 + B_{\theta,n}^2) dv \quad (1)$$

where D is the density of the electrical steel sheet, n and V are the harmonic order and volume of the electrical steel sheet. $B_{r,n}$ and $B_{\theta,n}$ are the n -th harmonics of the radial and circumferential components of the magnetic flux density. K_e , K_h , and f are experimental constants of eddy current and hysteresis losses obtained from the Epstein frame and the frequency of the magnetic field, respectively. When the same i_d and i_q are applied, the same flux density distribution is derived. Subsequently, only the f in (1) changes, enabling frequency-based scaling of iron loss. However, in the case of IPMSMs, the magnetic saturation exhibits nonlinearity of the harmonic components depending on the applied i_d and i_q . Consequently, the simple frequency-based scaling leads to increased error, particularly in the field-weakening operation. To alleviate the error, the iron loss modeling based on d - q parameters and saturation factor was performed, as follows:

$$P_{iron}(i_d, i_q, f) = \alpha \left(\frac{f}{f_{ref}} \right) \cdot \sum_{m=0}^M \sum_{o=0}^O (C_{m,o} \cdot i_d^m \cdot i_q^o) \quad (2)$$

where m and o represent the polynomial degrees. $C_{m,o}$ is the polynomial coefficient. α and f_{ref} are the scaling function of the magnetic saturation and reference frequency. The maximum error of the iron loss at f_{ref} was 5.13%, as depicted in Fig. 2. To account for magnetic saturation induced by i_d and i_q , the iron loss data under open circuit (OC) and short circuit (SC) conditions were utilized. As shown in Fig. 3, the magnetic saturation and frequency-dependent iron loss characteristics were influenced by the applied current. In particular, the loss increment with respect to f becomes more significant as i_d increases for the field-weakening operation. Thus, interpolation of the frequency-dependent iron loss properties by the OC and SC conditions was performed to estimate α .

The efficiency maps derived from the conventional and the proposed method are presented in Fig. 4 and Table I. The model used for the analysis is an IPMSM with 8-pole and 48-slot. Efficiency maps were calculated based on the same i_d and i_q , with a maximum error of -0.8% . Although an additional 80 points were required to extract iron loss data under OC and SC conditions, the total computational cost of the proposed method was reduced by 62.2%.

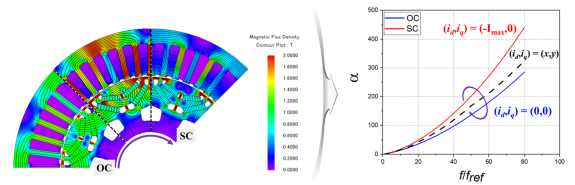


Fig. 3. The frequency-dependent iron loss property according to magnetic saturation.

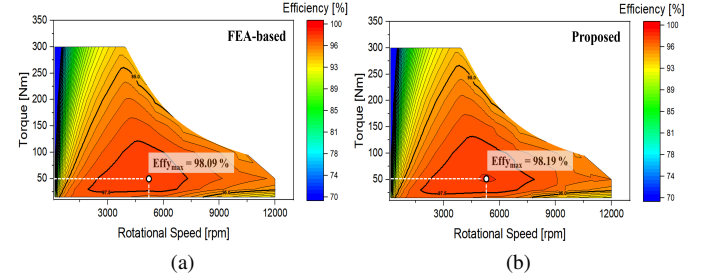


Fig. 4. The efficiency map and maximum efficiency point. (a) the conventional. (b) the proposed.

TABLE I
THE COMPUTATIONAL COST FOR EFFICIENCY MAP

Item	Conventional	Proposed	Unit
d - q parameter map	Analysis points	107	-
	Analysis time	428	s
Efficiency map	Analysis points	448	-
	Analysis time	4032	s
Total analysis time	4460	1688	s

CPU used in analysis : Intel(R) Core(TM) i9-12900KF 3.20GHz.

III. CONCLUSION

To reduce computational cost of iron loss analysis, this study employs polynomial regression for iron loss modeling. Furthermore, improved accuracy was achieved by incorporating the nonlinearity of harmonic components caused by magnetic saturation, based on iron loss data under OC and SC conditions.

In the manuscript, we aim to provide detailed information about the proposed method. Moreover, the proposed method validates not only the performance analysis but also its utility in the design stage through the optimal design of an IPMSM considering MEPA control.

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