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# Comparative Iron Loss Analysis of the Interior PMSMs for Electric Vehicles Considering the Effects of Temperature Variation

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**Abstract**—Accurately calculating iron loss in the extensively-used interior permanent magnet synchronous machines (IPMSMs) is challenging due to the effects of temperature variations, which can also be significant in automotive applications for optimizing efficiency. While the finite element method is a valuable tool for simulating and analyzing complex systems, including electric vehicle (EV) traction motors, it is essential to be aware of its limitations on computational cost and potential challenges when calculating iron loss in analyzing multi-physics effects. Therefore, this paper presents a comparative iron loss analysis between the improved analytical iron loss calculation model, finite element results, and experimental measurements of an IPMSM used in EVs, with a specific focus on considering the effects of temperature variation. By investigating the impact of temperature changes on iron loss by these obtained data, this study aims to provide valuable insights into validating the improved model's accuracy, assessing its computational efficiency, and identifying potential areas for improvement.

**Keywords**—Electric vehicles (EVs); thermal factors; permanent magnet machines; iron loss calculation

## I. INTRODUCTION

Interior permanent magnet synchronous motors (IPMSMs) stand out for their numerous advantages as traction motors in electric vehicles (EVs), like high power density, wide speed range, good mechanical strength and reliable robustness, which bring together performance, efficiency, reliability, and environmental benefits [1]. However, accurately calculating iron loss in IPMSMs is challenging because the operation of these motors within time-varying conditions of an EV drive cycle can lead to fluctuations in temperature. As temperature increases, the magnetic properties of the core materials, typically silicon steel in PMSMs, can change. Also, the permeability and hysteresis loss characteristics of the material are temperature-dependent, leading to alterations in the magnetic field behavior and subsequently affecting iron loss [2].

Several existing well-known methods are used for calculating iron loss in electrical machines, including IPMSMs. These methods vary in complexity and accuracy and are chosen based on the specific requirements of the analysis. For example, the Steinmetz equation is an empirical formula widely utilized to estimate iron loss in laminated magnetic cores. It is based on the core material's properties and the frequency of the magnetic field. While it is simple to apply, it may not accurately capture the effects of magnetic field distribution and temperature variation [3]. Hysteresis loop method involves constructing hysteresis loops for the core material at different operating points and frequencies. By calculating the area of the loops, hysteresis loss can

be estimated. However, this method can be time-consuming and may not account for the influence of temperature [4]. At present, finite element method (FEM) and analytical models are commonly used for the design optimization of permanent magnet synchronous motors. FEM is a numerical analysis means suitable for detailed electromagnetic simulations, which involves dividing the motor geometry into small elements and solving complex equations to calculate magnetic field distributions and losses [5]. FEM can provide highly accurate results but may require significant computational resources. Moreover, FEM also has difficulty in analyzing multi-physics effects, such as electrical, thermal, and mechanical effects. Although, analytical methods including loss separation models and magnetic equivalent circuit (MEC) models, are generally faster and more straightforward compared to FEA. They may not capture all loss components accurately [6].

This paper starts by investigating the impact of temperature rise on iron loss and delves into an in-depth comparative study of three existing ways: an improved analytical model proposed by our group, FEM and experimental measurement. It explores the sensitivity of these three methods to temperature fluctuations. This knowledge can aid in developing improved analytical models that account for thermal effects, thereby optimizing the design and efficiency of EV traction motors.

## II. COMPARATIVE STUDIES

### A. Proposed iron loss analytical models

The proposed models address both the spatial harmonics caused by stator slotting and carrier harmonics resulting from pulse width modulation (PWM) inverter. The models also predict iron loss in tooth and yoke regions separately, taking into account the impacts of magnetic saturation and temperature. To account for the thermal effects,  $K_h$  and  $K_e$  are both defined as functions of working temperature  $T_c$ . Therefore, the final iron loss model considering coupling effects is presented as (1). More detailed can also be found in our previous publication [7]:

$$\begin{aligned}
 P_{iron-3} = & \left\{ \frac{k_{h-PWM}^T K_h(T_c) \omega_s}{2\pi} \square B_{Tm}^\alpha + 8K_e(T_c) N_R N_S \left( \frac{B_{Lm}}{T} \right)^2 \right\} V_T \\
 & + \left\{ \frac{k_{h-PWM}^Y K_h(T_c) \omega_s}{2\pi} \square B_{Lm}^\alpha + \frac{4K_e(T_c) \omega_s (2 + \beta C_N N_S)}{\pi T \beta} \square B_{Lm}^2 \right\} V_Y \\
 & + \left\{ \frac{K_e(T_c)}{(N_W S)^2} \sum_{i=3,5,7,\dots}^n \left( \frac{V_n}{2\pi} \right)^2 \right\} (V_T + V_Y)
 \end{aligned} \tag{1}$$

## B. Numerical and Experimental results

Figures 1-4 compare the iron loss results obtained from the proposed model, FEM and experimental platform under various operating conditions including speeds ranging from 500-5500 rpm, temperatures from 30-90 °C, and 180 A phase currents. Table II presents the average errors of the results at different temperatures, where  $EM_j$  and  $EA_j$  ( $j = 30, 50, 70, 90$ ) represent the maximum and absolute average errors of iron losses, respectively, with respect to those obtained from the experimental platform at different temperatures.

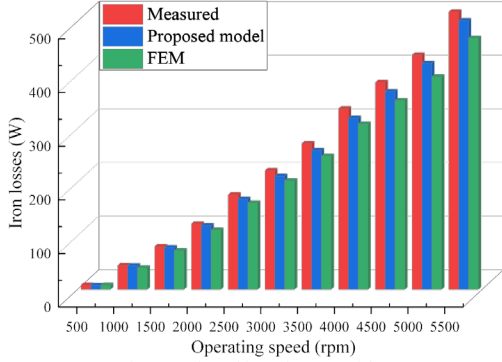


Figure 1. Comparative results of iron losses with 30 °C temperature

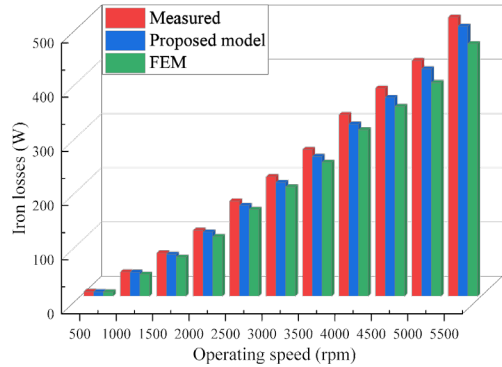


Figure 2. Comparative results of iron losses with 50 °C temperature

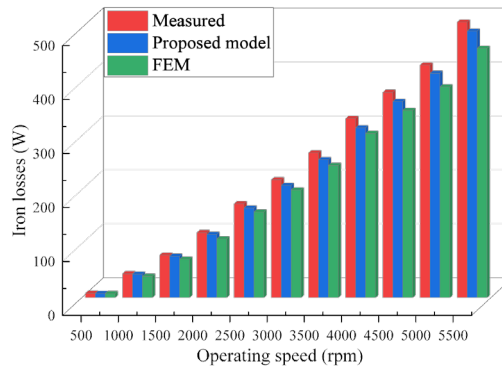


Figure 3. Comparative results of iron losses with 70 °C temperature

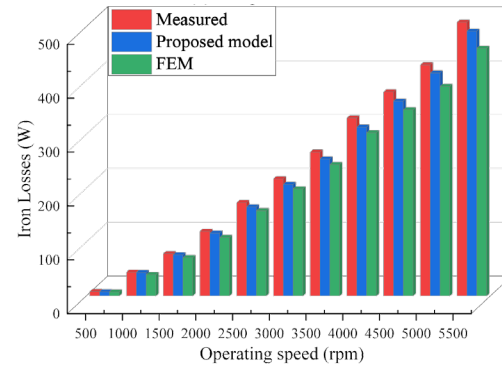


Figure 4. Comparative results of iron losses with 90 °C temperature

TABLE II  
ERROR ANALYSIS OF THE COMPARATIVE RESULTS

Items	$EM_{30}$ (%)	$EA_{30}$ (%)	$EM_{50}$ (%)	$EA_{50}$ (%)	$EM_{70}$ (%)	$EA_{70}$ (%)	$EM_{90}$ (%)	$EA_{90}$ (%)
FEM	10.37	9.15	10.42	9.29	10.39	9.35	10.34	9.12
Proposed	5.15	3.83	5.22	3.86	5.45	3.93	5.19	3.84

As seen, the improved analytical model significantly improves the accuracy of iron loss prediction under varying temperature conditions. The maximum and absolute average errors between estimated and experimental iron losses are less than 3.93% and 5.45%, respectively, which are approximately 50% lower than the errors produced by numerical FEM. The proposed model also takes multiphysics factors, particularly PWM harmonics, into account, exhibits better prediction accuracy than FEM, and has shorter computational time. Moreover, there is a deviation of about 10% from FEM, possibly due to the presence of PWM carrier harmonics and loss separation error. Nonetheless, the proposed iron loss analytical model performs satisfactorily and shows visible relationships between multi-factor effects and final iron loss values.

## III. CONCLUSIONS

This paper successfully tackles the crucial issue of accurately calculating iron loss in IPMSMs, which are widely used in EVs. Based on the improved analytical iron loss calculation model, a comprehensive comparative analysis with FEM and experimental measurements is conducted. Notably, the study incorporates the influence of temperature variation on the calculation performance. The results obtained from this investigation affirm the enhanced accuracy and computational simplicity of the proposed model across various operating speeds and temperature conditions, which can significantly contribute to the advancement of EV industry by improving motor design and efficiency.

Future work should focus on exploring the model's applicability to real-time iron loss calculation under more complex work points, leading to even greater insights and innovations in EV propulsion systems.

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