Rotor Induced Eddy Current Loss in Rectangular Bar Wave Windings of Permanent Magnet Electrical Machines for EV/HEVs

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This paper focuses on the sharp-wave eddy current loss induced by the rotor in the thick rectangular bar conductors of permanent magnet electrical machines. The mechanism of sharp waves of the instantaneous copper loss at certain rotor position are revealed. It shows that the sharp waves of the instantaneous copper loss waveform are caused by the moving rotor when the magnet edges pass through the slot openings. These induced sharp waves may significantly increase the AC copper loss, thus decreasing the motor efficiency, especially in the high-speed region. An analytical method to model the rotor induced eddy current loss is proposed based on the squared-field-derivation method and a magnetostatic field analysis. The proposed method could significantly reduce the calculation time compared to the numerical eddy current calculation. The analytical method is validated by transient finite element analysis (FEA).

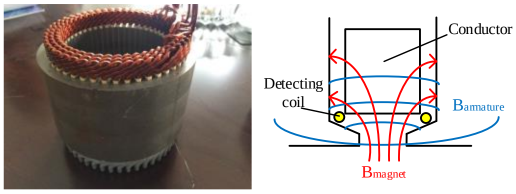
***Index Terms*—AC copper loss, eddy current, electrical vehicle/hybrid electrical vehicles (EV/HEVs), finite element analysis (FEA), rectangular bar wave windings.**

I. INTRODUCTION

THE utility of thick rectangular wire wave windings in electrical machines for electrical vehicle/hybrid electrical vehicles (EV/HEVs) (as shown in Fig. 1 (a)) have gained increasing interest due to its high slot filling factor, short end-winding, good manufacturability and excellent heat dissipation capability, etc. [1]. More EV makers tend to adopt this kind of windings in their new generation EV motors [1] [2]. However, significant eddy current losses may be induced in the thick bars especially at a high speed operation, thus reducing the machine efficiency and may cause winding local overheating.

The conductor in a slot suffers from the circumferential flux caused by the armature (blue) and the radial flux caused by the magnet (red), as shown in Fig. 1 (b). Existing findings mainly focus on AC copper loss caused by the skin effect and proximity effect on the armature side [3], while the eddy current loss caused by the rotor are rarely involved.

This paper focuses on the eddy current loss induced by the rotor in the thick rectangular bars of permanent magnet electrical machines. It shows that the rotor can cause distinct sharp waves in the instantaneous copper loss waveform at certain rotor positions. These rotor induced sharp wave loss may significantly contribute to the total copper loss. An analytical method is proposed to model the rotor induced eddy current loss based on the squared-field-derivation method and a magnetostatic field analysis. The proposed analytical method is validated by transient FEA.



(a) (b)

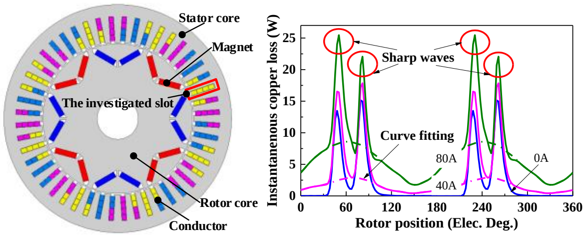
Fig. 1. (a) Stator with rectangular bar wave windings, (b) Magnetic field in the slot.

II. ROTOR INDUCED LOSS SHARP WAVES AND ITS MECHANISM

A. Sharp Waves of the Instantaneous Copper Loss

A 48-slot 8-pole interior permanent magnet (IPM) machine with rectangular bar wave windings is investigated in this paper, as shown in Fig. 2 (a). There are four conductors in each slot. As the PM rotor moves, eddy current loss will be induced in the conductors. Fig. 2 (b) shows that four distinct sharp waves occur in the instantaneous copper loss at certain rotor positions in an electrical period. These sharp waves may largely contribute to the average copper loss.

To evaluate the influence of these sharp waves, the average copper loss without considering these sharp waves are calculated by cutting away these sharp waves using the curve fitting method as shown in Fig. 2 (b). Table I lists the percentage of the sharp wave loss to the total copper loss. It can be seen that those sharp waves contribute a lot to the total copper loss, especially at high speeds and light loads. Therefore, it is essential to investigate and alleviate these sharp waves.



(a) (b)

Fig. 2. (a) Cross section of the investigated EV machine, (b) Sharp waves of the instantaneous copper losses under different current excitation within one stator slot at 8400rpm.

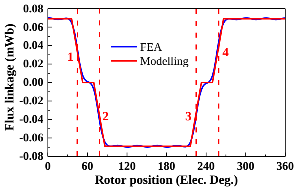
B. Mechanism of the Copper Loss Sharp Waves

To investigate those sharp waves in the instantaneous copper loss waveform, a detecting coil is placed near the slot opening to capture the rotor induced flux, as shown in Fig. 1 (b). A 2-D transient finite element analysis (FEA) is used to calculate the flux linkage of the detecting coil, as shown in Fig.

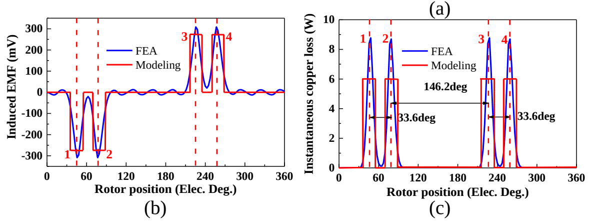
3 (a). It can be seen that four slopes exists in the flux linkage waveform. The variable flux linkage will induced four EMF sharp waves in the conductor as shown in Fig. 3 (b). As a result, eddy currents will be caused and the corresponding eddy current loss emerge as four sharp waves in the instantaneous copper loss waveform, as shown in Fig. 3 (c).

TABLE I SHARP WAVE LOSS PERCENTAGE UNDER DIFFERENT SPEEDS AND LOADS

	2800rpm	8400rpm	14000rpm
40A	41.6%	61.9%	66.7%
80A	15.3%	30.2%	35.3%
160A	4.1%	10.7%	13.3%



(a)



(b) (c)

Fig. 3. (a) Flux linkage, (b) Induced EMF of the detecting coil at the speed of 2800rpm, (c) Instantaneous copper loss within the conductors in the investigated slot at no-load at 2800rpm.

III. MODELING OF ROTOR INDUCED EDDY CURRENT LOSS

Based on the mechanism of the rotor induced loss sharp waves and the squared-field-derivation method [4], an analytical method combined with a simple magnetostatic field analysis is proposed to model the eddy loss. Fig. 4 (a) shows a conductor located in the rotor induced field. It assumes that the field is uniform along the conductor width direction. The field along the slot depth direction, however, decreases as the distance to the slot opening increases, as shown in Fig. 4 (b).

The time derivation of the flux equals to the EMF induced around the eddy current loop shown in Fig. 4 (a).

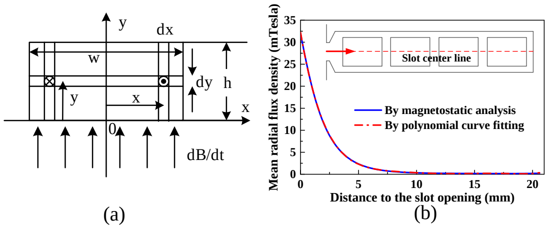
$$\frac{d\phi}{dt} = 2xl\frac{dB}{dt} \tag{1}$$

where l is the length of the conductor. The resistance of this path is

$$R = \frac{2l\rho_c}{dxdy} \tag{2}$$

where ρ_c is the copper resistivity. The instantaneous copper loss, then, can be obtained by integrating the differential term $((d\Phi/dt)^2/R)$ along the conductor width w and height h.

$$P_t = \int_0^h \int_0^{w/2} \left(2xl\frac{dB}{dt}\right)^2 \frac{1}{2l\rho_c} dydx = \frac{lw^3}{12\rho_c}\int_0^h \left(\frac{dB}{dt}\right)^2 dy \tag{3}$$



(a) (b)

Fig. 4. (a) Dimensions of a rectangular conductor in uniform magnetic field, (b) Mean radial flux density along the slot depth direction.

The previous observed four slopes of the flux through the conductors is the source of the eddy current loss in the conductor. It can be seen from Fig.3 (a) that the flux have an approximate linear relationship with the rotor position. Thus, the original four slopes can be modeled by four linearly changed slopes, as shown in Fig. 3 (a). These slopes will cause square waves of induced EMF and copper loss (Fig. 3 (b) and (c)). Therefore, the derivation of the flux can be expressed as

$$\frac{dB}{dt} = \frac{\Delta B}{\Delta t} \tag{4}$$

where ΔB is the flux variation of one slope and Δt is the time interval for the magnet edge to pass through the slot opening, which can be calculated by

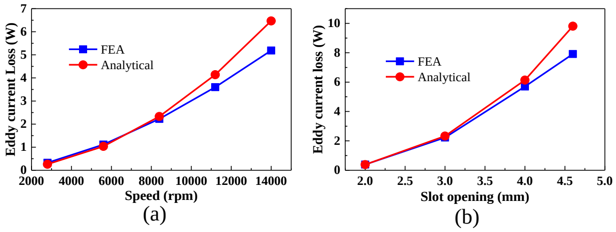
$$\Delta t = \frac{l_o}{\omega R_{si}} = \frac{30 l_o}{\pi n R_{si}} \tag{5}$$

Since ΔB depends on the depth of the conductor in the slot, a magnetostatic analysis is made to extract the relationship between ΔB and y. ΔB can be expressed as a function of y by the method of polynomial curve fitting, as shown in Fig. 4 (b).

The average copper loss, then, can be obtained as

$$P = \int_0^T P_t dt = 4\frac{\Delta t}{T}P_t = \frac{\pi n^2 plw^3 R_{si}}{5400 l_o \rho_c}\int_0^h \left(\Delta B(y)\right)^2 dy \tag{6}$$

where T is the electrical period. The results of the analytical method are compared with the ones obtained by transient FEA, as shown in Fig.3. It can be seen that good agreements are achieved.



(a) (b)

Fig. 5. Comparison of eddy current loss calculated by FEA and the analytical method, (a) with different speeds, and (b) with different slot openings.

IV. CONCLUSION

This paper reveals the mechanism of some sharp waves occurring in the instantaneous copper loss waveform at certain rotor positions. It shows that those sharp waves are caused by the moving magnet edges across the slot opening. These sharp waves could account for 66.7% of the total copper loss at a high speed. An analytical method is proposed to model the rotor induced eddy current loss based on the squared-field-derivation method and a magnetostatic field analysis. The results of the analytical method is validated by transient FEA.

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