

Novel eddy current loss suppression structure of permanent magnet motors with staggered slotting on permanent magnets

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A novel eddy current loss suppression structure is proposed for the permanent magnet motors based on staggered slotting on the permanent magnet (PM). Compared with the traditional PM structure that is completely disconnected axially, the novel structure has a similar loss suppression effect, but better mechanical properties and installation accuracy. Based on the analytical derivation and numerical calculations, the effect of the new structure on suppressing eddy current loss is demonstrated. A weight model is established for different design cases, which takes the slot size of the PM as variables. The influence of the new structure on the temperature rise and electromagnetic property of the motor is discussed based on a new perspective of the magnet-thermal coupling analysis.

Index Terms—Eddy current loss, permanent magnets, staggered slotting, permanent magnet motor.

I. INTRODUCTION

THE eddy current loss of the PM is a key problem affecting the electromagnetic performance of permanent magnet motors [1-2]. Axial and circumferential segmentation of the PM can increase the eddy current path and resistance, which is a common measure to suppress the eddy current loss [3]. However, the positioning errors are difficult to avoid when the segmented PMs are bonded or arranged together. When the errors are large, the PM will be difficult to insert into the rotor slots. Additional magnetic field harmonics may also be generated.

In this paper, a novel eddy current loss suppression structure of permanent magnet motors with staggered slotting on the PM is proposed. Compared with the previous structure of the axial slotting on the PM surfaces [4], the processing difficulty is lower, and the depth of the slot can be larger. It is proved that the effect of the slotted PM in suppressing losses is close to that of the traditional segmented PM. Also, the influence of the new structure is discussed by coupled calculations of the temperature rise and magnetic fields under the steady state condition of motors. The changes of the PM flux and torque caused by the PM slotting are comprehensively analyzed.

II. EDDY CURRENT LOSS SUPPRESSION ANALYSIS OF PERMANENT MAGNET WITH STAGGERED SLOTTING

The purpose of this research is to suppress the eddy current losses in the PM of interior permanent magnet synchronous motors. The model of the motor is shown in Fig. 1. The flux harmonics induce eddy currents in the PM, and eddy current losses are caused. A calculation model of the PM eddy current losses is established, as shown in Fig. 2(a). The length, width, and height of the PM are L , W , and h , respectively. According to the principle of the electromagnetic induction, there are

$$dP = \frac{E^2}{R} \quad (1)$$

$$E = -\frac{dB \cdot S}{dt} = -4xy \frac{dB}{dt} = -4 \frac{b}{a} x^2 B_m f \quad (2)$$

The resistance R of the eddy current loop can be represented by equation (3).

$$R = \rho \left(\frac{4x}{hdy} + \frac{4y}{hdx} \right) = \rho \frac{4x(W/L + L/W)}{hdx} \quad (3)$$

The eddy current loss of the PM can be represented by equation (4), where V and ρ are the volume and resistivity of the PM, respectively.

$$P = \int_0^W dP = \frac{V}{16\rho} \cdot \frac{W^2}{1 + (W/L)^2} (B_m f)^2 \quad (4)$$

To reduce eddy current losses of PMs, the segmentation of PMs is a common measure. The segmented PMs are bonded together by glue, and insulated from each other. Generally, the length L of the PM is much larger than its width W . When the PM is uniformly divided into N segments along the L direction, the total eddy current loss of these separated PMs becomes

$$P = N \cdot \frac{V/N}{16\rho} \cdot \frac{W^2}{1 + (W/(L/N))^2} (B_m f)^2 = \frac{V}{16\rho} \cdot \frac{W^2}{1 + N^2(W/L)^2} (B_m f)^2 \quad (5)$$

Comparing equation (4) with equation (5), it can be seen when the PM is divided, the eddy current loss is significantly reduced. However, since these segmented PMs are sequentially bonded, the dimensional tolerances are introduced into PMs. The PMs may be difficult to insert into the rotor slots, and the yield rate of the PMs is reduced.

A method is proposed to reduce eddy current losses in PMs by slotting, which increases the path and resistance of the eddy currents in the PM, as shown in Fig. 2(b). Since the PM is connected along the y -direction, the PM can easily remain regular shapes.

In the model of Fig. 2(b), the number of slots is N_s (an even number). The voltage E is slightly reduced due to the slotted structure. According to the change of eddy current paths, the increase factor for the resistance R is $(W+L+N_s \cdot W_s)/(W+L)$. The eddy current loss can be written by

$$P = \frac{V - N_s W_s L_s}{16\rho} \cdot \frac{1}{1 + N_s \frac{W_s}{W+L}} \cdot \frac{W^2}{1 + (W/L)^2} (B_m f)^2 \quad (6)$$

When W_s and L_s approach zero, the result of equation (6) is consistent with the case of equation (4) i.e., PM is not slotted. When W_s approaches W and L_s approaches zero, considering that L is much larger than W , $N=N_s+1$, the result of equation (6) is consistent with equation (5). It is proved the eddy current

loss suppression effect of slotting PMs gradually approaches that of the segmented PM method when W_s is increased. But if W_s is too large, the higher precision of slotting is required, and the mechanical strength of the PMs is decreased.

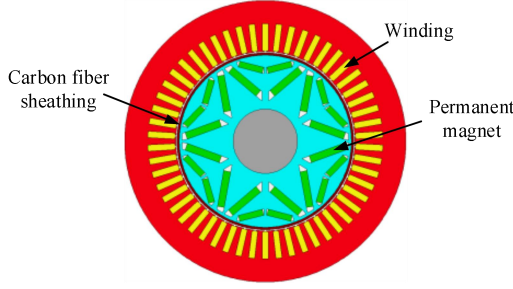


Fig.1. Model of the interior permanent magnet synchronous motor.

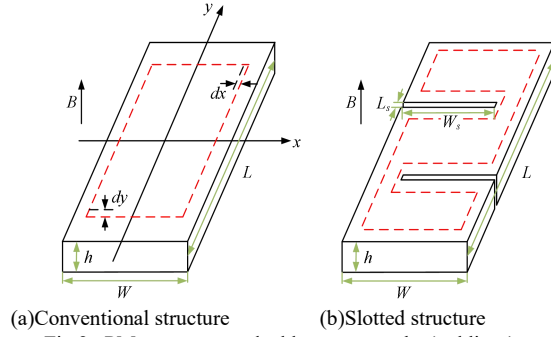


Fig.2. PM structures and eddy current paths (red lines).

III. WEIGHT MODEL FOR THE STRUCTURAL DESIGN AND OPTIMIZATION OF PERMANENT MAGNETS

L_s is a fixed value influenced by the cutting blade thickness. Based on a survey, $L_s \geq 0.2$ mm. The larger N_s and W_s , the better suppression effect of the eddy current loss. However, the volume and magnetic flux of the PM, as well as the motor torque will be reduced. In this paper, a method combining 3D simulation calculation and data fitting is employed to solve the impact of N_s and W_s on the eddy current loss. When $N_s=4$ and $W_s/W=0.9$, eddy current losses of the PM decrease from 56.03 W to 12.20 W, 78.2%. As shown in Fig. 3, the amplitude of the eddy current is significantly reduced, and the distribution of the eddy current is more uniform.

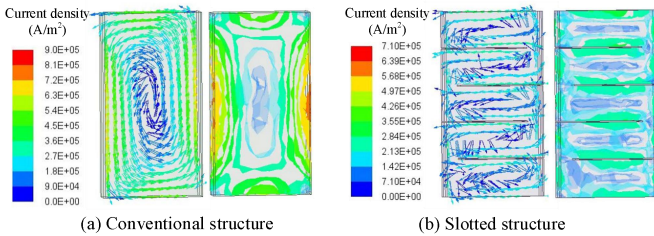


Fig.3. Simulation results of the PM eddy currents

The design formula based on the weigh model is given in equation (7), where P and T are the eddy current loss and torque of the conventional structure, respectively.

$$a \cdot \frac{P}{P(N_s, W_s)} + b \cdot \frac{T(N_s, W_s)}{T} = \text{Max}, \quad a + b = 1 \quad (7)$$

In the slotted PM in Fig. 2, N_s and W_s jointly determine the volume change and eddy current losses of the PM. In this paper, N_s and W_s are taken as variables, and multiple groups of variables are selected for finite element simulations. In this

way, the function of N_s , W_s , eddy current loss and torque can be fitted and established.

IV. MOTOR TORQUE CALCULATION BASED ON ELECTROMAGNETIC-TEMPERATURE COUPLING

A. Analysis of the Influence of Permanent Magnet Loss Suppression on Temperature and Torque

To consider the effect of actual controller excitation on PM losses, a joint simulation model of SVPWM drive circuit and motor electromagnetic structure is built. Under high frequency conditions, the increase of the eddy current losses of the PM will be obvious due to the excitation harmonics. At this time, the torque contributed by the decrease of PM temperature and increase of PM residual magnetic density can be higher than the torque reduction by the PM slotting. This trend depends on the amplitude of temperature changes of PMs under different working conditions. Thus, the equation (7) is corrected by the coupling calculation of electromagnetic and thermal models.

B. Weight model reconstruction by the correction function

After further corrections of torque-loss-temperature rise, the effect of loss suppression on the motor torque is reconstructed. Compared with the weights before the correction, the weight of a in equation (7) will be increased under the same design criteria, and the optimization results will be biased towards larger N_s and W_s . Meanwhile, the weight is also determined by the selection of the rated motor speed since the torque variation trend is opposite in high-speed and low-speed cases. It means that the proposed PM structure is more suitable for high-speed motors with large PM eddy current losses.

V. CONCLUSION

In this paper, an innovative eddy current loss suppression structure is proposed for the permanent magnet motors based on staggered slotting on the PM. This structure can obtain an eddy current loss suppression effect close to the complete segmentation method of PM. Also the regularity of PM can be maintained. It should be pointed that PM volume and motor torque reduction are key problems of this method. However, the reductions are not obvious considering the effect of temperature on the residual magnetic density. In the condition of the high PM temperature rise, the motor torque can be increased instead, which is attractive in the motor designs.

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