Analysis of the Impact of Current Ripple on the Eddy Current Loss of Axial-Flux Permanent Magnet Motor

Chen Chen, Youlong Wang
Key Laboratory of Power Electronics and Electric Drive, Institute of Electrical Engineering, Chinese Academy of Sciences
Beijing Engineering Laboratory of Electrical Drive System & Power Electronic Device Packaging Technology
E-mail: cchen@mail.iee.ac.cn

***Abstract*-This paper presents that the current ripple may increase the eddy current loss of axial-flux permanent magnet motor (AFPM). In the simulation of this paper, the ideal sine current and PWM ripple current are applied to the windings of AFPM separately, and the eddy current losses are obtained by finite element analysis (FEA) and analytic formulas. The effect of the current ripple on the eddy current losses of AFPM can be shown by comparing of the calculation results. Further, the measured efficiency map of manufactured AFPM proved this speculation.**

I. Introduction

Nowdays, the axial-flux permanent magnet machines have received increasing attention, and having been used widely in different fields [1]. The AFPM has the advantages of short axial size, light weight and good heat dissipation, but there is a serious current discontinuous phenomenon because of the small inductance value of winding.

There are harmonics with various frequencies in the discontinuous current, and the harmonics do have directly influence on the loss of AFPM. Particularly, the temperature of the magnets rising as the eddy current loss increasing in magnets, and this may cause the permanent magnets demagnetization fractional or integral. The characteristics of the motor will be affected directly under this condition.

In considering of the problems above all, the model is built to research the impact of harmonics on the loss of AFPM. The model is simulated by finite element method. The ideal sine current usually applied to windings in FEA, but it cannot simulate the practical condition. The harmonic with various frequencies is simulated by PWM ripple current in this paper, thus the result of simulation do reflect the real situation more accurately [2].

This paper proceeds as follows: The details of the verification method and simulation model are introduced in Section II. The calculation method and results of eddy current loss of windings and magnets are presented in Section III. Then section IV states the experimental results. And in section V, the last part of the paper, the conclusion is given.

Project 51107133 supported by NSFC

II. Verification Method And Simulation Model

A. Proposed Verification Method

In order to verify the impact of the ripple current on the eddy current loss of permanent magnets and windings, a contrast method is proposed as follows. In addition, the way of generation of PWM ripple current is also introduced in this part.

The ideal sine current is shown in Fig.1. To simulate the real situation, the exciting current is got through adding PWM current ripple over sine current signal. The generation mechanism of PWM ripple current is expounded as follows.

Under the assumption that the stator resistance can be neglected, and the frequency ratio carried to fundamental is large enough to make the average back electromotive force is constant.

$$i(t)=\begin{cases} I\cos(\omega_s t+\varphi)-At & 0\le t\le T_1 \\ I\cos(\omega_s t+\varphi)+B(t-T_1)-AT_1 & T_1\le t\le T_1+T_2 \\ I\cos(\omega_s t+\varphi)-A(t-T_1-T_2)+BT_2-AT_1 & T_1+T_2\le t\le T_1+T_2+T_3 \end{cases} \quad (1)$$

Where I is the amplitude of fundamental current. The instantaneous time is expressed by t. T_1, T_2 and T_3 are the switching time which depend on PWM switching pattern. ω_s is the fundamental electrical angular velocity. The factor A and B are defined as follows.

$$A=\frac{\sqrt{(E_0-\omega_s I_d L_{ad})^2+(\omega_s I_q L_{aq})^2}\sin(\omega_s t+\phi)}{2L_{ls}} \quad (2)$$

$$B=\frac{V_{dc}-\sqrt{(E_0-\omega_s I_d L_{ad})^2+(\omega_s I_q L_{aq})^2}\sin(\omega_s t+\phi)}{2L_{ls}} \quad (3)$$

Where L_{ad} and L_{aq} are the d-axis and q-axis armature reactive inductances. L_{ls} is the leakage inductance. E_0 is the peak value of no-load back electromotive force. V_{dc} is the DC bus voltage[3]. The formulas above indicate that when V_{dc} and back electromotive force remain as constants, the amplitudes of current ripples are determined by L_{ls} only. It is shown that the current ripples increasing as the leakage inductance decreasing. In another words, the current ripples can be restrained effectively by increasing the leakage inductance.

The PWM ripple current which can reflect the actual situation is shown in Fig.2.

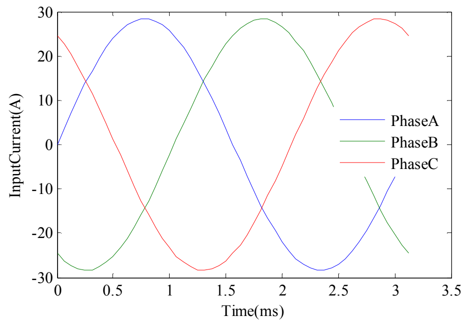


Fig.1 Ideal sine current

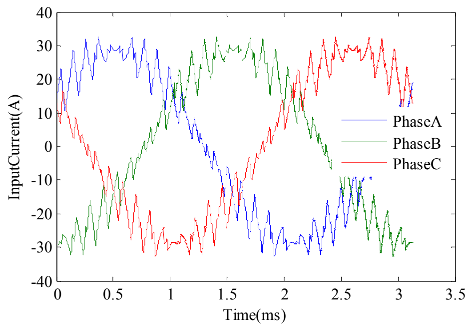


Fig.2 PWM ripple current

B. *Proposed Verification Method*

The simulation model of AFPM is shown in Fig.3. The winding disc is stator, which is in the middle layer of the model. The rotor contains two permanent magnet discs at each side of stator. The magnets are fixed on the core. The rated power of the AFPM is 4.5kW, the rated speed is 2400r/min, and the rated current is 20A. The 3D mesh of AFPM is shown as Fig.4.

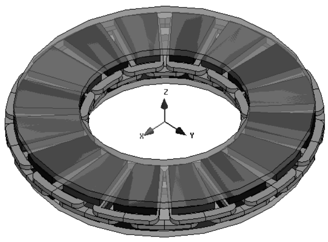


Fig.3 FEA model of AFPM


Fig.4 3D mesh of AFPM

III. Calculation Of Eddy Current Loss Of Windings And Magnets

A. *Proposed Verification Method*

The eddy current loss of windings is analyzed in this part. On the one hand, the axial components B_a and tangent components B_t of air gap flux density are obtained through simulation by FEM. One the other hand, the eddy current loss of windings could be calculated by analytic formulas.

In the calculation of eddy current loss, the proximity effect and skin effect of conductors are not considered, the end winding of AFPM stator is neglected, and the magnetic field of each calculated cell seems as constant.

The magnetic field is symmetric about the center of air-gap and the pole, so the space of windings distributed in 1/2 air-gap under a pair of poles are used to analysis in the calculation. The distribution of the windings under a pair of poles is shown as Fig.5. The whole AFPM contain 16 poles and 24 coils, and each coil contain 2 edges which are along radial direction, so there are 48 edges of the whole model, and 6 edges under a pair of poles.

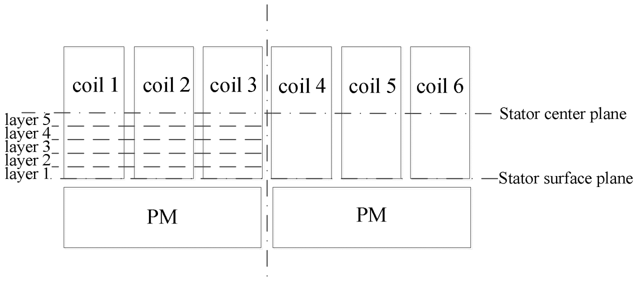


Fig.5 Distribution of the windings under a pair of poles

In order to analyze the eddy current loss of stator windings more accurately, the space of the windings is divided into 11 slices along radial direction, and each slice has the same radial length. Each slice is divided into 5 layers along axial direction, and each layer has the same thickness. The model is shown as Fig.6.

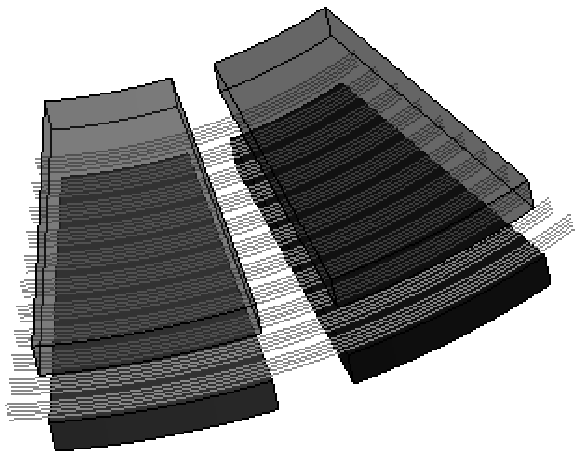
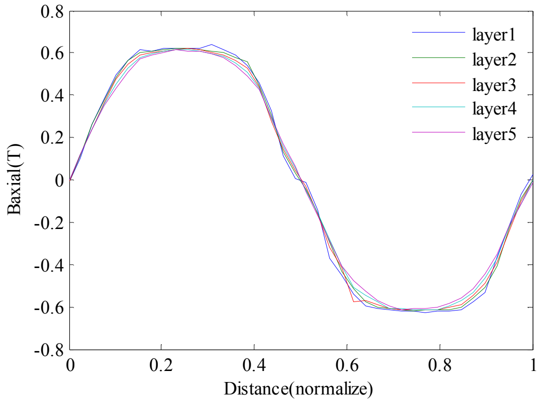


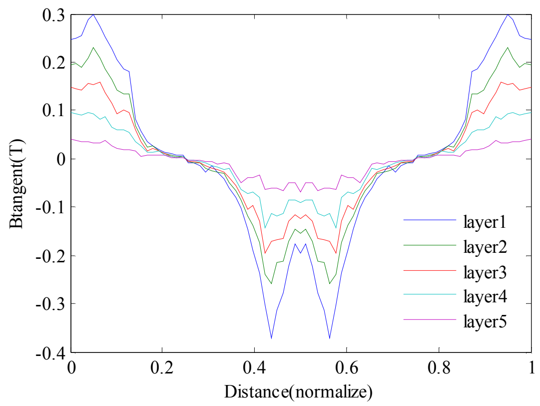
Fig.6 Slices and layers in model

The sine current and PWM ripple current are applied to the coil separately. Through finite element simulation, the axial components B_a and tangent components B_t of air gap flux density are obtained at the different diameters of each slice. This paper, which takes the middle radius 90mm as an example, showing the difference of the B_a and B_t when sine current and PWM ripple current were applied to the windings in separate, shown as Fig.7 and Fig.8.

According to the method mentioned above, the axial components B_a and tangent components B_t of the air gap flux density are got by finite element method(FEM). The fundamental and harmonic components of B_a and B_t are obtained by FFT.

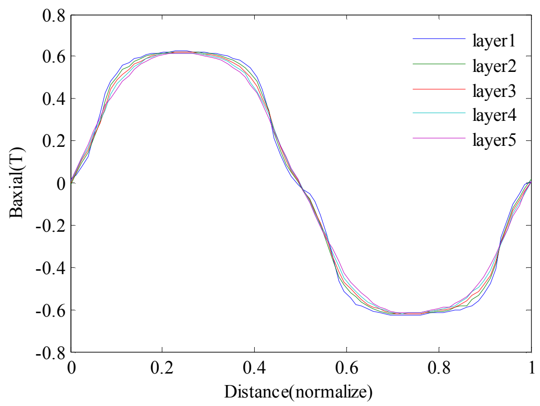


(a) B_a at 90mm

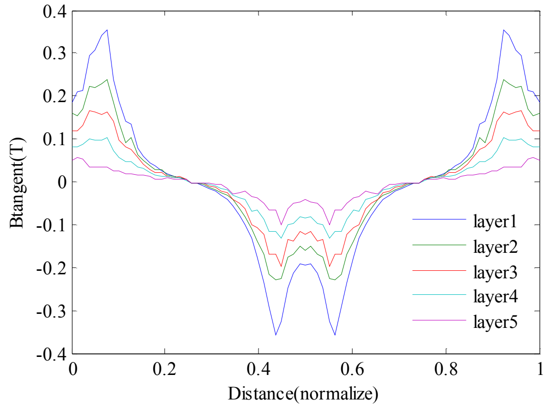


(b) B_t at 90mm

Fig.7 B_a and B_t at 90mm with sine current



(a) B_a at 90mm



(b) B_t at 90mm

Fig.8 B_a and B_t at 90mm with PWM ripple current

Then according to the reference material[4], the eddy current loss in single conductor can be calculated by formula (4).

$$P_s = \frac{\pi l_r d^4 \omega^2}{32\rho} \sum_{i=1}^{n} i^2 \left(Ba_i^2 + Bt_i^2 \right) \tag{4}$$

Where d is the diameter of the conductor, l_r is the length of each slice along radial direction, ω is the fundamental angle frequency, ρ is the resistivity of copper conductors, i is the harmonic order.

The eddy current loss of the jth layer can be computed by formula (5).

$$P_j = n_j \cdot P_s = \frac{\pi l_r d^4 \omega^2}{32\rho} \cdot n_j \sum_{i=1}^{n} i^2 \left(Ba_i^2 + Bt_i^2 \right) \tag{5}$$

Where n_j is the conductor number in the jth layer.

The eddy current loss of the kth slice can be computed by formula (6). Then, half of the total eddy current loss of the windings under one pole can be calculated by (7). Where l is the number of the conductor layers, s is the number of the slices.

$$P_{le} = \sum_{j=1}^{l} P_j = \frac{\pi l_r d^4 \omega^2}{32\rho} \sum_{j=1}^{l} n_j \sum_{i=1}^{n} i^2 \left(Ba_{ij}^2 + Bt_{ij}^2 \right) \tag{6}$$

$$P_{se} = \sum_{k=1}^{s} P_{le} = \frac{\pi l_r d^4 \omega^2}{32\rho} \sum_{k=1}^{s} \sum_{j=1}^{l} n_j \sum_{i=1}^{n} i^2 \left(Ba_{ijk}^2 + Bt_{ijk}^2 \right) \tag{7}$$

The result of calculation is extended to the whole AFPM model finally. The eddy current loss of the whole AFPM windings is obtained from formula (8).

$$P_e = 2*(2*p)*P_{se} \tag{8}$$

The parameter values of this model are given as TABLE I.

When the sine fundamental component current and PWM ripple current respectively applied to the stator windings, the values of eddy current loss of windings can be computed with above method. The total eddy loss of windings is 996.78W with sine current, and 1167.91W with PWM ripple current. The eddy current loss of windings increase 17.17%. The results indicate that the current ripple increasing the eddy current loss of windings of AFPM,

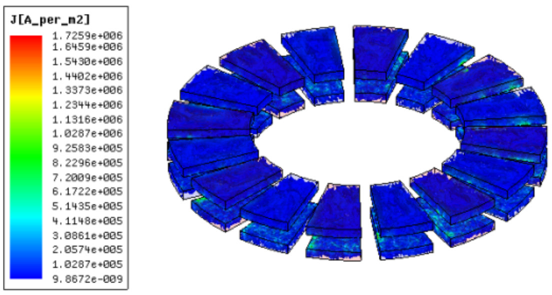
TABLE I
PARAMETER VALUES OF NUMERICAL COMPUTING MODEL

parameter	value	unit
d	0.8	mm
l_r	5	mm
ρ	0.0185	Ω·mm2/m
ω	2010.6	rad/s
n	19	——
l	5	——
s	11	——

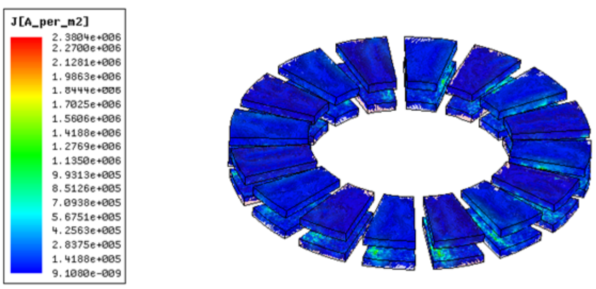
B. *Calculation of Eddy Current Loss of Magnets*

This simulation is developed under the conditions as follows: (1) The penetration depth of the magnetic fields is considered. (2) Assign insulating boundary condition to each piece of permanent magnet. (3) The electrical conductivity of the iron core is set to zero. (4) The transient field is used in the simulation.

At first, the eddy current density distribution in the magnets is obtained by finite element simulation, as shown in Fig.9. The eddy current density distribution in the magnets with sine current is shown in Fig.9(a), and the eddy current density distribution in the magnets with PWM ripple current is shown in Fig.9(b).



(a) Sine current



(b) PWM ripple current

Fig.9 Eddy current density distribution in the magnets

From the eddy current density distribution in the magnets, the impact of current ripple on the eddy current loss of magnets can be reflected intuitively. With calculation of finite element method, the average values of eddy current loss of magnets are 7.7025W and 10.841W under sine current and PWM ripple current respectively. The eddy current loss of magnets increase 40.75%. The results above prove that the current ripple greatly increased the eddy current loss of magnets of AFPM.

According to the calculation and analytical results above, the feasible measures should be taken to reduce the current ripple in practical designs. Based on the analysis of section II, the inductance could be connected to each phase of windings in series for reducing the current ripple.

IV. TEST RESULTS

The diagram of the performance test and measured efficiency map of the manufactured AFPM are given in this section, as shown in Fig.10 and Fig.11. The temperature rise under typical operating conditions of the manufactured AFPM can reflect the loss from another respect.

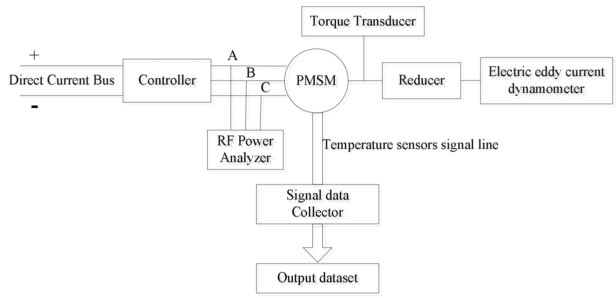


Fig.10 Diagram of the performance test

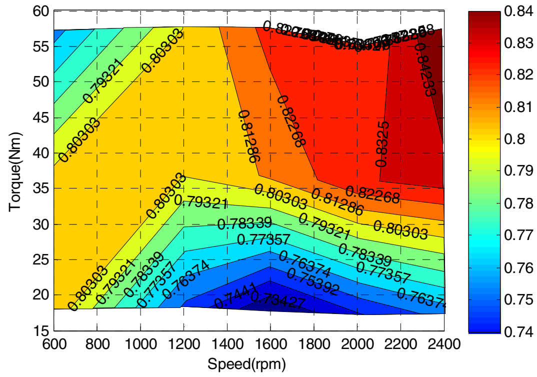


Fig.11 Efficiency map of AFPM

So as the discussion above, the eddy current loss increases when the PWM ripple current applied in the simulation of section V. The current discontinuous serious in the actual test, so the eddy current loss will be produced more. The basic reason for that is the small inductance value of AFPM winding. This paper suggests that the current continuous quality can be improved by series connection inductor between winding and power line.

V. CONCLUSIONS

In this paper, the discontinuous current of AFPM is simulated by PWM ripple current, and the eddy current density distribution is obtained by FEA. The simulation results show that the current ripple greatly increased the eddy current loss of AFPM. The test results of manufactured AFPM proved this speculation. Finally, this paper suggests that the discontinuous current can be improved by series inductor to each phase of windings.

REFERENCES

[1] Jian Li , Da-Woon Choi , Chang-Hum Cho , Dae-HyunKoo , and Yun-Hyun Cho, " Eddy-Current Calculation of Solid Components in Fractional Slot Axial Flux Permanent Magnet Synchronous Machines," IEEE TRANSACTIONS ON MAGNETICS, VOL. 47, NO. 10, pp. 4254 – 4257, Oct 2011.

[2] Deng, "Analytical modeling of eddy current losses caused by pulse-width-modulation switching in permanent-magnet brushless DC motors," IEEE Trans. on Magnetics, Vol. 34, 1998, pp. 3718-3726.

[3] D. G. Holmes and T. A. Lipo, *Pulse Width Modulation for Power Converters: Principles and Practice*, Wiley-IEEE Press, 2003.

[4] Rong-Jie Wang, Maarten J.Kamper， "Calculation of Eddy Current Loss in Axial Field Permanent-Magnet Machine With Coreless Stator," IEEE TRANSACTIONS ON ENERGY CONVERSION, VOL.19, NO.3, pp.532-538. Sept2004.