Study on Magnet Eddy Current Losses in Interior Permanent Magnet Machines for Aircraft Electric Green Taxiing Systems

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Abstract. The magnet eddy current of multi-layered interior permanent magnet (IPM) machines is studied in the paper for the aircraft electric green taxiing systems. The armature reaction flux density distribution, eddy current density and harmonic spectrum at the end of permanent magnet are analysed. A method to reduce the magnet eddy current of multi-layered IPM machines is presented. That is to increase the distance between outer permanent magnet and rotor surface and the distance between two layers of permanent magnet so as to provide a larger core path for armature reactive flux. This method can effectively reduce the magnet eddy-current loss of the multi-layered IPM machines and improve the operation efficiency.

1. Introduction

Using electric machines for the aircraft traction during taxi phase is a current technology [1]-[2]. Because of the advantages of high torque density, wide operation range of constant power and low rotor eddy current loss, the interior permanent magnet (IPM) synchronous machine can be used for the aircraft electric green taxiing systems [3]. When the permanent magnet synchronous machine (PMSM) is running at high speed, the spatial harmonic of the machine magnetic field caused by stator grooving, the spatial harmonic of the machine magnetic field caused by winding current and the temporal harmonic of the machine magnetic field will produce a lot of eddy current loss in the rotor permanent magnet [4]. Excessive eddy current loss of permanent magnet will lead to irreversible demagnetization at high temperature. Therefore, it is of great significance to study eddy current loss of permanent magnet of high-speed IPM machines.

Literature [5]-[6] optimized the stator tooth and rotor separation magnetic bridge of the built-in permanent magnet synchronous machine. After optimization of the structure, the eddy current loss of the permanent magnet is reduced by about 60%. The literature [7] studies the eddy current loss of the fractional slot centralized winding built in machine. The research results show that the eddy current loss on the fixed rotor core can be reduced by adding auxiliary magnetic barrier to the straight axis. By adding auxiliary magnetic barrier to the quadrature axis, the eddy current loss on the permanent magnet can be reduced.

In this paper, the magnet eddy current loss of multi-layered IPM machine is studied. The distribution of magnetic density, the eddy current density at the end of the permanent magnet and the harmonic spectrum of the pure armature reaction of the multi-layered IPM machine are studied, and a method to reduce the rotor eddy current loss of the multi-layered IPM machine is presented.
2. Machine Specification
Multi-layered IPM machine is composed of stator, rotor, wind-cooled housing and bearing. The rotor structural diagram of the high-speed multi-layered IPM machine is shown in Figure 1. PM1-PM3 are permanent magnets, bridge1-bridge2 are bridges, rib1 is the reinforcement of permanent magnet, and barrier1-barrier3 are permanent magnetic barriers, \( a_1 \) is the permanent magnet angle. The first layer of permanent magnet is composed of permanent magnet PM1 and PM2, and its shape is V-shaped. The second layer of permanent magnet is composed of permanent magnet PM3. When the two layers are superimposed, they can be seen as an inverted triangle, which is initial structure. The power rating is 30 kW continuous, the rated torque is 100 Nm, the over load torque is 200 Nm, the rated speed is 3000 r/min, the maximum speed is 9000 r/min, the reduction ratio of the gears is 36.

![Figure 1. Rotor of high-speed multi-layered interior permanent machine.](image1)

3. Study on Magnet Eddy Current Loss

3.1. Magnetic density distribution of pure armature reaction
Figure 2 shows the magnetic density distribution of pure armature reaction at 9000 r/min with inverted triangle structure. For the IPM structure, the permanent magnet is buried in the core. The armature reaction flux returns to the air gap and stator mainly through the core and the bridge. The bridge and reinforcement on the rotor provide an additional path for the armature reaction flux. For the initial structure, the second layer of permanent magnet PM3 is located at the outer edge of the rotor surface, which has a great hindrance to the armature reaction flux. Armature reaction after regional 1 magnetic flux, the part through the magnetic separation of magnetic bridge back to the air gap and stator, partly through regional 2 and through the first layer of the permanent magnet reinforcement back to another extreme.

![Figure 2. Magnetic density distribution of pure armature reaction at 9000 r/min with initial structure.](image2)
3.2. Eddy current loss density cloud of the permanent magnet

Figure 3 shows the eddy current loss density cloud of the permanent magnet with an initial structure at 9000 r/min, $h_1$-$h_2$ is the depth of two layers of permanent magnets, $i_1$ is the distance between two layers of permanent magnets. It can be seen from the figure that the eddy current loss of the permanent magnet is mainly concentrated in the end of the permanent magnet. The magnet eddy current loss of the initial structure is 86.5 W, which is relatively large and needs to be optimized.

![Eddy current loss density cloud of the permanent magnet](image)

**Figure 3.** Eddy current loss density cloud of the permanent magnet with an initial structure at 9000 r/min.

4. Optimization of Eddy Current Loss of Permanent Magnets

According to the above analysis of eddy current loss of the permanent magnet with initial structure, the second layer of permanent magnet PM3 is located at the outer edge of the rotor surface, which has a great obstacle effect on the armature reaction flux. Therefore, the rotor core region can be increased to provide a path for the armature reaction flux, so as to reduce the eddy current loss of the permanent magnet. Figure 4 shows the rotor structure diagram of the optimized high-speed multi-layered IPM machine.

![Optimized rotor structure](image)

**Figure 4.** The optimized rotor structure of high-speed multi-layered interior permanent magnet machine.

Figure 5 shows the magnetic density distribution of pure armature reaction at 9000 r/min for the optimized structure. For the optimized structure, the second permanent magnet layer depth $h_1$ is bigger than the initial structure, the optimized structure of iron core area of 1 is larger than the initial structure. The second permanent magnet and the first layer of the permanent magnet distance $i_1$ is bigger than the initial structure, the optimized structure of the core area of 2 is larger than the initial structure core area. The added core region of the optimized structure can provide a larger path for the armature reaction flux.
Figure 5. Armature reaction flux distribution of the optimized structure at 9000 r/min.

In order to analyse the eddy current density on the permanent magnets of the two structures, the rotor permanent magnets in Figure 2. and Figure 5. are added with point A, which is located at the end of the outermost permanent magnet. Figure. 6. shows the eddy current density and harmonic spectrum analysis of the ends of the permanent magnets of the two structures at 9000 r/min. The eddy current density of the permanent magnet with the optimized structure is smaller than that of the initial structure. The eddy current loss of the permanent magnet is directly proportional to the square of the eddy current density of the permanent magnet. Therefore, the eddy current loss of the permanent magnet with initial structure is smaller than that of the initial structure.

Figure 6. Eddy current density and harmonic spectrum analysis of the ends of the permanent magnets of the two structures at 9000 r/min. (a) Eddy current density profile. (b) Harmonic spectrum analysis results.

The eddy current density harmonic component of two IPM machines at 9000 r/min are shown in Table 1. As can be seen from the Table 1, the harmonics of eddy current density are mainly concentrated on the 6th and 12th. The 6th and 12th harmonic vortices of the optimized structure are much less dense than those of the initial structure.

Figure 7. shows the eddy current loss density cloud of the permanent magnet with the optimized structure at 9000 r/min. The magnet eddy current loss of the optimized structure is 45.2 W, which is 47.74% lower than that of the initial structure. Therefore, for double-layer IPM structure, increasing the distance between the depth of the outer permanent magnet and the number of layers of the permanent magnet can effectively reduce the eddy current loss of the permanent magnet.
Table 1. Eddy current density harmonic component of two structures at 9000 r/min.

| Harmonic component | Initial structure | Optimized structure |
|--------------------|-------------------|---------------------|
| 6th (A/mm²)        | 1750000           | 497057.75           |
| 12th (A/mm²)       | 1260000.07        | 826004.35           |
| 18th (A/mm²)       | 143909.78         | 34479.58            |
| 24th (A/mm²)       | 82253.85          | 101363.71           |
| 30th (A/mm²)       | 60278.35          | 11424.03            |
| 36th (A/mm²)       | 3953.63           | 42035.04            |
| 42th (A/mm²)       | 60278.35          | 84161.06            |
| 48th (A/mm²)       | 82253.85          | 98016.17            |
| 54th (A/mm²)       | 143909.78         | 39200.19            |

Figure 7. Eddy current loss density cloud of the permanent magnet with the optimized structure at 9000 r/min.

Table 2 shows the design parameters of two structures. It includes the depth of the permanent magnet, the distance between the layers of the permanent magnet, the Angle of the permanent magnet, the length of the permanent magnet PML and the width PMW.

Table 2. Design parameters list of two structures.

| Harmonic component | Initial structure | Optimized structure |
|--------------------|-------------------|---------------------|
| \( h_1 \) (mm)     | 3                 | 5.2                 |
| \( h_2 \) (mm)     | 19.5              | 25.9                |
| \( i_1 \) (mm)     | 4.6               | 8.8                 |
| \( a_1 \) (°)      | 116               | 117                 |
| PML (mm)           | 23                | 18.5                |
| PMW (mm)           | 4.5               | 4.2                 |

5. Conclusion

In this paper, the rotor eddy current loss of multi-layered high speed IPM machine is studied for the aircraft electric green taxiing systems. The distribution of magnetic density in pure armature reaction is studied. The eddy current density and harmonic spectrum at the end of permanent magnet are analysed. The results show that for the structure of two-layer permanent magnet, increasing the distance between the outer permanent magnet and the rotor surface and the distance between the two layers of permanent magnet, so as to provide a larger core path for the armature reaction flux, can effectively reduce the eddy current loss of the permanent magnet.
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References
[1] F. Re, “Assessing environmental benefits of electric aircraft taxiing through object-oriented simulation,” Soc. Automotive Engineers Int. J. Aerosp., vol. 5, no. 2, pp. 503-512, 2012.
[2] H. Oyori and N. Morioka, “Power management system for the electric taxiing system incorporating the more electric architecture,” The SAE Aero Tech Congress. Exhibition, Montréal, Canada, 2013.
[3] E. D. Ganev, “Electric Drives for Electric Green Taxiing Systems: Examining and Evaluating the Electric Drive System,” IEEE Electrification Magazine, vol. 5, no. 4, pp. 10-24, Dec. 2017.
[4] D. Gerada, A. Mebarki, N. L. Brown, C. Gerada, A. Cavagnino, and A. Boglietti, “High-speed electrical machines: Technologies, trends, and developments,” IEEE Trans. Ind. Electron, vol. 61, no. 6, pp. 2946-2959, Jun. 2014.
[5] Katsumi Yamazaki, and Atsushi Abe. “Loss Investigation of Interior Permanent-Magnet Machines Considering Carrier Harmonics and Magnet Eddy Currents,” IEEE Transactions on Industry Applications, 2009, 45(2):659-665.
[6] Katsumi Yamazaki, Yuji Kanou, Yu Fukushima, Shunji Ohki, Akira Nezu, Takeshi Ikemi, and Ryoichi Mizokami. “Reduction of Magnet Eddy-Current Loss in Interior Permanent-Magnet Machines With Concentrated Windings.” IEEE Transactions on Industry Applications, 2010, 46(6):2434-2441.
[7] Gilsu Choi and Thomas M. Jahns. “Reduction of Eddy-Current Losses in Fractional-Slot Concentrated-Winding Synchronous PM Machines.” IEEE Transactions on Magnetics, 2016, 52(7): 8105904.