Analysis on reducing eddy current loss of axial motor by permanent magnet segmentation

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Abstract—This paper gives the causes of eddy current loss of permanent magnet in axial permanent magnet motor, and puts forward the method of reducing eddy current loss by circumferential and radial combined sectional insulation of permanent magnet. The principle analysis and analytical formula derivation of permanent magnet sectional insulation to reduce eddy current loss are carried out. Finally, Maxwell three-dimensional finite element simulation is used to verify that the circumferential and radial combined sectional insulation of permanent magnet can greatly and quickly reduce the eddy current loss of permanent magnet of axial motor.

1. Introduction
Axial surface mounted permanent magnet synchronous motor has been widely used in wind power industry because of its compact structure, convenient assembly and easy realization of high power density. The permanent magnet of axial motor is generally directly placed in the air gap in a large area. Therefore, many air gap harmonic magnetic fields pass through the interior of the permanent magnet. These harmonic magnetic fields will produce eddy current loss in the interior of the permanent magnet and increase the temperature of the permanent magnet \cite{1}. If the temperature of permanent magnet is too high, it will produce irreversible demagnetization, which will reduce the efficiency of motor and unstable operation \cite{2}.

In addition, the changes of stator and rotor structure and air gap size of axial motor will affect the eddy current loss of permanent magnet. Reference \cite{3} Zou studies the relationship between the width of stator slot and the eddy current loss of motor rotor, and found that the eddy current loss in rotor increases with the increase of slot width. In reference \cite{4}, the temperature rise caused by eddy current loss of permanent magnet in motor with slotted stator side is analyzed, and the analytical equation in two-dimensional plane is established. Reference \cite{5} Zhang studies the temperature rise caused by eddy current loss under different working conditions of stator coreless axial permanent magnet motor, and makes a prototype experiment.
For reducing the eddy current loss of permanent magnet of axial motor, the method of segmented insulation of permanent magnet is generally adopted [6]. This method can quickly and effectively reduce the eddy current loss of permanent magnet, and has little impact on the performance of axial motor. The segments of permanent magnet are basically circumferential and radial segments. The effect of circumferential and axial segments of permanent magnet of radial motor on eddy current loss of rotor permanent magnet is studies in reference [7]. Reference [8] Yamazaki studies the change of processing cost caused by permanent magnet segmentation.

This paper combines the axial segmentation and circumferential segmentation methods of radial motor to reduce the eddy current loss of permanent magnet of axial motor. The three-dimensional finite element simulation shows that the proposed method can quickly reduce the eddy current loss of permanent magnet.

2. Principle of reducing eddy current loss by segmented insulation of permanent magnet

Eddy current loss occurs in permanent magnets because they are conductive and in an alternating air gap magnetic field. There are generally two reasons for the alternating magnetic field: one is the harmonic magnetomotive force generated by the stator armature, and the other is the uneven stator magnetic circuit caused by stator slotting. Therefore, eddy current loss will occur in permanent magnets. There are two corresponding methods to reduce eddy current loss. One is to reduce the harmonic magnetomotive force generated by the stator armature, but it is often expensive. The other is to insulate the permanent magnet in sections and increase the eddy current internal resistance of the permanent magnet to reduce the eddy current loss. This method is relatively simple and widely used [9].

The permanent magnet has conductivity and can be regarded as a whole conductor containing resistance. As shown in Figure 1, it is assumed that the width of the permanent magnet is a and the resistance in the width direction is \( R_a \). The length is b and the resistance in the long direction is \( R_b \). And there is a uniform and alternating effective flux \( \Phi \). Therefore, the alternating magnetic field is:

\[
B = \sqrt{2}\Phi \sin \omega t
\]

The eddy current loss generated when the permanent magnet is not segmented is:

\[
P_{loss} = \frac{u^2}{R} = \frac{\omega^2 a^2 b^2 \Phi^2}{2(R_a+R_b)}
\]  

The equivalent diagram of rectangular upward segmented insulation of permanent magnet is shown in Figure 1. From the figure, it can be calculated that the eddy current loss of permanent magnet after segmenting along the long direction is:

\[
P_{seg-loss} = \frac{u^2}{R} = \frac{\omega^2 a^2 b^2 \Phi^2}{2(R_a+R_b)}
\]  

Similarly, if the insulation is divided into sections along the width direction, the eddy current loss can be calculated as:

\[
P_{seg-loss} = \frac{u^2}{R} = \frac{\omega^2 a^2 b^2 \Phi^2}{2(R_a+R_b)}
\]  

Therefore, the eddy current loss formula after segmented insulation along the width direction can be obtained. From the formula and figure, we can deduce the formula of N segments along the width direction and M segments along the length direction, as shown below:

\[
P_{seg-loss} = \frac{u^2}{R} = \frac{\omega^2 a^2 b^2 \Phi^2}{2(mR_a+nR_b)}
\]

Then the eddy current loss ratio before and after segmented insulation can be obtained as:

\[
\frac{P_{seg-loss}}{P_{loss}} = \frac{R_a+R_b}{mR_a+nR_b}
\]  

It can be seen from formula 6 that in order to reduce the eddy current loss of permanent magnet, the value of M or n needs to be large, so that the eddy current loss can be significantly reduced. For radial motor, because the permanent magnet is generally magnetic tile or cube, it is easy to realize uniform segmentation in circumferential or axial segments, and the permanent magnet with uniform size is obtained by combining segments. The combination of segments can increase the values of M and N at the same time, so as to speed up the reduction of eddy current loss. For the permanent magnet of axial
motor, the general three-dimensional sector is in the majority, and the radial segmentation of the permanent magnet is also uniform, while when the circumferential segmentation and the radial and circumferential combined segmentation, the size of the permanent magnet is uneven. For the non-uniform size of permanent magnet obtained by axial motor combination, the above method is analyzed to verify whether it can be used to reduce the eddy current loss of permanent magnet.

![Fig.1 equivalent diagram of permanent magnet](image)

3. Three dimensional finite element simulation verification of axial permanent magnet motor

3.1. Axial motor model

The axial permanent magnet generator with rated power of 20kW is simulated by three-dimensional Maxwell finite element method. For axial motor, because many of its characteristics are related to radius, the three-dimensional calculation is more accurate. The parameters of the generator are shown in Table 1

| Parameter name                          | Value     |
|----------------------------------------|-----------|
| Rated speed /rpm:                      | 3000      |
| Power /kw                              | 20        |
| Number of poles                        | 12        |
| Outer diameter of stator / mm          | 190       |
| Stator inner diameter / mm             | 112       |
| Length of stator core / mm             | 48        |
| Stator / rotor steel profile           | DW310-35  |
| Number of stator slots                 | 36        |
| Air gap length / mm                    | 1         |
| Notch width / mm                       | 2.2       |
| Number of rotor poles                  | 12        |
| Outer diameter of rotor / mm           | 190       |
| Inner diameter of rotor / mm           | 112       |
| Rotor core height / mm                 | 12        |
| Conductivity of permanent magnet / (Ks / M) | 625       |
| Pole arc coefficient                   | 0.9       |
| Radial length of magnet / mm           | 39        |
| Magnetic steel type                    | NdFe30    |
| Thickness of magnetic steel / mm       | 4.5       |
According to the characteristics of the generator used and the symmetrical distribution of internal magnetic field, a three-dimensional model of 1/6 motor is established for verification. The motor model is shown in Figure 2.

![Fig. 2 three dimensional motor model](image)

3.2 Analysis of eddy current loss of permanent magnet with different sectional insulation

The eddy current density of the permanent magnet during radial segmentation is shown in Figure 3. It can be seen that the permanent magnet with uniform size can be obtained during radial segmentation. In Figure 3, the eddy current density diagram of the permanent magnet without radial segmentation and divided into 2, 3 and 4 segments is given. It can be seen from the figure that the eddy current density also decreases with the increase of the number of segments, and their eddy current losses of the permanent magnet are 253W, 175W, 59W, 45W.

![Fig. 3 radial permanent magnet segment](image)

3.2 Analysis of eddy current loss of permanent magnet with different sectional insulation

The eddy current density of the permanent magnet in circumferential segmentation is shown in Fig. 4. It can be seen that the size of the permanent magnet in circumferential segmentation is uneven compared with the size of the radial segmentation. Fig. 4 shows the eddy current density diagram of the permanent magnet divided into 2 and 3 segments in circumferential direction. Similarly, as the number of segments increases, the eddy current density also decreases. The eddy current losses of the permanent magnet divided into 2 and 3 segments are 105W and 51W respectively. The effect of circumferential segmentation twice is similar to that of radial segmentation three times, which shows that the circumferential effect is better than that of radial segmentation.
Fig. 4 circumferential segmentation

The eddy current density of the combined radial and circumferential segments of the permanent magnet is shown in Fig. 5. It can be seen that the size of the permanent magnet is also uneven. The eddy current density diagram of the combined radial and circumferential segments of the permanent magnet is given in Fig. 5. The eddy current loss of the permanent magnet in the combined segments is 53W. Compared with radial and circumferential segmentation, the combined segmentation can achieve the effect of three radial and two circumferential segmentation only by two segmentation. It can be seen that the combined segmentation method can more quickly and effectively reduce the eddy current loss of the permanent magnet of the axial motor.

Fig. 5 combined segmentation

4. Conclusion

This paper introduces the causes of eddy current loss of permanent magnet of axial permanent magnet motor, makes theoretical analysis, and deduces the analytical formula of eddy current loss. The sectional insulation method to reduce the eddy current loss of permanent magnet of axial permanent magnet motor is explored and verified. The conclusions are as follows:

(1) The comparison between theoretical analysis and simulation shows that the eddy current loss can be greatly reduced by segmenting the permanent magnet of axial permanent magnet motor.

(2) Although the size of the permanent magnet obtained by the radial and circumferential combined segmentation method is uneven, which is slightly different from the theoretical analysis, it can still quickly and effectively reduce the eddy current loss of the axial permanent magnet motor. Moreover, it can be seen from the experimental results that the eddy current loss of the permanent magnet can be quickly reduced even if the segmentation of the sector permanent magnet is uneven. It has certain reference significance for the optimization design of axial permanent magnet motor in the future.

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