3-D Analysis of Loss Distribution in an Interior Permanent Magnet Motor Driven by PWM Inverter

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Keywords: interior permanent magnet motor, 3-D finite element method, PWM inverter, eddy current loss, hysteresis loss

We have been analyzing several characteristics of an interior permanent magnet motor (IPM motor) driven by the three-phase sinusoidal currents. However, an IPM motor in the compressor of air conditioner is usually driven by the PWM inverter. It is important to clarify the electrical loss caused by the carrier of the PWM inverter. In this paper, we clarified the electrical loss and the torque characteristic of an IPM motor driven by the PWM inverter. The analyzed results of the motor driven by the inverter are verified through the comparison of those of the motor driven by the sinusoidal current.

Figure 1 shows the analyzed model of an IPM motor. Fig. 2 shows the 3-D finite element mesh. Fig. 3 shows current waveforms and harmonic spectrums. One is sinusoidal waveform, and the other is measured one that is driven by the PWM inverter.

Figure 4 shows the distributions of eddy current density vectors in the permanent magnet. In case of the inverter-drive the eddy current density vectors in front of rotation direction and in the upper part of the permanent magnet are larger than those of the sinusoidal

current-drive.

Figure 5 shows the contours of the eddy current loss in the magnet. It is found that the eddy current loss in the edge and upper part is larger than that of sinusoidal current-drive.

Figure 6 shows the iron loss characteristics. It is found that the eddy current loss in the stator core is especially large.

Figure 7 shows the eddy current loss characteristics in the permanent magnet. It is found that the eddy current loss of the inverter-drive is about 3.5 times larger than that of the sinusoidal current-drive.

Fig. 1. Analyzed model (1/4 region)

Fig. 2. 3-D finite element mesh

Fig. 3. Current waveforms

Fig. 4. Distributions of eddy current density vectors.

Fig. 5. Contours of eddy current loss

Fig. 6. Iron loss characteristics

Fig. 7. Eddy current loss characteristics (in magnet)

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Electrical loss of an interior permanent magnet motor (IPM motor) driven by the pulse width modulation inverter (PWM inverter) is analyzed using the three-dimensional finite element method (3-D FEM). The distributions of the eddy currents in the permanent magnet, the iron loss characteristics, and the torque characteristics were quantitatively clarified.

Keywords: interior permanent magnet motor, 3-D finite element method, PWM inverter, eddy current loss, hysteresis loss

1. Introduction

We have been analyzing several characteristics of an interior permanent magnet motor (IPM motor) driven by the three-phase sinusoidal currents⁽¹⁾⁽²⁾. However, an IPM motor in the compressor of air conditioner is usually driven by the PWM inverter. It is important to clarify the electrical loss caused by the carrier of the PWM inverter. The losses of an IPM motor driven by the PWM inverter has been studied⁽³⁾, however, the analyzed model is not taken into account the overhang of rotor core and the end-coil. In this paper, we clarified the electrical loss and the torque characteristic of an IPM motor driven by the PWM inverter, which took the effects of overhang of rotor and the end-coil into account. The analyzed results of the motor driven by the inverter are verified through the comparison of those of the motor driven by the sinusoidal current.

2. Analysis Method

2.1 Magnetic Field Analysis The fundamental equations of the magnetic field can be expressed using the magnetic vector potential A and the electric scalar potential ϕ as follows:

$$\text{rot}(\nu \text{ rot } A) = J_0 + J_e + \nu_0 \text{ rot } M \dots \dots \dots (1)$$

$$J_e = -\sigma \left(\frac{\partial A}{\partial t} + \text{grad } \phi \right) \dots \dots \dots (2)$$

$$\text{div } J_e = 0 \dots \dots \dots (3)$$

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where ν is the reluctivity, J_0 is the exciting current density, J_e is the eddy current density, ν_0 is the reluctivity of the vacuum, M is the magnetization of permanent magnet, and σ is the conductivity.

2.2 Calculation of Eddy Current Loss The eddy current loss W_{ed} in the permanent magnet is given as follows⁽⁴⁾:

$$W_{ed} = \frac{1}{\tau/2} \int_t^{t+\tau/2} \left\{ \int_{V_e} \frac{(J_e)^2}{\sigma} dv \right\} dt \dots \dots \dots (4)$$

where τ is the period of the eddy current waveform, V_e is the region of the conductor with the eddy current, J_e is the eddy current density, and σ is the conductivity.

The eddy current loss W_{ed} in the laminated magnetic steel sheet is estimated as follows⁽⁵⁾:

$$W_{ed} = \frac{K_e D}{2\pi^2} \int_{iron} \frac{1}{N} \sum_{k=1}^N \left\{ \left(\frac{B_r^{k+1} - B_r^k}{\Delta t} \right)^2 + \left(\frac{B_\theta^{k+1} - B_\theta^k}{\Delta t} \right)^2 + \left(\frac{B_z^{k+1} - B_z^k}{\Delta t} \right)^2 \right\} dv \dots \dots \dots (5)$$

where K_e is the coefficient of the eddy current loss, D is the density of the steel sheet, N is the number of iteration of analysis step, and Δt is the time interval of the time stepping method.

2.3 Calculation of Hysteresis Loss The hysteresis loss W_{hy} taking into account the major and minor loops of the hysteresis loop can be estimated as follows⁽⁵⁾:

$$W_{hy} = \frac{K_h D}{T} \sum_{i=1}^{NE} \frac{\Delta V_i}{2} \left(\sum_{j=1}^{Npr^i} (B_{mr}^{ij})^2 + \sum_{j=1}^{Np\theta^i} (B_{m\theta}^{ij})^2 + \sum_{j=1}^{Npz^i} (B_{mz}^{ij})^2 \right) \dots \dots \dots (6)$$

where K_h is the coefficient of the hysteresis loss, D is the density of the steel sheet, T is the period of analysis time, NE is

the number of the elements in the steel sheet and ΔV_i is the volume of the i -th element. N_{pr}^i , $N_{p\theta}^i$ and N_{pz}^i are the number of the maximum or minimum value of the flux density in the radial direction, the rotation direction and the z-direction of the i -th element, respectively. B_{mr}^{ij} , $B_{m\theta}^{ij}$ and B_{mz}^{ij} are the amplitude of the flux density of major and minor hysteresis loops in the radial direction, the rotation direction and the z-direction, respectively.

3. Analyzed Model and Conditions

Figure 1 shows the analyzed model of an IPM motor. Figure 2 shows the 3-D finite element mesh, which is 1/4 of the

Fig. 1. Analyzed model (1/4 region)

Fig. 2. 3-D finite element mesh (except the air)

(a) Waveforms (U-phase)

(b) Harmonic spectra (inverter)
Fig. 3. Current waveforms

whole region because of symmetry of the model. Figure 3 shows two current waveforms and the harmonic spectra. One is sinusoidal waveform, and the other is measured one that is driven by the PWM inverter. The carrier frequency is about 60 times of the sinusoidal coil current frequency. In order to consider the carrier harmonics accurately, the 1 period of the

Table 1. Analysis conditions

Number of poles	4
Coil current (A)	3.7
Number of coil turns (turn/slot)	125
Magnetization of magnet (T)	1.24
Conductivity of permanent magnet (S/m)	6.944×10^5
Frequency of coil current (Hz)	100
Revolution speed (min^{-1})	3,000
Coefficient of eddy current loss K_e	1.0×10^{-4}
Coefficient of hysteresis loss K_h	3.0×10^{-2}
Density of stator and rotor cores (kg/m^3)	7,650

Fig. 4. Distributions of flux density vectors (o-a section)

fundamental sinusoidal waveform is divided into 1,000 steps. Table 1 shows the analysis conditions. The analyzed results of the motor driven by the inverter are verified through the comparison of those of the motor driven by the sinusoidal current.

4. Results and Discussion

Figure 4 shows the distributions of flux density vectors at o-a section. Fig. 4(c) shows the difference between Figs. 4(a) and 4(b). From Fig. 4(c), it is found that there is a little difference in the direction of flux density vectors in the tip of the stator teeth.

Figure 5 shows the distributions of eddy current density vectors in the permanent magnet. From Fig. 5, it is found that the eddy current density driven by the inverter are larger than those driven by the sinusoidal current in front of the rotation direction and in the upper part of the permanent magnet.

Figure 6 shows the contours of the eddy current loss in the permanent magnet. From Fig. 6, it is found that the eddy current loss is larger than that driven by the sinusoidal current in the front and back of the rotation direction and the upper part of the permanent magnet.

Figure 7 shows the eddy current losses in the permanent magnet. It is found that the eddy current loss driven by the inverter is about 3.5 times larger than that driven by the sinusoidal current.

Figure 8 shows the contours of eddy current loss in the iron cores. It is found that the eddy current loss in the tip of the stator teeth and the rotor bridge is especially large. It is also found that the eddy current loss driven by the inverter is larger than that driven by the sinusoidal current.

Figure 9 shows the contours of hysteresis loss in the iron cores. It is found that the contour of the hysteresis loss driven by the inverter is similar to that driven by the sinusoidal current.

Figure 10 shows the iron loss in stator and rotor cores. It is found that the eddy current loss driven by the inverter in the stator core is especially large. It is also found that the

hysteresis loss driven by the inverter is nearly equal to that driven by the sinusoidal current.

Figure 11 shows the torque waveforms and the harmonic spectra. From Fig. 11(a), it is found that there are small torque ripples caused by the carrier of the PWM inverter. From Fig. 11(b), it is found that the high-frequency component of the torque is large. Consequently, the necessity for

Fig. 6. Contours of eddy current loss in permanent magnet

Fig. 7. Eddy current losses in permanent magnet

Fig. 5. Distributions of eddy current density vectors in permanent magnet

Fig. 8. Contours of eddy current loss in iron cores

Fig. 9. Contours of hysteresis loss in iron cores

Fig. 10. Iron loss in stator and rotor cores

Fig. 11. Torque waveforms and harmonic spectra

Table 2. Discretization data and CPU time

Number of elements	339,744
Number of nodes	61,472
Number of edges	410,725
Number of unknown variables	385,375
Number of time steps	1,000
Total CPU time (hours)	1,609

Computer used: Pentium 4 (3.0GHz) PC

the analysis taking into account the career of the PWM inverter was clarified because the influences of the career were large. Table 2 shows the discretization data and CPU time.

5. Conclusion

In this paper, we analyzed an IPM motor driven by the PWM inverter using the three-dimensional finite element method. The effects of the carrier of the PWM inverter on the distributions of the eddy currents in the permanent magnet, the iron loss characteristics, and the torque characteristics were quantitatively clarified. Consequently, it was found that the eddy current loss driven by the inverter was about 3.5 times larger than that driven by the sinusoidal current. It was also found that the eddy current loss driven by the inverter in the stator core was about 2.5 times larger than that driven by the sinusoidal current.

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