A Novel Rotor Structure of Claw-pole Motor Designed by Magnetomotive Force-based Simulation Method

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In this paper, we propose a novel rotor structure of claw-pole motor (CPM) to reduce harmonic iron loss. In order to realize this low iron loss structure, a magnetomotive force-based simulation method is presented to clarify the cause of harmonic iron loss. As the proposed method is based on mathematical theory, the rotor structure can be evaluated with a low computational cost. To validate its effectiveness, conventional and the proposed model are analyzed using the finite element method. The results indicate that the harmonic loss of the developed rotor is lower than that of the conventional rotor.

Keywords: alternator, mathematical model, claw pole motor harmonic iron loss

1. Introduction

Since fuel efficiency of automobiles needs to be improved to reduce the amount of CO2 emission, power generating efficiency of alternators needs to be improved for the improvement of automobile fuel efficiency. Claw-pole motors (CPMs) are widely used for alternators. Since the rotor of a CPM has a 3D-dimensional magnetic structure, in which a current field coil is included for magnetizing, the three-dimensional finite element method (3D-FEM) is widely used for evaluation of harmonic iron losses (1)–(4). On the other hand, it takes enormous calculation costs for 3D-FEM. Moreover, it seems difficult to grasp the relationship between the harmonic iron loss and rotor structure due to the complexity of three-dimensional magnetic distribution.

In Fig. 1, an equivalent circuit of an alternator is shown. The rotor of a CPM is synchronously rotated by the engine. Moreover, excitation current is supplied by the car battery for magnetizing the rotor. Thereby, induced voltage is caused in stator winding. When the induced voltage is higher than the bus voltage, generated current flows to the car battery. In other words, harmonic iron loss is caused mainly by harmonic rotor magnetomotive force. For this reason, iron loss characteristics of CPMs are quite dependent on harmonic MMF of the rotor. From this viewpoint, it can be seen that modeling of the rotor MMF is effective for designing the low iron loss structure. However, there are few previous works on the relationship of rotor MMF and harmonic iron loss (5)–(8).

In this paper, a mathematical MMF model of a CPM rotor is constructed. In this model, space and time MMF corresponds to the three-dimensional rotor structure. In addition, a novel rotor structure is obtained by using the MMF model. Thanks to this process, the relationship of the rotor structure and harmonic iron loss can be clarified. Moreover, it takes low computational costs because it uses mathematical based simulation.

To validate the effectiveness, the presented rotor is analyzed using 3D-FEM. From the results, harmonic iron loss of the presented rotor is lower than that of the conventional rotor. In Table 1, defined parameters used in this paper are summarized.

2. Basic Study with 3D-FEM Simulation

2.1 Analysis Model

Figures 1 and 2 show the equivalent circuit and analysis model, respectively, and the motor specifications are summarized in Table 2. When the induced voltage of stator coils is higher than the bus bar voltage, the current, which corresponds to the excess voltage, is supplied to the car battery. In this section, no-load and generation mode are analyzed using the finite element method for clarifying the relationship between the rotor MMF and iron loss. In the no-load condition, the radial component of flux density is calculated to evaluate the harmonic MMF of ordinal claw-pole motor. Moreover, detailed loss analysis is conducted to evaluate the harmonic iron loss.

2.2 MMF Analysis

Figure 3(a) shows the rotor surface structure of a conventional claw-pole motor. Moreover the MMF waves at selected axial positions at $z = z_1, z_2$ are
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Fig. 1. Equivalent circuit

Fig. 2. Analysis model

Table 2. Motor specification

| Battery voltage (V) | 12.6 |
|---------------------|------|
| Stator outer radius (mm) | 69.0 |
| Number of stator slot | 96 |
| Phases and poles | 3 phases, 16 poles |
| Coil connection | Y |

shown in Fig. 3(b). In this paper, radial direction of gap magnetic flux density is evaluated as characteristic of rotor MMF to clear the relationship between rotor MMF and iron loss. From the results, rotor MMF is quite dependent on the rotor surface structure. Specifically, the rotor MMF time changes like a trapezoid. This is because the rotor edge at an oblique line part in Fig. 3(a) should make the time change of the rotor MMF smooth. In addition, it can be seen that there is an asymmetrical relationship between the peak widths \( w_n(z_1) \) and \( w_s(z_1) \) of N and S pole MMF, the same as the width of \( w_n(z_1) \) and \( w_s(z_1) \) in \( z_1 \) position. For this reason, it can be assumed that the rotor MMF can be expressed by the rotor surface structure.

Figure 3(c) shows Fourier series expansion of the rotor MMF at \( z = z_1, z_2 \). It is found that the 1st harmonic component of the rotor MMF is the same for \( z = z_1, z_2 \). This is due to the same amplitude and the same total peak width \( (w_n(z_1) + w_s(z_1)) = (w_n(z_2) + w_s(z_2)) \) of rotor MMF. On the other hand, it is found that there are 2nd, 4th, and 6th harmonic components of the rotor MMF at \( z = z_1 \). This is because the surface width is asymmetrical between N/S pole at \( z = z_1 \).

2.3 Iron Loss Analysis

In Table 3, analysis conditions are summarized. Moreover analysis results of harmonic iron loss are shown in Fig. 4. It can be assumed that odd frequency components (1, 3, 5, etc.) of iron loss are caused by the rectangular distribution of the MMF. From this viewpoint, the amount of the odd component is dependent on the fundamental component. On the other hand, even frequency components (2, 4, 6, etc.) of iron loss are due to the asymmetrical structure of claw-pole motors, denoted in the previous section. Moreover, it can be assumed that reduction of even components of the iron loss do not contribute directly to the fundamental component. Since the fundamental component of the MMF needs to be maintained, it seems effective that the even component of iron loss would be reduced by decreasing the even component of MMF.

In Fig. 5, the 1st and even components of iron loss distribution are shown. The 1st component of the iron loss is caused in the whole stator. Compared to this, the even component of the iron loss is concentrated at the point of \( z = z_1 \). This is because the even component of rotor MMF is mainly caused at the above points. From the results, it can be seen that the even component of the iron loss is quite dependent on the rotor surface structure. Therefore, harmonic iron loss of the claw-pole motors can be reduced by changing the rotor...
surface structure. In this paper, rotor MMF is modeled using the Fourier series expansion denoted in the next section. Then, reduction of iron loss is confirmed using 3D-FEM.

3. Rotor Structure Analysis with MMF Model

3.1 MMF Model In Fig. 6, the simplified rotor MMF model, which corresponds at height $z = z_{i}$, is shown. Then, the assumption that the MMF waveform is trapezoidal, and the peak amplitude of the MMF waveform at $z = z_{1}, z_{2}$ is almost the same, is considered in Fig. 6. Moreover, the widths $a'(z), b'(z)$ of the MMF model are equal to the electric angle [rad] width of the rotor surface structure. From the assumptions, peak width of the rotor MMF can be defined as follows:

$$w_{a}'(z) = \frac{w_{a}(z)}{R} \times P \quad \cdots \quad (1)$$
$$w_{b}'(z) = \frac{w_{b}(z)}{R} \times P \quad \cdots \quad (2)$$

In Eqs. (1) and (2), $R$ and $P$ denote rotor outer radius and the number of pole pairs. Then, the model waveform is rewritten by Fourier series expansion as follows:

$$F(z_{i}, \omega t) = \frac{a_{0}(z_{i})}{2} + \sum_{n} a_{n}(z_{i}) \cos(n\omega t) \quad \cdots \quad (3)$$

In Eq. (3), Fourier series coefficients are calculated as

$$a_{0}(z_{i}) = \frac{2}{\pi} \int_{0}^{\pi} F(z_{i}, \omega t) \cos(n\omega t) d\omega t$$
$$= \frac{2}{\pi} \left[ \int_{0}^{\pi/2} h_{a} \cos(n\omega t) d\omega t + \int_{\pi/2}^{\pi} -h_{a} \cos(n\omega t) d\omega t \right]$$
$$+ \int_{w(z_{i})}^{\pi/2} \left( \omega t - \frac{w_{a}'(z_{i})}{2} \right) h_{b} \cos(n\omega t) d\omega t$$
$$+ \int_{-\pi/2}^{-w_{a}'(z_{i})/2} -h_{a} \cos(n\omega t) d\omega t$$
$$= \frac{4}{\pi} \frac{h_{a} + h_{b}}{n^{2}} \sin \left( \frac{\pi + \frac{w_{a}'(z_{i}) + w_{b}'(z_{i})}{2}}{2} \right) \times \sin \left( \frac{\pi - \frac{w_{a}'(z_{i}) + w_{b}'(z_{i})}{2}}{2} \right) \quad \cdots \quad (4)$$

From Eq. (4), the 1st and 2nd frequency coefficient at the height $z = z_{i}$ is calculated as

$$a_{1}(z_{i}) = \frac{4}{\pi} \frac{h_{a} + h_{b}}{w_{a}'(z_{i}) + w_{b}'(z_{i})} \sin \left( \frac{\pi}{2} + \frac{w_{a}'(z_{i}) - w_{b}'(z_{i})}{4} \right) \times \sin \left( \frac{\pi}{2} - \frac{w_{a}'(z_{i}) + w_{b}'(z_{i})}{4} \right) \quad \cdots \quad (5)$$
$$a_{2}(z_{i}) = \frac{h_{a} + h_{b}}{\pi} \sin \left( \pi + \frac{w_{a}'(z_{i}) - w_{b}'(z_{i})}{2} \right) \times \sin \left( \pi - \frac{w_{a}'(z_{i}) + w_{b}'(z_{i})}{2} \right) \quad \cdots \quad (6)$$

It can be seen from the $\sin$ member of Eq. (5) that the 1st component of the rotor MMF is hardly dependent on the asymmetry between $w_{a}'(z_{i})$ and $w_{b}'(z_{i})$. On the other hand, it is found from the $\sin$ member of Eq. (6) that the second frequency component of the rotor MMF is due to the asymmetric structure of the rotor surface denoted as the relationship between $w_{a}'(z_{i})$ and $w_{b}'(z_{i})$ (i.e., $w_{a}'(z_{i}) \neq w_{b}'(z_{i})$). Figure 7 shows time frequency components of the rotor MMF at $z = z_{1}, z_{2}$ designed by Eq. (4). It can be seen from Fig. 3(c) and Fig. 7 that low frequency components of the gap magnetic flux on the rotor MMF simulation are almost the same. In addition, it is found from Fig. 7 that there are no even frequency components of the rotor MMF at height $z = z_{2}$. From Eq. (4) and
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Fig. 7. Time frequency components of rotor MMF at each height calculated by Eq. (4)

Fig. 8. Conventional and proposed shape

Fig. 9. Comparison of induced voltage

Table 4. Rotor surface width

|          | Conventional shape | Proposed shape |
|----------|-------------------|----------------|
| \(w_n(z_1)\) [mm] | 1.5              | 4.7            |
| \(w_s(z_1)\) [mm] | 4.7              | 4.7            |
| \(w_s(z_2)\) [mm] | 7.9              | 4.7            |

depends on the area of the rotor surface, fundamental MMF can be maintained by the above operation. In Table 4, each rotor surface width in the conventional and proposed shape is shown.

To investigate the fundamental component of the conventional and present rotor MMF, induced voltage in the no-load condition is compared in Fig. 9. From these results, it can be seen that the fundamental component of the claw-pole motor can be maintained by maintaining the area of the rotor surface structure. In the next chapter, rotor MMF and iron loss are analyzed using the finite element method. In addition, the difference of iron loss reduction effect between Y and Δ connection is also analyzed.

4. Inspection of Iron Loss Reduction Effect of the Proposed Shape

4.1 MMF Analysis Figures 10 and 11 show comparisons of waveform and time frequency components, respectively, of the gap magnetic flux in the conventional and proposed shape calculated by no-load simulation. It is found that in the proposed shape, the second and 4th frequency components of iron loss are reduced by 21.4% and 85.8% respectively because the rotor surface width at each pole is more symmetrical. However, it is found from Fig. 11 that although the even frequency coefficient equals zero mathematically in Eq. (4), the second frequency component in the result is not zero. From Fig. 8(b), the rotor edge width at N/S pole at height \(z = z_1\) is different in the proposed shape. In addition, it is found from Fig. 10 that each electric pole width is different in the proposed shape. This means that although the rotor surface width at the N/S pole is the same, the electric pole width is asymmetrical due to the difference of the rotor edge width. The fact should make the rotor MMF slightly asymmetrical and it is not considered in the rotor MMF model of Fig. 6.

4.2 Iron Loss Analysis Figure 12 shows power output in the conventional and proposed shape in the same current condition calculated by iron loss simulation. It is found that the power output in each shape is almost the same due to the rotor surfaces having the same area. In Table 5, analysis
conditions are summarized. Figure 13 shows the distribution of harmonic iron loss in the proposed shape. It is found from Fig. 5 and Fig. 13 that although there is a large amount of the even frequency component in the conventional shape, the even component, which is caused near height \( z = z_1, z_3 \) is reduced in the proposed shape.

Figures 14 and 15 show each frequency component of iron loss in each shape Y, \( \Delta \)-connected. Although even component of iron loss can be reduced by selecting the proposed rotor shape, odd component is the same level as conventional rotor shape. For this reason, analysis results of \( \Delta \)-connected stator are added in Fig. 15. Since 3rd time frequency component of circulation current, which weakens the 3rd component of the magnetic field, is generated by using the \( \Delta \)-connected stator, it can be assumed that combination of proposed rotor shape with \( \Delta \)-connected is effective for reducing the motor iron loss. It can be seen from Fig. 14 that the 2nd component of iron loss in the proposed shape is almost half the amount of the 2nd component in the conventional shape. From Fig. 11, the 2nd component of the gap magnetic flux in the proposed shape is smaller by 21.4% in the proposed shape.
is assumed that the iron loss is proportional to the square of magnetic flux density, the iron loss in the proposed shape should be smaller by 38.3%, which is consistent with Fig. 14. Then, it is found that although the 6th frequency component of the no-load gap magnetic flux at \( z = z_1 \) is increased in Fig. 11, the 6th frequency component of harmonic iron loss is reduced in Fig. 13. It is assumed that the 6th frequency component of gap magnetic flux is reduced not at \( z = z_1 \) but at the other heights.

It is found from Fig. 14 and Fig. 15 that although the even frequency component is almost the same, the 3rd frequency component is quite different between Y and \( \Delta \) connection. There is no 2nd frequency component of current in the armature coil independent of coil connection because the rotor MMF at heights \( z = z_1, z_3 \) have an opposite-phase relation. Contrary to this, there is a 3rd time frequency component of circulation current which weakens the magnetic field in the \( \Delta \) connection, which reduces the 3rd frequency component of iron loss. Therefore, the proportion of the 2nd frequency component of iron loss is large in the \( \Delta \) connection, which means that the iron loss reduction effect of the proposed shape in the \( \Delta \) connection is larger than that in the Y connection. The 2nd iron loss in the Y and \( \Delta \) connections is reduced by 48.3% and 46.3%, and the total iron loss is by 25.6% and 13.5% respectively.

Thus, it is found that the total iron loss is reduced mainly due to the reduction of the second frequency component in the proposed shape. It means that it is effective to eliminate the asymmetry of the rotor MMF for the improvement of power generating efficiency. It is assumed that the rotor MMF model is also effective for reduction of the other frequency components of iron loss. Moreover, effect of iron loss reduction in proposed rotor shape can be improved by using the \( \Delta \)-connected stator in which 3rd frequency component of circulation current is generated.

5. Conclusion

In this paper, we modelize the rotor MMF of CPMs mathematically. In addition, we propose a rotor structure to reduce harmonic iron losses, and verify the iron loss reduction effect of the structure numerically with magnetic field simulation. As a result, it is shown that the MMF mathematical model can represent each frequency component of the rotor MMF at each height, and it is possible to analyze harmonic iron loss with the model. The MMF model should be effective to reduce the other frequency component of iron loss. On the other hand, there is the difference of the result of the frequency component of rotor MMF between the MMF model and the simulation. This is thought to be because the asymmetry of the rotor edge at the N/S pole is not considered in the MMF model. In the future, a more accurate MMF model will be developed, and the iron loss reduction effect in the proposed shape will be verified by experiment.

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