Comprehensive Analysis of the AC Copper Loss for High Speed PM Machine With Form-Wound Windings

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Abstract The skin effect and proximity effect at high frequencies would greatly increase the AC copper loss of high speed permanent magnet machines (HSPMMs), especially for form-wound windings. However, the influence of some factors on the AC loss of the form-wound winding is still unclear in the existing research. Therefore, this paper presents comprehensive research on the AC copper loss of HSPMM with form-wound windings. Firstly, the model of eddy current field considering the skin effect and the proximity effect for form-wound windings is established, and the AC losses of each stator slot and each conductor at high frequency are obtained. In addition, the factors affecting the AC loss are comprehensively analyzed through the eddy current field, including the conductor size, the number of conductors per slot, and the operating temperature. Furthermore, the influence of strand wire sizes on temperature distribution of HSPMM is also implemented by establishing a temperature calculation model. Finally, the theoretical results are verified by testing the AC resistances of five coils at different frequencies and the temperature characteristic of an HSPMM prototype with form-wound windings.

Index Terms Permanent magnet machine, AC resistance, copper loss, form-wound windings, temperature.

I. INTRODUCTION

Due to the small volume and high efficiency, high speed permanent magnet machines (HSPMMs) have a wide range of applications in flywheel energy storage, air compressor, distributed power generation systems, hydrogen fuel cells and other fields [1]–[3]. However, the special characteristics of HSPMMs, such as high frequency, high speed, and high loss density, would bring great challenges to the small power loss, safe mechanical stress, and low temperature distribution [4]–[6]. These challenges severely restrict the reliable application and development of the HSPMM in the industrial field [7], [8]. The operating frequency of the HSPMM can be as high as 1000 Hz, and the stator winding would produce a large skin effect and proximity effect at a high frequency, which would significantly increase the AC copper loss of the stator winding [9]–[11]. At the same time, due to the small size and high loss density of the HSPMM, the AC loss at high frequency would further deteriorate the temperature distribution of the HSPMM, and even cause local overheating of the windings, thereby affecting the service life [12]. Clearly, a complete study on the AC loss of the stator winding at high frequency is very critical for the design and reliable operation of the HSPMM [13].

For round wire windings, by selecting a suitable wire diameter, the AC loss at high frequency can be well suppressed [14]. Some research results show that when the diameter of the round wire is smaller than its skin depth, the AC loss of the round wire at high frequency can be slightly larger than DC loss [15], [16]. For high power HSPMMs, form-wound windings are usually adopted. The strand wire size of form-wound windings is usually much larger than round wire size, which results in more significant skin effect and proximity effect than those in the round wire windings [17]–[19].
The AC/DC resistance ratio of form-wound windings for an HSPMM with open slot and semiclosed slot is analyzed based on a constant conductor size in [20]. In addition, the influence of the winding temperature on the AC/DC resistance ratio for the form-wound winding is achieved in [21], which shows the AC/DC resistance ratio gradually decreases along with the temperature increases. As known, the DC resistance of the winding increases with temperature, which leads to greater DC losses at higher temperature. This opposite trend of the AC/DC resistance ratio and DC resistance at high temperature make it still unclear about the changing trend of AC loss with temperature under different frequencies in the available literature. Besides, the large number of conductors per slot and large conductor size would increase the skin effect and proximity effect of the conductors, which have a large impact on the AC/DC loss ratio. Nevertheless, in the existing research, the AC loss of the form-wound winding is mostly analyzed based on the constant conductor size and the constant number of conductors per slot, and the quantitative influence of different conductor sizes and the number of conductors per slot on the AC/DC loss ratio has not been summarized. Furthermore, different strand wire sizes would produce different AC losses at the same frequency, which inevitably has a certain impact on the temperature distribution. However, the extent of influence of conductor sizes on temperature distribution at different frequencies is unclear based on the existing literature. Therefore, comprehensive research on the AC loss of form-wound windings at high frequencies should be presented by considering more factors, such as the number of conductors per slot, the conductor sizes, the influence of operating temperatures on AC loss under different frequencies, and the influence of strand wire sizes on temperature distribution, etc. These studies are very critical for the reasonable design of HSPMMs with form-wound windings to effectively reduce the AC copper loss and temperature distribution at high frequency.

Therefore, in this paper, a comprehensive study on the AC copper loss of the HSPMM with form-wound windings is carried out, including the AC loss distribution of each stator slot and each conductor, the influence of the conductor size, the number of conductors per slot and winding temperature on the AC copper loss, and the influence of strand wire sizes on temperature distribution. Firstly, the calculation model of eddy current field considering the skin effect and the proximity effect for form-wound windings is established. The AC losses of each stator slot and each conductor at high frequency are obtained by the calculation model. In this model, all conductor models should be established. Due to the symmetry of the designed HSPMM, some cooling channels are found in the stator slots and the stator shell. The cooling air can pass through the opened cooling channels, thereby ensuring a low machine temperature. Some key design parameters of the HSPMM can be found in Table 1.

### Table 1. Some key design parameters of the HSPMM.

| Parameter name                  | Value |
|---------------------------------|-------|
| Stator slot number              | 48    |
| Number of poles                 | 4     |
| Number of conductors per slot   | 6     |
| Stator outer diameter (mm)      | 420   |
| Stack length (mm)               | 214   |
| PM thickness (mm)               | 15    |
| Sleeve thickness (mm)           | 7     |

is manufactured. The theoretical analysis is verified by the AC resistance test of the coils at different frequencies and the temperature test of the prototype.

### II. ANALYSIS OF AC COPPER LOSS OF THE HSPMM

#### A. STRUCTURE PARAMETERS OF HSPMM

In this paper, a 400 kW, 10 000 rpm HSPMM is designed, as shown in Fig. 1. For this machine, four poles are designed, and a carbon fiber sleeve of 7 mm is adopted to ensure the safety of the rotor during high speed rotation. Forty-eight rectangular stator slots and double-layer form-wound windings are designed in this stator. Besides, for high speed machines, a good heat dissipation system must be designed to ensure a reasonable temperature distribution. In the HSPMM, some cooling channels are found in the stator slots and the stator shell. The cooling air can pass through the opened cooling channels, thereby ensuring a low machine temperature. Some key design parameters of the HSPMM can be found in Table 1.

#### B. AC COPPER LOSS AT HIGH FREQUENCY

It is known, a great skin effect and proximity effect would be produced for form-wound windings at high frequency, which significantly increases the AC resistance or AC loss of the winding. The ratio $k_{ac}$ of AC copper loss to DC copper loss is usually adopted to reflect the trend of skin effect and proximity effect at high frequency. In order to obtain the AC winding loss at high frequency, the eddy current field calculation model is adopted. In this model, all conductor models should be established. Due to the symmetry of the designed...
HSPMM, only a quarter model is employed to replace the entire model, as shown in Fig. 2. For the HSPMM, the number of conductors per slot is 6, and each conductor is composed of two wires of 8.5 mm × 2 mm (8.5 mm in width and 2 mm in thickness), so there are 12 conductors in a stator slot, as shown in Fig. 2(a). In addition, a small mesh size is carried out on the conductor to consider the skin effect and proximity effect at high frequency.

Through the finite element analysis in the eddy current field, the current density distribution at different frequencies can be obtained, as shown in Fig. 3. In this simulation, a current of 1 A is set. It is seen that as the frequency increases, the skin effect and proximity effect of the conductors become obvious, resulting in a substantial increase in current density. Fig. 4 shows the ratio of AC/DC loss at different frequencies. At the frequency of 100 Hz, the AC/DC loss ratio is slightly larger than 1, while the AC/DC loss ratio is close to 6 when the frequency is increased to 1000 Hz.

In this analysis, there are a total of 12 stator slots, and their order has been shown in Fig. 2. The AC copper loss of each stator slot at 1000 Hz is also obtained through the eddy current field, as shown in Fig. 5. It is clear that, when...
two layers of windings in a stator slot are in the same phase, the AC losses have the same result, such as stator slots of 1, 2, 5, 6, 9, 10. Similarly, when two layers of windings in a stator slot are at different phases, the AC losses have another result, such as stator slots of 3, 4, 7, 8, 11, 12. Besides, the AC loss of each conductor is also obtained, as shown in Fig. 6. It is seen, when the two layers of windings in a stator slot are in the same phase, the AC loss of the conductor is the largest in the middle and the smallest on both sides. When two layers of windings in a stator slot are the different phases, the closer the conductor is to the air gap, the greater the AC loss. It is proved that when the conductors in a stator slot belong to different phases, the AC losses of different phases will affect each other. Therefore, in the AC copper loss analysis, the conductor models of two stator slots can be used instead of more conductor models. One is that all conductors in a stator slot belong to the same phase. The other is that the conductors in a stator slot belong to different phases.

III. INFLUENCE FACTORS OF AC LOSSES AT HIGH FREQUENCY

A. INFLUENCE OF CONDUCTOR SIZE ON AC LOSSES

The influence of wire thickness on the AC loss is obtained in eddy current field analysis by setting 1A AC current. The current density distribution under different wire thicknesses is shown in Fig. 7. As the wire thickness increases, the skin effect of the conductor gradually increases at a high frequency. Fig. 8 shows the ratios ($k_{ac}$) of the AC/DC copper loss with frequency under different wire thicknesses. As seen, the wire thickness has a significant effect on the ratio of the AC/DC copper loss at high frequencies. As the wire thickness increases, the ratio of the AC/DC loss increases sharply at high frequencies. When the conductors of 1 mm thickness are used, the AC/DC copper loss ratio is lower than 1.5 at 1000 Hz. The AC/DC copper loss ratio would increase to 10 at 1000 Hz when the conductors of 3.5 mm thickness are used. However, as the wire thickness increases, the DC copper loss would gradually decrease, as shown in Fig. 9. Therefore, when the thickness of the wire gradually increases, due to the opposite trend of DC copper loss and AC/DC copper loss ratio, it is uncertain for the trend of AC copper loss at different frequencies. In order to clearly show how the wire thickness affects the AC copper loss, the change trend of AC copper loss with wire thickness is also obtained, as shown in Fig. 10. As seen, due to the opposite trend of AC/DC copper loss ratio and DC copper loss with wire thickness, the AC copper loss gradually decreases with the increase of wire thickness at low frequency. However, when the frequency is larger than a certain value, the AC copper loss decreases first and then increases gradually with the increase of wire thickness.
Similarly, the influence of the wire width on the AC/DC copper loss ratio, the DC copper loss and the AC copper loss is also analyzed, as shown in Figs. 11-13. On the one hand, as the wire width increases, the AC/DC copper loss ratio gradually increases. On the other hand, as the wire width increases, the DC copper loss gradually decreases. Due to their opposite trend, the variation of AC copper loss with wire width is also uncertain at different frequencies, as shown in Fig.13. At low frequencies, the AC copper loss would gradually decrease as the wire width increases. However, when the frequency increases to a certain extent, the AC loss would present a gradually increasing trend as the wire width increases.

FIGURE 11. AC/DC copper loss ratio with wire width at different frequencies.

FIGURE 12. DC copper loss with wire width.

FIGURE 13. AC copper loss with wire width at different frequencies.

FIGURE 14. Current density with the number of conductors per slot at 1000 Hz.

Clearly, the width and thickness of the wire would have a large impact on the AC/DC copper loss ratio and AC copper loss. As the conductor size increases, the AC/DC copper loss ratio would greatly increase at high frequencies. However, as the conductor size increases, due to the opposite trend of the DC copper loss and the AC/DC copper loss ratio, the AC copper loss would show different trends at different frequencies.

B. INFLUENCE OF THE NUMBER OF CONDUCTORS IN STATOR SLOT ON THE AC LOSSES

In order to obtain the influence of the number of conductors in the stator slot on the AC loss, the calculation models of the number of different conductors per slot are established in the eddy current field, and the AC current of 1A is given, and the wire of 8.5mm × 2mm is kept same. Fig. 14 shows the effect of the number of conductors in the stator slot on the current density distribution at 1000 Hz. It is seen, with the increase of the number of conductors per slot, the proximity effect of conductors increases obviously, which leads to the increase of the current density. The influence of the number of conductors in each slot on the AC/DC loss ratio at different frequencies is also obtained, as shown in Fig. 15. In the analysis of Fig. 15, the wire size of 8.5mm × 2mm is kept consistent. As seen, as the number of conductors per slot increases, the ratio of AC/DC loss under high frequency increases sharply. The combined effect of different wire sizes and different numbers of conductors per slot on the AC/DC loss ratio is shown in Fig. 16. As shown, when the conductors with a small thickness are used, such as 8.5mm × 1mm, the number of conductors per slot has less influence on the AC/DC loss ratio. When a large conductor thickness is used, such as 8.5mm × 3mm, the increase in the number of conductors in each slot would significantly increase the AC/DC loss ratio.

C. INFLUENCE OF THE OPERATING TEMPERATURE ON THE AC LOSSES

As known, the electrical conductivity of copper gradually decreases with the increasing temperature, as shown in Fig. 17, which would inevitably affect the AC loss at high
The electrical conductivity of copper varies with temperature. In order to obtain the AC loss at different temperatures, the AC current of 1A and the wire of 8.5mm × 2mm is used in this analysis. Fig. 18 shows the current density distribution at different operating temperatures at 1000 Hz. It is seen that as the temperature increases, the electrical conductivity of the conductor becomes smaller, resulting in a gradual decrease in the current density of the conductors.

The ratio of AC/DC loss with frequency at different operating temperatures is also obtained, as shown in Fig. 19. It is seen, as the frequency increases, the influence of the operating temperature on the AC/DC loss ratio becomes more obvious. At 200 Hz, the AC/DC loss ratio at 180 °C is slightly reduced compared to that at 20 °C. However, at 1000 Hz, the AC/DC loss ratio is as high as 6 at 20 °C, and it is reduced to about 2.5 at 180 °C. As seen, as the temperature increases, the AC/DC copper loss ratio would reduce, while the DC copper loss would gradually increase. Therefore, the AC copper losses at different temperatures would be affected by the combination of the AC/DC copper loss ratio and the DC copper loss. Fig. 20 shows the AC copper losses of the windings at different frequencies and temperatures. Clearly, when the frequency is low, such as 200 Hz and 400 Hz, as the temperature increases, the AC loss gradually increases, which
is consistent with the conventional theory. However, when the frequency is higher than a certain value, such as 800 Hz and 1000 Hz, as the temperature increases, the AC loss gradually decreases. This is because when the frequency is higher than a certain value, the decrease in the AC/DC copper loss ratio would be greater than the increase in the DC copper loss as the temperature increases. It is concluded that due to the opposite trend of AC/DC loss ratio and DC resistance with temperature, at low frequencies, the AC loss of the winding increases with the increase of temperature. However, when the frequency is higher than a certain value, the AC loss gradually decreases as the temperature increases.

IV. INFLUENCE OF STRAND WIRE SIZES ON TEMPERATURE DISTRIBUTION OF HSPMM

For the HSPMM, air ducts are provided in the shell and stator slots. In order to evaluate the influence of AC loss at different frequencies on temperature distribution, the temperature calculation model is built in Ansys-CFX, as shown in Fig. 21. Due to the symmetry of the model, a quarter model is established to simplify calculations. In this calculation, the air inlet is set to a velocity of 2.5 m/s, and a temperature of 30 ℃.
In order to obtain the AC copper loss under different conductor sizes, the total cross-sectional area of conductors in each slot is kept the same, and the number of conductors per slot is set to 6 in this analysis. At the same time, it is known in the previous analysis that the temperature has a great influence on the AC loss. In this analysis, the winding temperature is set to 120°C to remove the influence of operating temperature on the AC loss. When the strand wire size of 8.5mm × 4mm is adopted, it has 6 conductors in each slot, and the RMS current of each conductor is 565 A. When the strand wire size of 8.5mm × 1mm is adopted, it has 24 conductors in each slot, and the RMS current of each conductor is 141 A. The AC copper losses under different strand wire sizes and frequencies can be complied by the eddy current field analysis, as shown in Fig. 22. It is seen, as the frequency increases, a large strand wire size would greatly increase the AC copper loss, which inevitably has a great impact on the temperature distribution of the HSPMM.

The temperature distribution of the HSPMM under different wire sizes and frequencies is obtained through Ansys-CFX, as shown in Figs. 23-24. In the analysis, the AC losses under different wire sizes and different frequencies are added as the heat source of the stator winding, and other losses, such as iron loss and PM loss, remain unchanged. It is seen, as the frequency increases, the temperature of the machine would increase. When a small strand wire size is used, the increased temperature at high frequency is not noticeable. However, when a large strand wire size is selected, the temperature of the machine would increase sharply along with the increasing frequency. When the wire of 8.5mm × 4mm are used, the maximum temperature exceeds 500°C at 800Hz and 1000Hz, which is much greater than the maximum temperature in other cases, resulting in the temperature not being shown in Fig. 24. The excessively high temperature has no
meaning for the machine. At the same time, in order to better show the temperature comparison under other conditions, the maximum temperature of wires of size 8.5mm × 4mm under 800Hz and 1000Hz is not shown in Figure 20 in the previous manuscript. It is concluded that a small strand wire size should be adopted to effectively reduce the winding temperature during high-frequency operation.

V. AC RESISTANCE TEST OF COILS AND TEMPERATURE TEST OF HSPMM

A. AC RESISTANCE TEST OF DIFFERENT COILS

In order to obtain AC resistance of the winding at different frequencies, an AC resistance measuring instrument is used. In this test, an AC current of 1A is set, and the AC resistance at different frequencies can be obtained by changing the frequency of the AC current. Five coil cases (Coils A-E) with different numbers of conductors per slot and different wire sizes are employed to obtain the AC resistances under different conductor sizes, as shown in Fig. 25. The AC resistances of the five coils at different frequencies are tested by the AC resistance measuring instrument. In this test, the coils are kept at room temperature of 25 °C. The test processes of five coils are shown in Fig. 26.

The test results and calculation results of the five coil cases at different frequencies are compared, as shown in Fig. 27. Clearly, when the frequency is low, the theoretical calculation
results are in good agreement with the experimental test results. When the frequency increases, the theoretical calculation results are a bit larger than the experimental test ones, because the actual coils have the influence of the winding ends. There is no magnetic core at the end of these coils. Thus, the AC loss of the coil ends at high frequency is very small. In theoretical calculations of the AC loss, the ends and the effective parts of the coils are considered the same. In general, the test results of five different coils are basically consistent with the theoretical analysis results, which verifies the theoretical analysis.

### B. TEMPERATURE TEST OF HSPMM

In order to better verify the theoretical analysis, a 400kW, 10000rpm HSPMM is manufactured. In this prototype, a strand wire of 8.5mm × 1.8mm and a 7mm carbon fiber sleeve are used. An experimental test platform is established to obtain the current and temperature characteristics of the prototype at full load, as shown in Fig. 28. In the test platform, the prototype is driven through an inverter, and a large fan is used to keep the temperature low by the air cooling ducts in the stator slot and shell. The current of this prototype at full load operation is obtained through the power analyzer, as shown in Fig. 29. It is seen, when the prototype is running at full load, the RMS value of current is 570A, which is very close to the rated current of 565A.

In addition, in order to obtain the temperature distribution of the windings, temperature sensors are installed inside the stator winding ends. At the rated operation, the temperature of the winding is obtained by the temperature sensor, as shown in Fig. 30. In the test, cooling air is produced by the cooling fan. This prototype is cooled through cooling channels opened in the stator slots and shell. It is seen, the winding temperature tends to be stable after about 2 hours of operation, and the measured winding temperature is about 119 °C, which is very close to the analysis result of 124 °C. Therefore, the measured results of the AC resistance and the temperature of the HSPMM are consistent with the theoretical analysis ones, which verifies that the theoretical analysis of the AC copper loss at high frequency.

## VI. CONCLUSION

In this paper, the AC copper losses of HSPMM with form-wound windings were studied comprehensively, and the influence of AC losses on the temperature distribution of the HSPMM was implemented. Moreover, the theoretical analysis was verified by testing the AC resistance of multiple form-wound windings at different frequencies and the temperature characteristics of the prototype. Based on the above analysis, some key conclusions can be summarized as follows.

1. When the two layers of windings in a stator slot are of the same phase, the AC copper losses of the two layers of conductors are the same. When the two layers of windings in a stator slot are of different phases, the AC copper losses of the two layers of conductors will affect each other, which leads to different AC copper losses from the stator slots with two layers of windings in the same phase.

2. The conductor width and thickness have a significant effect on the AC copper loss. When a large conductor size is used, as the number of conductors per stator slot increases, the AC/DC loss ratio would increase sharply.

3. Winding temperature has a great influence on the AC/DC loss ratio at high frequency. As the winding temperature increases, the AC/DC loss ratio would be greatly reduced. Due to the opposite trend of AC/DC loss ratio and
DC resistance with temperature, at low frequencies, the AC loss of the winding increases with the increase of temperature. However, when the frequency is higher than a certain value, the AC loss gradually decreases as the frequency goes up. While a large strand size is adopted, the AC copper loss on the winding temperature of HSPMM is very limited along with the frequency goes up. While a large strand size is adopted, the AC copper loss under high frequency would significantly increase the winding temperature of the HSPMM than that under low frequency, causing the winding temperature to overheat.

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