IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received June 4, 2021, accepted June 25, 2021, date of publication July 5, 2021, date of current version July 23, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3094833

Analysis of Copper Loss of Permanent Magnet Synchronous Motor With Formed Transposition Winding

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This work was supported in part by the National Natural Science Foundation of China under Grant 51977053.

ABSTRACT In recent years, the hairpin winding flat wire motor has received more and more attention because of its high power density and high torque, but the problem of increased AC copper loss caused by the increase of its wire diameter has restricted the use of the motor. Aiming at the problem of large AC copper loss in hairpin winding flat wire motors, this paper introduces the use of formed transposition windings into permanent magnet synchronous motors. Through analysis and comparison, the transposition bar suitable for permanent magnet synchronous motor is determined, and a method of inter-turn transposition that can improve the slot full rate of the motor is proposed. Taking a 223kW permanent magnet synchronous motor as an example, the transient field of the stator bar under 360° transposition was calculated by using the field-circuit combined three-dimensional(3-D) finite element method. By calculating the data, combined with the AC copper loss calculation method of the formed transposition winding given in the article, the distribution of the DC copper loss, eddy current copper loss and circulating copper loss of the motor is obtained. Compared with hairpin windings, the use of formed transposition windings can reduce the AC copper loss of the motor to a certain extent, the feasibility of using the formed transposition winding in the permanent magnet synchronous motor is verified.

INDEX TERMS Permanent magnet synchronous motor, formed transposition winding, hairpin winding, AC copper loss.

I. INTRODUCTION

As the permanent magnet synchronous motor is more and more widely used in the field of new energy vehicles, the requirements for the performance and efficiency of the motor itself are getting higher and higher. Replacing round wires with flat copper wires can further improve the slot full rate of the motor. The existing flat copper wires have a larger wire diameter than round wires, which can reduce the DC copper loss of the motor windings. The increase of its own contact area also makes it better for heat dissipation, more in line with the needs of permanent magnet synchronous motors for modern vehicles [1]– [3]. At this stage, the hairpin winding flat wire motor has received widespread attention due to its high torque and power density, and has been used in vehicle drive motors by many electric vehicle manufacturers. Figure 1 (a) shows a flat wire winding for vehicles. Each turn of the coil is composed of a hairpin-formed conductor, which is inserted into the stator slot, and the series coil is welded at the end. However, the use of the existing hairpin winding flat wire structure has certain limitations. The winding itself has a large wire diameter, and the skin effect and approach effect will produce a large amount of AC copper loss in the winding, especially when the motor speed is high, it will be further aggravated AC copper loss [1], [4]–[6]. Although increasing the number of parallel branches combined with reasonable transposition connections between different layers of windings can suppress AC loss to a certain extent, the number of parallel branches will be limited due to the limitation of the number of slots and the number of turns per slot. Therefore, this method can only suppress the AC loss of the motor in a certain range [7], [8]. AC copper loss will cause local overheating of the motor and decrease in motor performance [9].

In order to solve the above problems, this paper introduces the use of formed transposition winding into

The associate editor coordinating the review of this manuscript and approving it for publication was Fulvio Schettino.

permanent magnet synchronous motors. The formed winding is to process and shape multiple strands into a whole wire bar. Figure 1 (b) shows a kind of formed winding. Combining the formed winding with the transposition structure in Figure 1(c) can make the formed transposition winding shown in Figure 1(d). It can further reduce the AC copper loss of the motor through the parallel connection of multiple transposition strands on the basis of the higher slot full rate of the flat wire motor. Different from the hairpin winding, the suppression of AC copper loss by the formed transposition winding will not be limited by the number of parallel branches and the arrangement of complex windings. There are many transposition methods of the Multi-Turn coil. However, most transposition methods are only suitable for large AC motors with single turn coils, not for motors with multi turn coils in slots. For permanent magnet synchronous motors with multiple turns and short axial length, the continuous transposition bar is better. It can reduce the impact of the transposition process on the full rate of the motor slot while completing the transposition of the strands [10], [11]. In this paper, a new transposition method combined with the continuous transposition bar is proposed. Existing strand transposition generally adopts empty transposition or insufficient transposition to offset the leakage inductance potential generated by the strand at the end of the motor [12], [13]. For permanent magnet synchronous motors with short winding ends, 360° transposition of the strands in the slot can be used.

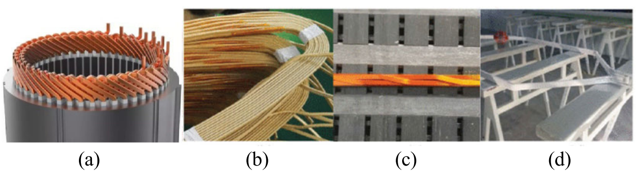

FIGURE 1. Winding type. (a) Flat wire winding. (b) Formed winding. (c) Transposition winding. (d) Formed transposition winding.

Currently, the research on formed transposition windings is mainly concentrated on large AC motors, and there are many mature methods for calculating the electromagnetic field of transposition winding [14], [15]. Analytical method, two-dimensional finite element method, and quasi-three-dimensional finite element method are commonly used methods, but they all have their own limitations. Many assumptions and neglects are adopted in the calculation process of analytical method, which cannot accurately consider the influence of strand transposition shape and core saturation on the calculation results; two-dimensional finite element method and quasi-three-dimensional finite element method cannot accurately simulate the transposition bar [12], [16], [17]. In this paper, the 3-D FEM is used. The 3-D finite element calculation takes a long time. It takes about a month to calculate on a computer with 128g running memory and 48-core CPU. But the rated operation condition of the motor can be simulated under the premise of accurately considering the shape of transposition bar and complex magnetic field distribution. Through the finite element calculation results, combined with the given calculation method of AC copper loss, the distribution of AC copper loss can be calculated more accurately.

This article takes a permanent magnet synchronous motor with a rated power of 223kW as an example, and introduces the use of formed transposition windings into the motor, a global model of the motor with 360° full transposition of the stator bar is established. The field-circuit coupled 3-D finite element transient field calculation of the motor under rated conditions; According to the calculation method of AC copper loss of formed transposition winding, the DC copper loss, eddy current copper loss, and circulating copper loss of the motor are respectively calculated and their distribution rules are analyzed. Under the premise of the same computing environment and ensuring the same output performance of the motor, the AC copper loss of the two cases of the hairpin winding and the formed transposition winding of the motor was compared. The effectiveness of the formed transposition winding on the suppression of AC copper loss and the feasibility of its application in permanent magnet synchronous motors are verified.

II. PHYSICAL MODEL AND FIELD RESULT OF COPPER LOSS CALCULATION

A. GLOBAL MOTOR MODEL AND PARAMETERS

Figure 2 shows a 3-D global model of a 60-slot/8-pole 223kW permanent magnet synchronous motor with formed transposition windings. The model includes the motor stator and rotor, formed transposition windings with ends, plate-formed permanent magnets and shafts. The shape and positioning of strands in the end region will have some effect on copper loss calculation, so winding losses should include both the end turns and the coil-to-coil jumpers. In order to ensure the accuracy of the calculation, the transposition part in the groove, end turns and the coil-to-coil jumpers are modeled accurately. The finite element calculation model is based on the physical model, and the excitation in the winding is given

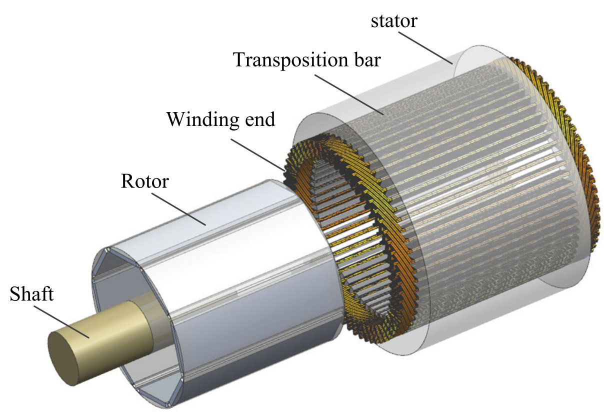

FIGURE 2. The global model of permanent magnet synchronous motor with formed transposition winding.

by the external circuit. The main parameters of the motor are shown in the Table 1.

TABLE 1. Main parameters.

parameter	value
Rated power/kW	223
Rated torque/kN • m	1.6
Slot/pole	60/8
Rotor outer diameter/mm	297
Rotor inner diameter/mm	100
Stator inner diameter/mm	300
Stator outer diameter/mm	445
Axial length/mm	342
Extension length of winding end/mm	40

B. IN-SLOT TRANSPOSITION BAR

The formed transposition winding in this paper is composed of continuous transposition bar. This kind of wire bar has a more compact structure than Roebel bar, and is more suitable for smaller permanent magnet synchronous motors. For the motor in this article, the use of continuous transposition bar can have two more strands per slot compared to the Roebel bar, which can increase the slot full rate of the motor by 5%. The continuous transposition bar also can reduce the AC copper consumption of the motor by increasing the number of strands in parallel. The overall structure of the wire bar is shown in Figure 3. The wire bar is divided into two rows in the slot cutting direction, one of which is vacant for a strand position. The remaining strands fill up the vacancies in the groove axial direction in a counterclockwise direction to complete the overall transposition.

The specific transposition method of the wire bar adopts the inter-turn interlaced 360° transposition. The transposition structure diagram is shown in Figure 4. The two-turn coils in the same layer of the motor are wound together for transposition. Since the degree of transposition is 360 degrees, the same strand has the same position at both ends of the groove. The two half turn coils are separated at the ends, and then connected with the corresponding half turn coils in another slot through the end joint sleeves cover to form a complete coil. The continuous transposition bar structure determines that if each turn of the coil is transposed separately, a strand position must be vacated in each turn of the coil. For the PMSM with 4 coils per slot in this paper, 4 strand positions must be vacated in one slot. After adopting inter-turn interlaced transposition, the two turns of coils in the same layer are wound together and transposed. Only two strand positions are needed for transposition in one slot, and the slot full rate of the motor can be increased by 5%. Moreover, each strand can pass through the entire inner space, which can further counterpoise the unbalanced electric potential induced by the leakage magnetic field of the strand, and further suppress the circulation effect.

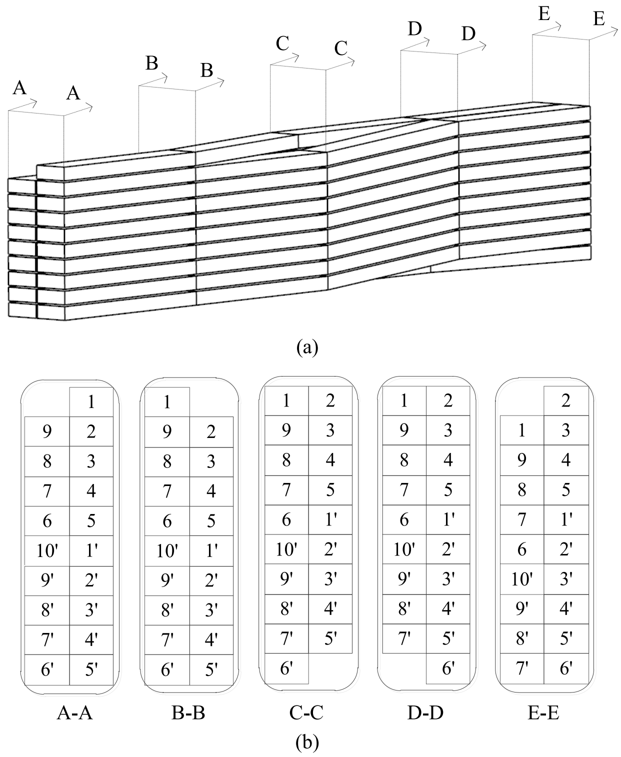

FIGURE 3. Continuous transposition bar. (a) Transposition structure. (b) Cross-sectional views of overhead view.

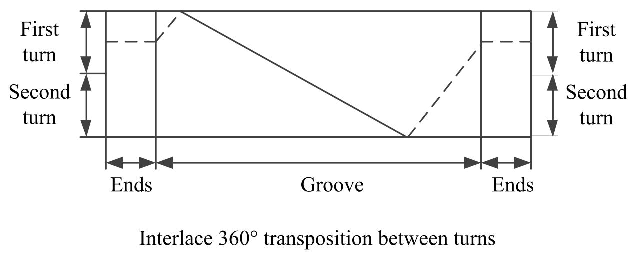

FIGURE 4. Schematic diagram of 360° transposition of inter-turn interlacing.

C. CIRCUIT COUPLING MODEL

In this paper, the PMSM coils are arranged by stacked winding. The strands in a coil are in a parallel relationship in one of the slots, and are in a series relationship with the strands in the corresponding other slot. The connection between the motor strands needs to be realized through an external circuit, the specific connection mode of the external circuit is shown in Figure 5. It shows the stranded circuit connection diagram taking the one-phase winding of the motor as an example, and the strand component numbers correspond to the components in the circuit according to "slot number, turn number, strand number." The connection mode of the other two-phase circuits is relative to this, and finally constitutes a complete external circuit. The connection relationship between the strand and the coil is realized by the series and parallel connection of the corresponding components of the external circuit, and finally realize the coupling calculation

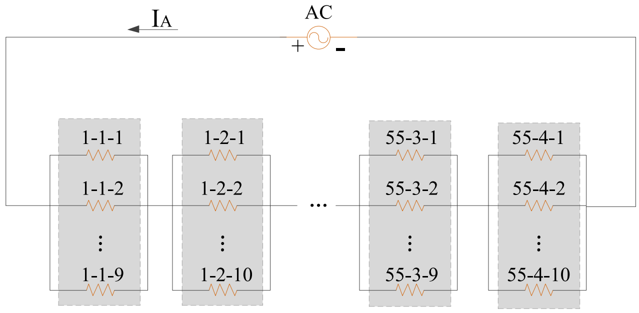

FIGURE 5. Strand connection circuit diagram.

of the field circuit. Figure 6 is a schematic diagram of the arrangement of conductors in a slot.

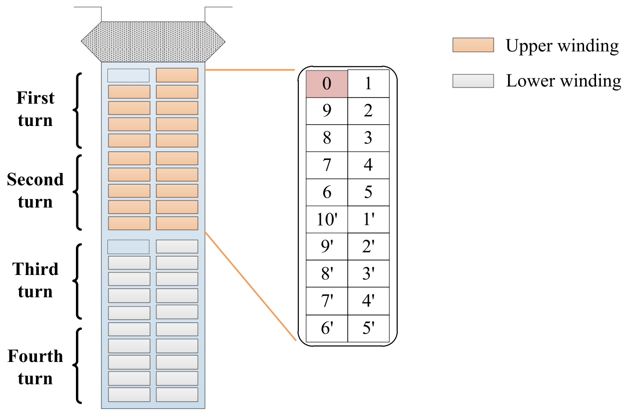

FIGURE 6. Arrangement of conductors in the slot.

D. HAIRPIN WINDING MODEL

In order to verify the effectiveness of formed transposition windings on the suppression of the AC copper loss of the motor. This paper compares the copper loss of permanent magnet synchronous motor motors with formed transposition windings and hairpin windings. In order to ensure the effectiveness of comparison, only the formed transposition winding in the motor model is replaced with the hairpin winding, and the output performance of the motor is guaranteed to be unchanged. The hairpin winding coil does not use stranded wires in parallel, and the entire winding has no transposition structure. The main difference between the formed transposition winding and the hairpin winding is that multiple parallel transposition windings replace a whole conductor of the hairpin winding. Ignoring the other variables of the two calculation models will not have an impact on the problem to be described in this article. Therefore, the comparison of the models in the article can represent the difference between the influence of the formed transposition winding and the hairpin winding on the AC copper loss of the permanent magnet synchronous motor. The structure diagram of the hairpin winding is shown in Figure 7. The comparison diagram of the end section of the formed transposition winding and the hairpin winding slot is as follows Shown in Figure 8.

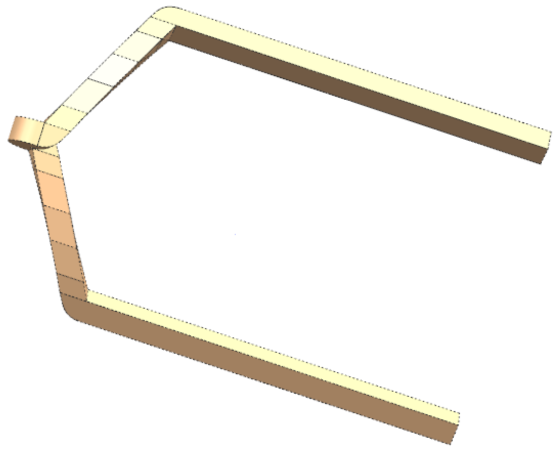

FIGURE 7. The structure of the hairpin winding.

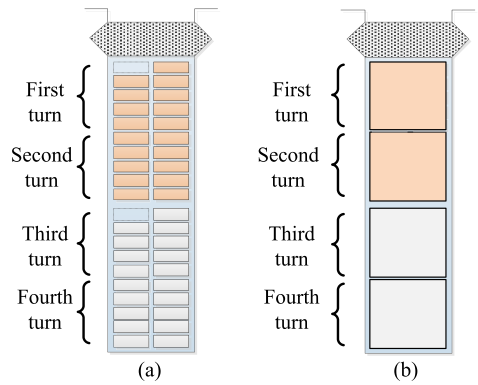

FIGURE 8. Schematic diagram of hairpin winding structure. (a) Formed transposition winding. (b) Hairpin winding.

E. CALCULATION RESULTS OF MAGNETIC FIELD

By combining the electromagnetic equation and the mechanical motion equation, the 3-D FEM fully considers the influence of iron core saturation effect and conductor skin effect, it also analyzes the actual distribution of magnetic field and eddy current inside the motor. 3-D FEM can truly reflect the physical process of the motor and obtain the winding distribution of medium current.

The electromagnetic equation and the mechanical motion equation can be solved simultaneously by using the 3-D FEM transient field, which satisfies the equation as follow:

$$\nabla \times \nu \nabla \times \boldsymbol{A} = \boldsymbol{J}_s - \sigma \frac{\partial \boldsymbol{A}}{\partial t} - \sigma \nabla \nu \tag{1}$$

where $\boldsymbol{A}$ is magnetic vector potential, $\boldsymbol{J}_s$ is current density, ν is the speed of moving objects, σ is dielectric conductivity. After calculation, the field calculation result can be obtained.

Figure 9 shows the magnetic density distribution of the stator iron core of the motor obtained after the 3-D FEM calculation of the motor. The magnetic density distribution of the entire iron core is symmetrical, and the maximum magnetic density of the teeth reaches 2.2T. The overall

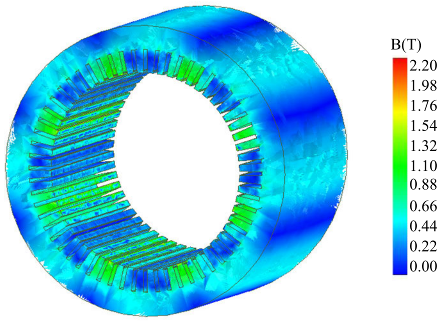

FIGURE 9. Stator core magnetic density distribution.

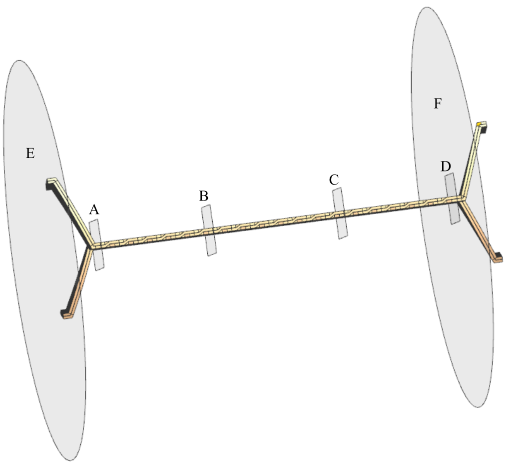

FIGURE 10. Transposition bar.

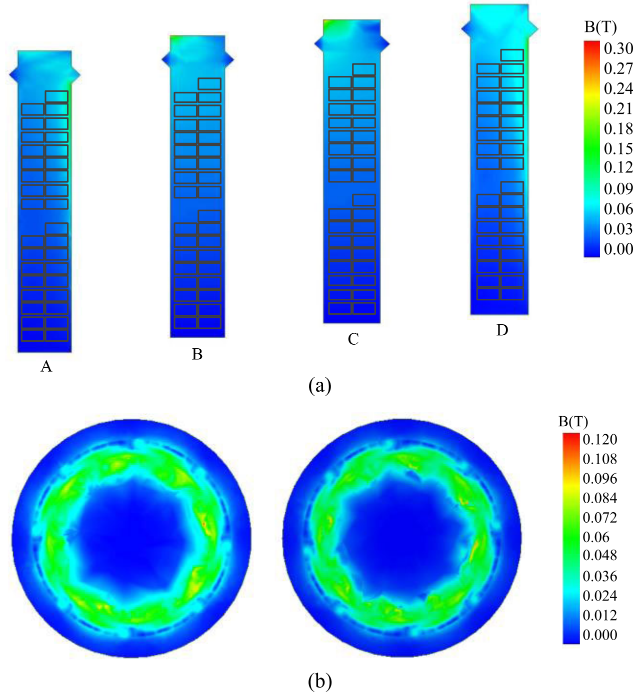

FIGURE 11. Field calculation result. (a) Leakage magnetic flux density clouds of the sections in a slot. (b) Leakage magnetic flux density clouds of the sections in the end region.

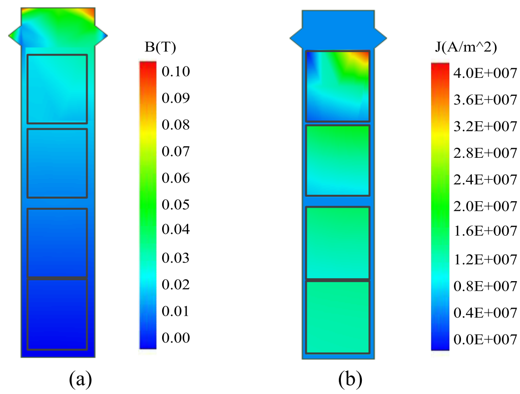

FIGURE 12. Field calculation result. (a) Leakage magnetic flux density clouds of the sections in a slot. (b) Electric density distribution of conductor in slot.

magnetic density is distributed within a reasonable range and meets the design requirements.

Figure 11 shows the distribution diagram of the leakage magnetic flux in the slot and the end section of the bar. The leakage magnetic flux in the slot decreases from the notch to the bottom of the slot, and the maximum value of the slot leakage flux is 0.3T. Affected by the end coils, the magnetic density distribution in the middle of the slot is more even than the magnetic density distribution at the end. The magnetic density distribution at the end is consistent with the shape of the coil end.

Figure 12 shows the distribution of leakage magnetic flux density and conductor section in the slot of hairpin winding. It can be seen from the figure that the slot notch leakage magnetic flux is very large, and the electric density is also affected by the leakage magnetic flux, and the distribution at the slot notch is very uneven. Because there is no transposition structure in the hairpin winding, the distribution of magnetic density and electric density of each section in the axial direction of the slot is basically the same. The hairpin winding at the slot notch has the problem of high local temperature rise due to high local electric density.

III. COPPER LOSS CALCULATION AND ANALYSIS

The AC copper loss of the formed transposition winding includes three parts, the DC copper loss that is not related to the current frequency, the eddy current copper loss caused by the skin effect and the proximity effect, and the circulating current copper loss caused by the unbalanced potential between the strands. In order to determine the influence of different winding structures on AC copper loss, it is necessary to analyze and calculate the distribution of each type of copper loss in the winding.

A. DC COPPER LOSS

Each turn of the formed transposition winding is made up of multiple strands, and each strand must have a certain thickness of insulating material. And because the transposition needs to vacate a certain strand of wire, the DC resistance of the formed transposition winding will increase compared with the same specification hairpin winding. For the formed transposition winding in this article, the DC resistance of each strand is as follow:

$$r_{dc} = \rho \frac{L_w}{\zeta_w S_w} \tag{2}$$

where ρ is resistivity, L_w is the strand length per turn, ζ_w is the copper full rate of the strand, S_w is the cross-sectional area of each turn of the strand. For hairpin winding and formed transposition windings, ζ_w can be calculated by:

$$\zeta_w = \frac{L_r \cdot L_z}{(L_r + 2\delta_f)(L_z + 2\delta_f)} \tag{3}$$

where L_r and L_z are the lengths of the two sides of the rectangle corresponding to the copper axial section in the strand, δ_f is the thickness of the strand insulation. The DC copper loss in a strand is as follow:

$$P_{cuw\_dc} = \left(\frac{1}{N} I\right)^2 r_{dc} \tag{4}$$

where N is the number of parallel strands per turn of the coil, I is the effective value of the current flowing in each turn of the coil.

After theoretical calculations, the copper full rate and DC copper loss of the formed transposition winding and the copper full rate and DC copper loss of the hairpin winding flat wire motor are shown in Table 2. It can be seen from the calculation results that the undivided hairpin winding has a 13.3% greater copper full rate than the formed transposed winding. Under rated operating conditions, the DC copper loss of the whole machine is 841W smaller than that of the formed transposition winding. It accounts for 76.2% of the DC copper loss of the formed transposition winding.

TABLE 2. DC copper loss comparison.

parameter	Copper full rate(%)	Bar DC loss(W)	Whole machine DC loss(W)
Formed transposition winding	80.4	59.03	3541
Hairpin winding	93.7	45	2700

Figure 13 is a comparison diagram of the DC copper loss of the two windings with the current change. It can be seen from the figure that as the current increases, the DC copper loss of the formed transposition winding increases more than that of the hairpin winding. When the motor is overloaded and the current reaches 300A, the DC copper loss of the formed transposition winding is 1236W larger than that of the hairpin winding.

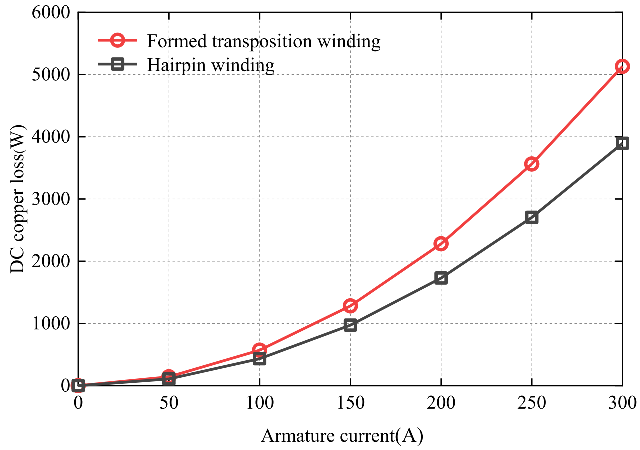

FIGURE 13. DC copper loss comparison.

B. EDDY CURRENT COPPER LOSS

The eddy current copper loss of the winding is caused by the proximity effect and the skin effect. All these effects will cause the uneven current distribution in the winding, and further lead to the reduction of the equivalent cross-sectional area of the winding. Due to the complex distribution of the magnetic field in the motor, in order to accurately calculate the eddy current copper loss of the formed transposition winding, a 3-D finite element method must be combined. Calculate the 3-D FEM transient field of the motor's global model. The specific calculation method is as follows:

Take a strand as an example, the average value of the total AC copper loss can be defined as:

$$P_k = \frac{1}{2}\int_{V_k} \frac{\dot{\boldsymbol{J}} \cdot \dot{\boldsymbol{J}}^*}{\sigma} dV = \sum_{i=1}^{E} \frac{1}{2}\int_{v_i} \frac{|\dot{\boldsymbol{J}}_i|^2}{\sigma} dv \tag{5}$$

where V_k is the volume of the strand, $\dot{\boldsymbol{J}}$ Is the instantaneous value of current density, $\dot{\boldsymbol{J}}^*$ is Conjugate vector of $\dot{\boldsymbol{J}}$, σ is conductivity, E indicates the number of units in V_k, V_i is the volume of the i unit, $\dot{\boldsymbol{J}}_i$ represents the instantaneous value of current density in the i unit.

The AC resistance of the strand can be calculated as:

$$r_{ac} = \frac{P_k}{I_k^2} \tag{6}$$

where I_k is the effective value of the current flowing in the strand, then the average value of eddy current loss in a strand can be expressed as:

$$P_e = (I_k)^2 (r_{ac} - r_{dc}) \tag{7}$$

After the 3-D transient calculation of the motor, the total AC copper loss of a bar in a slot is shown in Figure 14. After the waveform is stable, the maximum loss can be found to be 122W, and the average value is 67W. Finite element calculations have obtained the effective value of the current in the strands, combined with the given eddy current loss calculation method and then the total eddy current copper loss of the conductor in a slot is 6.04W.

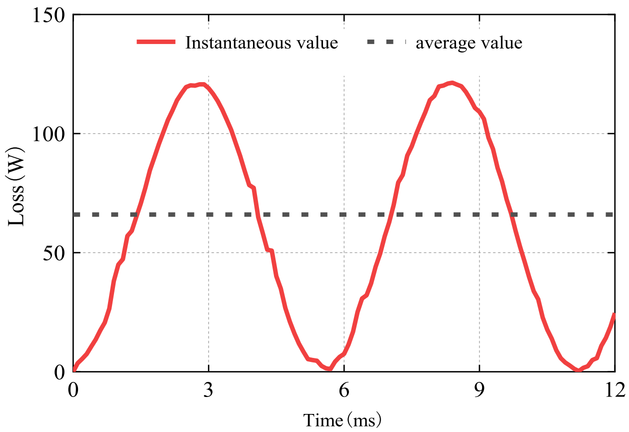

FIGURE 14. Total loss of wire bar in slot.

Figure 15 is the curve of the eddy current copper loss of the forming transposition winding and the hairpin winding with the increase in speed. Since multiple parallel strands can effectively suppress the eddy current loss of the motor, as the motor speed increases, the eddy current loss of the hairpin winding motor grows faster than the formed transposition winding. Therefore, the formed transposition winding is more suitable for permanent magnet synchronous motors with higher speed than the hairpin winding. Formed transposition winding can greatly reduce the eddy current copper loss caused by high frequency alternating current.

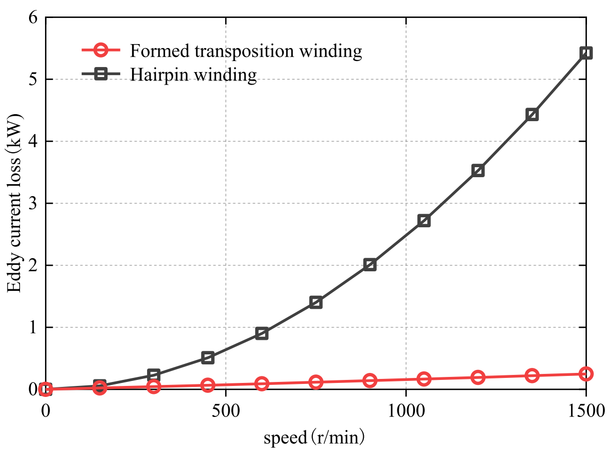

FIGURE 15. Eddy current copper loss.

C. CIRCULATING CURRENT LOSS

The formed transposition winding coil adopts multiple strands and is wound in parallel. Due to the different position of each strand in the magnetic field, the potential of each strand induced by the magnetic field is also different. Different induced electric potentials lead to the formation of a circulating current between the strands. Circulating current will cause different current amplitudes and phases between different strands, which will further affect the performance of the motor. Formed transposition windings can make each strand evenly in each magnetic field position in the slot by transposing the strands in the slot, so it can effectively suppress the circulation phenomenon. The calculation method of the average circulating current loss of the formed transposition winding is as follows:

The curve of current variation with time in each strand can be obtained by calculating the transient field of 3-D finite element of PMSM. Calculate the root mean square of the curve can get the effective value of the current in the strand. Effective value calculation formula can be defined as:

$$I_k = \frac{\sqrt{\sum_{j=1}^{n} I_j^2}}{n} \tag{8}$$

where n is the number of points for each periodic curve, I_j is instantaneous current of j. Effective value of circulating current of each strand is as follow:

$$I_k^* = \left| \frac{1}{N} I - I_k \right| \tag{9}$$

Average value of circulating current loss for each strand P_s is as follow:

$$P_s = \left| I_k^2 - \left(\frac{1}{N} I \right)^2 \right| r_{dc} \tag{10}$$

The stator groove of the motor is an open groove, and the flux leakage at the notch is larger, which has a greater influence on the current in the strand wire. Therefore, the influence of the transposition winding on the strand current can be explained by extracting the current distribution of the first turn coil of the notch. Figure 16 is the calculated curve of the current change with time in the 9 strands of the first turn of the coil in the slot. It can be seen that the distribution of the current between the strands shows a sinusoidal trend as a whole, and the phase of the current between each strand is basically the same. It shows that the transposition of the bar can restrain the circulating current between strands and reduce the influence of the magnetic leakage field on the current in strands.

The distribution diagram of the effective value of the conductor current in the slot is shown in Figure 17. Since the second-turn coil and the fourth-turn coil have one more strand than the first-turn coil and the third-turn coil, the effective value of the strand current is smaller than the first-turn coil and the third-turn coil as a whole. The effective value of the current is evenly distributed in the respective coils, and the difference between the maximum value and the minimum value is within 2A.

The calculation result of the circulating current loss in the strand is shown in Figure 18. The maximum circulating current loss in the strand is 0.161W. After calculation, the circulating current loss of the upper bar and the lower bar are 0.791W and 1.152W respectively, and the circulating current loss of the conductor in the entire slot is 1.943W. As far as the AC copper consumption of the entire

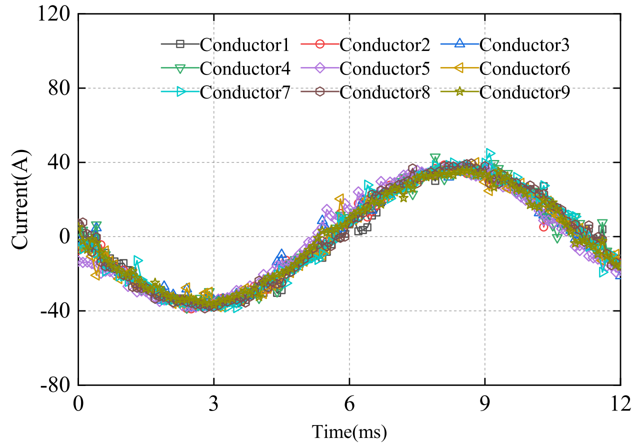

FIGURE 16. Current in the first turn of the coil strand.

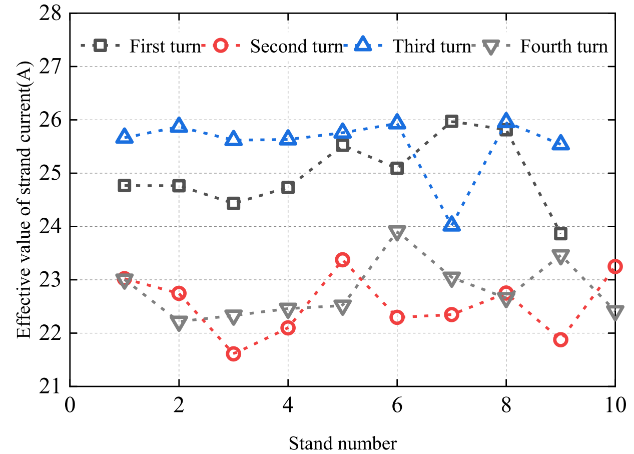

FIGURE 17. Distribution diagram of effective value of strand current.

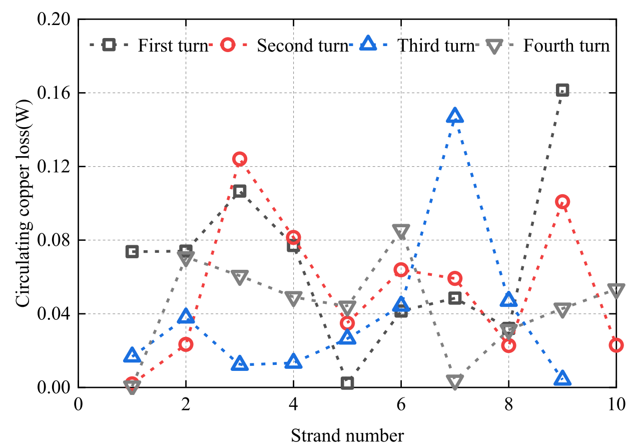

FIGURE 18. Distribution diagram of strand circulating current loss.

motor is concerned, the proportion of circulating copper consumption is very small, it only accounts for about 3%. For the hairpin winding, each turn of the coil does not use stranded wire in parallel, so there is no circulating current loss.

IV. TOTAL AC COPPER LOSS

The total AC copper loss in the winding consists of three parts, and it can be expressed as:

$$P_{cu} = P_{dc} + P_e + P_s \tag{11}$$

Under the rated operating conditions of the motor, the proportion of DC copper loss, eddy current copper loss and circulating copper loss in the formed transposition winding and the hairpin winding is shown in Figure 19. It can be seen from the figure that the eddy current copper loss accounts for the largest proportion in the hairpin winding, and there is no circulating current loss; In the formed transposition winding, the DC copper loss accounts for the largest proportion, reaching 88.08%, and the eddy current copper loss and the circulating current copper loss account for only a small part, indicating that the bar transposition gains are obvious.

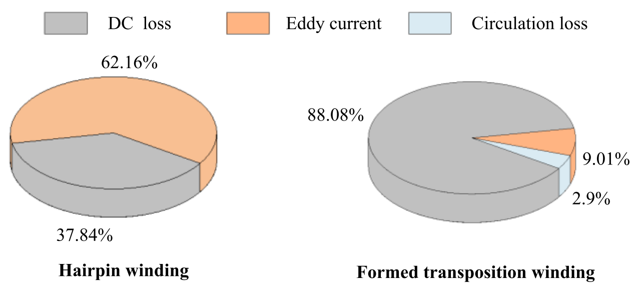

FIGURE 19. Structure diagram of copper loss composition of different windings.

The comparison chart of the distribution of AC copper loss in the two windings is shown in Figure 20. It can be seen from the loss comparison that the DC copper loss of the formed transposition winding and the hairpin winding is not much different. The eddy current copper loss of the hairpin winding is much larger than that of the formed transposition winding. The circulating copper loss only exists in the formed transposition winding, but it accounts for a small proportion.

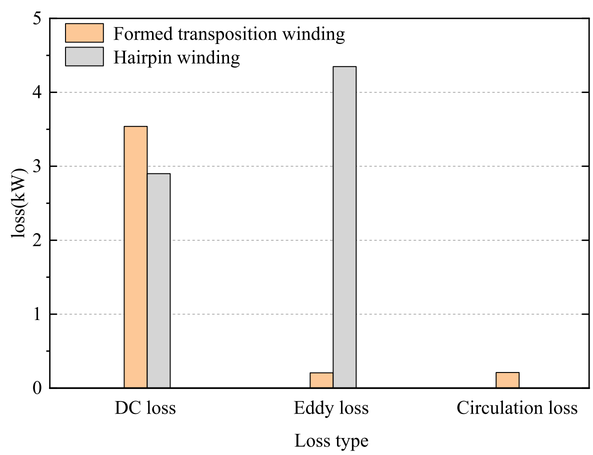

FIGURE 20. Copper loss distribution comparison.

The total loss of the hairpin winding is greater than that of the formed transposition winding.

Table 3 shows the specific values of DC copper loss, eddy current copper loss, circulating current copper loss and total copper loss under rated conditions of formed transposition windings and hairpin windings.

TABLE 3. Comparison of copper loss values.

parameter	DC loss(W)	Eddy current loss(W)	Circulating current loss(W)	Total copper loss(W)
Formed transposition winding	3541	362.4	116.6	4020
Hairpin winding	2700	4550	0	7250

It can be seen from the table that the eddy current loss of the formed transposition winding is reduced by 4187.6W compared with the eddy current loss of the hairpin winding. The total copper loss of the formed transposition winding is 4020W, which is 3230W less than the hairpin winding. The formed transposition winding effectively weakens the eddy current loss and the total AC copper loss in the winding through the parallel and transposition of the strands, which can effectively solve the local temperature rise problem of the motor, and the total heat generation of the motor has been reduced. The whole calculation results verify the feasibility of formed transposed windings in permanent magnet synchronous motors, and the application of formed transposed windings in permanent magnet synchronous motors has great potential.

V. CONCLUSION

Aiming at the large AC loss of hairpin winding flat wire motors, this paper proposes to introduce the use of formed transposition windings into permanent magnet synchronous motors. The AC copper losses of the formed transposition winding and the hairpin winding are calculated and compared separately. The results show that the formed transposition winding can effectively suppress the AC copper loss of the motor, and the following conclusions are drawn:

1) Each turn of the formed transposition winding adopts multiple strands in parallel. The insulation thickness between the wires and the free transposition space causes the DC copper loss of the permanent magnet synchronous motor with the formed transposition winding to increase compared with the hairpin winding flat wire motor.

2) The formed transposed winding can effectively suppress the eddy current loss in the winding and the circulating current loss between the strands by parallel connection and transposition of multiple strands, so as to effectively solve the problem of local heating of motor. Compared with the hairpin winding, the application of the formed transposition winding reduces the eddy current loss of the motor in this paper by 92.035%. The amplitude and phase of the current in the parallel strands of the same turn of the formed transposition winding are basically the same, the waveform is sine wave, and the distortion rate is not large.

3) For the permanent magnet synchronous motor in this article, after replacing the hairpin winding with formed transposition winding, the AC copper loss value of the motor can be reduced by 44.55%. The overall performance of the formed transposition winding is better than that of the hairpin winding, and its application in permanent magnet synchronous motors has great potential.

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