Design of Conductor Cross Section to Reduce Temperature Rise of High Slot Fill Aluminum Winding in High-Speed Permanent Magnet Machines

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ABSTRACT: This paper proposes a novel conductor cross section of high slot fill aluminum winding in high-speed and high power density electric machines for transportation applications such as electric vehicles and electric aircrafts. The maximum rotational speed and the power density are 50,000 min^{-1} and 10 kW/kg, respectively. The maximum current frequency is 3.3 kHz with the number of rotor poles is eight; and therefore, it has serious winding AC loss. The high slot fill aluminum winding is a great solution to reduce both DC and AC losses. The loss reduction contributes to reduce the temperature rise of the winding. In this paper, the cross-sectional shape of the aluminum distributed winding is proposed to reduce the temperature rise at high-speed region. In experiments, it is shown that the proposed winding in a prototype motorette can reduce the temperature rise more than 50% at 3.3 kHz.

KEY WORDS: aluminum winding, AC loss, high-speed machine, WLTC driving cycle, energy consumption

1. INTRODUCTION

Traction motors for electric vehicles and electric aircraft applications requires high efficiency and high power density. Aluminum windings tend to use instead of copper windings to improve their performances, and the aluminum winding electric machines have been studied [1]-[2]. It can reduce the motor weight because it has low mass density of approximately one-third compared to copper windings [3]-[4]. However, the efficiency of the motor is low because aluminum windings with low electrical conductivity increase DC resistance. Therefore, the slot fill factor has been improved for reducing DC resistances [5]-[7]. In [6] and [7], compressed round aluminum windings are proposed. The compressed aluminum windings are deformed into a polygonal shape and tightly adhered; therefore, the slot fill factor is increased up to 77%. The measured DC resistance is reduced compared to conventional stranded copper windings, and the DC loss is reduced by 33%. On the other hand, winding AC losses are increased at high-speed regions. On the other hand, aluminum windings have advantage for AC loss reduction in high frequency region because of lower eddy current losses due to low electrical conductivity compared to copper windings [8]. In addition, winding structures have been studied for AC loss reduction.

In [9], an additive manufacturing aluminum winding that is formed to avoid leakage fluxes around stator tooth tips is proposed for reducing winding AC losses. There are free spaces in the slot close to the stator tooth tip. In [10], divided conductors are installed in the free space. In addition, a transposition method is proposed for connecting the divided conductors to reduce circulating currents.

In [11], aluminum alloy windings with additively manufactured hollow conductors for inserting cooling pipes are proposed. The winding is also not placed near the stator tooth tips. In [12], the winding AC loss is reduced by changing electrical conductivities in each turn.

In [13], a mixed winding with the aluminum and the copper materials is proposed. The aluminum and copper conductors are installed near the stator tooth tip and the slot bottom, respectively. This winding topology is one of the solutions to reduce the AC loss with reduced DC loss. It still has free spaces in the slot to avoid leakage fluxes.

The authors have proposed a high slot fill aluminum winding machine [14]. The slot fill factor is 83.8% because coil shapes are different in each layer of conductors. The winding losses are compared based on the same structure with copper and aluminum windings. In the 3D-FEM calculation, the aluminum winding reduces winding losses at high frequency over 820 Hz. In [16], the prototype machine with the proposed high slot fill aluminum winding is fabricated and tested. The measured efficiency is high because the measured winding loss is low in wide speed region from low frequency to 933 Hz. In [17], their efficiency maps in 2D-FEM analysis are reported, and the proposed aluminum winding machine can extend high efficiency region compared to the round copper winding machine. On the other hand, the measured efficiency is competitive at high-speed region because AC losses are increased in the closest conductor from the stator tooth tip. Furthermore, in order to reduce the AC loss of the winding at high speeds, we proposed a pentagonal winding structure with a winding shape close to the tip of the stator teeth to avoid the leakage flux between the adjacent stator tooth tips [18].

In this paper, a novel conductor cross section of the high slot fill aluminum winding, which is installed in electric machines with high-speed and high power density, is proposed to reduce the temperature rise. The maximum rotational speed is 50,000 min^{-1}, and the electrical frequency is 3.3 kHz with eight-pole surface permanent magnet rotors. The proposed winding has a unique coil shape to avoid leakage fluxes around the stator tooth tip. The proposed structure significantly reduces the AC loss at 3.3 kHz. In experiments, it is demonstrated that the temperature rise is reduced by 50% or less compared to that of a previous winding in the motorette stator.

2. Proposed High Slot Fill Aluminum Winding

2.1. Design of conductor cross sections

Figure 1 shows the structure of an eight-pole surface permanent magnet machine with distributed aluminum winding. The stator and rotor core materials are 10JNEX900 with a sheet thickness of 0.1 mm. The numbers of poles and slots are 8 and 24, respectively. The number of turns is ten per slot so that the number of series turns is 80 per phase. The rotor has eight permanent magnets, which are covered with a carbon fiber reinforced plastic (CFRP) sleeve. The permanent magnet material is N40SH.

Figure 2 shows the enlarged cross-sectional view of the stator slot and the distributed aluminum winding. The cross-sectional area of the windings is 8.38 mm^2, and it is the same in each conductor. The conductor shapes are different in each turn, and it depends on the slot structure. Let us assign the conductor number from the tooth tip to the slot bottom as 1 to 10.

Figure 3 shows the proposed coil cross-sectional shape. Only high loss density region is removed to reduce AC loss. In the layer 1 and layer 2, that of 0.1 W/mm^3 or greater is eliminated so that the cross-sectional areas are slightly decreased. The other conductor cross-sectional areas are also decreased as it approaches the stator tooth tip because the radial thickness of the conductors is constant of 1.16 mm. As a result, the conductor cross-sectional areas of layer 1 and layer 10 are 4.86 mm^2 and 11.10 mm^2, respectively.

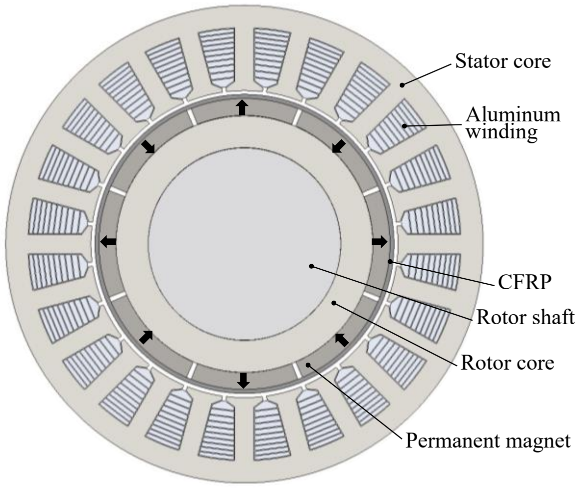


Fig. 1. Eight-pole surface permanent magnet machine with distributed aluminum winding.

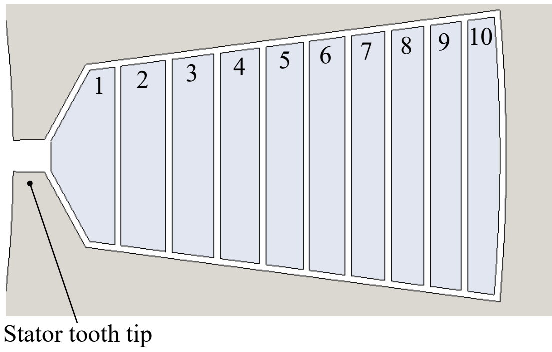


Fig. 2. Enlarged cross-sectional view of stator slot and aluminum windings.

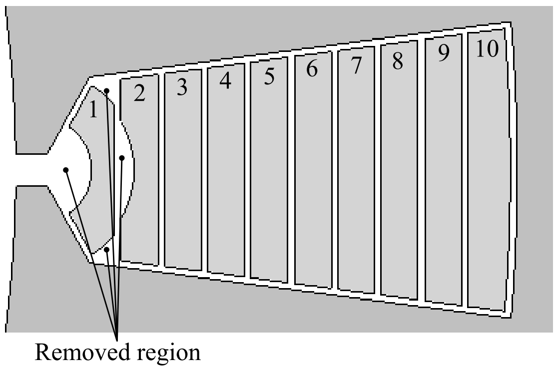


Fig. 3. Proposed coil cross-sectional shape with loss concentration areas removed.

3. 3D-FEM analysis

3.1. Calculated loss density distribution

Figures 4(a) and (b) show calculated loss density distributions in the previous and the proposed coils. The rms current and the frequency are 30 A and 3.3 kHz, respectively. The loss density is concentrated at first and second turns that are close to the stator tooth tip. It is caused by the eddy current loss due to fringing fluxes between adjacent the tooth tips. On the other hand, the loss density is reduced in the proposed coil structure as shown in Fig. 4(b). In general, the first turn is removed to reduce the AC loss. However, it unfortunately increases the DC loss because the cross-sectional areas of each turn are decreased. On the other hand, only the loss concentration regions in the first and second turns are removed in the proposed coil. It has a great advantage of reducing both DC and AC losses.

4. Experimental Result with Prototype Motorette

4.1. Fabricated prototype motorette and experimental system

Figure 5 shows the prototype coil of the proposed aluminum winding with insulation coatings. The adjacent layers are connected by cold-welding process [15]. The coil material is pure aluminum which electrical conductivity is 35.0 MS/m at the room temperature. In order to try to validate the effectiveness of the proposed coil structure, only one coil is fabricated.

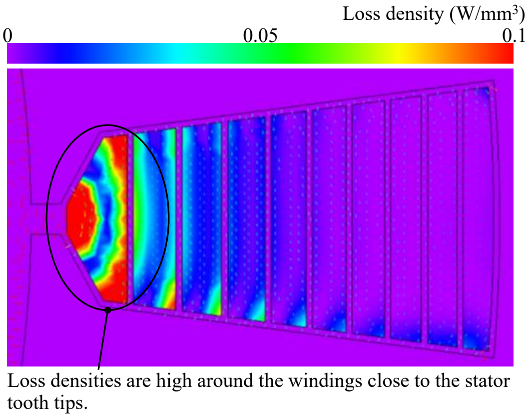
Figure 6 shows enlarged view of the fabricated aluminum winding. The top and second layers are corresponding to layer 1 and 2, respectively. The proposed coil structures are successfully manufactured, and it is acceptable for evaluating the winding loss reduction. The temperature rise of the first layer is measured in the proposed and previous windings.

Figure 7 shows the measurement system of the winding loss and coil temperatures. The prototype aluminum winding is connected to an input and output cables, and then, a single-phase SiC inverter is connected. It is used to provide the current of 3.33 kHz. The voltage and the current are measured in the power analyzer. In the laptop PC, the amplitude and the frequency of the current are changed, and then, the current feedback control is carried out in the controller installed on the inverter bode. The DC power supply is used when the DC loss is measured. In addition, coil temperatures are measured by the infrared thermography.

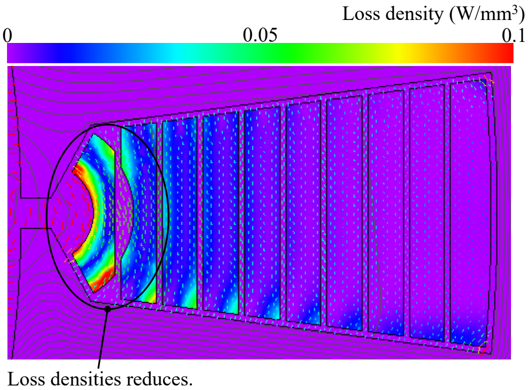
4.2. Comparison of measured and calculated transient temperature rise

Figure 8 shows the measured slew-rate °C/s of the short-time temperature rise. The vertical axis indicates degree per second which unit is corresponding to the winding loss per thermal capacitance of each turn. The proposed aluminum winding significantly reduces the measured temperature slew-rate compared to that of the previous winding. This result means that the winding loss is reduced more than 50% in the proposed winding. Therefore, it is successfully demonstrated that the proposed aluminum winding structure effective to reduce AC loss with keeping low DC loss.

Figure 9 shows measured temperature rises of the previous and the proposed aluminum windings. The average temperature of all layers is shown. The temperature rise is high in the previous winding because the winding loss is high compared to the proposed winding even when the identical current waveform is supplied. The proposed winding reduces the short-time transient temperature rise from 0 s to 4 s by 20%. In addition, the steady-state average temperature is small in the proposed winding. The difference of the temperature between the previous and proposed



(a) Previous



(b) Proposed

Fig. 4. Calculated loss density distribution at 3.3 kHz and 30 A_{rms}.

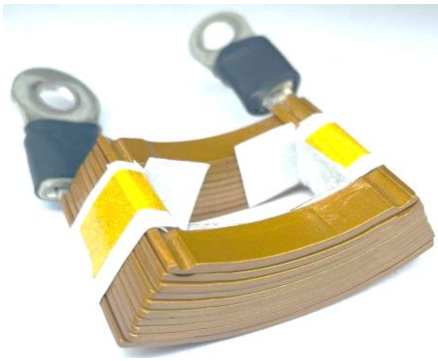


Fig. 5. Fabricated proposed aluminum winding.

Fig. 6. Enlarged view of fabricated aluminum winding.

winding is approximately 10℃. Therefore, the proposed winding has a great advantage to reduce the coil temperature.

Figures 10(a) and 10(b) shows measured temperatures of the previous and the proposed windings. The temperature of the end-winding is measured by an infrared thermography (PI640i, Optris). The current rms and the frequency are 30 A and 3.3 kHz. The temperature rise is high at first layer that is the closest from the stator tooth tip as shown in Figs. 2 and 3 because the AC loss is concentrated around there as shown in Fig. 4. The heat is transferred to other layers due to conductions, convections, and radiations, and then, the temperature is mostly uniformed. On the other hand, there is a hotspot that has the highest temperature. At the steady-state, the hotspot temperatures are 173.3℃ and 162.7℃, respectively. The reduction effect that of the proposed winding is 10.6℃. Therefore, this experiment verifies that the proposed winding significantly reduces the hotspot temperature.

4. CONCLUSIONS

This paper presents a novel coil cross section of the high slot fill aluminum winding. It significantly reduces the winding AC loss while maintaining small DC loss. In the experiment, the measured slew-rate of the coil temperature rise can be reduced more than 50% compared to that of the previous winding. In addition, the proposed winding reduces the steady-state coil temperature over 10.6℃. It is great advantage for thermal managements in high-power density electric machines.

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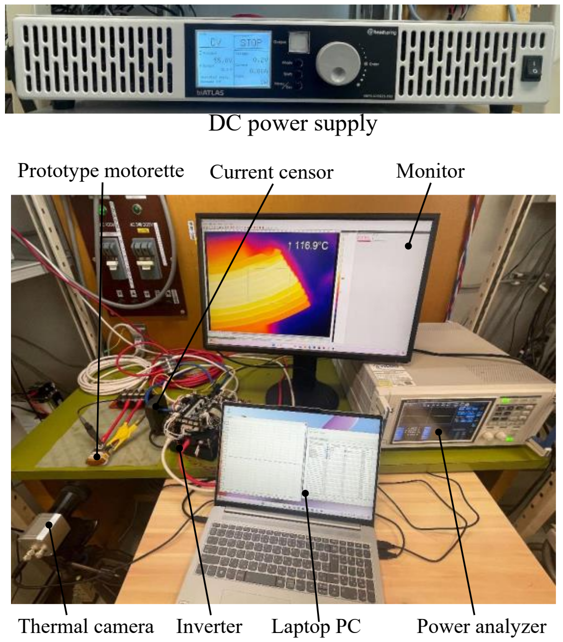

Fig. 7. Measurement system of winding loss and temperature.

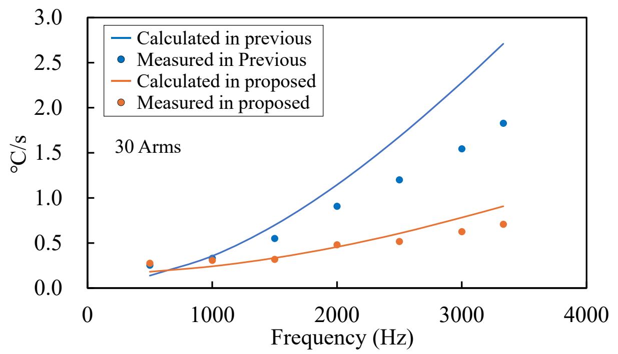

Fig. 8. Measured slew-rate of temperature rise of first-layer and calculated ratio of winding loss and thermal capacitance.

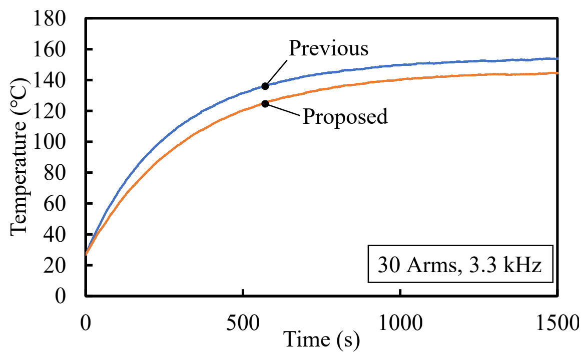

Fig. 9. Measured temperature rises of previous and proposed aluminum winding.

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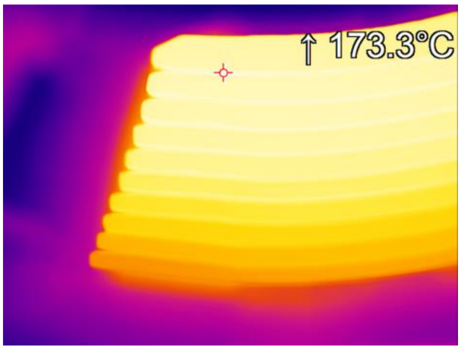
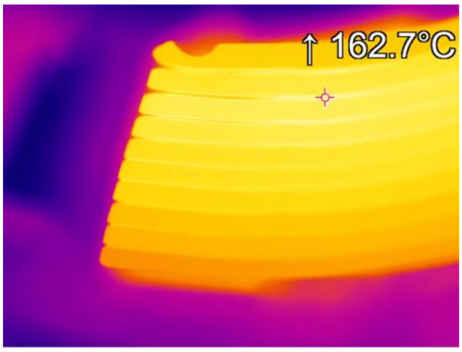


(a) Previous



(b) Proposed

Fig. 10. Measured thermal images of (a) previous and (b) proposed windings at steady-state.