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Effects of Conductor Materials for Reducing Winding Loss in Permanent Magnet Synchronous Machines

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ABSTRACT: This paper presents a design of high slot fill aluminum winding in permanent magnet machines for reducing winding losses. Generally, there is a trade-off between the winding weight and the winding losses. The winding DC loss is reduced with an increase of cross-sectional areas of conductors. In general, the aluminum winding is effective for reducing the winding weight, on the other hand, the winding loss is high because the electrical conductivity is low. In this paper, the conductor material is changed in each turn because the winding loss is concentrated in the closest conductor from the stator tooth tip. An aluminum alloy that has relatively low electrical conductivity is assigned to the first layer. In 2D-FEM analysis, it significantly contributes for reducing winding AC losses compared to that of previous aluminum winding machine. In addition, shapes of the stator tooth tip and the first layer of conductors are improved. This manuscript presents that these improvements are significantly effective for reducing winding losses.

KEY WORDS: winding loss, aluminum alloy, permanent magnet machine, 2D-FEM analysis

1. INTRODUCTION

Aluminum windings have been studied for traction motors of electric vehicles [1] and aerial applications [2]. It is effective for reducing motor weight because the mass density is approximately one-third compared to copper windings. However, the motor efficiency is low due to low electrical conductivity. Therefore, the slot fill factor has been improved for reducing DC resistances [3]-[4]. In [3], an outer rotor permanent magnet machine with aluminum winding has been proposed. It has segmented stator teeth, and compressed aluminum coils are installed in stator slots with high slot fill factor of 75%. In [4], the compressed aluminum coils have been improved, and the slot fill factor is increased up to 77.9%. The measured DC resistance is successfully reduced compared to conventional copper windings of bobbin-wound coils. On the other hand, winding AC losses are increased at high-speed region.

In [5], additive manufacturing aluminum windings have been proposed, and unique coil shapes have been proposed for reducing winding AC losses. There are free spaces close to stator tooth tip in the slot for avoiding leakage fluxes, and as a result, it is supposed that the slot fill factor is approximately 50%. In [6], divided conductors are added to the free space, as a result, the slot fill factor is improved up to 75%. In addition, a transposition method is proposed for connecting the divided conductors. In [7], unique hollow conductors are additively manufactured. It has great advantage of low winding AC losses at high-speed regions. The electrical conductivity of the coil material is investigated for minimizing winding AC losses. It is supposed that the slot fill factor is approximately 50% because hollow conductors are used, and there are no conductors close to stator tooth tips to reduce AC losses due to leakage fluxes. There is a trade-off between increasing the slot fill factor and reducing the winding AC loss.

In [8], motor efficiencies are compared in rectangular copper and aluminum windings in calculations. When winding AC losses are dominant in winding losses, the aluminum winding machine is high efficiency. The sum of DC and AC losses is low compared to the copper winding because AC losses are relatively low due to the low electrical conductivity. Therefore, aluminum windings have great potential for improving efficiency.

In [9], two materials of aluminum and copper alloys of additive manufacturing are compared in terms of electrical, mechanical and thermal properties. The winding volume of the copper alloy is rather high compared to the aluminum one due to the mechanical constraint. As a result, the aluminum alloy reduces winding AC losses in the calculation result.

In [10]-[11], comparisons of copper and aluminum windings have been discussed. In [10], winding losses are measured with a part of stator that has a multi-stranded winding. The measured winding loss of the aluminum winding is low compared to that of the copper winding at high frequency region over 500 Hz. On the other hand, a ratio of AC and DC resistances of the winding is more than three at 900 Hz. In [11], comparison of energy consumptions of IPM machines with rectangular conductors in an urban driving cycle is reported. The energy consumption is high in the aluminum winding because the efficiency is low in low-speed region. In [12], high slot fill aluminum windings have been proposed. It is an edge wound-winding with high slot fill factor of 76%. It is computationally verified that the power consumption of the winding in a driving cycle can be reduced by improving the slot fill factor.

For reducing both DC and AC winding losses, high slot fill aluminum winding machine has been proposed in [13]-[14]. Fig. 1 shows the proposed aluminum winding machine reported in [15]. The slot fill factor is improved to 83.8% because coil shapes are different in each layer of conductors. The proposed aluminum windings consist of eight concentrated coils per phase that have four turns per each coil. The four conductors are connected by cold-welding so that we can design optimal conductor shapes for increasing the slot fill factor. In addition, winding losses are compared to copper winding that has the identical coil structure with the proposed aluminum winding. In the 3D-FEM calculation, the aluminum winding reduces winding losses at high frequency over 820 Hz because the winding AC loss is low compared to that of the copper winding [14]. The aluminum winding machine is fabricated and tested, and the efficiency is significantly improved [15].

In this paper, the conductor material is changed in each turn because the winding loss is concentrated in the closest conductor from the stator tooth tip. An aluminum alloy that has relatively low electrical conductivity is assigned to the first layer. In 2D-FEM analysis, it significantly contributes for reducing winding AC losses compared to that of previous aluminum winding machine. In addition, shapes of the stator tooth tip and the first layer of conductors are improved. This manuscript presents that these improvements are significantly effective for reducing winding losses.

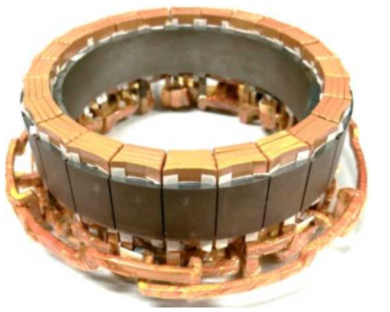
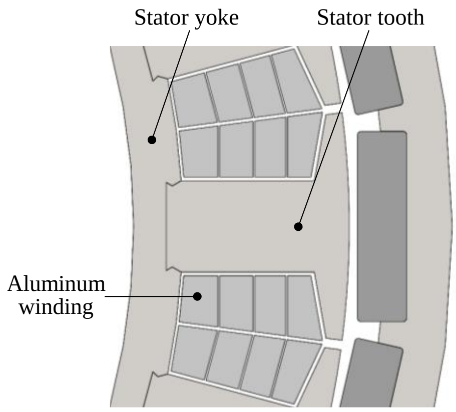
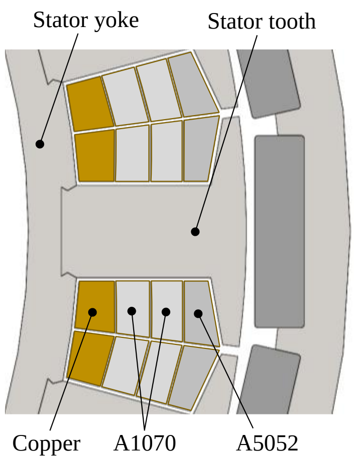


Fig. 1. Prototype stator with high slot fill aluminum winding.



(a) Aluminum winding



(b) Proposed winding with aluminum alloys and copper

Fig. 2. Enlarged cross-sectional views of previous aluminum winding and proposed winding structure with aluminum alloys and copper materials.

2. PROPOSED WINDING STRUCTURE WITH THREE CONDUCTOR MATERIALS

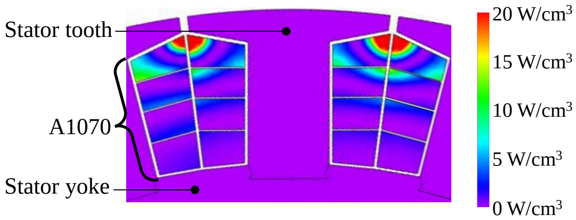
Fig. 1 shows the prototype stator with previous aluminum winding that has very high slot fill factor of 83.8%. It can reduce winding DC loss because the winding DC resistance is reduced by 27% compared to that of a round copper winding that has the identical weight. In addition, aluminum materials have another great advantage of reducing winding AC losses due to low electrical conductivity. In fact, we have demonstrated high efficiency in experiments of the prototype aluminum winding machine compared to the round copper winding machine. On the other hand, the measured efficiency is saturated at high-speed region because winding AC losses are drastically increased at the closest conductor from the stator tooth tip. In this manuscript, we propose a new winding concept with three materials of pure aluminum, aluminum alloys and pure copper for reducing both winding DC and AC losses.

Figs. 2(a) and 2(b) show enlarged cross-sectional views of previous aluminum winding and proposed winding structure with aluminum alloys and copper materials. In Fig. 2(a), the previous aluminum winding has four series turns per tooth, and it is installed as concentrated windings. These four conductors have different cross sections for increasing the slot fill factor. Each layer of conductors is separated, and then, these parts are connected by cold-welding. The stator core is divided into a yoke and 24 teeth for inserting assembled conductors. In Fig. 2(b), the proposed winding also has four series turns, and three materials are assigned to each turn. Aluminum alloys are assigned from first to third turns, and only the fourth turn has pure copper material. Low electrical conductivity is better to reduce the winding AC loss so that A5052 is chosen in the first layer from the stator tooth tip. Electrical conductivities of two aluminum alloys of A5052 and A1070 are 20.3 MS/m and 35.96 MS/m, respectively. The latter one is close to pure aluminum. We assign the material to second and third turns because these layers slightly generate winding AC losses.

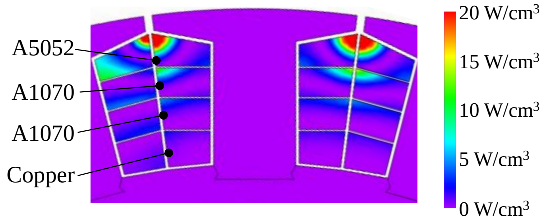
3. CALCULATIONS OF WINDING LOSSES IN 2D-FEM ANALYSIS

Fig. 3(a), 3(b) and 3(c) show calculated loss density distributions in conductors. At high-speed region, winding AC losses are generated by skin effects, proximity effects and eddy current losses. The loss density is concentrated at around corners of the closest conductor from the stator tooth tip. It is caused by eddy current losses due to fringing fluxes between stator tooth tips [13]. When the conductor material is changed from A1070 to A5052, the loss density is slightly decreased as shown in Fig. 3(b). In Fig. 3(c), stator tooth tips are improved for reducing fringing fluxes between tooth tips. In addition, corners of the first layer of conductors are cut for avoiding fringing fluxes. These improvements are significantly effective for reducing eddy current losses. As can be seen in Fig. 3(c), it can reduce loss densities compared to that of Fig. 3(a) and 3(b).

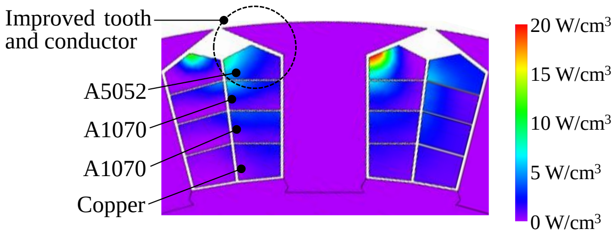
Fig. 4(a) and 4(b) shows calculation results of winding losses of the closest conductor from the stator tooth tip in 2D-FEM analysis. Fig. 4(a) shows the current waveform of U-phase winding. The current RMS and frequency are 56 A and 1.167 kHz, respectively. In Fig. 4(b), three winding losses of the previous aluminum winding, improved structures (I) and (II) are shown. The previous aluminum winding includes high AC loss so that the loss is increased when the current is close to 0 A. In case of the improved structure (I), the peak value can be reduced by 35% because the conductor material is changed from A1070 to A5052. It means that low electrical conductivity is effective for reducing winding AC loss. In addition, the peak value can be extremely



(a) Previous aluminum winding

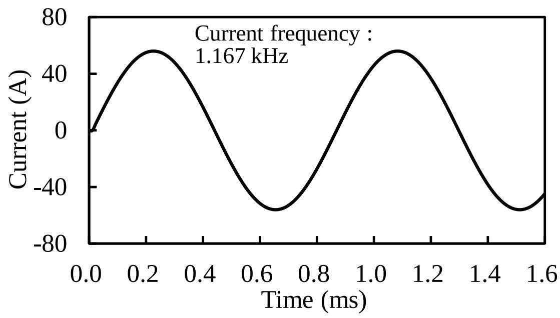


(b) Improved structure (I) with three conductor materials of A5052, A1070 and pure copper

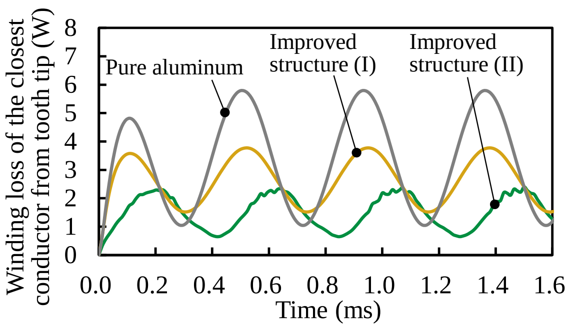


(c) Improved structure (II) with improved stator tooth tip and shape of first layer of conductor from the tooth tip

Fig. 3. Calculated loss densities of high slot fill conductors in three structures at 1.167 kHz.



(a) U-phase current waveform at 1.167 kHz



(b) Calculated winding losses

Fig. 4. Calculated winding losses of the closest conductor from tooth tip.

reduced by 60% in the improved structure (II). Therefore, it is computationally verified that the proposed stator tooth tip structure and shape of the first layer of conductors also contribute for reducing winding losses.

Fig. 5 shows calculated total winding loss per phase. Each phase has 32 series turns because there are four turns in each segmented tooth in 24-slot stator core. When the coil material is copper in the previous structure in Fig. 2, the winding loss is increased from 10 W to approximately 100 W at around 2 kHz. The ratio of AC to DC loss is shown in Fig. 6, and it is approximately 10 in the case of copper material. When the coil material is changed to aluminum of A1070, the total winding loss can be reduced in high-speed region over 820 Hz. Therefore, the ratio is reduced by half in Fig. 6. Furthermore, the proposed structure of Fig. 3(c) significantly reduces winding losses, and the decrease is 60% from the previous structure with the copper winding. This calculation results analytically verify that the proposed coil shapes, coil materials and the stator tooth tip structure are considerably effective to reduce winding losses. The ratio is also very low in the proposed structure. It means that the proposed structure and material effectively reduces AC loss, and it can be utilized to high-speed machines.

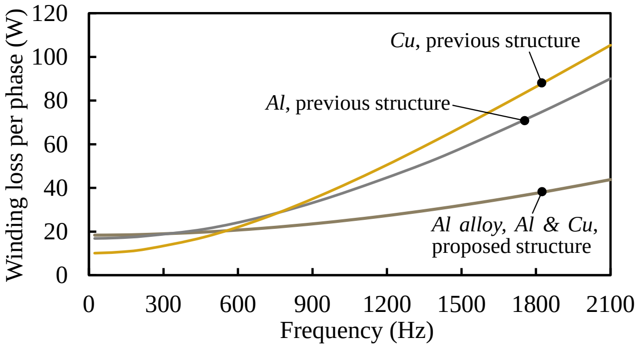


Fig. 5. Calculated total winding loss per phase.

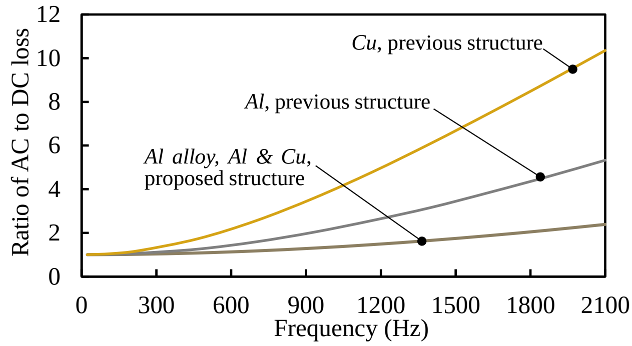


Fig. 6. Ratio of AC to DC winding loss.

4. CONCLUSION

This paper presents new winding configurations for reducing winding losses. Effects of conductor materials are verified in 2D-FEM analysis, and the aluminum alloy is a good choice as the closest conductor from the stator tooth tip because the peak value can be reduced in the winding loss. In addition, the proposed stator tooth tip structure and shape of the first layer of conductors also contribute for reducing winding losses. In calculation results, the proposed structures and materials can reduce winding losses by 60% compared to that of the previous structure with the copper material.

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