

Optimal Design of PMSG with Hybrid Hairpin Winding for Gas Turbine Engine Considering Reduction of AC Copper Loss

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In this paper, the optimal design of hybrid hairpin winding permanent magnet synchronous generator(PMSG) for gas turbine engine is derived considering the reduction of AC copper loss. The hybrid hairpin winding includes aluminum conductor to overcome the weakness of AC copper loss by the wide area of the hairpin winding. The aluminum conductors have lower electrical conductivity than copper conductors and trade-off relationship between DC and AC copper losses. In case of PMSG for gas turbine engine, the operating region is focused on high-speed region, so the effect of reducing AC copper loss is emphasized. The material combination and size of the conductors were optimized based on the algorithm to reduce the copper losses including AC and DC copper losses. In addition, the weight and cost of PMSG were also reduced according to the characteristics of aluminum.

Index Terms—AC copper loss, AC resistance, aluminum conductor, hairpin winding, generator.

I. INTRODUCTION

HAIRPIN WINDING is effective winding method, which is a widely used in various applications of electric machines. This contributes to a higher fill factor and to improve output density. However, each conductor of a hairpin winding has a relatively large cross-sectional area, which could be a problem in the high-speed region of the electric machine. The rotating speed of an electrical machine is proportional to its frequency, and in the high-frequency range, AC copper losses in the conductor increase rapidly due to skin effect, proximity effect, leakage flux, and etc. And they are more susceptible when the conductor has a large cross-sectional area.

One of the methods for mitigating AC copper loss is the utilization of aluminum conductors. Aluminum could replace copper as a conductor because it is lightweight, low cost, and flexible to machine, but it has lower electrical conductivity. The low electrical conductivity typically leads to increased resistance; it can be advantageous in the case of AC copper losses, where the magnitude is inversely proportional to resistance. The lower conductivity of aluminum is advantageous in high-speed region [1]–[5], also for hairpin winding [6]–[8].

The generators for gas turbine engines begins to generate over a certain level of rotating speed, so their primary operating range is the high-speed and high-frequency region. Consequently, AC copper loss is the main loss element in engine generators, and the use of aluminum conductors is highly effective in reducing AC copper loss and AC resistance.

This paper focuses on the study of design optimization with hybrid hairpin winding to improve efficiency while reducing weight and cost by using aluminum conductors. Hybrid hairpin winding is proposed considering optimal combination of copper and aluminum conductors. The aluminum is applied to the air-gap region conductor, because the air-gap region is where the AC copper losses are most significant because of the leakage flux between the stator tooth tips.

II. PMSG OF GAS TURBINE ENGINE

The model analyzed in this paper is a permanent magnet synchronous generator(PMSG) for gas turbine engine with hairpin winding. Consequently, the entire operating region of the generator is in the high-speed and high-frequency range, which are over 15,000 rpm and 750 Hz.

The proportion of iron losses is relatively small, due to the characteristics of generators based on back electromotive force and rectifier circuit. However, the effects of copper losses, especially AC copper losses, are based on the amplitude and frequency of current, and the proportion of AC copper losses in the total losses of the generator is high.

III. AC COPPER LOSS AND ALUMINUM CONDUCTOR

AC copper loss has numerous factors. A significant portion of the AC copper loss is a leakage flux between the teeth tips of the stator in the air-gap region. Therefore, the study focuses on reducing the AC copper loss in the conductors near air-gap region.

Aluminum conductivity is approximately 60% of copper conductivity as shown in Table I. Resistance, which can be expressed as DC resistance, tends to be inversely proportional to the conductivity, with aluminum conductors being about 1.5 times higher than copper conductors. The copper loss, which can be expressed as DC copper loss, is also proportionally larger. However, the AC copper loss(P_{AC}) could be expressed as (1) in terms of the conductivity [1]. And aluminum conductors could reduce the AC copper loss as the conductivity ratio in (2).

$$P_{AC} = \frac{\pi}{64} \cdot \sigma \cdot l \cdot d^4 \cdot \frac{dB^2}{dt} \propto \sigma \quad (1)$$

$$\frac{P_{AC}^{Al}}{P_{AC}^{Cu}} = \frac{\sigma_{Al}}{\sigma_{Cu}} \simeq 0.61 \quad (2)$$

TABLE I
MATERIAL CHARACTERISTICS.

Properties	Copper (Cu)	Aluminum (Al)	Unit
Electrical Conductivity	5.80×10^7	3.50×10^7	S/m
Mass Density	8930	2700	kg/m ³
Cost*	9.091	2.571	\$/kg

* Available: <https://www.lme.com/en/Metals/Non-ferrous>

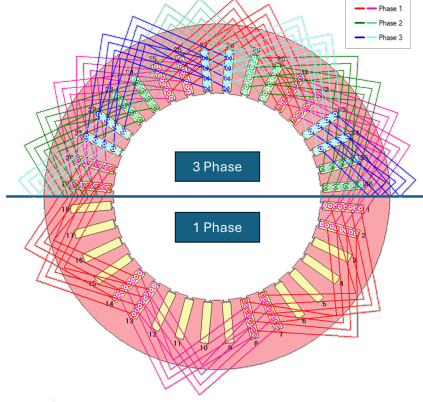


Fig. 1. Hairpin winding pattern.

IV. WINDING STRUCTURE

The base model analyzed in this paper utilizes a two-layer winding of 8-turn hairpin. The conductor winding is a periodic pattern, with half of the conductors wound counter-clockwise (CCW) and the others wound CW as shown in Fig. 1. Consequently, the conductors can be represented by four conductor pairs, and the performance of each conductor pair can be analyzed, including losses due to size and material. Despite the variation in size and material composition among the conductor pairs, they are connected in a periodic pattern, resulting in a uniform resistance across each phase. This eliminates concerns about the circulating current or unbalance due to phase resistance variations.

V. OPTIMIZATION

The optimal design is derived through the algorithm-based optimization process. Variables for optimization are the size and material of the four-conductor pair of the hairpin winding as shown in Fig. 2. Under the constraint of identical other conditions, including the winding fill factor, multi-objective functions include the weight of the generator, losses in the operating range, and efficiency. The copper loss reduction as a representative result of the optimization is shown in Fig. 3, it compares models of copper conductor, aluminum conductor, hybrid conductor, and proposed optimal conductor.

VI. CONCLUSION

In this paper, aluminum conductors were applied to the hairpin winding of the gas turbine engine PMSG, and the algorithm based optimal design was derived. The PMSG of gas turbine engine usually works in high-speed region, and the AC copper loss is the main loss and heat source, especially in the case of hairpin winding. Therefore, the aluminum is proposed

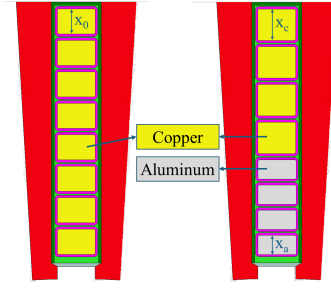


Fig. 2. Combined hairpin conductors with variation in size and material.

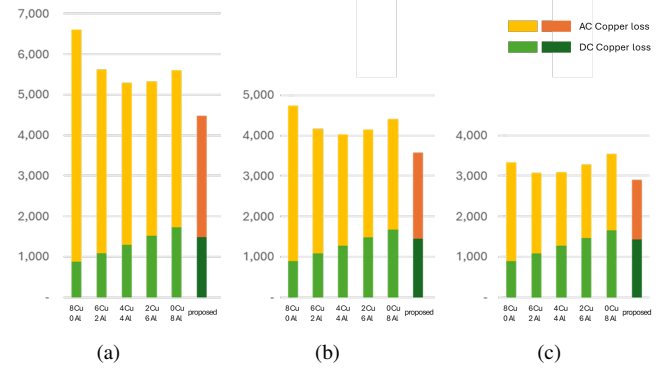


Fig. 3. Comparison of copper losses according to conductor types at (a) 30,000 rpm, (b) 24,000 rpm, and (c) 18,000 rpm.

to reduce the AC copper loss and weight, cost additionally. The proposed model has about 10 to 30 % reduced copper loss compared to general copper hairpin winding. In addition, the weight and cost also decreased about 5 % and 2%, respectively.

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