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Development of Low-Loss Technology Using Continuous Wave Winding

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ABSTRACT: We are developing a small and lightweight direct-drive system to realize in-wheel EVs. This drive system aims to improve the torque density of the motor by making the stator larger in diameter, thinner and flatter. In this paper, we will report on the concept of low-loss technology using a continuous wave winding structure with a flat sheet-piece coil. We analyzed the magnetic field effects between coils in a slot using FEA and quantified the effects of harmonic loss due to differences in coil layout. This analysis revealed that the loss reduction effect of continuous wave coils can be attributed to the coil space factor. A quantitative comparison of the space factor between a continuous wave coil and a conventional concentrated winding coil revealed that the continuous wave coil can reduce copper loss by approximately 10% compared to the conventional structure.

KEY WORDS: EV and HV system, motor drive system, in-wheel motor, windings

1. INTRODUCTION

In recent years, technological development and investment activities have become more active to realize a carbon-free society. In the automotive sector, there has been a shift from gasoline-powered vehicles to electric vehicles (EVs). In current EVs, the drive system is located on the chassis, limiting the interior space, including the space for installing the battery. For this reason, in-wheel motors are attracting attention because they can expand the interior space by mounting themselves inside the wheel.(1) However, conventional in-wheel motors have low power density, which increases the unsprung mass and requires a complete overhaul of the existing suspension(2), creating new challenges.

To address these issues, previous research has examined multi-polarization(3) and concentrated winding(4) as technologies that can improve power density. Especially, fractional slot concentrated winding (FSCW) is known as a technology that can simultaneously improve power density and reduce torque pulsation, making it suitable for use in in-wheel motors. However, conventional concentrated winding is unable to ensure a sufficient space factor, posing issues in terms of efficiency. In addition, when multi-polarization is implemented, the number of jumper connection points increases significantly, posing issues in terms of manufacturability and assembly.

Against this background, this paper summarizes the issues with conventional concentrated winding and describes a coil structure that was developed as a technology to resolve these issues. We then describe the assembly method and connection features of the developed coil structure and finally discuss the loss reduction effect of the developed coil structure.

2. CONPARISON OF WINDINGS

In this chapter, we compare conventional winding methods and summarize the issues in multi-polarized direct drive motors. As shown in Fig. 1, there are two types of stator coil winding methods: distributed winding, in which the coil is wound across multiple slots, and concentrated winding, in which the coil is wound in a spiral shape around one tooth. The FSCW shown in Fig. 1 is one form of concentrated winding, but as will be described later, its motor characteristics are significantly different from concentrated winding with a 2:3 series (2P/3S series) combination of the number of magnetic poles (P) and the number of slots (S), so it is described separately here.

Distributed winding is superior to concentrated winding in that it can increase the winding factor, which indicates the magnitude

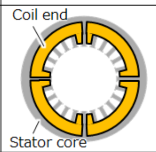
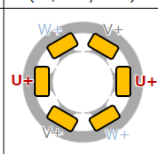
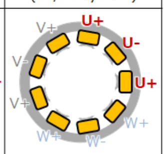
Winding type	Distributed	Concentrated (2P/3S system)	FSCW (8P/9S system)
Stator coil end			
Weight of coil end	× Heavy	○ Light	○ Light
Winding factor (∼torque)	○ Max. 1.0	× 0.866	○ 0.945
Torque ripple	○ Small	× Large	○ Small
Coil filling factor (rectangular wire)	○ High	× Low	× Low
Viability of super multi poles	× Too many slots	× Too many wires connecting coils	× Too many wires connecting coils

Fig. 1. Comparison of winding types

of the effective magnetic flux linking the coil and can qualitatively reduce torque pulsation. It is also superior in that it can increase the coil space factor (the ratio of the coil-cross-sectional area to the slot-cross-sectional area) when using rectangular wire.

Concentrated winding, on the other hand, is superior in that it can reduce weight by making the coil ends smaller. While both the winding factor and torque pulsation deteriorate with 2P/3S concentrated winding, the winding factor and torque pulsation can be improved to the same extent or even more than with 8P/9S fractional slot concentrated winding compared to distributed winding. However, the low coil space factor is an issue because two coils are placed adjacent to each other in the same slot.

Furthermore, a common issue with both distributed and concentrated winding is the difficulty of ensuring ease of manufacturing and assembly for multi-polarized direct drive motors. Specifically, the number of slots is large in distributed winding, while the number of jumper connection points is enormous in concentrated winding. As described above, issues exist with both winding methods, but in this report, we have investigated a method of simultaneously improving the coil space factor in the slot and simplifying the jumper wires for concentrated winding and fractional slots, which allow for weight reduction and have an excellent winding factor and torque ripple.

2. CONTINUOUS WAVE WINDING

Concentrated winding is known as a structure in which one coil is wound around one tooth. Fig. 2 shows a cross-sectional view of conventional coils in fractional slot concentrated winding and continuous wave coils. The conventional coils require a winding nozzle to wind the conductor around the teeth for the semi-closed slot structure. To make the space for the winding nozzle to move, a dead space is formed within the slot, resulting in a low coil space factor. In addition, the conventional coils require jumper wires and their connection process to electrically connect the coils, which worsens manufacturing efficiency in multi-polar motors.

Therefore, in this report, we focus on the unique configuration of fractional slot concentrated winding, in which two or more sets of same-phase coils are continuous in the circumferential direction, and develop a new winding structure, continuous wave winding, that simultaneously improves the coil space factor in the slot and simplifies the jumper wires. As shown in Fig. 3, the developed continuous wave winding has a wave-wound structure in which the coil is wound across multiple teeth. With the continuous wave winding, there is no dead space in the slot, so the coil space factor can be improved.

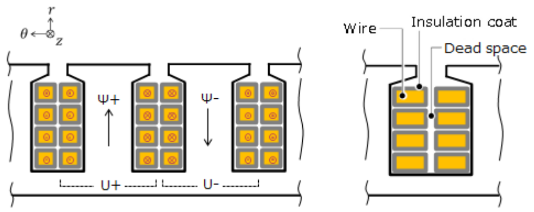


Fig. 2 Cross-sectional views of conventional coils.

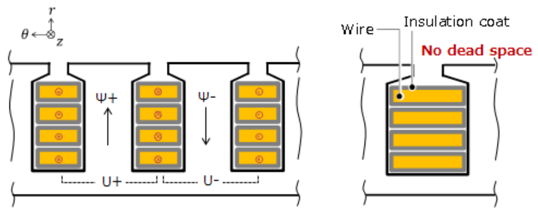


Fig. 3 Cross-sectional views of continuous wave coils.

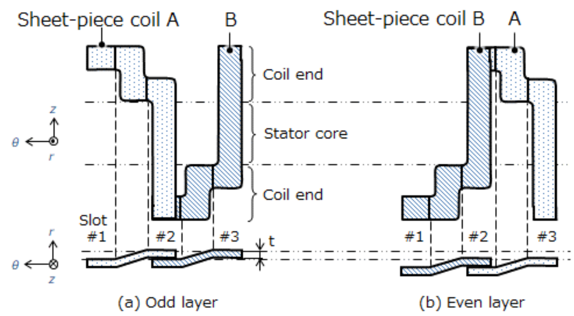


Fig. 4 Sheet-piece coils and their assembly

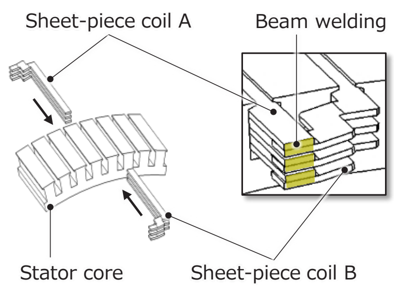


Fig. 5 Assembly of continuous wave coil.

The continuous wave winding coil is constructed by incorporating L-shaped coil pieces (hereafter referred to as sheet-piece coils) A and B into the stator core, as shown in Fig. 4. As shown in Fig. 5, the sheet piece coils are stacked radially with the required number of turns and inserted from both ends of the stator core. After that, they are beam welded from both sides to make them conductive, forming an electrically continuous wave winding coil.

3. LOSS REDUCTION

2.1. Eddy current

Fig. 6 shows the wiring diagram of a continuous wave winding coil spanning three teeth. In Fig. 6(b) the solid line of the coil indicates that it passes along the upper side of this paper, and the dotted line of the coil indicates that it passes along the lower side of this paper. There are two types of coil arrangements: slots that accommodate only coils of the same phase, and slots that accommodate coils of two different phases (different phase slots).

In the developed continuous wave winding, the coils of two different phases in the slot are stacked alternately in the radial direction to minimize the number of types of sheet piece coils and the coil length. The eddy current of the coils due to this layout are unknown. To investigate this, we performed loss analysis taking into account the effects of inverter harmonics for each of Cases 1 and 2, where the coils of the same phase are arranged together in the racial direction in Case 1 and the coils of different phases are arranged alternately in the radial direction in Case 2.

Fig. 7 shows the analysis results of the harmonic copper loss of the coils in each layer in the different phase slots. The solid bars represent Case 1, and the open bars represent Case 2. Wires 1 to 6 in the graph correspond to the coil layer numbers, with Wire 1 being closest to the gap. Comparing the harmonic copper loss of the coils in each layer, there was almost no difference between Case 1 and Case 2, and by arranging the different phase coils alternately, as in Case 2, which is the same as the actual machine, there was no increase in harmonic loss. Although the difference in loss was small, Case 2 had slightly smaller losses and in particular Wires 3 and 4, which are in the center of the lamination direction, had lower losses by about 10% to 20%.

Fig. 8 shows the eddy current distribution of the coils in each layer in slots at a certain time. In Case 1, the coils of the same phase were grouped together, which made it easy for bias to occur in the magnetic flux distribution in the slot. On the other hand, in Case 2, the coils of the different phases were stacked alternately, so the magnetic flux distribution in the slot was closer to uniform than in Case 1, and the eddy currents were slightly smaller.

From these results, it became clear that the influence of the coil layout on the magnetic field was small, and therefore the loss reduction effect due to differences in coil layout was due to the coil space factor.

2.2. Space factor

In the slot cross section of the conventional concentrated winding structure (see Fig. 2) and the slot cross section of the newly developed continuous wave winding structure (see Fig. 3), the coil space factor per slot turn was calculated when the circumferential gap (dead space in Fig. 2) of the conventional concentrated winding is in the range of 0 to 2, assuming that the insulation thickness between the coils is 1.

The results are shown in Fig. 9. The space factor for the continuous wave winding structure with six turns per slot is set to 1 pu. In the conventional concentrated winding structure, the space factor varies depending on the thickness of the circumferential gap, resulting in a band-shaped region. The space factor is highest when the circumferential gap is zero, which is the theoretical limit. However, this theoretical limit is for open slots, and in the case of

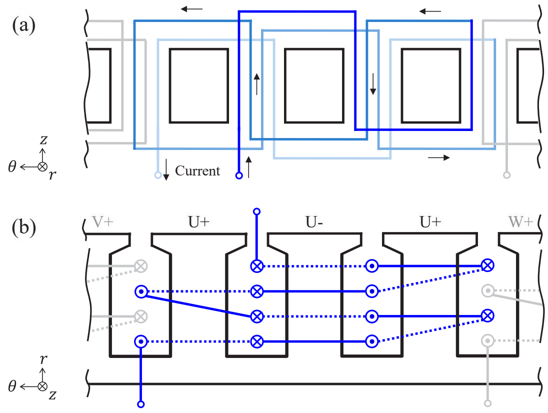


Fig. 6 Wiring diagram of the continuous wave coil.

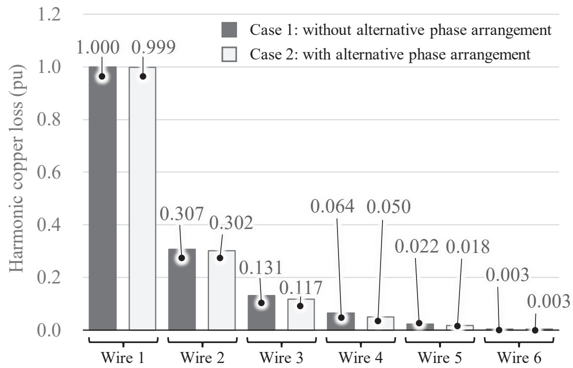


Fig. 7 Comparison of calculated harmonic copper losses.

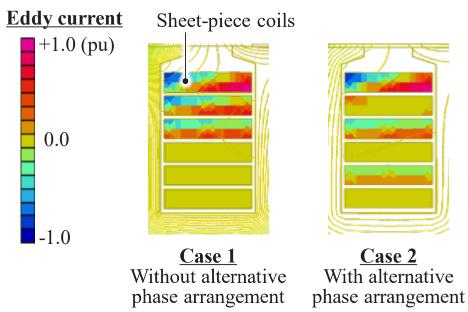


Fig. 8 Eddy current distribution.

a semi-closed structure, it is necessary to provide a moving space for the winding nozzle, which further reduces the space factor. In contrast, the space factor of the newly developed continuous wave winding structure is about 10% higher than that of the conventional concentrated winding structure, even though it is based on the semi-closed structure. Specifically, it was found that when there are six turns per slot, the space factor of the continuous wave winding is 11% higher.

Assuming that the coil ends are the same for both, the improvement in space factor can be directly converted into a reduction in winding resistance. Therefore, by applying the continuous wave winding structure, it is expected that copper loss can be reduced by 11% compared to when using the conventional concentrated winding structure.

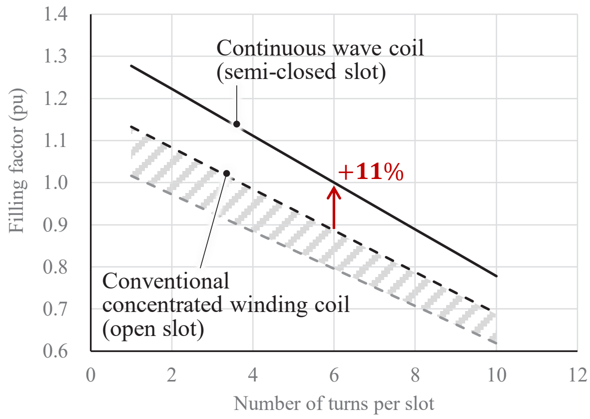


Fig. 9 Comparison of the filling factors between conventional concentrated winding coil and continuous wave coil.

4. PROTOTYPE STATOR

Fig. 10 shows the appearance of the prototype stator. The developed stator is sized to fit into a 19-inch wheel and is an inner stator type. The stator uses the newly developed continuous wave winding coil. The space factor is 80%, which is expected to be a significant improvement over the 60-70% of conventional concentrated winding.

By applying this developed structure, the coils can be mounted at a high density, which allows the radial thickness of the stator to be thinner, thereby making the stator lighter.

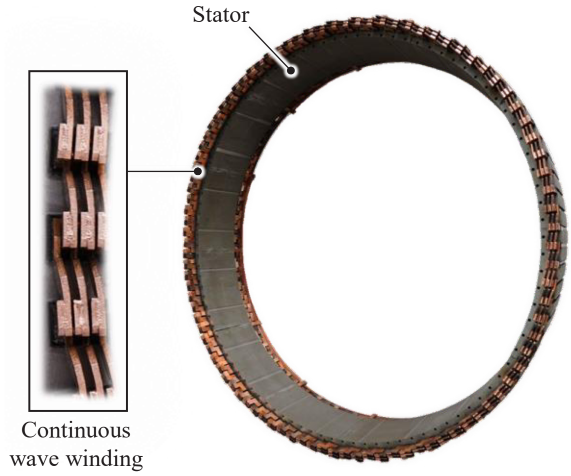


Fig. 10 Prototype stator.

5. CONCLUSIONS

In this study, we targeted multi-polarized direct drive motors adopting FSCW which allow for weight reduction, have an excellent winding factor, and torque ripple. We developed a new winding structure, a continuous wave winding, that simultaneously improves the coil space factor in the slot and simplifies the jumper wires.

The developed continuous wave winding has a wave winding structure in which the coil is wound across multiple teeth and is characterized by the fact that the coils do not come into contact in the circumferential direction in a slot. This makes it possible to increase the space factor by more than 10% compared to conventional concentrated winding coils, and we anticipate that copper loss can be reduced by approximately 10%.

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