

Development of Stator for Thin Electric Motor

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ABSTRACT

Lap winding was adopted as the winding method for the stator in order to increase the efficiency and reduce the size of an electric motor to be fitted into a hybrid electric vehicle. This has enabled the motor to be made thinner and loss of the motor to be reduced. Three nozzles are utilized to wind from the outer circumference around I-shaped split cores, enabling the length of the braided winding overhang to be minimized, and reducing the length of the winding. The use of multi-hole alignment nozzles and a jig for fixing the winding has increased the space factor. In addition, employing a two-step stamping process in which the first load is applied to increase the internal diameter and the second is applied in the axial direction has enabled the height of the winding overhang to be limited to 10 mm. As a result, operation efficiency has been improved by 7%.

1. Introduction

Deepening concern towards global environmental issues has increased the expectations being placed on low-pollution vehicles, such as hybrid cars, fuel cell vehicles, and the like. The motors which provide the traction sources for these vehicles are required to display high torque and power density, achieved by increasing efficiency and reducing size and weight. The effectiveness of changing the winding of the coil from the conventionally employed lap winding to concentrated winding is well known as a method of improving performance for the purpose of reducing loss and decreasing the size of the motor, as described in a number of recent papers⁽¹⁾⁻⁽³⁾. However, little research has been directed towards finding methods of improving performance employing the lap winding structure, which has a high effective rate of use of magnetic flux. The characteristics of lap winding and concentrated winding are compared in Table 1. Lap winding has a winding factor of 1.0, while that of concentrated winding is 0.866. In identical rotors, it is therefore possible to reduce the current in a lap-wound coil, which leads to decreasing copper loss. In addition, unlike concentrated winding, the distribution of magnetomotive force in lap windings is a sine wave, meaning that there are

fewer harmonic waves in the stator flux, and therefore less iron loss and noise than in concentrated windings. The superiority of lap winding from the perspectives of winding factor and harmonic waves in the stator flux demonstrated by these considerations led to it being selected as the winding method for the motor, despite the fact that the size of the winding overhang increases when this method is used. This research project also focused on improving the core structure and winding method to achieve the goals of reducing the size of the motor and minimizing loss.

Table 1 Comparison of winding types

Factor	Effect	Winding type	
		Lap winding	Concentrated winding
Winding overhang	Thickness	—	good
	Copper loss	—	good
Winding factor	Copper loss	good	—
	Iron loss	good	—
Harmonic wave of stator flux	Necessity of high voltage parts in inverter	good	—
	Torque ripple	good	—
	Noise	good	—

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2. Development Goals

The loss occurring in stators can be broadly divided into copper loss and iron loss (hysteresis loss and eddy current loss). Copper loss is determined by the square of the current multiplied by wiring resistance. It is therefore possible to reduce it by reducing either winding resistance or the current in the winding. The use of lap winding increases the winding factor, enabling the current in the wires to be reduced. Winding resistance increases in proportion to the length of the wire and decreases in inverse proportion to cross-sectional area. Reducing the length of the wire and increasing the space factor inside the slots are both effective methods of reducing winding resistance. Higher diameter wire cannot be employed for lap winding. Comparatively lower diameter wire is employed to increase the number of parallel wires, thus increasing the total cross-sectional area. A further benefit of lap winding is that it produces less iron loss than concentrated winding. The aim of this research project was therefore to achieve a balance between an overhang height equivalent to that produced by concentrated winding, which was conventionally considered difficult using this method, and a space factor equivalent to that of inserted winding, by exploiting these benefits described above and decreasing the bulge of the winding overhang in order to reduce the size of motor and copper loss. Figure 1 shows the development targets established for this project.

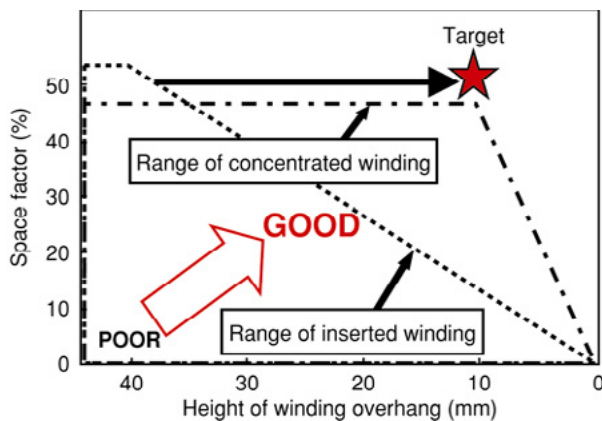


Fig. 1 Relation between space factor and height of winding overhang

3. Methods Employed

3.1. Balancing Smaller Winding Overhang with Reduction of Copper Loss

The formation of the winding overhang into the braided structure shown in Fig. 2 was considered as a method of balancing a reduction in the size of the overhang with an increased space factor. Lap winding produced by a conventional inserter winding machine overlaps the ends of each phase of wire with the ends of other phases in the same slot, thereby increasing the height of the overhang, as shown in Fig. 3. If the curvature of the bundles of wires is increased to lower the overhang, spaces are produced in the slots, reducing the space factor. Figure 4 shows a schematic of this phenomenon. To prevent this, in the new method the section of each phase of bundled wire which has been wound is braided with the sections of other phases which are beginning to be wound to form the winding overhang, enabling the achievement of a high space factor while lowering the overhang. In addition, adjustment of the positioning of the

braided sections has enabled flexibility in the choice of the number of crossings in the braid, making it possible to freely adjust the height of the overhang and the space factor. The following six factors were considered in the development of the new method:

- (1) Minimizing the length of the braided overhang by winding the coil from the outer circumference using three nozzles.
- (2) Splitting the core into I-shaped sections to enable winding from the outer circumference.
- (3) Increasing the curvature of bundles by employing split winding using groups of multiple wires.
- (4) Using a multi-hole alignment nozzle to align the wires in the slots.
- (5) Employing a jig for fixing winding to improve the space factor in the slots.
- (6) Reducing the height of the winding overhang by employing low-tension lacing and a two-step stamping process for formation in which loads are applied first to increase the internal diameter and then in the axial direction.

As a result, the winding overhang was reduced in size and copper loss was reduced, enabling the motor to be made thinner and loss to be reduced.

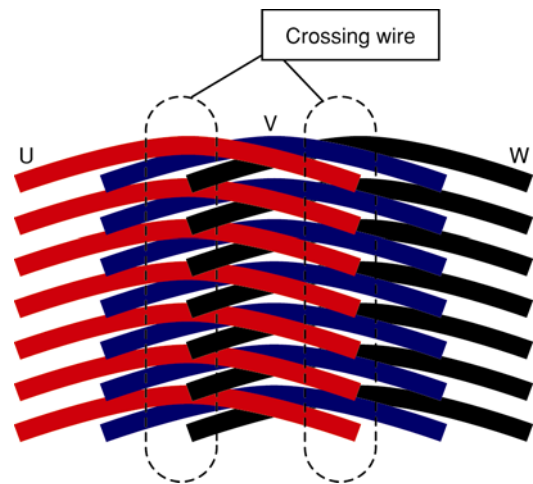


Fig. 2 Method of crossing wire



Fig. 3 Winding overhang produced by insert coil Machine

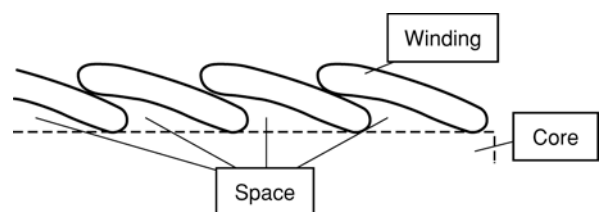


Fig. 4 Reduction of space factor

3.2. Reducing the Length of the Wiring

Table 2 shows the specifications of the prototype open-slot stator for use in an inner rotor motor. The reduction of the length of the wiring was prioritized to make the unit thinner and reduce copper loss, and nozzle winding enabling winding directly to the core was employed. Winding multiple wires simultaneously increases the size of the winding machine and the number of wire bobbins, leading to an increase in production costs, therefore, the wires to be wound in parallel have been separated into groups for winding in the slots. To further reduce the length of the wire used for the overhang, three nozzles (U phase, V phase and W phase) are operated simultaneously, to enable the overhang to be formed into braids. Figure 5 shows the position of the nozzles used to wind each phase. To enable accurate adjustment of the wiring overlap, a multi-hole adjustment nozzle is adopted, in which only one wire is utilized in each nozzle hole and the nozzle holes are aligned. A jig is employed to fix the winding, enabling the positions at which the wires cross to be controlled. The use of these methods has enabled the length of the winding to be reduced by 29%. The multi-hole alignment nozzle is shown in Fig. 6, the jig for fixing the winding is shown in Fig. 7, and the resulting reduction in the length of the winding is shown in Fig. 8.

Table 2 Stator specifications

Outer diameter (mm)	260.0
Inner diameter (mm)	200.9
Core length (mm)	40.0
Number of slots	48
Wire diameter (mm)	$\Phi 0.5$
Number of turns	5
Winding type	Lap winding
Number of poles	4



Fig. 5 Nozzles for winding of three phases

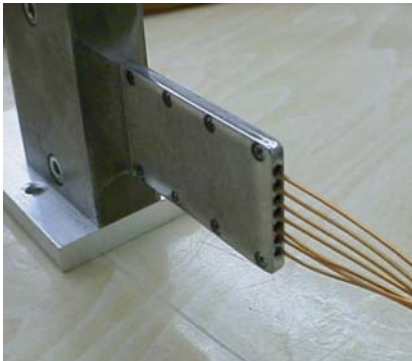


Fig. 6 Multi-hole alignment nozzle



Fig. 7 Jig for fixing winding

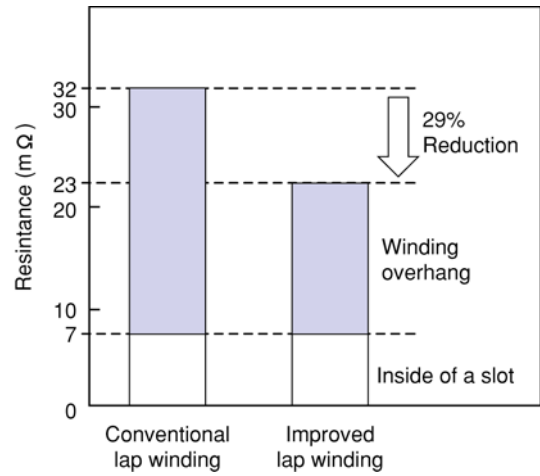


Fig. 8 Effect of reduction of length of winding

3.3. Increasing the Space Factor Inside the Slots

When winding from the inner circumference of an integrated stator using nozzles, the space factor inside the slot is reduced to ensure the paths of movement of the nozzle. The research discussed in this paper made a high space factor a priority, and therefore ensured the paths of movement of the nozzle on the external circumference. A split core structure, divided into I-shaped teeth and back yokes, was adopted and the opening was positioned on the external circumference. Figure 9 shows the split core structure, and Fig. 10 shows a flow chart of the winding process. The I-shaped teeth are fitted on a jig for fixing the teeth of the winding machine, and the nozzles wind the wiring from the outer circumference. The jig for fixing winding shown in Fig. 7 is also used to prevent the inserted wiring from moving in the slot. When the winding of each group of wires is completed, the jig moves towards the outer diameter of the coil. The alignment of the wires inserted in the slot by the multi-hole alignment nozzle (Fig. 6) is shown in Fig. 11. The nozzle does not rotate during winding, and the wires therefore cross at $n \times (n-1)$ places for n wires in each turn. This enables each wire to be made a uniform length, which produces the same effect of equalization of impedance as that obtained in the standard process of dislocating the bundles of wires by twisting. After the completion of winding, the insulating paper is folded and the back yokes are inserted. At this time, the spaces between the wires in the slots are compressed. The combination of the methods described above has increased the space factor in the

slots. Each back yoke has two semi-circular projections, as shown in Fig. 9. The projection on the inner side functions to prevent the I-shaped teeth from moving, while the projection on the outer circumference functions to increase the cylindricity of the core. The space factor in the slots has increased to 48.3% from a figure of 40.3% measured before the improvements described above. Figure 12 shows the space factor before and after the improvements.

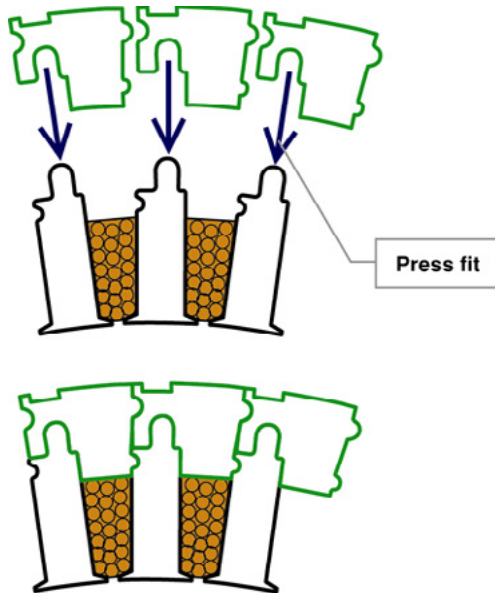


Fig. 9 Structure of split core

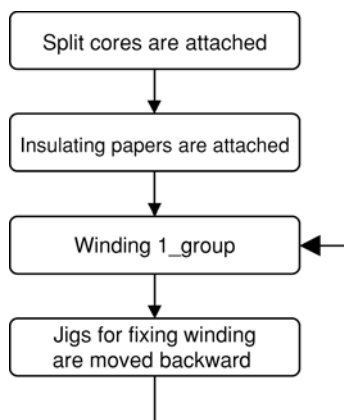


Fig. 10 Winding process



Fig. 11 Winding aligned inside a slot

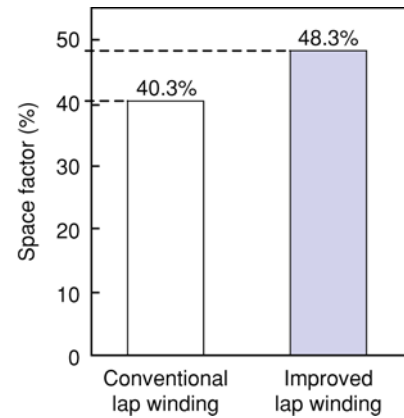


Fig. 12 Space factor of winding

3.4. Making the Motor Thinner

The winding overhang is stamped to decrease its volume, to enable the motor to be made thinner. In conventional lacing, force is applied to the lacing materials to bind the wires in the winding overhang in the process of winding the lacing. Slight stamping is applied when the coil is in its final form, and there is comparatively little deformation of the wires. In the new process, the winding overhang is stamped after lacing, and there is therefore considerable deformation of the wires. For this reason, the lacing is applied at a lower tension than in the conventional method. This method exploits the fact that when the winding overhang is stamped, the peripheral length of its cross-section increases, in order to achieve an equivalent binding force on the wires to that achieved by the standard process. Figure 13 shows a conceptual diagram of this method. The wires used in the lacing do not stretch, which has increased both the binding force on the winding and the space factor of the winding overhang. Because it was found that the wiring bends when it is stamped once in the axial direction, the stamping process has been divided into two steps. The winding overhang is first stamped to increase the internal diameter and then stamped in the axial direction. This has reduced mechanical stress on the wiring to a minimum, and enabled the wiring in the winding overhang to maintain its mesh shape during stamping. Figure 14 shows the two-step stamping process, and Fig. 15 shows the thinness of the winding overhang after stamping.

	Without string	With string
Before stamp		
After stamp		 Space factor improves by increase of binding force

Fig. 13 Method of increasing force which binds winding overhang

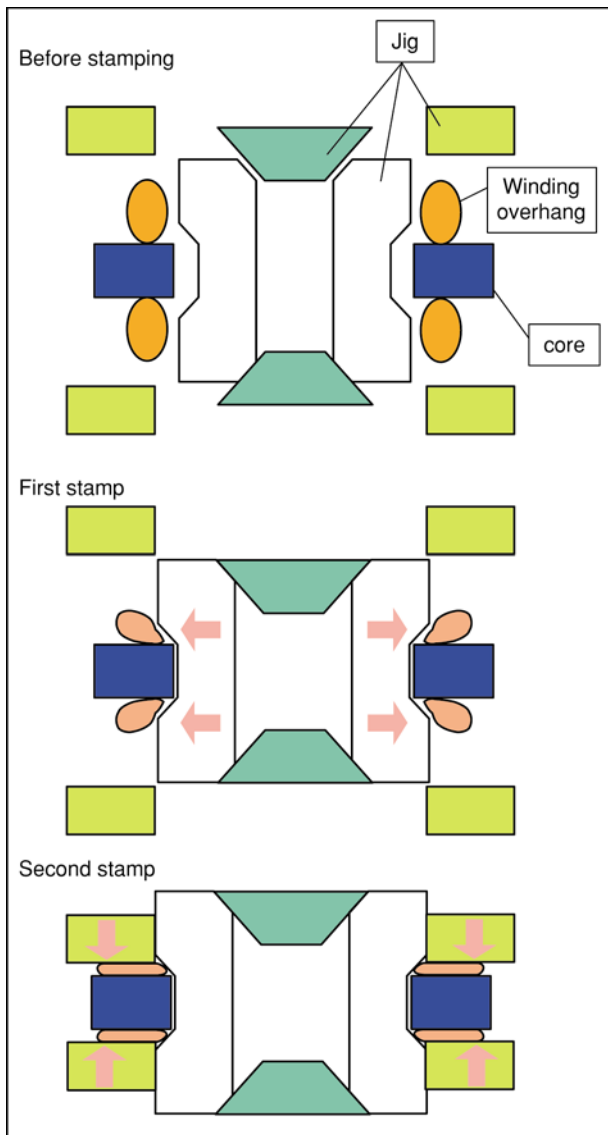


Fig. 14 Stamping process of two steps

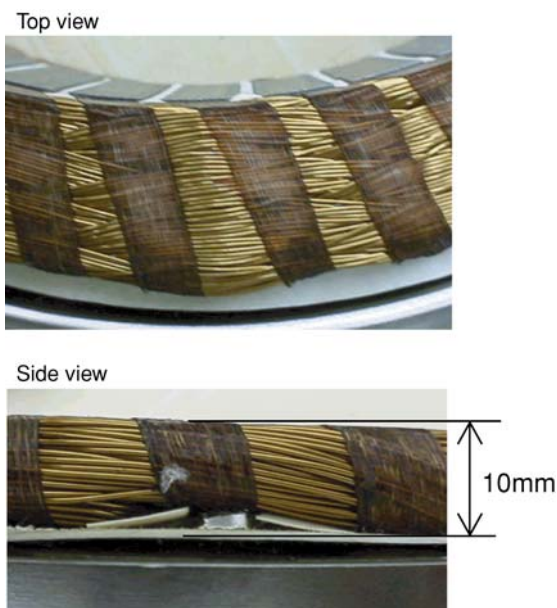


Fig. 15 Winding overhang after stamping process

4. Verifying Motor Performance

Operation efficiency and axial output were evaluated in the hybrid vehicle induction motor shown in Fig. 16. A 41% reduction in primary copper loss in comparison to the conventional method was confirmed. A breakdown of contribution shows 29% resulted from the reduction of the length of the wiring and 12% from the increase in the space factor.

The height of the winding overhang was verified as having been reduced to 10 mm. The reduction of primary copper loss increased operation efficiency by 7%. Reduction of the drop in voltage due to wiring resistance has increased axial output by 16%. These improvements in operation efficiency and axial output are shown in Fig. 17.



Fig. 16 Induction motor for hybrid vehicle

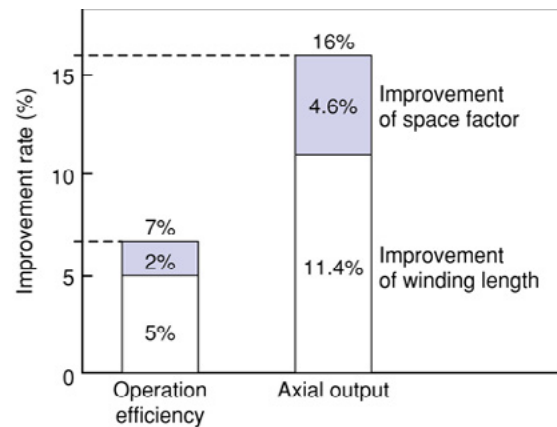


Fig. 17 Improvement of operation efficiency and axial output

5. Confirmation of Ease of Production

Figure 18 shows the stator assembly process. The automation of the new winding process with the development of a winding machine enables a stator to be wound in 45% less time than required to wind a Honda stator of equivalent size with concentrated winding using bobbin winding. The comparison in winding time is shown in Fig. 19.

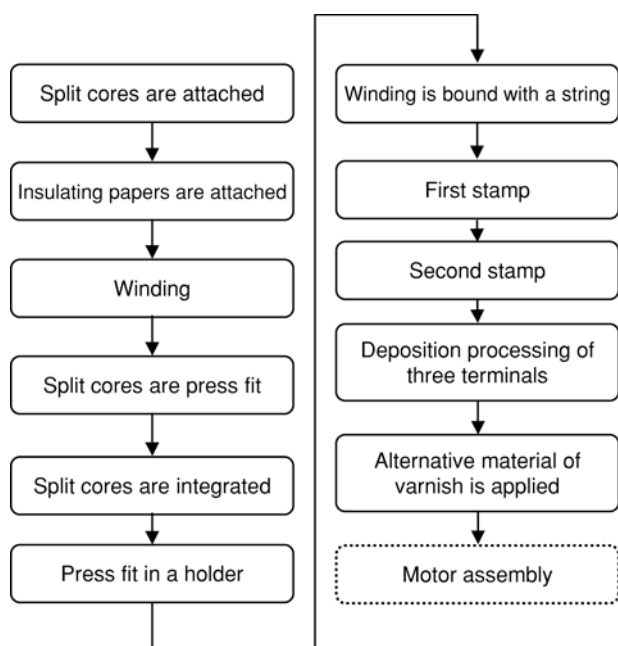


Fig. 18 Assembly process of stator

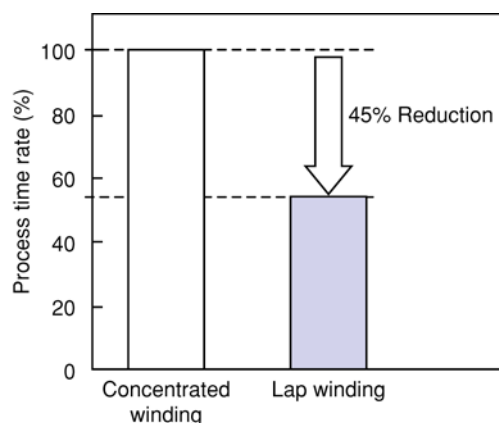


Fig. 19 Comparison of winding time

6. Conclusion

The issue of increased wiring length and winding volume of the winding overhang when the lap winding method is employed were focused on in order to make motors thinner and reduce loss of the motor. The following results were achieved by improvements to the core structure and the winding method:

- (1) The height of the winding overhang has been reduced to 10 mm, equivalent to that achieved in concentrated winding, and a space factor of 48.3% in the slots has been achieved, equivalent to the space factor of inserted winding.
- (2) The increase of the space factor in the slots and the reduction of the length of the wiring have reduced coil resistance and increased operation efficiency by 7% and power by 16%.
- (3) The development of an automatic winding machine has enabled the stators to be wound using the new process in 45% less time than required to wind a Honda stator of equivalent size using bobbin winding.

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