Design of the End-Coil Structure with Square Conductor for the Automobile ISG

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Abstract
This paper presents the stator winding method necessary for the high torque density, high efficiency and size reduction of an electric motor. We uses a Finite Element Method (FEM) to comparatively analyze the changes of performance in vehicle-mounted induction motor type Integrated Starter Generator (ISG) when it uses circular and square conductor. In addition, by analysing air flow, this study uses Computational Fluid Dynamics (CFD) method to analyze cooling performance by form of end-coil. By these results, we have effort to find the optimum end-coil shape that can increase the efficiency of motor performance and cooling effect.

Keywords: ISG(Integrated Starter Generator), square conductor, electric motor, FEM, CFD

1 Introduction
This paper presents stator winding method necessary for the high torque density, high efficiency and size reduction of an electric motor and an actuator. In general, circular conductor is used in an electric motor and an actuator for the winding process of coil through which current flows to them and the continuous use of existing winding equipment. However, circular conductor has a limit of about 45% or lower slot fill factor, which is the area ratio of conductor in a motor slot. Using circular conductor causes much dead space in the total volume of a motor, which reduces torque density and requires a bigger size of a motor. Therefore, it is required that a technology replaces circular conductor with square conductor to maximize the performance of a motor and an actuator. However, it also becomes important to analyze the performance of the extended end-coil form to find an optimum shape of end-coil necessary for designing highly efficient electric motor. Particularly, the form of end-coil has a great impact on cooling performance. Many researchers have studied on coil winding method [1]. But, most of the existing studies have focused on the improvement of torque density by increasing slot fill factor.

The present study employs FEM (Finite Element Method) to comparatively analyze the changes of performance in vehicle-mounted induction motor type ISG motor (Integrated Starter Generator) when it uses circular and square conductor. In addition, by examining air flow, this study uses CFD (Computational Fluid Dynamics) method to analyze cooling performance by form of end-coil part. By doing so, the present study aims to find the optimum form of end-coil part that can increase the efficiency of motor performance and cooling effect.

In this paper, the finite element analysis is carried out to analyze the motor with the circular conductor in the vehicle integrated starter generator. Also, in order to obtain the accurate thickness of the end coils considering the winding process, a method is used by calculating the thickness along the size and shape of the square conductor. In addition, CFD is adopted to analyze the cooling effect automobile ISG.
1.1 Winding method using square conductor

Recently, the requirement of the electrical motor with high voltage system increases compared to the low voltage system as the automobile power. Certain current density should be achieved for the large enough current density to obtain the high output characteristic. However, the winding production technique using the present circular conductor has the limitation of slot fill factor. Therefore, Japan leads to the development of winding methods using square conductors nowadays, where Hair-pin and Stepwise methods are introduced as in Figure 1. If the square conductor is utilized, the thickness of end-winding will increase due to the coil shape and size. Thus, the winding method which can reduce the end-winding thickness is required to improve the motor performance.

![Hair-pin](image1)

(a) Hair-pin

![Stepwise](image2)

(b) Stepwise

Figure 1: Winding method using square conductor

[2] shows the Stepwise winding method can reduce the motor volume of the hybrid electric vehicle effectively with a 10% size reduction and 15% end winding thickness reduction, compared to the normal circular copper wire motor. Moreover, [3] compares the permanent magnet motor using Hair-pin winding to the normal winding, where the maximum output has been increased by 34%. Thus, the winding method using the square conductor is useful for the low voltage, high current motor development.

2 Characteristic of ISG with circular conductor

Figure 2 and Table 1 show the shape and specification of the basic model as an induction motor of ISG. As shown in this figure, the rotor diameter is 100 mm, the number of parallel circuit equals 1 and the thickness of end winding is about 25 mm. Figure 3 shows the dynamo test equipment setup.

![Dynamo test equipment setup](image3)

Figure 3: ISG & Dynamo test equipment setup

![Isog using circular conductor](image4)

Figure 2: ISG using circular conductor

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Table 1: Specification of the ISG with circular conductor

Figure 4 shows the characteristic curves of efficiency, power and so on, which are obtained from the test results versus speed based on the basic model.

![Characteristic curves](image5)

(a) Torque and efficiency
In this paper, the winding method of the Hair-pin shape have been examined for the end-coil thickness calculation according to the size and coil pitch of the square copper conductor. Final thickness of the end-coil has been calculated through the implementation of various shapes, which is expected to be same with that of the circular conductor.

Figure 4: Characteristic of ISG according to speed (Output power:8kW)

The output performance test is implemented according to the optimum slip condition from FEM, where the phase voltage is limited to 48 V considering automobile battery capacity. It shows that the current achieves 510 A with the maximum torque load at 2050 rpm, and the maximum efficiency is obtained as 75% at 5000 rpm.

3 Design of ISG Using Square Conductor

Figure 5 shows the topology of ISG, where the new motor with square conductors is designed as same specifications to take advantage of the rotor in the basic model. Stator outer diameter and the number of slots are also designed same, whereas, the phase resistance can be decreased by 47% compared to the basic model. The width and the height of square conductor is 4.0mm and 5.6mm, respectively.

Figure 6 shows the structure of a single winding, which is designed to form coils using the square type copper conductor.

Figure 7 presents the performance analysis of the ISG models designed using the square conductor by finite element analysis. It shows the current can achieve 440 A with 8 kW loaded at 2050 rpm, which is 8% higher current value than that of the circular conductor model. The maximum efficiency can be achieved about 17% higher than the improved basic model, which has the efficiency as 88%.
Figure 7: Characteristic of ISG according to speed
(Output power: 8kW)

Figure 8 and Figure 9 show the velocity field according to the rotor rotation of the proposed model with square conductors via the CFD fluid analysis. Analysis of the proposed model with square conductor illustrates the probability of air flowing through the created channel at the end-coil region for effectively cooling. In the future, it’s possible to suppress the temperature rise during installation compared to the circular conductor model, such as the cooling fans can be used conveniently to predict the heat radiation effect.

Figure 10 shows the end-coil shape of prototypes using square conductor. In the figure, we know that the height of end-coil is similar to the calculated value in Figure 6.
4 Results
This paper has designed the ISG motor with the maximum output 8 kW using square conductors, the performance analysis of which has been done corresponding to the normal circular conductor model. Height of the end-coil has been calculated based on the size and shape of the square conductors, also, the FEA result of square conductors model is compared to the experimental results of the circular conductor model. In the future, the performance improvement of the square conductor model needs to be evaluated. In addition, it is useful to perform the production and performance analysis through such process for the winding design and manufacture with square conductors.

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References

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