Compact High-Torque Motors for e-Axle on New Electric Vehicles

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Abstract

A new compact high-torque motor was developed for an e-Axle that integrates a motor, an inverter, and a gearbox. To achieve compactness and high torque in the new motor, a thin rectangular-wire was used for the stator coil, and the winding structure was optimized. In this paper, we report on the electromagnetic design and provide an overview of the issues involved in improving productivity.

1. Introduction

Recently, automobile electrification has progressed in response to global warming countermeasures and stricter environmental regulations. To meet the requirements of increased cabin space, reduced aerodynamic drag, sufficient space for a battery, and crash safety, the drive unit (e-Axle) integrating a motor, inverter, and gearbox must be downsized. To downsize e-Axle (Fig. 1), it is necessary to reduce the motor size, which accounts for a large proportion of the e-Axle volume and has a significant impact on the unit shape.

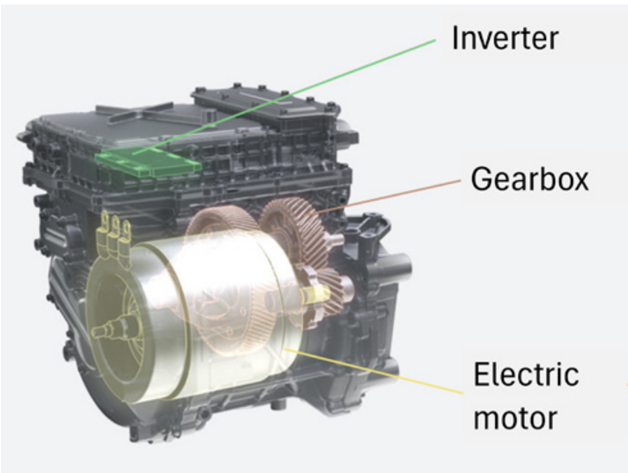

Fig. 1 Main components of e-Axle
Image Source: Nissan Motor Co., Ltd.

To downsize a motor while ensuring sufficient torque and power output, it is important to have a large number of turns in the stator coil (hereinafter referred to as “turn number”) within a limited space and to devise a structure that can carry a large current.

A new motor was designed to improve torque per motor volume (hereinafter referred to as “torque density”) and power per motor volume (hereinafter referred to as “power density”), which are indicators of compactness and high performance.

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2. Winding structure of the stator coil

To achieve miniaturization and high performance, it is important to develop a winding structure for stator coils. The motor for the new e-Axle has a stator coil with a rectangular cross-section made of a rectangular wire (Fig. 2). This structure increases the torque by increasing the number of turns and ensures sufficient power output by optimizing the parallel winding structure.

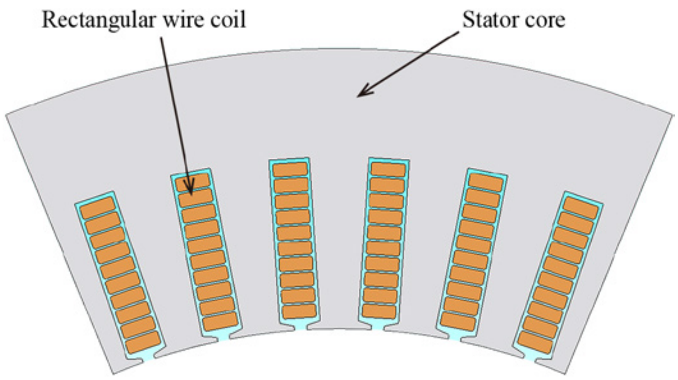

Fig. 2 Stator cross-section

2.1 Winding structure for increased motor torque

The torque of an interior permanent magnet synchronous motor (IPMSM) is expressed as follows:

$$T = T_m + T_r = \frac{p}{2}\{\psi_a i_q + (L_d - L_q) i_d i_q\} \quad (1)$$

where T is the motor torque, T_m is the magnetic torque, T_r is the reluctance torque, P is the number of poles, ψ_a is the flux linkage produced by the magnet, i_d, i_q are the d- and q-axis currents, respectively, and L_d, L_q are the d- and q-axis inductances, respectively.

In general, the contribution of the magnetic torque T_m is high in the high-torque range. Hence, to intuitively show the effect of the winding structure on torque, the magnet torque $T_m = \frac{p}{2}\psi_a i_q$ in equation (1) was studied. The parameters that correlate with the magnetic torque are expressed in Equation (2).

$$T_m \propto \frac{p}{2} N_{turn} N_{series} \Phi I_{coil} \quad (2)$$

where N_{turn} is the turn number per slot, N_{series} is the number of coils in series, Φ is the magnetic flux, and I_{coil} is the coil current.

The motor torque is proportional to the number of poles, turns, and coils in series, as well as to the magnetic flux and coil current. However, increasing the number of poles and the magnetic flux without changing the motor size has a large cost impact, for instance because of an increase in the number of magnets. In addition, increasing the coil current is difficult because of the limitations of high-power systems such as inverters and the limitations of motor-cooling performance. Therefore, our objective was to increase the magnetic torque by increasing the number of turns.

To increase this number without changing the slot cross-sectional area, it is necessary to reduce the cross-sectional area and clearance of the coil. To reduce the coil cross-sectional area while reducing the coil loss, a thin rectangular-wire was used. In the new e-Axle motor, a competitive 10-turn stator coil was achieved by developing a stator production technology that leverages a thin rectangular-wire.

2.2 Winding structure to secure motor power output

The motor output is expressed in Equation (3).

$$P_{out} = \eta P_{in} = \eta 3 V_{phase} I_{phase} cos\theta \quad (3)$$

where P_{out} is the motor power, η is the motor efficiency, P_{in} is the motor input power, V_{phase} is the motor phase voltage, I_{phase} is the motor phase current, and $cos\theta$ is the power factor.

In a parallel-winding structure, the input current is distributed across multiple coils; thus, the relationship between the motor phase current and the coil current when the number of coils in parallel is denoted as $N_{parallel}$ is expressed in Equation (4).

$$I_{phase} = N_{\text{parallel}} I_{coil} \tag{4}$$

As shown in Figs. 3 (a) and (b), the number of coils per phase is 8, which is the product of the numbers of coils in series and in parallel.

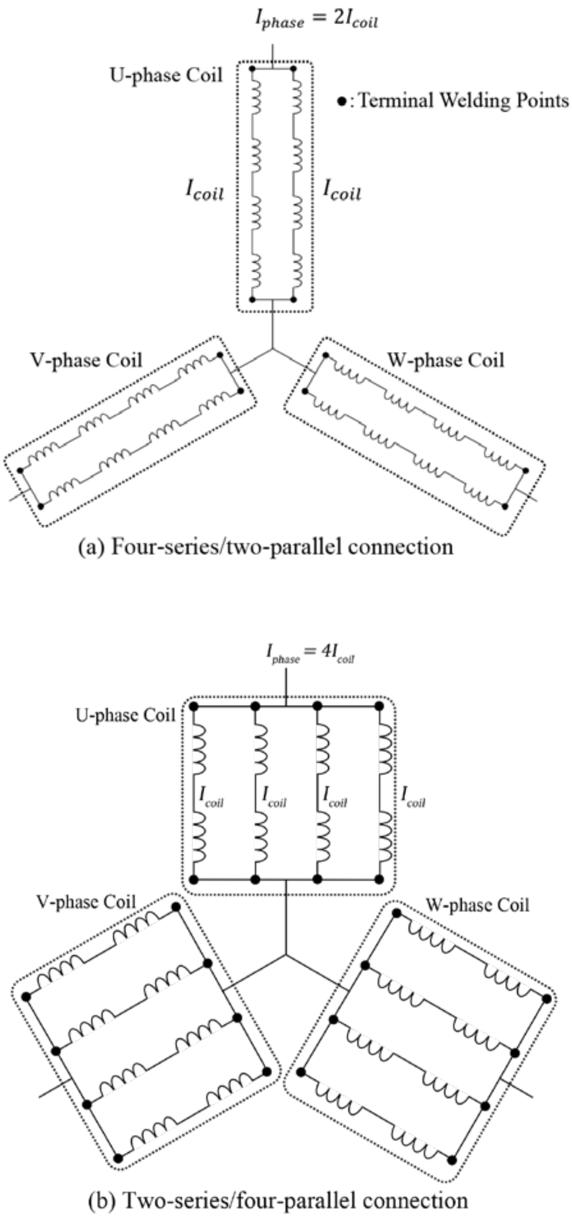

Fig. 3 Three-phase coil connection diagram

To ensure high motor power output, the motor phase current must be proportional to the motor phase voltage, as expressed in Equation (3). However, as expressed in Equation (4), the motor phase current is determined by the product of the coil current and the number of coils in parallel, and the coil current is restricted by the heat resistance and cooling functions. Therefore, a high motor phase current was achieved by increasing the number of coils in parallel.

In the new e-Axle motor, high motor power output is produced using four coils in parallel by improving the welding of the stator and busbar terminals of the rectangular wire.

Competitive torque and power density values were obtained by increasing the number of turns to 10 and the number of coils in parallel to four without increasing the motor size, achieving both high torque and high power output (Fig. 4).

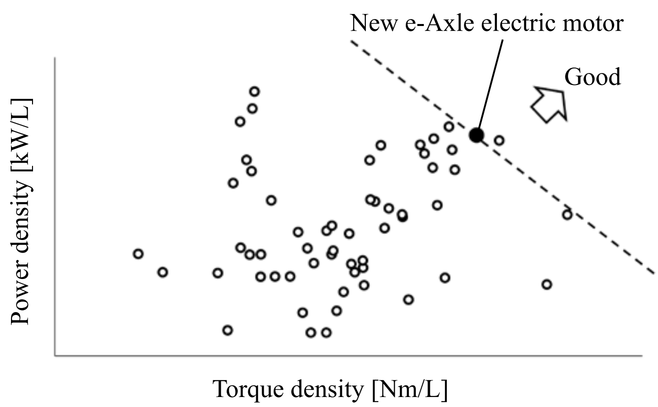

Fig. 4 Torque density vs power density of e-Axle electric motor

3. Challenges in ensuring productivity

3.1 Formation of thin rectangular-wire coils

Because of the concentration of bending stress during the formation of thin rectangular-wire coils, problems occur when the enamel coating breaks or peels on the tensile side, wrinkles form on the compressive side, and shape variations occur after formation. To ensure that the stress generated in the enameled coating does not exceed the proof stress even after considering variations, the bending dimensions during coil formation were controlled, and the appropriate enameled coating material was selected.

3.2 Control of the amount of varnish in the slot

Owing to the use of a 10-turn stator coil with a thin rectangular-wire, the degree of non-uniformity in the clearance within the slot increases. This highlights the need to control the amount of varnish used.

Productivity was ensured by optimizing the injection volume of the varnish such that it could be filled in the shortest amount of time without overflowing, while considering the amount of varnish to guarantee sufficient adherence strength.

3.3 Increase in the number of welding strikes

The stator coil and three-phase terminal block busbars were welded together with their respective copper terminals (Fig. 5).

The four-parallel configuration of the rectangular wire resulted in a total of 24 welding points, as indicated by ● in Fig. 3 (b). In response to the increase in the number of welding points, a new and efficient welding method was developed by controlling the positioning and dimensional accuracy in the welding process.

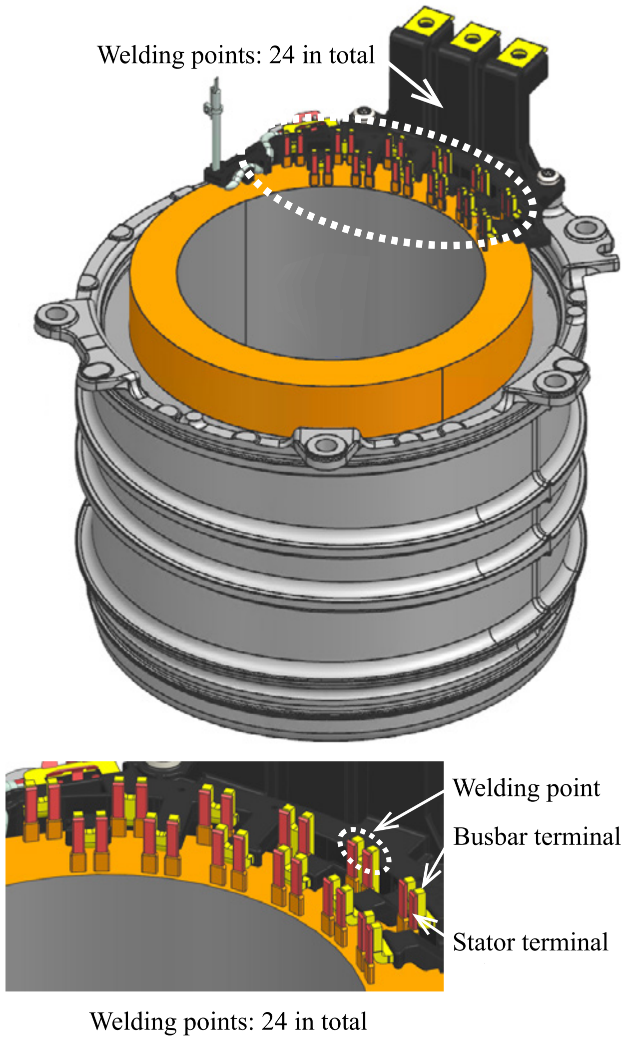

Fig. 5 Welding points of stator coil and busbar

4. Summary

- A new type of motor for e-Axle was developed to achieve small size, high torque, and high power output.
- A high torque density was obtained using a thin rectangular-wire for the stator coil, which enabled a high turn number of 10 without increasing the size.
- High power density was achieved by securing sufficient phase currents using four stator coils in parallel.
- To improve productivity, a coil-forming design, control of the amount of varnish in the slot, and welding methods for rectangular wires and busbars were developed.
- Competitive torque and power density values were obtained, making the new e-Axle compact and high-performance.

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