# Downsized 48V motor winding structure for an EV powertrain

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**Abstract**

Activities to achieve carbon neutrality in recent years have heightened the necessity of electrified vehicles. At the same time, the increased cost of electrified vehicles must be suppressed.

Considering low voltage systems for cost reduce, high current is needed to achieve target output. In order to realize a high power low voltage system, we studied the 48V system as an example.

However, because of the low voltage system, a motor winding structure is required that can accommodate the high current needed for achieving higher motor output. In this development project, a parallel motor winding structure was adopted in combination with the transmission, thereby sufficiently suppressing the increase in the motor size to enable vehicle installation.

This paper describes the technology applied to achieve a parallel motor winding structure.

## 1. Purpose

Activities to achieve carbon neutrality in recent years have heightened the necessity of electrified vehicles. At the same time, the increased cost of electrified vehicles must be suppressed. One means of accomplishing that is to adopt a 48V system that can be installed at relatively low cost. However, because of the low voltage of a 48V system, a motor winding structure is required that can accommodate the high current needed for achieving higher motor output. In this development project, a parallel motor winding structure was adopted in combination with the transmission, thereby sufficiently suppressing the increase in the motor size to enable vehicle installation.

This paper describes the technology applied to achieve a parallel motor winding structure.

## 2. Development aim

The motor to be developed this time is expected to be installed in small vehicles.

Targeting for an output power equivalent to that of convensional small car , and using high-rotation speed motor in order to make it even more compact.

The performance values required of the motor and inverter were therefore defined as follows:

- Adoption of a 48V power source
- Maximum inverter current of 905 Arms
- Adoption of a double-star connection with a maximum phase current per star connection of 452 Arms
- Motor output of 32 kW or more
- Maximum motor speed of 20,000 rpm
- Target motor torque of 32 Nm

### 2.1 Technical issues to be addressed and their solutions

The following issues had to be addressed in developing a motor to achieve the performance requirements noted above.

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(1) Maintaining the current density of the motor coils so as to accommodate the increased current needed for higher motor output would require increasing the cross-sectional area of the coils and also making the area of the slots larger. In that case, the stator volume would also become larger, thus degrading vehicle mountability. Moreover, increasing the current density while keeping the stator volume the same would result in larger heat generation, thereby degrading thermal performance.

In this project, it was necessary to maintain the motor size on account of the vehicle mountability requirements. Therefore, a method was needed for suppressing the current flowing per unit area while keeping the current density the same as before.

(2) Owing to the compact, high-speed motor design, there was concern about large iron loss when the motor was driven in the high-speed range. There was also concern about the possibility of a sharp increase in the motor temperature because of its smaller thermal capacity on account of the compact design.

## 2.2 Selection of winding specifications for resolving the technical issues

### 2.2.1 Defining the number of motor winding turns

Winding specifications were examined in this project based on a previously developed high-output motor. When a two-turn specification was applied to that motor, the required output was not attained because induced voltage larger than the battery voltage occurred at low operating speeds. On the other hand, with a one-turn specification, the maximum current exceeded 1,000 Arms, which was an unacceptable current value for the motor in this project.

Therefore, a study was made of an intermediate 1.5-turn specification. The required motor output was obtained, but the coil arrangement with the 1.5-turn specification caused the coil filling factor in the slots to vary. Accordingly, four 1.5-turn windings in series were changed to two 3-turn windings in series in a double-star connection.

With the adoption of a double-star connection, the target output per star connection was set at 16 kW, enabling the target motor output of 32 kW to be attained while suppressing the current density (Fig. 1).

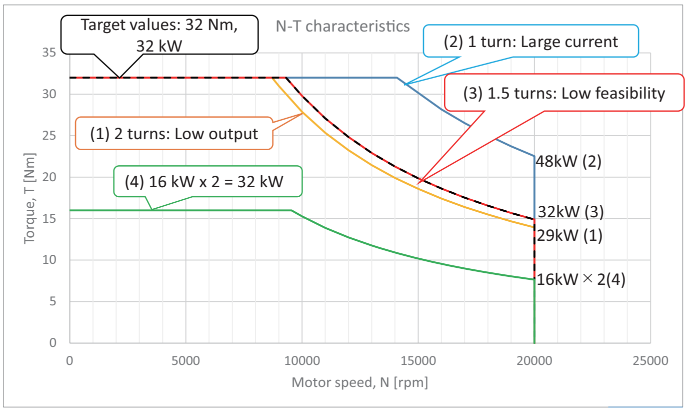


**Fig. 1 Relationship between number of winding turns and motor output**

### 2.2.2 Measure against iron loss in high-speed area

Double-layer, short-pitch distributed windings were adopted to reduce iron loss in the high-speed area. One advantage of short-pitch distributed windings is that the induced voltage waveform more closely resembles a sinusoidal wave. As a result, it leads to a reduction of high-harmonic components and reduces iron loss. In addition, shortening the coil pitch also reduces the copper wire length, which can be expected to reduce copper loss as well.

Combined with the use of double-layer windings in this project, the coil circumference was further shortened for an additional reduction of copper loss.

## 3. Parallel Winding Structure Issues and Their Solutions

This chapter considers double-layer, full-pitch, 3-turn windings in a double-star connection. Owing to the odd number of turns, they are divided between 2-turn slots and 1-turn slots. Because no more than three turns can be put in one slot, coils are inserted in same-phase slots between the double star connection in combinations of two turns and one turn or one turn and two turns. The magnetomotive force distribution is proportional to the number of turns of the coils in the slots, so the maximum value occurs between slots with 2-turn coils.

As shown in Fig. 2, a comparison based on the V-phase reveals that the slots with 2-turn coils of v1 and v2 windings differ, causing a phase difference in the magnetomotive force distribution. As a result, it produces an induced voltage waveform like that shown in Fig. 3 in which there is a phase shift equal to one slot. A phase difference occurs between the magnetic flux generated by the v1 winding and that generated by the v2 winding, giving rise to a possibility that mutual magnetic interference might occur when controlling the motor. As a measure to prevent that, the induced voltage waveforms of the v1 and v2 windings between the double star connection must be in the same phase.

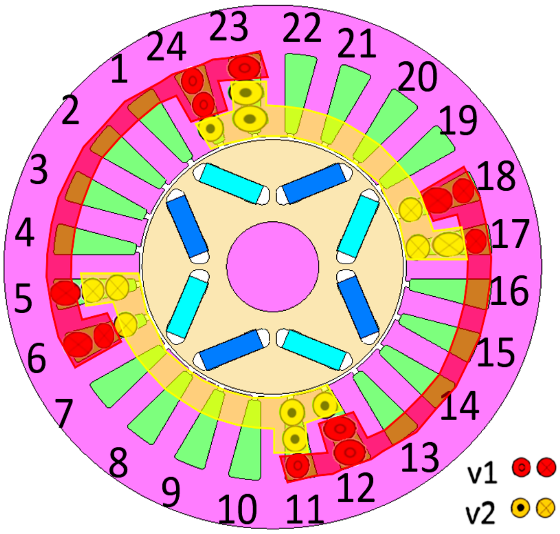


**Fig. 2 Winding diagram for double-layer, full-pitch distributed windings**

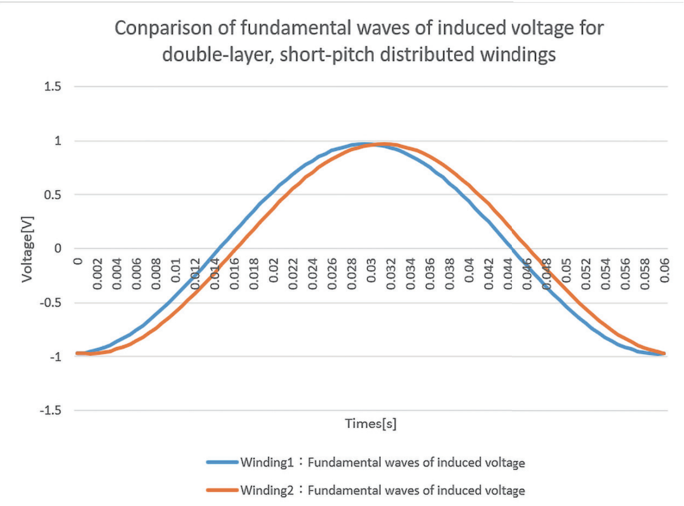


**Fig. 3 U-phase induced voltage waveforms for double-layer, full-pitch distributed windings**

In this project, short-pitch windings were adopted to change the winding arrangement, and a winding method was applied that shortened the coil pitch. As a result, in relation to the positions where the 2-turn and 1-turn v1 windings were placed, the v2 windings were arranged in the same way at positions shifted by 6 slots and an electrical angle of 180 ° el. As a result, the same phase was obtained for the induced voltage of each phase (Fig. 4).

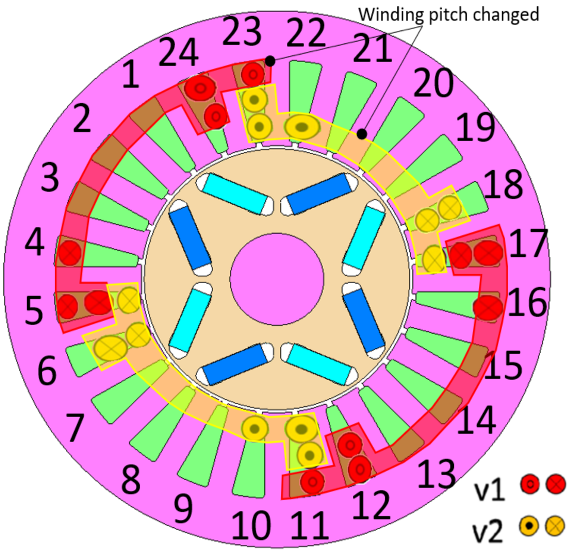


**Fig. 4 Winding diagram for double-layer, short-pitch distributed windings**

As shown in Fig. 5, the winding changes described here made it possible to achieve the same phase for the induced voltages of the v1 and v2 windings.

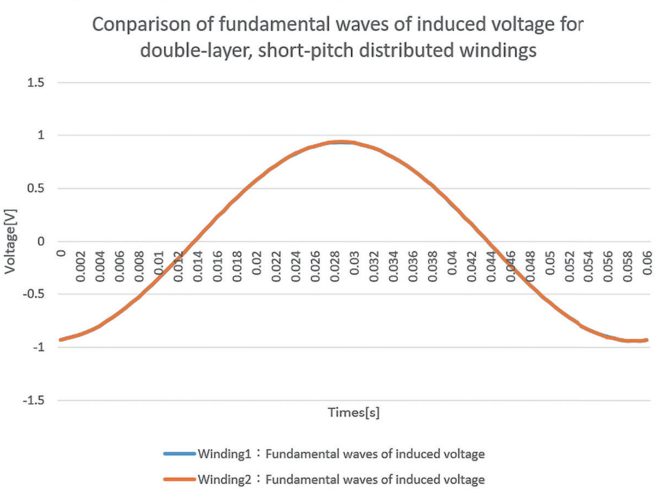


**Fig. 5 U-phase induced voltage waveforms for double-layer, short-pitch distributed windings**

The final coil arrangement is shown in Fig. 6. The respective arrangement of the U-phase and W-phase coils between the double-star connection has the same positional relationship as that of the V-phase coils mentioned above. This coil arrangement eliminated any phase difference between the induced voltages.

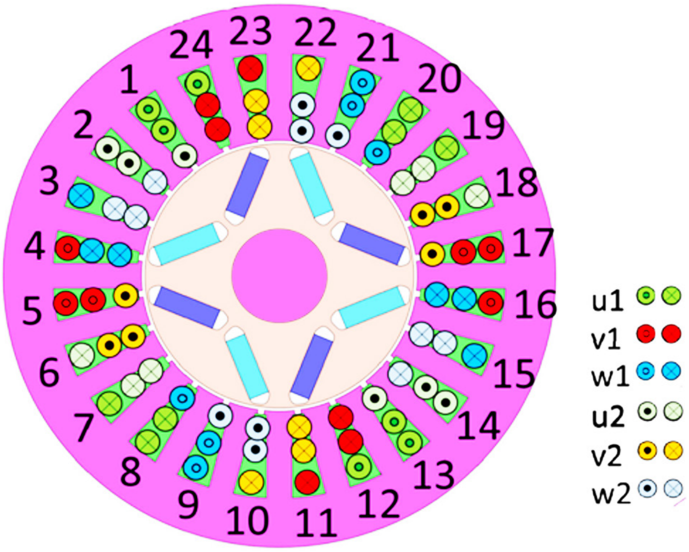
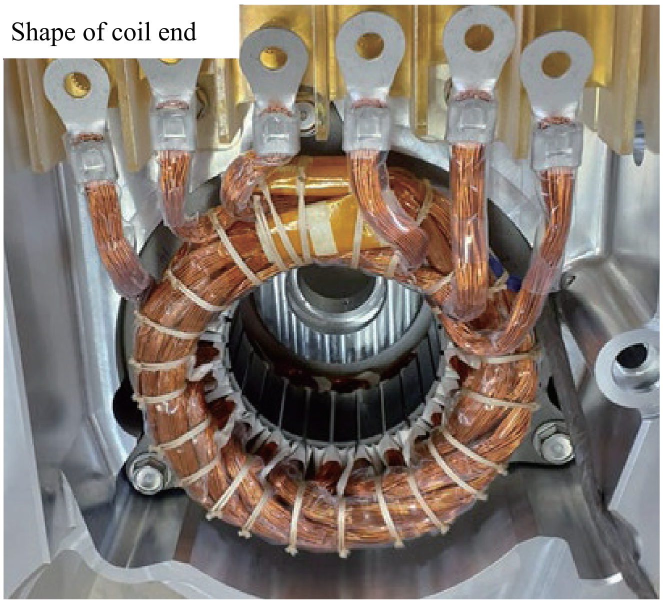


**Fig. 6 Final winding arrangement**

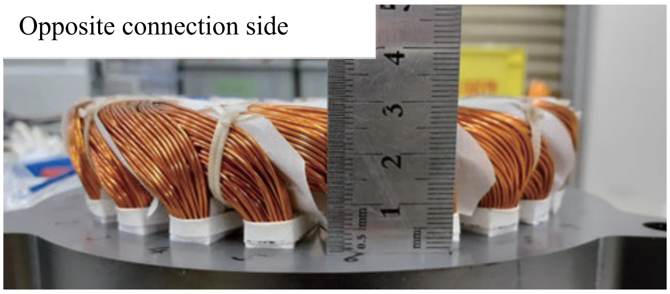
## 4. Results

A motor was manufactured and was confirmed performance and electric characteristic. The picture in Fig. 7 shows the appearance of the motor coil.

Shape of coil end



Opposite connection side



Connection side

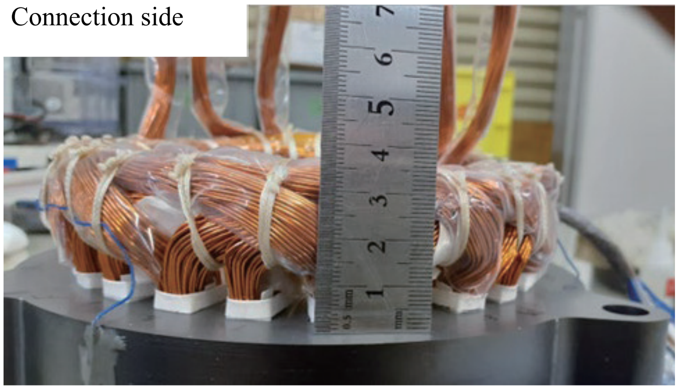


**Fig. 7 Photos of windings (appearance/opposite the connection side/connection side)**

The coils were manufactured according to the wiring arrangement that was examined in this study, and the coil ends were made smaller by adopting double-layer lap windings.

A current density of 17.7 Arms/mm$^2$ was obtained with the manufacturing specification.

Figure 8 shows the induced voltage waveforms measured for the motor. As shown in the figure, the results confirmed that there was no phase difference in the U-V line voltage between the double-star connection.

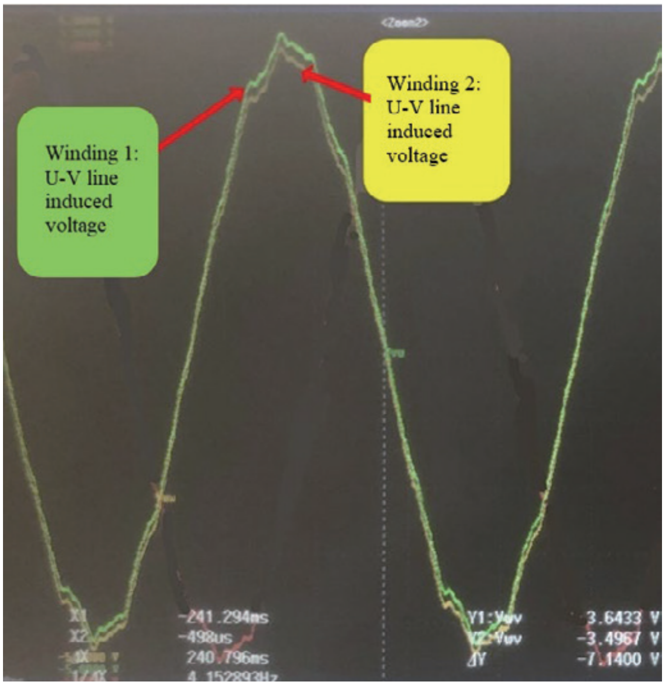


Fig. 8 Measured induced voltage waveforms

Figure 9 shows the measured output torque of the motor. The motor produced output torque almost as intended. Because the motor was not closely calibrated with the inverter, torque dropped in the vicinity of 3,000 rpm. However, the motor was in the range of its maximum torque, so if optimally calibrated, it is expected to reach the target output level as calculated.

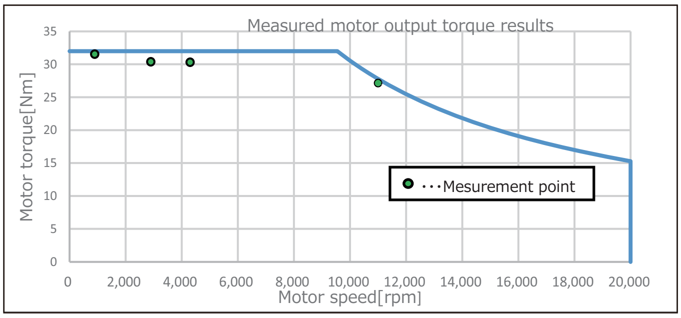


Fig. 9 Measured motor output results Measurement point

The results of a simulation revealed that there was a margin in the magnetic circuit for further motor output. With the adoption of permanent magnets having high residual magnetic flux density, it expected that the motor can produce output up to 42 kW and torque up to 41 Nm, as shown in Fig. 10.

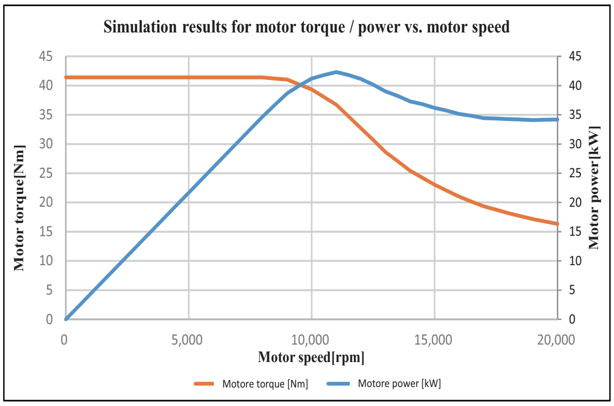


Fig.10 Simulation results for motor torque/power vs. motor speed

Simulation results for iron loss and copper loss are shown in Fig. 11. Short-pitch windings were adopted for this motor with the aim of reducing iron loss in the high-speed area. As a result, iron loss in the simulation was reduced by approximately 22% compared with full-pitch windings.

In contrast, it is projected that copper loss may worsen by around 7% in the low-speed, high-torque area owing to the reduced torque constant resulting from the adoption of short-pitch windings. The reduction of iron loss in the high-speed area also reduced the copper loss value by approximately 35%. That is attributed to the fact that a smaller current is needed to produce the required torque. It is planned to measure the precise iron loss and copper loss values in future work.

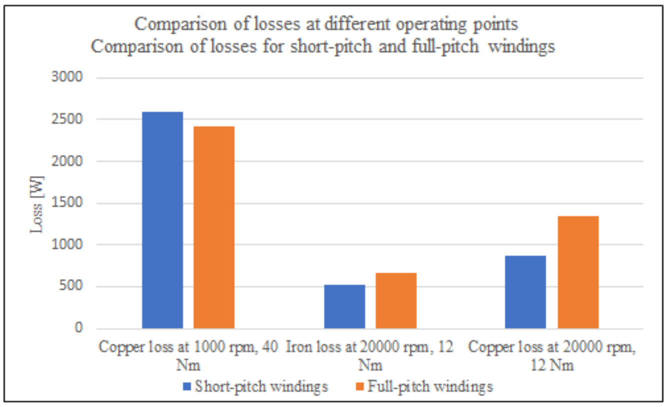


**Fig.11 Comparison of losses at different operating points**

Driving tests were conducted using a prototype vehicle mounted with the newly developed motor. Figure 12 shows the relationship between the driving force obtained and the vehicle speed. The results confirmed that the vehicle delivered satisfactory performance.

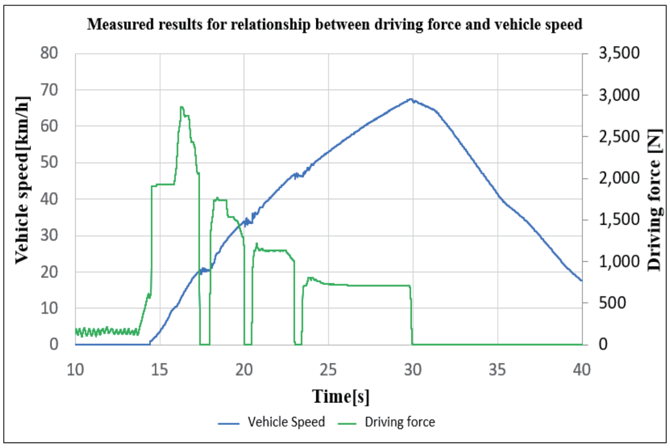


**Fig. 12 Measured results for driving force vs. vehicle speed**

## 5. Conclusion

Obtaining high motor output power with a 48V system has been regarded as being difficult. However, in this project, by adopting the parallel winding structure of the motor, the increase in the motor has been avoided, and the system has been reduced and the mounting on a small vehicle (Fig. 13). It was confirmed that the technology presented here resolved both the issue of increased iron loss due to higher operating speeds and the issue of accommodating high current levels owing to the low voltage and high motor output power.

Increased motor output can also be obtained with the same technology at other voltage levels, not limited to 48V systems. Therefore, this technology can contribute to system downsizing along with reducing costs and material usage.

**Fig. 13 Photo of prototype demonstration vehicle**

## 6. References

(1)Hiroaki Matsumori Electric and mechanical technology seen from the EV drive system E-AXLE, Japan AEM Society Journal VOL.30, NO.1 (2022).

(2)Nikkei Crosstech "EV light tiger" is 48V drive, 4WD prototype car by Valeo and Gunma University, https://xtech.nikkei.com/atcl/nxt/column/18/01537/00121/

(3)Car Watch Valeo, Japan Premiere of Micro Electric Vehicle "48V Light e-City Car" at "Automotive Engineering Exposition 2022 YOKOHAMA."

(4)MONOist Bosch long-term cooperation with CATL, preparing for 48V hybrids, which will increase to 20% of new cars, https://monoist.itmedia.co.jp/mn/articles/1909/06/news041.html

(5)Daiki TANAKA, Akira SUWABAYASHI, Junichi ASAMA: Downsized 48V Motor Winding Structure for an EV Powertrain, EVTeC2023.

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