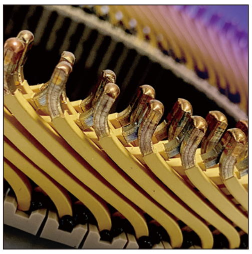
SUMITOMO ELECTRIC TECHNICAL REVIEW
No. 98 · APRIL 2024
FEATURED TOPIC



Stator Architecture Advancements for Improved Traction Motor Performance

Shuhei MYOJO*, Yusuke MITSUGI, Volker Uwe STRUEKEN, Shintaro MORINO, and Kazuhiro IKEDA

The growing emphasis on mitigating global warming has highlighted the need for sustainable solutions in the e-mobility sector. In response, the automotive industry requires traction motors that deliver increased speed, torque, and efficiency. Through the integration of advanced technologies in stator magnet wire and slot cooling, we have successfully developed a downsized stator architecture for traction motors. This innovative design concept maintains maximum torque while achieving significant size reduction. Furthermore, the production process for this stator contributes to a reduction in CO_2 emissions by approximately 30%, compared to conventional stators.

Keywords: electric vehicle, motor, stator, insulation, cooling

1. Introduction

The transportation sector has been one of the main culprits for global warming due to its high share of the CO_2 emissions responsible for it. As necessary countermeasures to reduce emissions, there is already a response to this with a wide variety of drive concepts as hybrids or purely electric vehicles. This market and product variety will grow: Due to emerging sustainability trends, companies are prompted to invest in further research on traction motors.*1 (1) The demand for higher performance, lower power consumption, and lower costs should be met by increasing speeds, torque, and higher efficiencies as well as cost-effective production conditions.

In recent years, distributed magnet wire of wires with almost square cross-sections has been used in the stators of electric drive motors. That type of magnet wire is called hairpin technology. The cross section has greatly improved the ratio of magnet wire in the stator slot, effectively reducing size and weight, as well as lowering the amount of copper required, since less wire is needed overall. AutoNetworks Technologies, Ltd. aims to further improve the copper space factor of the magnet wire*2 and thus optimize the size of the stator. The actual prototype is shown in Photo 1.

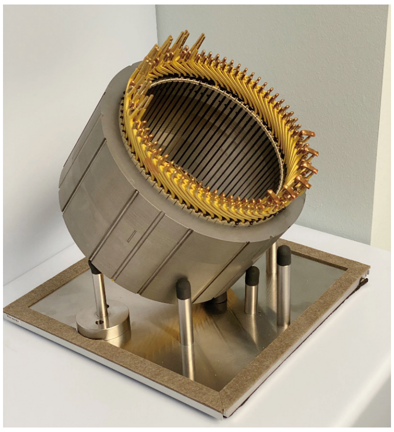


Photo 1. Prototype stator

2. Optimization between Copper Space Factor and Insulation

Higher speeds and shorter battery charging times – an important purchase criterion for electric vehicles – require higher voltages. It is expected that 800 V technology will become more widespread in charging stations, for example. On the motor side, the magnet wire insulation of the magnet wire must withstand the higher voltages. Generally, thicker insulation coatings are used for this purpose, which in turn leads to a lower copper space factor of the magnet wire. Motors that offer high torques must be able to handle high currents. Therefore the copper space factor of the magnet wire must be high, so that the heat generation associated with higher currents is also suppressed at the same time. Both thicker insulation layers and higher copper space factor result in an increase in the size of the motor, which goes against the trend toward miniaturization and optimization of the housing.

An optimum compromise must be found between the copper space factor of the magnet wire, the insulation, and the heat transfer coefficient. Also, the assembly process must be considered in terms of cost and sustainability.

3. Insulation Performance

The steep surge voltage generated by the inverter surge circuit increases as the length of the wiring between the inverter and motor increases. The peak value can then reach twice the inverter voltage.(2) When a certain voltage between the magnet wires is exceeded, minute discharges (partial discharges) may occur on the surface of the magnet wire film. As these partial discharges consequently occur continuously, the coating erodes and gradually loses its function, eventually leading to dielectric breakdown. Longer-lasting and more powerful electric motors therefore require magnet wire that can suppress the occurrence of partial discharge even at high frequencies and high voltages. The critical limit value, which means, the partial discharge inception voltage (PDIV)*3, is a measure of the insulation performance and can be described analogously to Dakin's Eq.[(3)] thanks to the good agreement – here, the thickness of the insulating layer is described by d and its dielectric constant by ε_r, Eq. (1):

[Dakin's Eq.]

$$V = A \times (2 \times t/\varepsilon_r)^{0.46} \quad \cdots\cdots (1)$$

A: Constant
V: PDIV (Vp)
ε_r : Dielectric constant*4 of Insulation Layer
t : Insulation layer thickness (μm)

Equation (1) clearly shows that the layer thickness must increase quadratically with PDIV. Thicker insulating layers prevent the higher copper space factor of the magnet wire in the slot, which is particularly desired for high-voltage systems (for example, with 800 V). Given the importance of insulating performance and the drive to keep insulating layer thickness as low as possible, many companies are engaged in research on PDIV.[(4)]

4. Cooling System

There are two types of cooling methods for electric drive motors: oil-cooled and water-cooled systems. In the oil-cooled system, an electric pump is gradually applying oil to the motor, but this is much more complex and costly to implement and is therefore less commonly used. In the case of water cooling, cooling lines are located in a water jacket enclosing the stator, which is provided with a layer varnish and insulation paper, including the enameled copper wires. Varnish and insulation paper have a high thermal resistance, which affects the cooling performance. If the thickness of the copper wire enamel is also increased for better insulation, even less heat can be dissipated. Insulation ideally contributes to cooling.

5. Magnet Wire with Low Dielectric Constant

In order not to increase the thickness of the layer, but rather to be able to reduce it, it is recommended to use insulating material with a low dielectric constant – as can also be seen in Dakin's Eq. A commonly used technique is to introduce air (with $\varepsilon_r \approx 1$) into the layer; this significantly reduces the higher dielectric constant of the insulating layer. A newly developed method can be used to introduce air bubbles of controlled size and uniform distribution into Polyimide (PI) coatings. The thickness of the insulation can thus be significantly reduced compared to the frequently used Polyamideimide (PAI) coatings, which in turn has a positive effect on the copper space factor of the magnet wire.

6. Optimized Stator Concept

The concept is based on increasing the copper space factor in coordination with optimized insulation while simultaneously increasing the cooling performance and is compared with a conventional solution in Fig. 1. In the case of the copper wires wound using the hairpin technology, a production method was devised with a smaller angular radius compared with conventional magnet wire. This has already improved the copper space factor by 4.4 % without changing the slot size of the stator.

The extent to which the copper space factor can be further increased to accommodate higher currents while reducing thermal resistance to improve cooling performance was investigated. Analysis of the slot structure revealed found. By removing the varnish and insulation paper and instead filling the slots with epoxy resin, heat dissipation was greatly improved, leading to improved cooling performance.[(5)] Figure 2 shows that the thermal conductivity is about three times higher. As a result, a concept stator was developed specifically for high voltage and high currents.

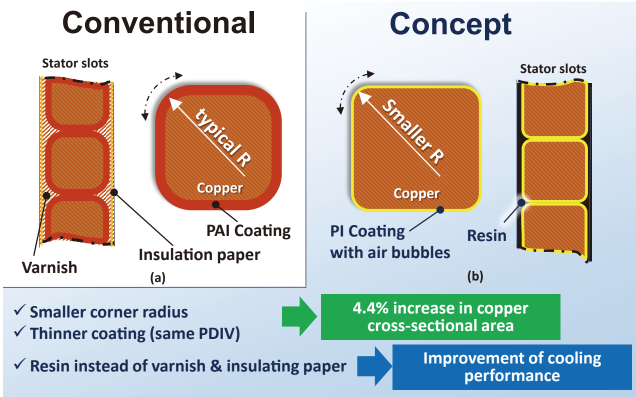


Fig.1. Structural comparison of conventional stator (a) and concept stator (b)

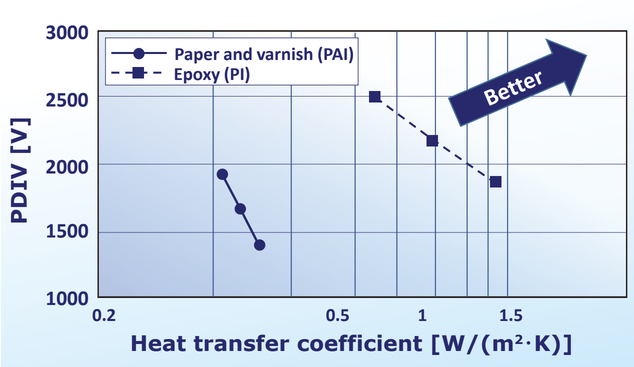


Fig. 2. Improve PDIV and heat transfer coefficient

7. Verification of Cooling Performance

When a direct current of 200 A is applied per U, V, and W phase of the stator, simulations calculate that the maximum temperature of the concept stator is 4°C lower than that of a conventional reference stator. Physical testing by an independent external laboratory showed the maximum temperature of the concept stator to be 2.6°C lower. This confirms the accuracy of the simulation results.

To further test the cooling performance, a simulation was conducted in which a direct current of 400 A per phase was applied. A delta of the maximum temperature between the two stators of 34.0°C was calculated in favor of the concept stator. Here, physical tests were performed internally under the same conditions using a thermal camera, Fig. 3, showed that the maximum temperature of the concept stator was 39.3°C lower than that of the reference stator– clear evidence of the significant temperature reduction.

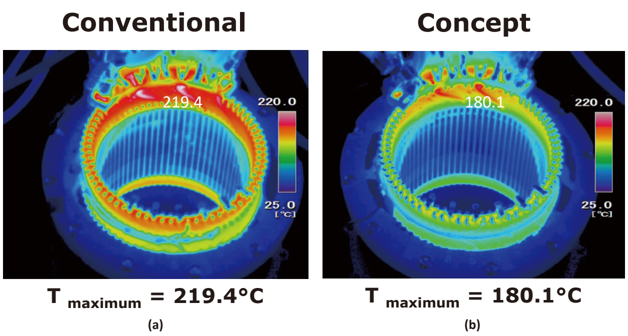


Fig. 3. Stator temperature measured by thermal camera

8. Performance Improvement and Size Reduction

The increased copper space factor of the magnet wire and the lower temperature resulting from this and from the improved cooling performance contribute to a significantly greater degree of freedom in the stator design. Within the scope of this research, the concept enabled an increase in maximum torque of 10.9% compared with the reference stator.

Applying the previous results, a different take was to investigate the effect of reducing the size of the motor while maintaining the maximum torque with respect to the reference value. Considering that torque is proportional to the motor length under the same conditions, the length can be reduced by 9.6% for the same power. A comparison with reference is shown in Fig. 4.

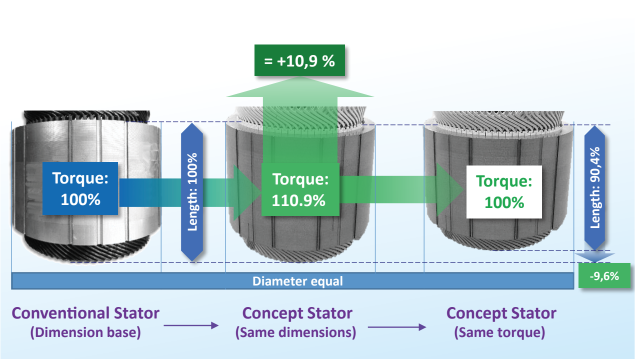


Fig. 4. Torque and size comparison with conventional stator

9. Reduction of Environmentally Hazardous Substances

This stator concept can reduce not only the amount of raw materials used, such as copper, but also the amount of environmentally hazardous substances used in the engine, as further investigations showed. Eliminating the energy-intensive varnish drying by replacing it with epoxy resin helps to reduce CO_2 emissions per electric drive motor in the production process chain by around 30%, as shown in Fig. 5.

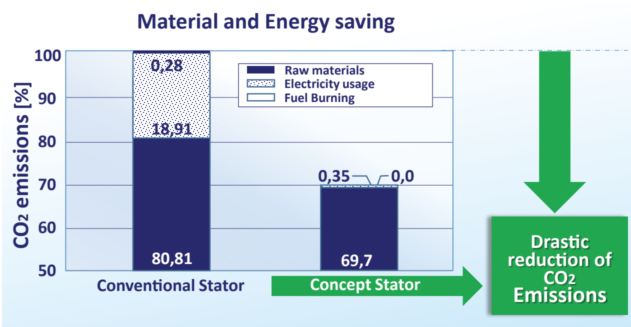


Fig. 5. Reduction potential of CO_2 emissions for production according to the stator concept Compared to the reference stator

10. Conclusion

With the new stator slot concept, both the size of the motor at the same torque and the amount of hazardous substances can be reduced compared to the reference. In addition, the elimination of the varnish and the insulation paper allows for improved performance while increasing cost efficiency compared to other conventional motor designs.

The concept development is still in its initial phase and will be further advanced. With the results presented, it already offers design approaches to the automotive industry to respond to the demand for more power, higher efficiencies, lower costs, and decarbonization intentions for sustainable mobility.

Technical Terms

*1 Traction motor: An electric motor that drives hybrid and electric vehicles. Also called a main motor.

*2 Copper space factor of the magnet wire: The ratio of the cross-sectional area of the magnet wire conductor to the cross-sectional area of the slot in the motor core where the magnet wire fits. The larger this ratio, the greater the motor output per size.

*3 Partial discharge inception voltage (PDIV): The voltage at which a discharge begins between magnet wires. If discharge occurs, the insulation film may deteriorate and motor life may be shortened.

*4 Dielectric constant: A value that indicates the ease of polarization of an insulator. The lower the relative permittivity, the higher the PDIV.

References

(1) Akatsu, K., Future Development in Traction Motor and Inverter for EV/HV. In: Journal of Society of Automotive Engineers of Japan 76 (2022), no. 6, pp. 46-53
(2) Tsuji, K. et al., Propagation of Inverter Surge and Voltage Distribution in Motor. In: IEEJ Transactions on Industry Applications 126 (2006), no. 6, pp. 771-777
(3) T. W. Dakin .et al., "Effect of Electric Discharges on the Breakdown of Solid Insulation," AIEE Part I: Communication and Electronics, 73 (1954), pp.155-161
(4) Ota, S. et al., "Rectangular Magnet Wire for Electric and Hybrid Electric Inverter-Drive Motors," SEI TECHNICAL REVIEW, No.88, pp.44-48 (April 2019)
(5) Yamamoto, S. et al., Development of Direct Cooling Stator Structure Using High Thermal Conductive Epoxy Molding Compounds. In: 2022 International Power Electronics Conference (IPEC-Himeji 2022- ECCE Asia), 2022, pp. 407-414

Contributors
The lead author is indicated by an asterisk (*).

S. MYOJO*
• AutoNetworks Technologies, Ltd.

Y. MITSUGI
• AutoNetworks Technologies, Ltd.

V. U. STRUEKEN
• Sumitomo Electric Wiring Systems Components and Electronics Europe Ltd.

S. MORINO
• AutoNetworks Technologies, Ltd.

K. IKEDA
• Ph.D.
General Manager, Sumitomo Electric Industries Automotive Europe GmbH