

Circulating Current Loss Reduction and Cooling Performance Enhancement for Generators in eVTOL Aircraft

Yuuta ISHII¹
Shogo SHINOZAKI¹

Tsubasa NAKATOMI¹
Hiromu KAMIYAMA¹

ABSTRACT

A generator with high power density was developed with the goal of installation in a gas turbine hybrid power generation system for electric vertical take-off and landing aircraft. The goal of this study was to achieve the output power, weight, and regeneration efficiency demanded of this generator. One challenge is overheating of the windings due to circulating current loss, which increases with the frequency, so reduction of loss and enhancement of cooling capacity are needed to mitigate overheating. To address this, loss prediction based on electromagnetic field analysis and a technique for evaluating circulating current loss using an actual device were used to verify the principle of circulating current loss, and the loss reduction effect of winding transposition was clarified. In addition, cooling performance was enhanced by applying additive manufacturing technology to the housing. A generator with the stator and cooling structure from this study was produced, performance tests were conducted, and the design target power density value was achieved.

1. Introduction

With progressing urbanization and population concentration, severe traffic congestion and growing environmental impact are becoming challenges for urban areas. Urban air mobility has been proposed as one method for addressing these challenges, and active efforts are underway to research and develop technology related to electric vertical take-off and landing aircraft (eVTOL)⁽¹⁾.

Due to their vertical take-off and landing capability, eVTOL do not need runways and can operate in urban spaces, so use is anticipated for air travel mainly within and around cities⁽²⁾. In addition, electrification of the propulsion system increases design flexibility, such as the ability to freely set the number of motors for propeller propulsion. This enables provision of redundancy, as even if there is an issue with one motor, the other motors can compensate for it. Furthermore, research and development is underway to leverage the eVTOL advantages of lower noise and environmental impact due to electrification⁽²⁾⁻⁽³⁾. However, eVTOL that are powered solely by batteries have limited battery capacity due to the relationship between the aircraft's total weight and thrust, which restricts the flight range⁽³⁾. In contrast to these fully electric eVTOL, Honda is focusing on development of a hybrid eVTOL with the goal of a flight range suitable for long-distance inter-city travel such as in North America to provide the joy of travel in a shorter time.

Honda is integrating its own aircraft engine development technology and electric technology cultivated in the FIA Formula One World Championship to develop a hybrid power unit that combines an aircraft engine and a battery⁽⁴⁾.

Figure 1 shows the architecture of the eVTOL gas turbine hybrid power generation system under development⁽⁴⁾. This system is configured to switch between electric power generated by rotating a generator with a gas turbine and battery power depending on the flight status. The power unit needs to provide high output power in

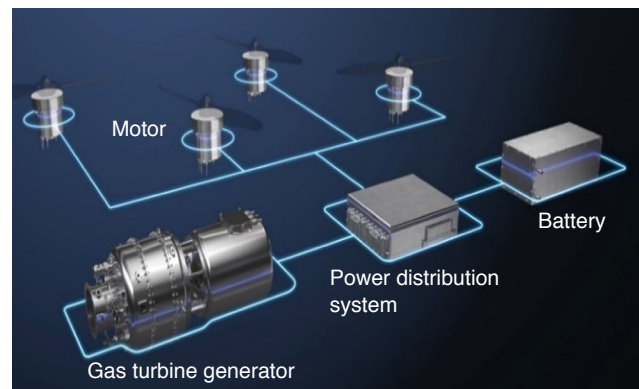


Fig. 1 Architecture of Honda's gas turbine hybrid system

¹ Research Center of Excellence
E-mail: yuuta_ishii@jp.honda

vertical take-off and landing mode, which has a high load. On the other hand, as it is important to reduce the aircraft weight to realize long-distance flight, a high-efficiency and lightweight power unit is also a key requirement. Therefore, the generator that is the main component of this system needs to be compact and lightweight with high output power, which calls for high power density.

Figure 2 shows the power density ranges demanded of generators for eVTOL and motors for automobiles, as considered by Honda. This shows that generators for eVTOL have power densities multiple times that of motors for automobiles.

This study set a goal of higher output power and power density compared to other companies, as shown in Fig. 2, and confirmed in tests that the target values were achieved. This paper reports the test results and the insights gained.

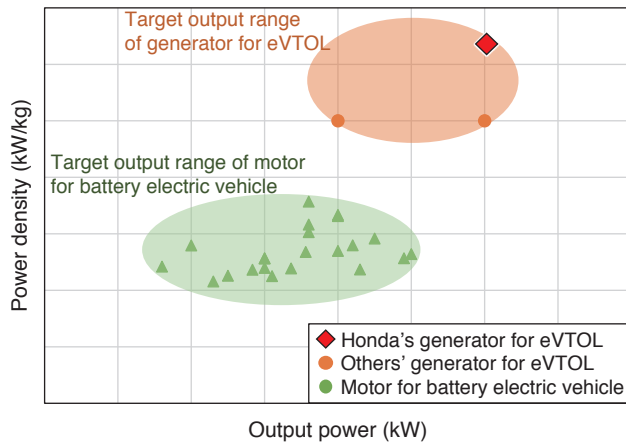


Fig. 2 Relationship between output power and power density

2. Generator Specifications

Figure 3 shows the appearance of the generator, and Fig. 4 shows a schematic of the structure. The generator mainly comprises a stator, a rotor, and a housing for cooling. The stator is fastened to the housing, and when the rotor rotates due to external shaft input, an induced voltage is generated by the rotor magnets and current flows, which the stator converts to output power. Also, the housing has coolant flow paths that help dissipate the heat generated by the stator.

Table 1 shows the basic specifications of the generator in this study. The rated rotational speed is assumed to be 50,000 rpm or more, and the rated output power is assumed to be on the order of several hundred kW. To accommodate the centrifugal force of high-speed rotation, this study used a surface permanent magnet synchronous motor (SPMSM) with permanent magnets bonded to the rotor surface and reinforced with a protective sleeve.

Table 1 Generator specifications

Motor type	SPMSM
Rotational speed	> 50,000 rpm
Output power	Order of several hundred kilowatts

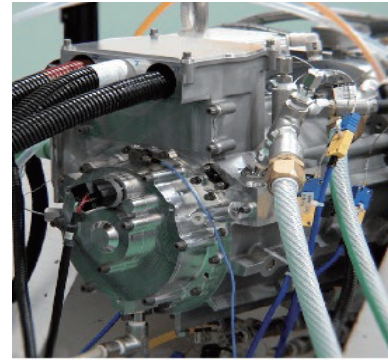


Fig. 3 Appearance of generator

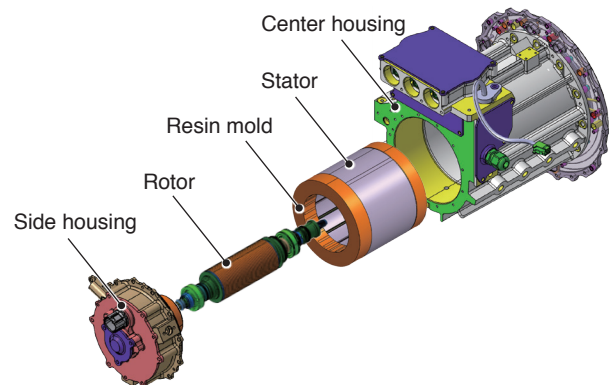


Fig. 4 Generator structure

3. Study Goals

Figure 5 shows a verification flow illustrating the challenges and approaches for the requirements of this generator. In order to achieve a compact size, light weight, and high output power, the eVTOL power unit aims for continuous output power operation in the high-rotational-speed range multiple times that of mass-produced automobile motors.

Generators rated for high rotational speeds are assumed to experience AC copper loss when energized. AC copper loss is broadly classified into three types: loss due to the skin effect and proximity effect stemming from the carrier frequency of the pulse width modulation (PWM) converter; eddy current loss due to the flux linkage of the permanent magnet; and circulating current loss due to the

winding arrangement. For the first two types, reducing the strand thickness can be expected to help reduce the loss⁽⁵⁾. However, it has been reported that when many strands are arranged in parallel, circulating current loss can occur due to the difference in the induced voltage between strands, resulting in increased loss⁽⁶⁾.

The high-rotational-speed generator in this study arranges many strands in parallel to reduce AC copper loss due to high frequencies, which makes the impact of circulating current loss more noticeable. As a result, circulating current loss is anticipated to increase, leading to excessive heat generation in the windings. Therefore, understanding circulating current loss in the high-frequency range is key to increasing the output power of high-rotational-speed generators.

However, in the rotational speed range of mass-produced motors, noticeable circulating current loss is not observed, and it has not been a major factor for consideration. In addition, circulating current loss is not easy to directly evaluate from externally measured quantities such as the phase currents once the actual generator is completed, and it has only been indirectly understood as part of the total loss measured in energization tests. From this perspective, methods to quantitatively predict circulating current loss in the design stage and evaluate it through tests were still insufficient for development of a high-rotational-speed generator.

Therefore, this study verified the prediction of circulating current loss by electromagnetic field analysis that accurately reproduces the strands in an actual generator and examined a testing method capable of evaluating circulating current loss using the stator unit prior to completion of the generator.

When attempting to achieve both cooling of the heat generated in the windings and size reduction, reducing the generator volume while maintaining a fixed efficiency limits the heat dissipation area, which makes enhancement of cooling performance important. Cooling methods are broadly divided into oil cooling, which directly cools the windings, and water-cooling, which cools via water paths within the housing⁽⁷⁾. Oil cooling can achieve high cooling

performance due to oil agitation from rotation, but fluid friction loss is expected to increase at high rotational speeds, making it a challenge to apply to high-rotational-speed generators. In contrast, water cooling can cool the windings in the slot via the stator core, but the cooling effect becomes lower in the coil end parts that are not connected to the core⁽⁷⁾. Therefore, the applicability of water cooling was increased by adopting a structure that fills the coil-end parts with high-heat-resistant resin mold. This study verified cooling performance through thermal analysis and actual generator tests using a housing structure with resin mold applied and the water-cooling paths considered, with the goal of enhancing the heat transfer coefficient.

From the above, this paper covered the following items:

- (1) Establishment of a method for evaluation and reduction of circulating current loss; and
- (2) Verification of a housing structure for water-cooling.

Based on these verifications, the goal of this study was to achieve the design target power density value in performance tests by producing a generator equipped with a new cooling structure and a stator with reduced circulating current loss.

4. Evaluation and Reduction of Circulating Current Loss

4.1. Circulating Current Loss

Figure 6(a) shows the cross-section of the stator slot and the arrangement of strand bundles, with four strands selected from among the windings and numbered. Figure 6(b) shows a schematic of circulating current generation in the selected strands. Here, the phase current flowing through the windings is I_{phase} , the circulating current generated by energization is I_{circ} , the induced voltage is V , and the magnetic flux density is B . When phase current is flowed through the strand bundle, ideally a uniform current flows in each strand. In reality, however, the magnetic flux tends to concentrate on the side of the iron core, which has high permeability, due to the self-magnetic fields generated by the current flowing in each strand and its interaction with adjacent strands. As a result, the magnetic flux density distribution in the slot is not uniform, and differences in the arrangement of strands in the slot result in differing flux linkage levels of each strand. These differences in flux linkage lead to uneven induced voltage between strands and circulating current can occur within the strand bundle. Circulating current loss increases with the frequency, leading the windings to generate heat. While this is not an issue in the rotational-speed range of motors for mass-produced automobiles, it becomes noticeable when the goal is continuous operation at high-rotational speeds such as in this study.

The principle of circulating current generation was verified using electromagnetic field analysis. Figure 7 shows the cross-section of the stator slot in the analysis

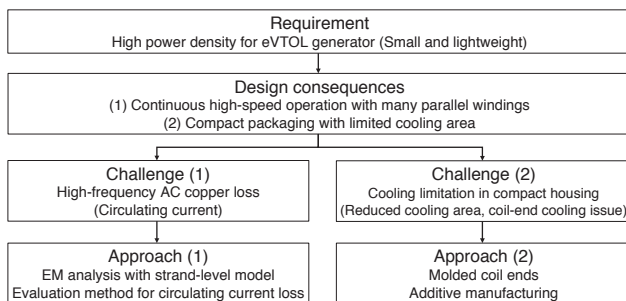
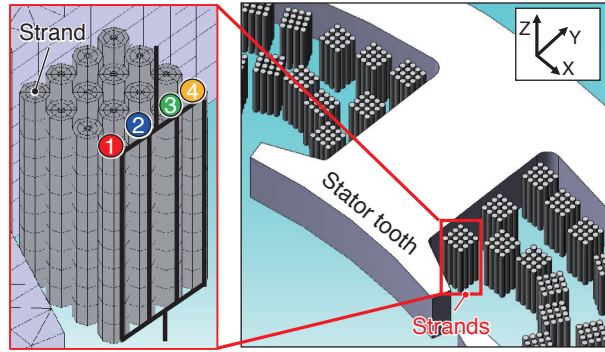
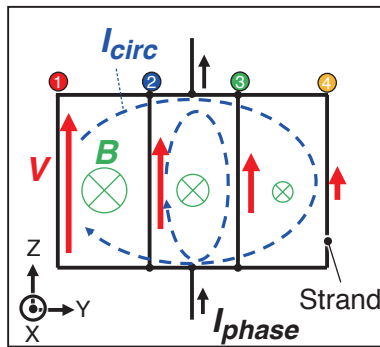


Fig. 5 Overview of challenges and technical approaches

model. The number of turns in this model was set at seven based on the required rotational speed and the limit voltage of the converter, and the number of parallel strands was set at 45 to reduce loss, with each strand modeled individually. Analysis was performed using the 2D finite element method, and the current waveform flowing in each strand was calculated when a sine wave current is applied at the



(a) Strand bundle in the stator slot



(b) Schematic of circulating current generation

Fig. 6 Strand bundle and circulating current model

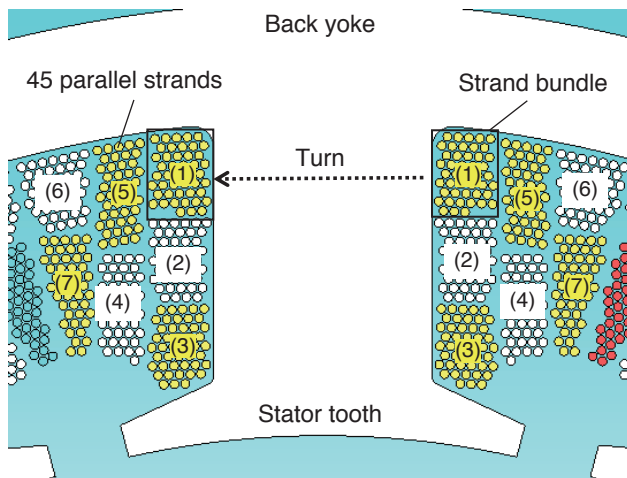


Fig. 7 Cross section of stator

frequency condition corresponding to the rated rotational speed.

Figure 8 shows the strand current waveforms calculated by performing electromagnetic field analysis on the analysis model shown in Fig. 7. Arbitrary analyzed waveforms are indicated by dashed lines, and the ideal waveform is indicated by the red line. Here, the ideal strand current when circulating current is not generated has the same amplitude and phase in all strands. In contrast, the strand current waveforms calculated by the analysis exhibited differences in current amplitude and phase, indicating that there were differences in the induced voltage between strands, with the result that circulating currents with differing current levels were generated in each strand.

The above results confirmed that circulating current can be reproduced by electromagnetic field analysis.

4.2. Loss Reduction Effect of Transposition

This section confirms the effect of the stator winding specification on circulating current loss. One method for reducing circulating current loss is transposition, which involves twisting the strand bundles when switching turns at the coil-end part in the winding process⁽⁸⁾.

To evaluate the effect of transposition, circulating current loss was calculated using electromagnetic field analysis for the conditions without transposition and with 180° transposition. Figure 9 shows the analysis models with a single representative strand marked by a red circle, along with the transposition locations and the strand numbering. Figure 9(a) shows the arrangement of strands without transposition, where the strand bundles within the same slot are arranged in the same manner as the numbering shown in the figure. Figure 9(b) shows the arrangement of strands with transposition, where the strand bundles are twisted 180° at the coil end so that the arrangement is transposed by 180° within the same slot. By reversing the arrangement of strands in adjacent bundles in this way, the differences in the induced voltage between strand bundles

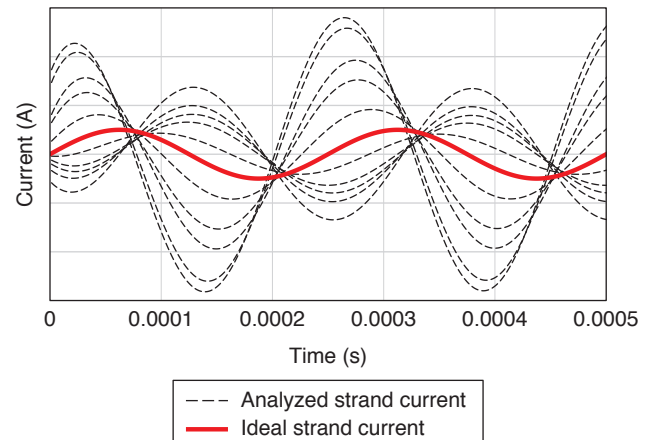


Fig. 8 Calculated strand current waveforms

can be negated, which is expected to reduce circulating current loss.

Figure 10 shows the analysis result of circulating current loss for each model in Fig. 9 when energized by a sine wave current at the frequency condition corresponding to the rated rotational speed. Application of 180° transposition was confirmed to reduce circulating current loss by 77%, making transposition an effective method for reducing circulating current loss.

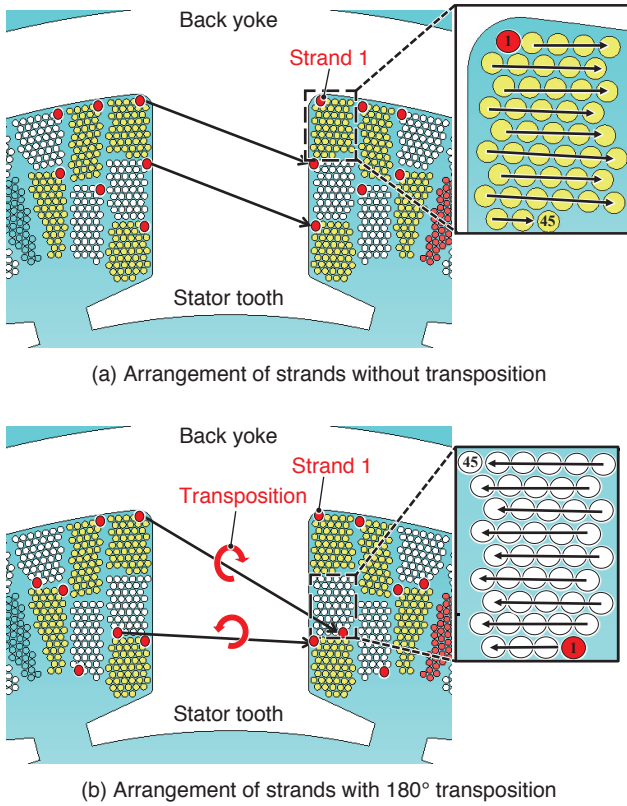


Fig. 9 Analysis models

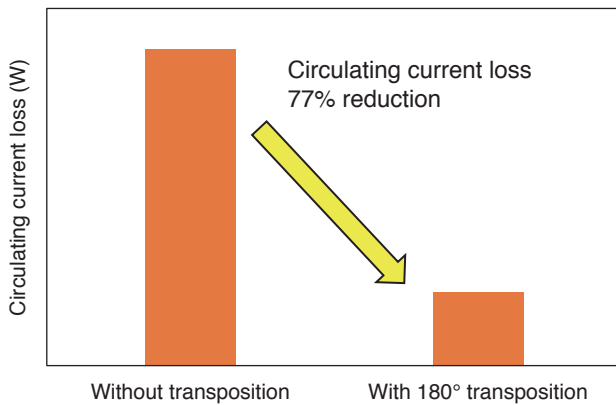


Fig. 10 Reduction of circulating current loss by 180° transposition

4.3. Examination of Transposition Location

The proposed method does not limit winding transposition to the coil-end position and applies 180° transposition in the slot axial direction. This study refers to this method as transposition within slot. Figure 11 shows 3D model drawings of each transposition method. Figure 11(a) shows the conventional transposition, and Fig. 11(b) shows transposition within slot. For easier comprehension, the figures show nine strands per strand bundle and assume the state with the windings transposed by two turns. Transposition within slot involves twisting the strand bundles inside the slot, so the strand positions can be controlled by reversing the strand arrangement at the slot opening and at the back of the slot. With this configuration, each strand is neatly arranged, which helps to negate differences in the induced voltage between strand bundles, so circulating current loss reduction effects can be expected.

4.4. Test Methodology

The method proposed to evaluate circulating current loss measures the stator loss by energizing the stator unit alone and then performs loss separation to evaluate the AC copper loss including circulating current loss.

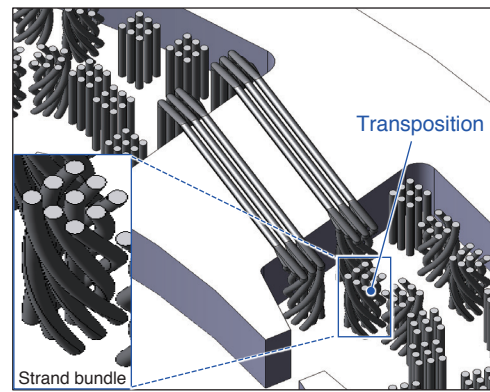
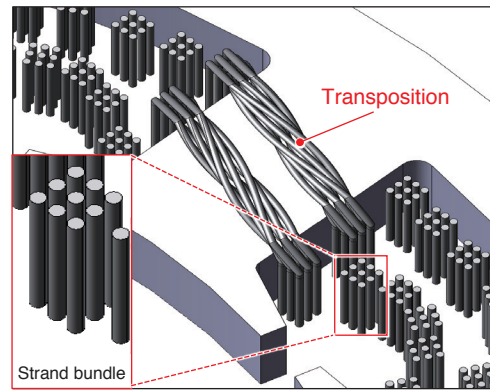


Fig. 11 Stator transposition structures

Figure 12 shows the test configuration for evaluation of circulating current loss, and Fig. 13 shows the test environment. Normally, when energizing a synchronous generator with a PWM converter, the rotation signal of the rotor is fed back to command the three-phase AC current to be synchronized. However, this method performs verification using only the stator unit, so rotation pulse signals from the rotor cannot be obtained. Therefore, simulated rotation pulse signals are generated by an encoder to simulate the rotation of the rotor, enabling control of the three-phase AC current and simulation of the energized state of an actual generator. At this time, since a rotor is not assembled, the electric power supplied to the stator does not become mechanical power and is instead consumed as stator heat generation. Thus, the stator loss is output as electric power integrated value of the three-phase active power measured by a power meter, so it can be quantified and evaluated. Normally, when simulating continuous rated output power, it is necessary for the winding temperature to reach saturation. However, the goal of this method is to confirm the loss tendency through short-time energization to help prevent overheating of the stator windings.

Here, the breakdown of stator loss is classified into DC copper loss, AC copper loss including circulating current

loss, and stator core iron loss. The DC copper loss W_{dc} is expressed by Eq. (1), where R is the phase resistance corrected for the measured winding temperature, and I_{phase} is the rated phase current effective value.

$$W_{dc} = 3RI_{phase}^2 \quad (1)$$

The stator core iron loss W_i was calculated using electromagnetic field analysis, and is expressed by Eq. (2), where $Wh_i(B)$ is the hysteresis loss in each element, $We_i(B)$ is the Joule loss in each element, B is the magnetic flux density in each element, and f is the frequency corresponding to the rated rotational speed.

$$W_i = \sum_i^n (Wh_i(B, f) + We_i(B, f)) \quad (2)$$

Here, by noting the stator loss obtained from the experimental result as W_{loss} , the AC copper loss W_{ac} , which includes circulating current loss, is expressed by Eq. (3).

$$W_{ac} = W_{loss} - W_{dc} - W_i \quad (3)$$

An actual stator A with conventional transposition and an actual stator B with transposition within slot were made, and the loss of each stator was evaluated through energization tests. Figure 14 shows the AC copper loss W_{ac} including circulating current loss measured in each stator when energized by a sine wave current at the frequency condition corresponding to the rated rotational speed. Stator B was confirmed to have a loss reduction effect of 61% compared to stator A. Based on this result, strand bundles with high winding temperatures were selected from among the strand bundles of both stators, and the current of arbitrary strands selected from those bundles was measured. The circulating current was evaluated by confirming the amplitude and phase of each strand current.

Figure 15 shows the current waveforms of arbitrary strands when energized by a sine wave current at the frequency condition corresponding to the rated rotational speed. The black lines are the measured current, the red line

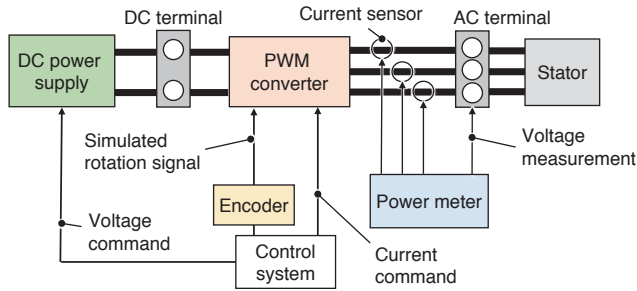


Fig. 12 Test configuration for stator loss evaluation

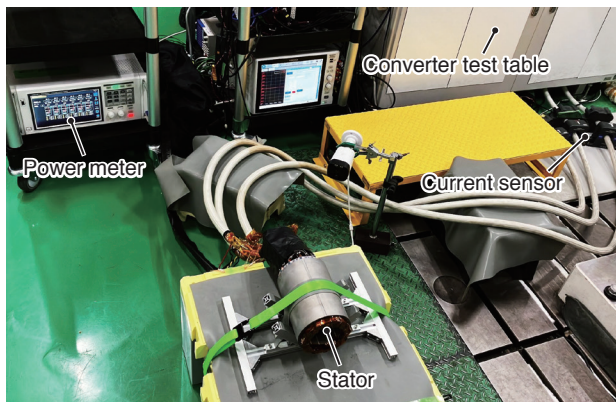


Fig. 13 Test equipment for stator loss evaluation

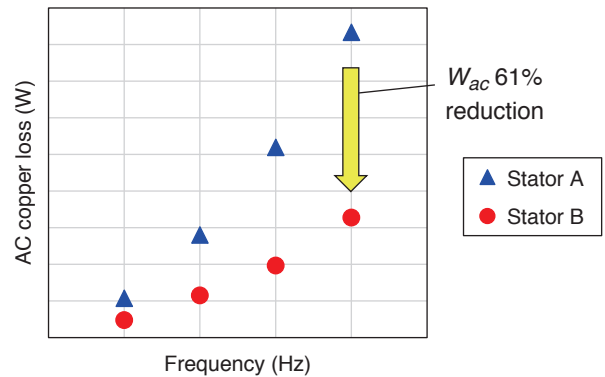


Fig. 14 AC copper loss evaluation results including circulating current loss

is the ideal current waveform, and the dashed line is the current waveform from the analysis result for the condition without transposition shown in Fig. 8.

The stator A strand current shown in Fig. 15(a) exhibits a lower current amplitude compared to the condition without transposition. However, the amplitude and phase in each strand differ from the ideal waveform, and generation of circulating current was confirmed. In contrast, the stator B strand current shown in Fig. 15(b) exhibits smaller changes in amplitude and phase compared to the stator A strand current, and a lower circulating current was confirmed. From the above, the relative arrangement of the strands in stator B is closer to the ideal arrangement shown in Fig. 9(b), and the effect of transposition within slot was demonstrated as an effective means to reduce circulating current loss. Stator B with transposition within slot was therefore adopted as the specification.

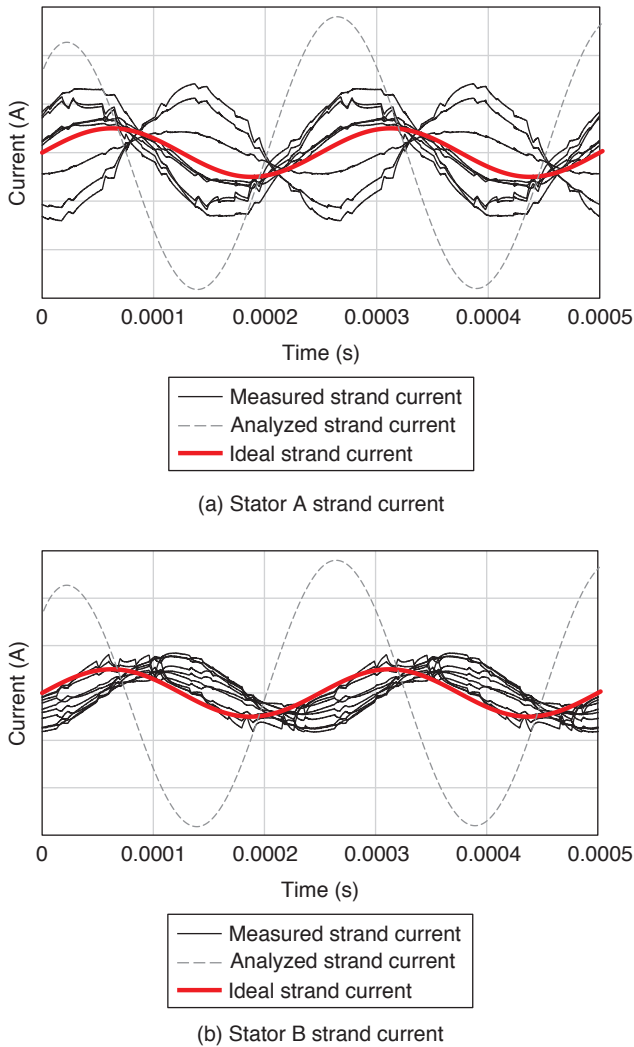


Fig. 15 Measured strand current waveforms

5. Evaluation of Cooling Performance

5.1. Verification of Feasibility of Achieving Cooling Performance

Figure 16 shows the analysis model with high heat-resistant molded resin applied. By filling the coil ends with molded resin that has high thermal conductivity, heat transfer paths can be formed between the windings and the housing. In general, among cooling water path structures within motor housings, helical structures exhibit good heat removal performance, such as a higher heat transfer coefficient, a larger surface area, and a lower winding temperature⁽⁹⁾. This study adopted a helical structure and examined a configuration that supplies long life coolant (LLC) as the coolant. Thermal analysis was performed on this structure to confirm the necessary heat removal rate. In this analysis, the amount of heat generated in rated output power operation was applied to the coil-end part, and the thermal conductivity of the molded material was set to 3.4 W/mK. LLC was assumed as the coolant, with the supply temperature set to 40°C and the flow rate set to 10 L/min. The heat removal rate under these conditions was evaluated by calculating it from the difference in temperature obtained by passing coolant through the water path.

The analysis result confirmed that heat removal rate enhancement of at least 20% is needed to accommodate the expected loss. In this cooling structure, enhancement of cooling performance by considering the flow path structure of the housing is important for achieving high power density.

5.2. Verification of Cooling Structure

Figure 17(a) shows an analysis model of a cast-in helical water-cooling structure, and Fig. 17(b) shows an analysis model of an axial water-cooling structure made by applying additive manufacturing (AM) technology to the housing. This structure is referred to hereinafter as an AM water-cooling structure. By applying AM technology, many small-diameter water paths can be formed, achieving a dense flow path structure to enhance the heat transfer coefficient. Thermal analysis was performed on these models, and the heat removal rate of each structure was compared. This analysis focused on models using a dummy heater that simulates the stator. LLC was assumed as the

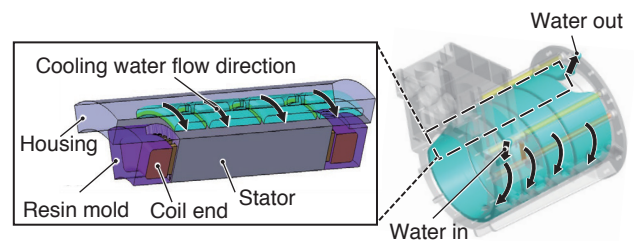


Fig. 16 Cooling structure model for thermal analysis

coolant, with the supply temperature set to 40°C and the flow rate set to 10 L/min. Each model in Fig. 17 was set to the same volume for comparison purposes. Analysis was first performed by applying the expected heat generation amount to the model in Fig. 17(a), and the temperature of the heater was obtained. This temperature was then applied to the heater of the model in Fig. 17(b) to analyze the heat generation amount under equivalent temperature conditions, and the heat removal rate was calculated based on the coolant temperature difference.

The analysis result confirmed that the heat removal rate of the AM water-cooling structure is 1.3 times that of the helical structure. However, as the goal of this analysis was to confirm the heat removal enhancement effect, the analysis result was not verified using test data. A sub-component was therefore made by fastening the stator B adopted in Section 4.4. to a housing with an AM water-cooling structure and filling with molded resin, and an actual device test was performed by energizing the stator. This test result confirmed that while the winding temperature rose due to energization, it did not exceed the set upper limit temperature.

The test used the stator energization method described in Section 4.4. The windings were continuously energized while inputting simulated rotation pulse signals corresponding to the rated rotational speed. At this time, energization was continued until the winding temperature no longer changed over time and the saturation state was reached. LLC was provided as the coolant, with the temperature set to 40°C and the flow rate set to 10 L/min.

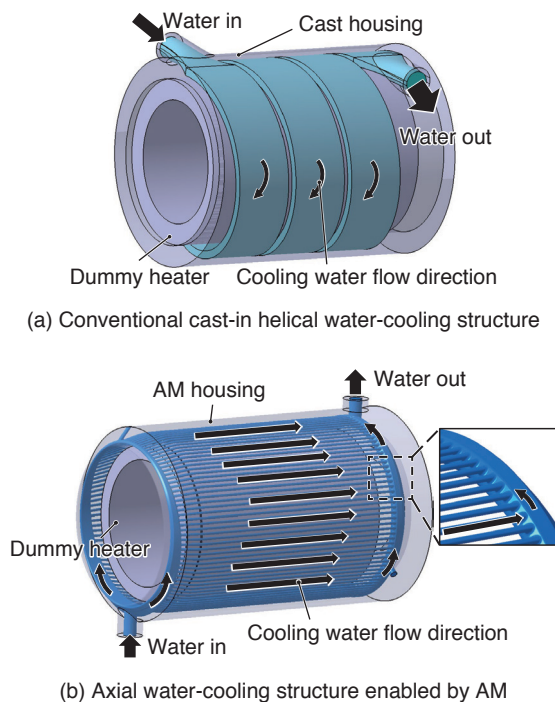


Fig. 17 Water-cooling housing structure

Figure 18 shows the relationship between the phase current obtained by the test and the highest winding temperature. This figure also plots the rated phase current value, which corresponds to the design target output power value. The result confirmed that a phase current 1.3 times the rated phase current value can be energized. Thus, since this results in a sufficiently low saturation temperature relative to the upper limit winding temperature, the target output power can be achieved, and the AM structure was adopted as the specification.

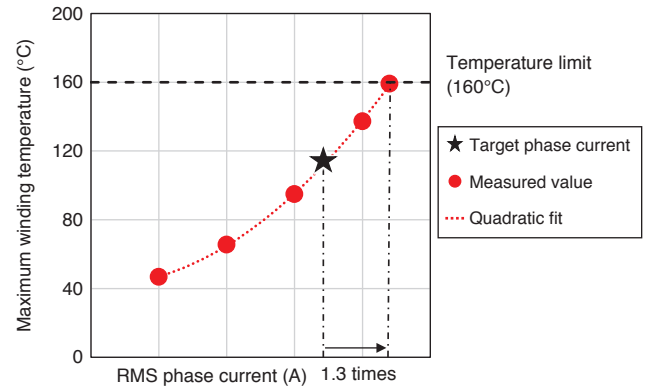


Fig. 18 Relationship between maximum winding temperature and phase current in AM structure

6. Evaluation of Output Power Performance

6.1. Test Overview

A generator was made by filling molded resin into stator B with transposition within slot and applying an AM water-cooling structure. Performance tests were conducted using this specification, and the output power characteristics and cooling performance characteristics were confirmed.

Figure 19 shows the configuration of the performance test. In this test configuration, the rotational speed of the dynamo is increased to achieve a load equivalent to that of a gas turbine, that load is connected to the generator, and regenerative operation is enabled by converter control. Energization was continued in the state with the rotational speed of the dynamo controlled to operate the generator at the desired rotational speed until the generator winding temperature no longer changed over time and the saturation state was reached. The coolant conditions were the same as those in the previous chapter.

6.2. Test Result

Figure 20 shows the relationship between the regenerative output power of this generator and the highest winding temperature. This figure also shows the rated output power line, and it was confirmed that this generator can maintain continuous energization for 10 min. or more

up to operating points that exceed the rated output power, while staying below the set upper limit temperature.

Figure 21 shows an efficiency map for the torque obtained from the test results and the rotational speed. This figure also plots the measured regenerative output power in

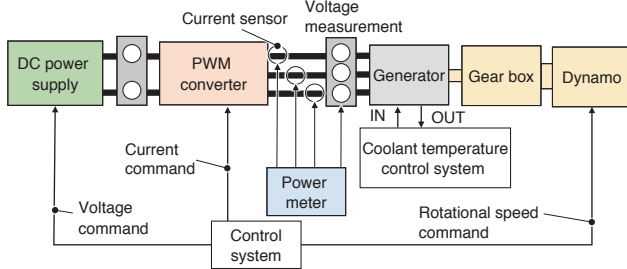


Fig. 19 Configuration of generator performance test setup

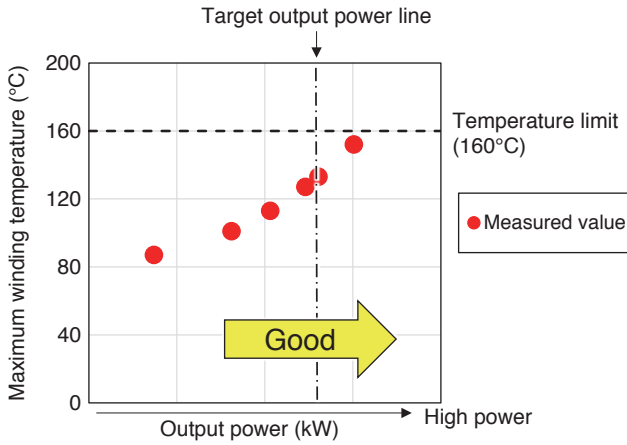


Fig. 20 Relationship between maximum winding temperature and output power in generator assembly

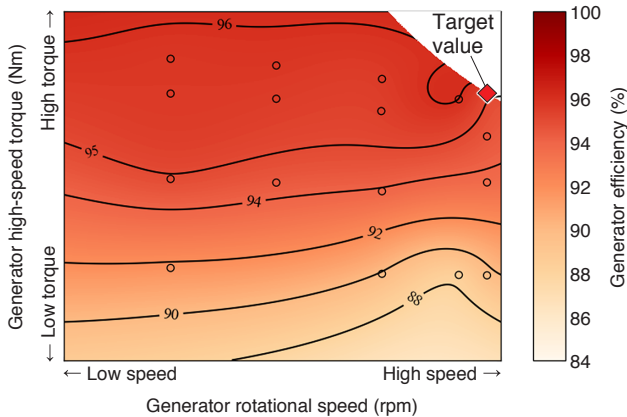


Fig. 21 Generator efficiency map as function of torque and rotational speed

the regenerative operation range. It was confirmed that this generator can operate continuously for 10 min. or more at a power generation efficiency of at least 95% in the high torque and high rotational speed range at rated output power.

7. Conclusion

A stator that applies transposition within slot to reduce circulating current loss and a housing structure that applies AM technology to the housing to enhance cooling performance were developed for use in the generator that is a key component of the gas turbine hybrid system for eVTOL. A generator using these technologies was produced and achieved the design target power density value. The following insights were also gained from proving tests.

- (1) The principle of circulating current generation due to strand arrangement was verified using electromagnetic field analysis, and transposition of the windings was confirmed to have a circulating current loss reduction effect. Furthermore, circulating current loss in differing stator transposition specifications was compared from the actual measurement results of AC copper loss including circulating current loss. Based on these results, a stator specification with a large loss reduction effect was selected.
- (2) Verification by thermal analysis showed that an AM water-cooling structure that applies AM technology to construct dense cooling water paths while using high-heat-resistant molded resin achieves a heat removal rate 1.3 times that of a cast-in helical water-cooling structure. In addition, the heat removal rate of the housing was evaluated by applying the stator loss evaluation method. A generator with this AM water-cooling structure was produced, and the cooling performance and rated output power were demonstrated.

The future goal is to further increase the power density for operation under environmental conditions that simulate flight.

References

- (1) Ugwueze, O., Statheros, T., Bromfield, M. A., Horri, N.: Trends in eVTOL Aircraft Development: The Concepts, Enablers and Challenges, AIAA SciTech Forum, AIAA 2023-2096, (2023), doi: 10.2514/6.2023-2096
- (2) Thomas, G. L., Malone, B. P.: Power System Redundancy Design Trends for All-Electric eVTOL Quadrotors, AIAA SciTech Forum, AIAA 2023-1209, (2023), doi: 10.2514/6.2023-1209
- (3) Zong, J., Zhu, B., Hou, Z., Yang, X., Zhai, J.: Evaluation and Comparison of Hybrid Wing VTOL UAV with Four Different Electric Propulsion Systems, Aerospace, Vol. 8, p. 256, (2021), doi: 10.3390/aerospace8090256
- (4) Honda Motor Co., Ltd.: https://global.honda/en/tech/eVTOL_gas_turbine_hybrid_system/, (accessed 2026/01/07)

- (5) Suzuki, T., Nirei, M., Horiuchi, M., Sato, M., Bu, Y., Mizuno, T.: Interior Winding Synchronous Motor for Reducing AC Loss in Ultra High Speed Rotation Range, *Journal of the Japan Society of Applied Electromagnetics and Mechanics*, Vol. 28, Issue 2, p. 122-127, (2020), doi: 10.14243/jsaem.28.122 (in Japanese)
- (6) Yamazaki, K., Yui, H., Ohguchi, H., Shuto, M.: Loss Analysis of Permanent Magnet Synchronous Machines by Considering Circulating Currents of Armature Windings, *IEEJ Transactions on Industry Applications*, Vol. 138, Issue 6, p. 553-560, (2018), doi: 10.1541/ieejias.138.553 (in Japanese)
- (7) Sugimoto, S., Kori, D.: Study of Cooling Performance and Losses Evaluation for Water- and Oil-cooled Motor, *IEEJ Transactions on Industry Applications*, Vol. 138, Issue 5, p. 378-383, (2018), doi: 10.1541/ieejias.138.378 (in Japanese)
- (8) Kono, T., Asama, J., Shida, H., Hasebe, T.: Evaluation of Circulating Current Losses in Electric Motors with Distributed Winding Using Aligned Multi-Parallel-Wires, *IEEJ IAS Conference Proceedings*, No. Y-83, (2022) (in Japanese)
- (9) Wang, Q., Wu, Y., Niu, S., Zhao, X.: Advances in Thermal Management Technologies of Electrical Machines, *Energies*, Vol. 15, Issue 9, Article 3249, (2022), doi: 10.3390/en15093249

■ Author ■



Yuuta ISHII



Tsubasa NAKATOMI



Shogo SHINOZAKI



Hiromu KAMIYAMA