

Development of a nacelle for a medium-sized wind power generator

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Abstract

In order to reduce environmental burdens through carbon neutrality, a circular economy, and so on, it is important to produce and consume energy locally and to create new value by utilizing reused parts. Among measures to realize these is a plan for a medium-sized wind power generator that reuses automotive parts and is connectable to the power grid. In order to participate in the Environmental Technology Verification Program by the Ministry of the Environment and contribute to resolving social issues, we have launched the development of a nacelle for this medium-sized wind power generator, the first nacelle to be produced in Japan.

1. Introduction

As demand for renewable energy is increasing, there is a plan for a medium-size wind power generator with a 50 kW-level power generation output, which assumes a self-consumption type power supply and which can be connected to a power grid, in order to disseminate distributed electric power and reduce investments in infrastructure in sparsely populated areas.⁽¹⁾ This output is equivalent to that of an EV, and the system consists of an increaser and a generator. We have also forayed into the electric PT field, and aim to provide inexpensive and high-quality components in a short period by utilizing this core technology and reusing automotive parts.

2. Overview of the development of the nacelle for a medium-sized wind power generator

2.1 Development concept

As described earlier, the power generation output was set to 50 kW, which can be connected to low-voltage power grids in Japan, assuming a self-consumption type power supply. The size of the generator was designed to a scale suitable for the site of a business office (Fig. 1), and the price was also set to a level economically operable for a single business owner.

In addition, considering the fact that the wind turbine is to be installed in living area, we decided to ensure quietness to prevent noise problems. And in order to reduce both costs and environmental burdens, we decided to reuse automotive parts and build a circular system.

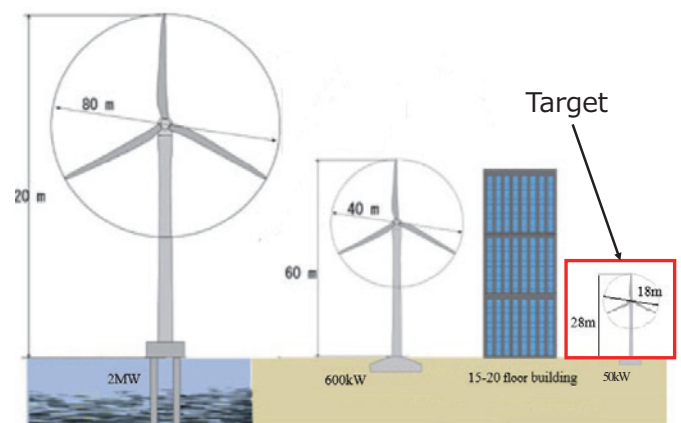


Fig. 1 Power generation and wind turbine size

2.2 Overview of the specifications of the medium-sized wind power generator

As an example, the main specifications of the demonstration wind power generator actually produced are shown below.

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1) Overview of the wind turbine

- Rated output: 50 kW (target, rated speed of main shaft: 60 rpm)
- Rated wind speed: 11 m/s
- Cut-in and cut-out wind speeds: 3.0 - 25.0 m/s
- Tower height: 18.9 m
- Rotor diameter: 18.2 m

For reference, Fig. 2 shows the definition of the general output characteristic that will help understand the performance of wind power generators.

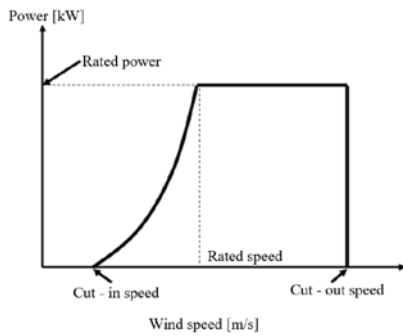


Fig. 2 Power curve of wind turbine

2) Overview of the nacelle (Fig. 3)

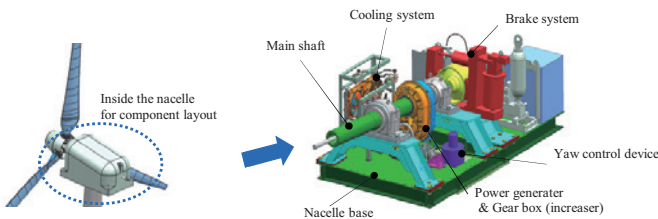


Fig. 3 Inside the nacelle

Generator: Mechanical-electrical separate type (generator for commercial automobile reused)

Increaser: Parallel 5-axis type

Cooling system: Water cooling control type (cooling system for commercial automobile reused)

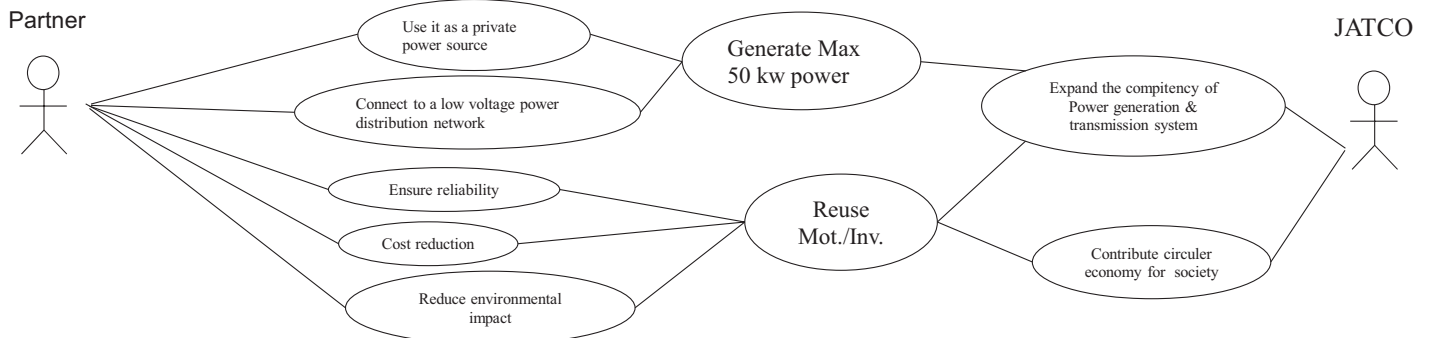


Fig. 4 Use case diagram for wind turbine system

Main shaft brake: Non-excitation actuated type drum brake
 Yaw control device: Phase-driven motor provided with a brake

Size of nacelle: 4.4 m (L) × 2.2 m (B) × 2.4 m (H)
 (size excluding cowl: 3.0 m (L) × 1.7 m (B) × 1.2 m (H))

Mass of nacelle: 5,212 kg

3. Development process and key technologies

3.1 Development process

We decided to apply to this development process the system engineering (SE) we have established over the years. Applying SE enables us to design the linkage of requirements between the sub-system, the nacelle, and the wind turbine and each system level, their functions, and components for the nacelle for wind power generation, a new area of development in which we lack experience without omission. Furthermore, establishing a V-process evaluation system and planning verification at each level allowed us to perform efficient experimental verification without introducing large-sized equipment.

The sections that follow will show specific examples and key technologies.

3.2 Hardware system design

We analyzed the requirements from the higher-order wind turbine system to the nacelle system based on a use case diagram (Fig. 4). As mentioned above, the reuse of used automotive motors and inverters is important for this development in order to realize a power generation output as a self-consumption type power supply and reduce environmental burdens.

Next, in order to extract all functions and constituent elements of the nacelle without omission and to determine the necessary prerequisites for the design of each element, we elucidated the five main functions the nacelle system will assume, and the IN-OUT physical quantities between them and the constituent elements and the peripheral elements using a context diagram based on a small-sized wind power generator available on the market (Fig. 5).

- [Function 1] Generating power → Power generation increaser
- [Function 2] Yawing → Yawing system
- [Function 3] Stopping the main shaft rotation → Main shaft brake system
- [Function 4] Maintaining power generation performance → Cooling system
- [Function 5] Monitoring and communicating the condition → Cooling system control unit

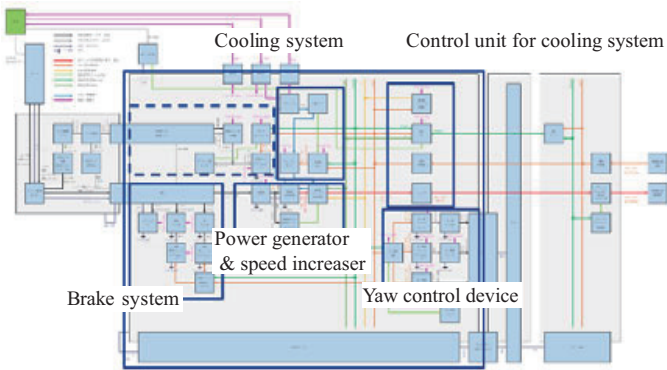


Fig. 5 Context diagram

Then, we defined the requirements of each element, allocated target values, and implemented detailed design. For the power generator, the main component, we reused a motor and an inverter for an automobile available on the market, whose regenerative output was close to the target value. In addition, we set the speed of the main shaft to 60 rpm to ensure quietness, and designed the motor to run with maximum efficiency by adjusting the gear ratio of the increaser to 102.8. Table 1 and Fig. 6 show the specifications of the power generation increaser designed in this way.

Table 1 Function and specifications for wind power

Request (R)	Function (F)	Specifications (L)
Generate electricity	Generate electricity	Motor regeneration output *Kw Voltage 240-400V
	Transmit power (Determine the motor operating point)	Speed increase ratio 102.8
	Transmit power (Ensure reliability)	Spindle maximum input torque 7,958 Nm Spindle maximum speed 70 rpm
Ensure quietness (Main shaft speed 60rpm)	Reduce transmission loss	Transmission efficiency *%
Operate continuously	Control inverter water temperature	Water cooling mechanism (for commercial vehicle use)
	Lubricate gearbox parts	Built-in electric pump

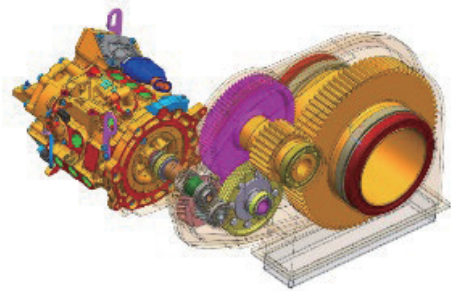


Fig. 6 Exterior of power generator & increaser

The nacelle system designed in this way consists of more than approximately 130 parts, and we applied many reuse designs to realize the development concept of this medium-sized wind power generator, referring to automobiles and industrial equipment. Reused automotive parts accounted for approximately 30% of all parts of the demonstration wind power generator, and the reuse rate is expected to further increase ahead of mass production (Table 2).

Table 2 The reuse rate of automotive parts

	Prototype	Mass production
Nacelle ASSY	29%	Approximately 40%
Power generator & increaser	38%	Approximately 50%
	Motor	←
	Inverter	←
	Lubricating oil pump	←
	Sensor	←
	Lubricant fluid	←
		Gear
	O-rings, etc.	
Nacelle system	12%	16%
	Cooling system	←
	Coolant	←
		Sensor

3.3 Control system design

Looking at the systems for the entire wind power generator, we undertook to control (1) through (4), below, to maintain and manage the generator.

- (1) Control of the operating volume for the water cooling auxiliary equipment of the generator
- (2) Lubricant amount control and temperature monitoring of the increaser
- (3) Startup and stop control of auxiliaries based on commands from the higher-order system
- (4) Request to the higher-order system to stop when an abnormal state is detected

Figure 7 shows the scope of control development.

Since a wind power generation system is an unknown field to us and the wind power generator manufacturer, who was a joint development partner, was operating in a different cultural area from the automobile industry, the clarification and consistent sharing of the required specifications was an important issue. Thus, by using timing charts and other SE tools, we were able to share the specifications inside and outside the company. Figure 8 shows an example of a timing chart when an agreement was reached with the joint development partner on control specifications.

For the control development process, we adopted the Model Based Development (MBD) process, which we adopt as a standard process. This enables us to utilize the company's control model library and flexibly assign personnel in charge

of control development. It also offers such advantages as the feasibility of front loading for verification using Model In the Loop Simulation (MILS) and Hardware In the Loop Simulation (HILS) even when actual hardware is still incomplete.

This time, we adopted a Programmable Logic Controller (PLC), which is a general-purpose controller for industrial use. However, an MBD development environment using our standard C language base was not prepared for the PLC. For this reason, we constructed an MBD development environment for PLCs and performed the in-house development of basic software to be implemented in PLCs.

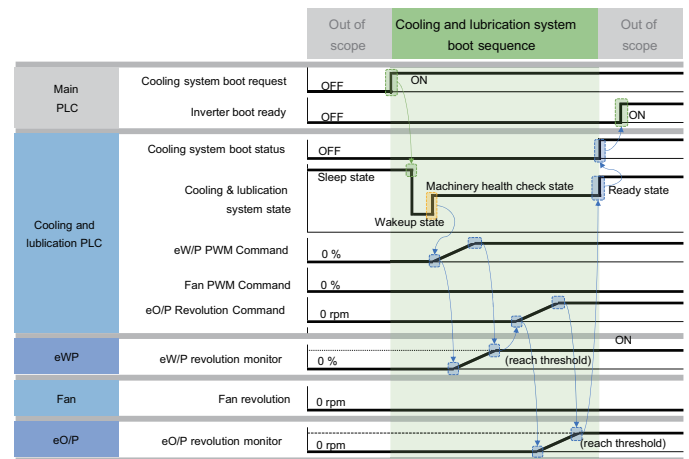


Fig. 8 Timing chart

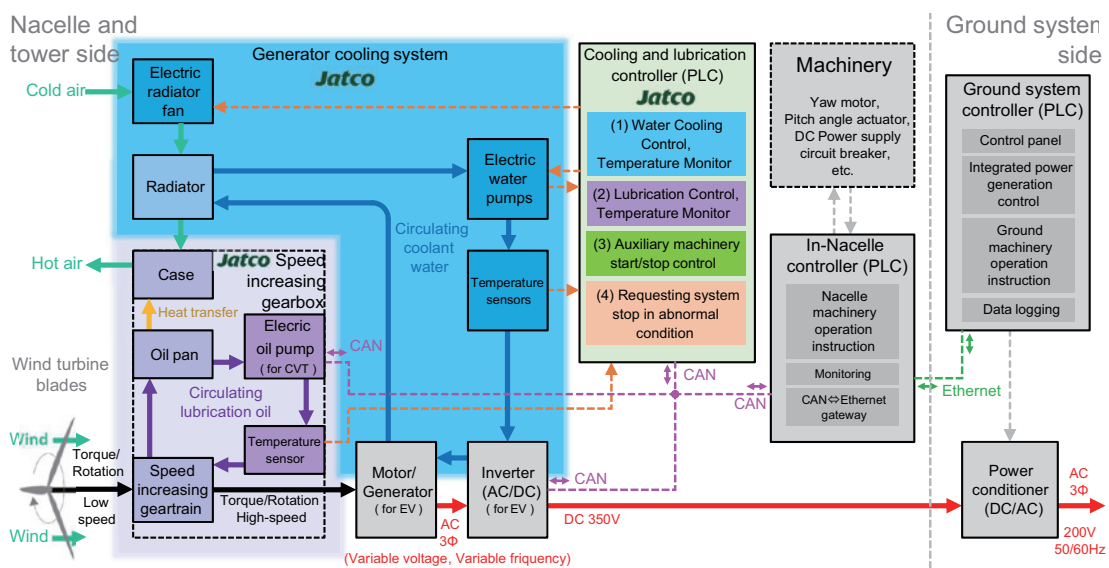


Fig. 7 Concept block diagram

Figure 9 shows an overview of the MBD development environment for PLCs and the software structure.

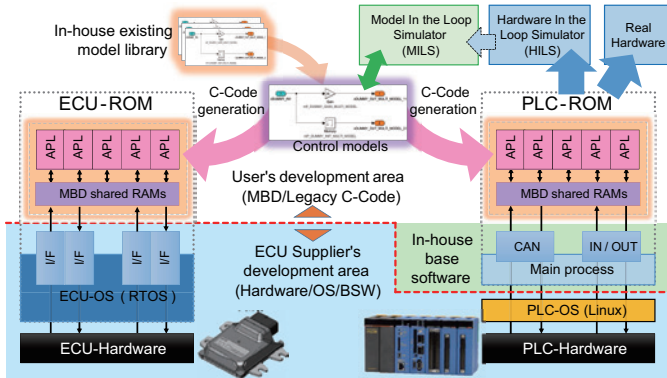


Fig. 9 Overview of MBD development environment and software structure

In addition, Fig. 10 shows the core part of the control model actually developed through the MBD process. Although this figure does not include processing such as input and output and shows only the core application part, we can see that the functional layout complies with Fig. 7.

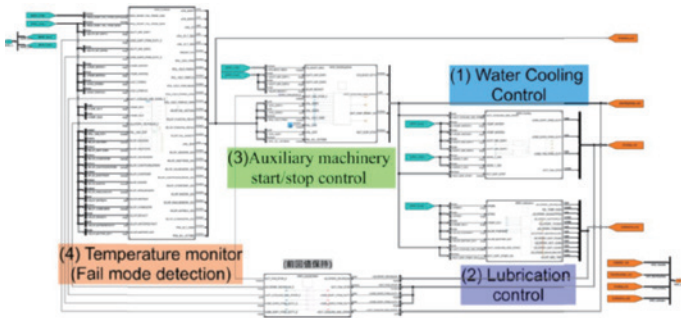


Fig. 10 Control model diagram (core part)

In the MILS verification, we performed operational verification at an early stage with a plant model connected to this core part. And in the subsequent HILS verification, we performed verification using an actual PLC by joining the core part to the basic software part of the PLC concurrently developed and to communication and input/output models into execution form. We thereby confirmed before the experiment that the control functions worked without problems within the scope of the assumed behavior of sensors and actuators.

We successfully reduced the development period through the utilization of an existing model library, development through the flexible organization of teams, and the front loading of the verification by applying MBD to these PLCs and operating MILS and HILS. In addition, as a side effect, we were able to form the foundation for the development scheme that applies MBD and reuses the control model library for automobiles also in PLC control development using our production equipment.

3.4 Experimental verification

We also applied the V-process, which is used for automobile development processes, to experimental verification as is the case with design. We were able to reduce the risk that issues would be detected in subsequent processes because in the V- process, we follow the steps of detecting issues in each process and taking measures against them before moving to the next process. This time, we set three separate processes, namely sub-system, nacelle, and wind turbine, and verified the required specifications in each process.

Table 3 shows the relationship between the respective processes and main verification items.

As the first step, we verified the sub-system. We verified the basic performance and reliability of the wind turbine, such as the power generation capacity and cooling water and oil temperatures, and its reliability with the generator and the increaser combined.

Next, we verified the nacelle. We operated the nacelle in various patterns by combining the generator and the increaser with peripheral units, and verified the impact of mutual interference, functions such as the startup and stop sequences, and reliability. As the final step, we are currently verifying the overall performance, functionality, durable reliability of the wind turbine in its assembled state.

Table 3 Relation between each process and testing items

Process	Performance verification	Functional verification	Reliability verification	Durability verification
Sub-system	○		○	
Nacelle		○	○	
Wind turbine	○	○	○	○

Here, the verification system for the sub-system is shown in Fig. 11. Since the maximum torque produced by the sub-system reaches as high as approximately 8,000 Nm, it is impossible for existing equipment for verifying automotive components to deal with it. However, if new equipment is introduced for performing verifications, there is concern it may cause a heavy cost to be incurred by introducing it and, what is more, the development schedule will be delayed due to a long delivery period. For this reason, we connected two prototypes, one of which was to be used for driving and the other for power generation, in this verification to build a verification system. As a result, it became possible for us to significantly reduce the cost of introducing the verification system, and we also performed the verification without hindering the development schedule.

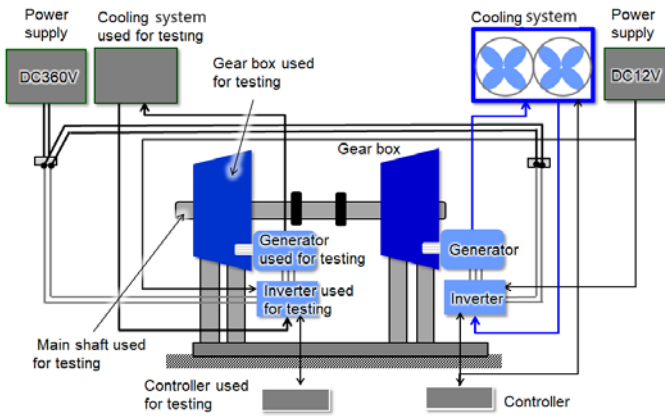


Fig. 11 Test system of sub-system

Next, the verification system for the nacelle is shown in Fig. 12. The nacelle is composed of multiple units such as a main shaft, its peripheral units, a turning unit, and other units. However, since the rotor of the wind turbine was not installed, we could not perform a verification while rotating the main shaft with wind or another external force. Thus, we operated the nacelle using the generator as the drive unit. As a result, we were able to verify the impact of mutual interference and functions, such as the startup and stop sequences.

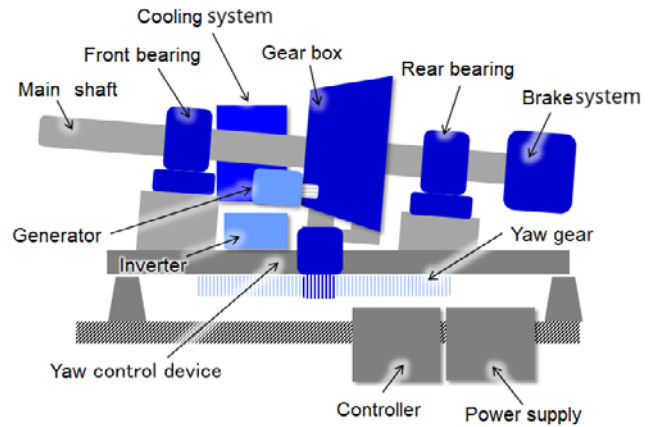


Fig. 12 Test system of nacelle

4. Verification results

Table 4 shows part of the verification results of the sub-system and the nacelle. As shown in Table 4, the required specifications were fulfilled in each verification.

Table 4 Testing results

Process	Items	Verification results
Sub-system	Rated power	○
	Rated speed	○
	Rated torque	○
	Efficiency	○
	Maximum coolant temperature in generator	○
	Maximum oil temperature in gear box	○
Nacelle	Sequence operation of start-stop	○
	Rotating operation of main shaft	○
	Operation of brake mounted on main shaft	○
	Yaw turning operation of nacelle	○

Here, the verification results of the efficiency of the generator and the increaser, which is one of the main indicators of the performance of the wind turbine, are shown in Fig. 13. The results confirm that setting an appropriate gear ratio for the increaser ensures the use of an efficient region of an automotive motor and contributes to realizing satisfactory power generation efficiency.

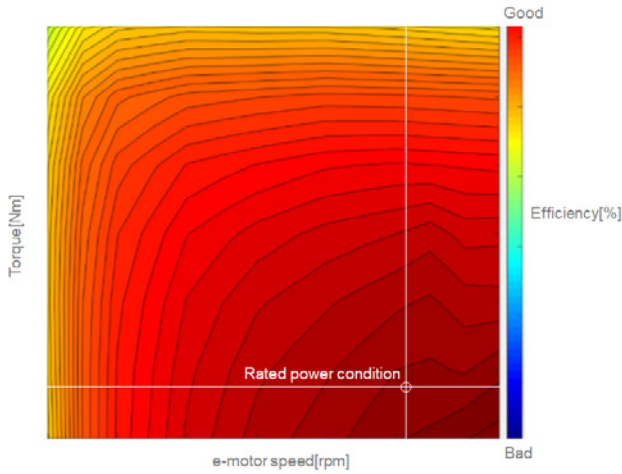


Fig. 13 Efficiency testing result

Next, the evaluation results of temperatures during continuous operation are shown in Fig. 14. This time, the nacelle was equipped with a PLC implemented with new control logic for the purpose of applying automotive cooling devices, such as a radiator, to the wind turbine, and both the temperature of the motor and that of the inverter were below the allowable range. This verifies that the wind turbine is capable of operating continuously without problems for a long time as is required for wind turbines.

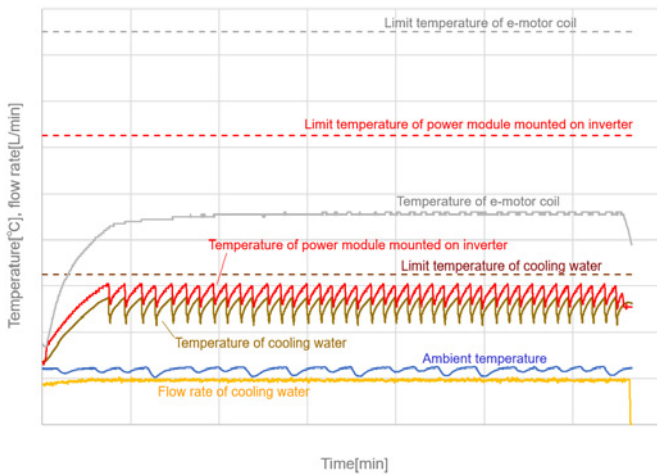


Fig. 14 Temperature testing result

The nacelle thus produced for the actual unit test was incorporated into the wind power generation tower for the demonstration experiment. Figure 15 shows the nacelle, and Fig. 16 shows the wind power generator.

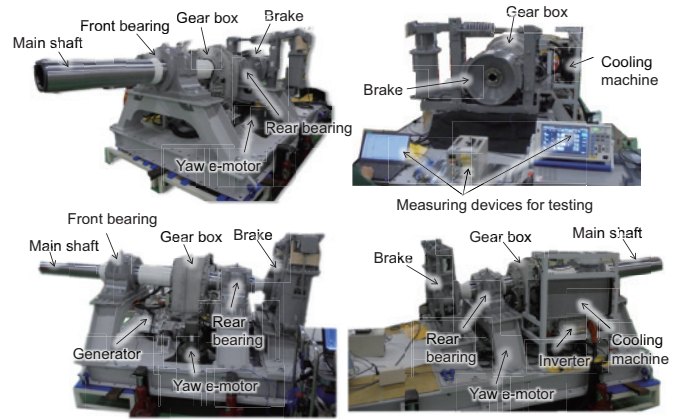


Fig. 15 Nacelle used for testing



Fig. 16 Wind turbine generator

5. Summary

We took on the challenge of developing Japan's first nacelle for 50-kw wind power generation under commission from the Ministry of the Environment and completed the prototyping of the demonstration wind power generator. Reductions of development periods and costs can be expected from the reuse of many automotive parts. In particular, we were able to verify the power generation performance and reliability of an actual generator by using a motor and an inverter for a car available on the market for the generator. In this verification, we confirmed the feasibility of the reuse of automotive parts. The SE we have established through the development of ATs and CVTs is also effective for this development.

6. Afterword

In the future, we aim to develop a technology for controlling power generation, charging, and the electric power supply by connecting a battery to the nacelle system (electric power management). By acquiring this technology, which means connecting a motor, an inverter, and a speed reducer to a battery and operating them (driving an EV) as desired, we will be able to open up a new vista as a system supplier (Tier 0.5).

7. References

(1)Zephyr Corporation: Commissioned Operation Report on Regional Co-Creation and Cross-Sector Type Carbon Neutrality Technology Development and Demonstration Project (Development and Demonstration of Technology Concerning Low-Voltage Wind Power Generators) (to be issued in 2024).

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