Featured Articles

Development of 5-MW Downwind Turbine and Floating Substation Facility for Offshore Wind Power

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OVERVIEW: To meet the societal demand for greater use of renewable energy, Hitachi is working on developing equipment that can be used in offshore wind farms. In terms of wind turbines, up to now Hitachi has developed 2-MW downwind turbines, and it is drawing on this experience to develop a more reliable 5-MW downwind turbine. A prototype turbine is currently being moved into commercial operation. This article describes the performance/function testing carried out during trial operation, and the test results. Since Japan has few areas of shallow coastal water, floating offshore wind farms are promising, so this article also describes the development of the floating substation facilities these wind farms will require.

INTRODUCTION

FOSSIL fuel depletion, global warming, and concern for the energy mix are resulting in rising societal demand for renewable energy sources. Wind power is one of the more cost-competitive renewables, and its use is being promoted worldwide. Offshore wind farms offer benefits such as a reduction in land-based sites, high or stable wind speeds, and low incidence of environmental problems such as noise. Many such sites are being planned inside and outside of Japan.

Hitachi has developed wind turbines to meet the societal demand for renewables. It installed a 2-MW downwind turbine prototype (model HTW2.0-80) in 2005, with 96 units of this model installed in Japan so far. In 2010, Hitachi installed seven units of the same model in the open ocean (a first in Japan), and added eight more units in 2013. Also in 2013, the company installed a floating offshore wind turbine off the coast of Nagasaki, and another off the coast of Fukushima[1]. These facilities are the first of their kind in Japan, and only the third of their kind worldwide.

Hitachi is currently developing a more cost-effective 5-MW downwind turbine (model HTW5.0-126). A prototype turbine was constructed in March 2015 on coastal land in Kamisu, Ibaraki Prefecture, and began commercial operation in September 2015. The development concept[1] and development process[2] have been discussed in previous articles. This article will discuss the performance/function testing done on the prototype turbine.

Since Japan has few areas of shallow coastal water, floating wind turbines and substations are needed. The development of the world's first floating offshore substation is discussed below.

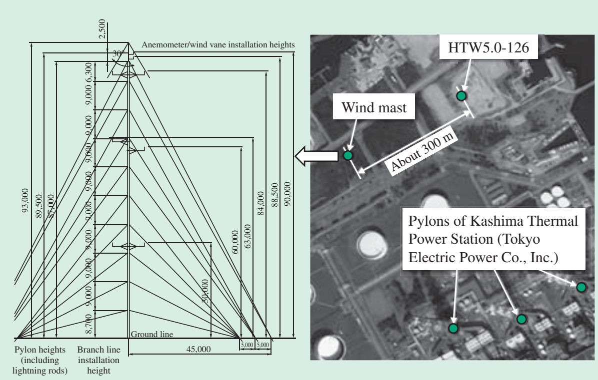
HTW5.0-126: BASIC SPECIFICATIONS, FEATURES

To withstand the typhoons that strike Japan and neighboring regions, the HTW5.0-126 was designed for an extreme wind speed of 55 m/s, in excess of the Class I standard specified by the International Electrotechnical Commission (IEC). Drawing

TABLE 1. HTW5.0-126 Basic Specifications
An output voltage of 33 kV was selected due to the cost effectiveness of using undersea cable for connecting to the land-based grid.

Rated output	5,000 kW
Rotor diameter	126 m
Number of blades	3
Rotor orientation	Downwind
Tilt angle	–8 deg
Output control	Pitch, variable speeds
Coning angle	5 deg
Extreme wind speed	55 m/s
Average wind speed	10 m/s
Turbulence category	A
Speedup ratio	1:40 (approx.)
Generator	Permanent magnet synchronous generator
Power conditioning system (PCS)	Full converter

Fig. 1—Photograph of the HTW5.0-126 Prototype Turbine.
The prototype turbine was installed in March 2015 in Kamisu, Ibaraki Prefecture, and is undergoing various types of performance/function testing.



* Google Maps is a trademark of Google Inc.

Fig. 2—Aerial Photograph of the HTW5.0-126 Prototype Turbine Site and Side View of the Wind Mast.
To determine the prototype turbine's generation performance, a wind mast was constructed near it to measure parameters such as wind speed. The aerial photograph of the prototype turbine site is from Google Maps(3).*

on Hitachi's previous wind turbine development experience, a downwind turbine rotor position was selected, providing superior performance during power failures in high winds and ensuring easy tower clearance. Table 1 lists the basic specifications of the HTW5.0-126, and Fig. 1 shows a photograph of it.

To increase reliability, the unit's structure features a medium-speed gear drive system, a shaft driven by dual-bearing outer ring drive, and passive cooling system.

HTW5.0-126 TRIAL OPERATION

Power Generation Performance Testing

In the vicinity of the HTW5.0-126 prototype turbine, Hitachi has installed a wind mast at the same 90-m height as the wind turbine's hub, and is evaluating the power curve. Fig. 2 shows an aerial photograph of the site, and the side view of the wind mast. The wind mast is installed about 300 m west-southwest of the wind turbine, wind speed and the wind direction height distribution, air pressure, temperature, and humidity are being measured.

Fig. 3 shows the measured power curve. Since there are pylons belonging to the Kashima Thermal Power Station (owned by the Tokyo Electric Power Co., Inc.) located on the south side of the wind turbine, the data for the southern wind direction has been omitted from the analysis. Although the wind turbine's method of operation is currently being adjusted,

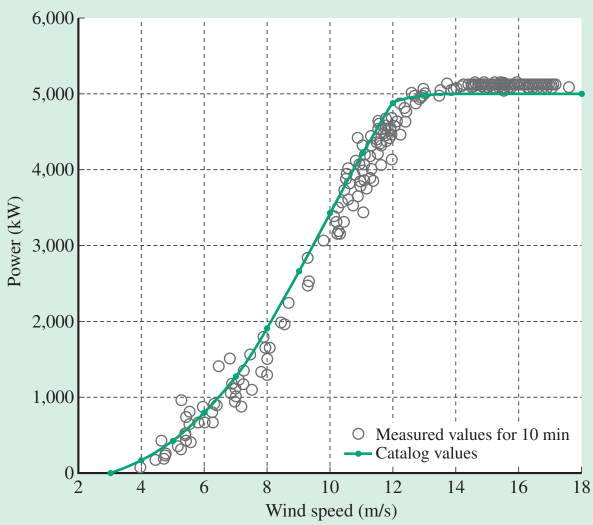


Fig. 3—Measured Power Curve Values.
The curve shows the correlation between the power and the wind speed measured by the wind mast at the height of the wind turbine hub. The performance obtained closely resembles the anticipated catalog values.

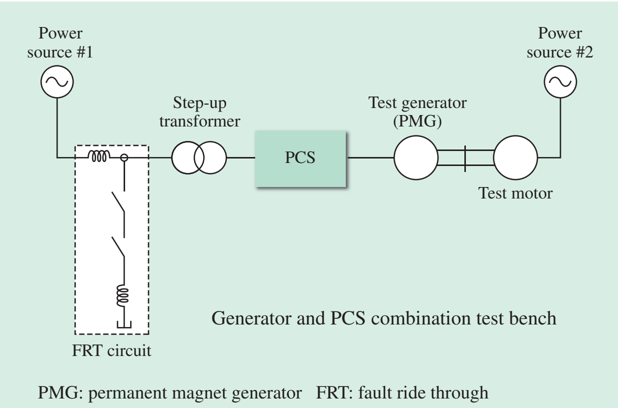


Fig. 4—Factory Testing Configuration (FRT Function Verification).
The generator to be tested was driven by a test motor, and an FRT circuit simulating a voltage drop was installed on the grid output side of the PCS.

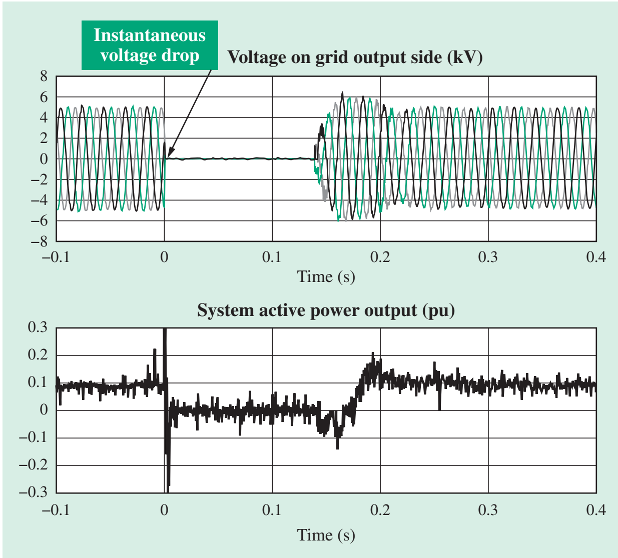


Fig. 5—Example FRT Function Test Waveforms.
This example shows that output continued during the 0.15-second interval in which the power voltage dropped to 0 V. Generation output recovered within 0.1 seconds after the voltage was restored.

Hitachi has verified that performance similar to the expected values can be obtained.

Test of Continuous Operation during Grid Faults

The HTW5.0-126 downwind wind power generation system comes with an fault ride through (FRT) function provided as a standard feature. When an instantaneous voltage drop occurs due to a grid fault, the FRT function allows the system to continue operating without taking the turbine offline as long as the grid voltage drop level and voltage drop time are within the specified ranges. Factory testing of a combination of the generator and power conditioning system (PCS) has verified that this function meets the specification requirements. Fig. 4 shows the factory test configuration. The FRT circuit simulates a voltage drop during a grid fault. Fig. 5 shows an example factory test waveform. Hitachi has verified that the generation output was covered within the time specified by the Japanese standard(4) after the grid voltage was restored.

Hitachi is also conducting grid fault continuous operation testing on the HTW5.0-126 prototype turbine. This verification testing is done by inserting an FRT circuit between the wind turbine and the network substation used for connecting to the power company, and checking the behavior of the entire wind power generation system. It is scheduled to be completed within FY2015.

Cooling Performance Testing

To cool the nacelle and tower, the HTW5.0-126 uses a passive cooling system that has no fan for the radiator. Computational fluid dynamics was used to design the nacelle shape and radiator placement to obtain the air flow needed for cooling.

For the nacelle cooling system and tower cooling system during operation of the prototype turbine under load, Fig. 6 shows the correlation between the temperature of the cooling water (relative to the outside air) after passing through the radiator and the nacelle wind speed. The diagram shows that the cooling water temperature is low when the nacelle wind speed is high, resulting in higher cooling efficiency, and verifying the validity of the cooling system design.

Load Evaluation Testing

When designing the wind turbine, the loads on various turbine parts and cross-sections were calculated using aeroelastic analysis. These loads were used as input conditions to evaluate strength by calculating stresses on detailed models using methods such as the finite element method (FEM). Verifying upstream loads is important when evaluating the structural soundness of wind turbines(5).

The loads on the wind turbine parts are currently being verified. The results of verification of the flapwise bending moment (‘flap bend’) on the blade roots are presented here. Measurement was done using strain gauges installed on the positive and negative pressure sides in the flapwise. The difference between the two measurements was divided by 2 to remove

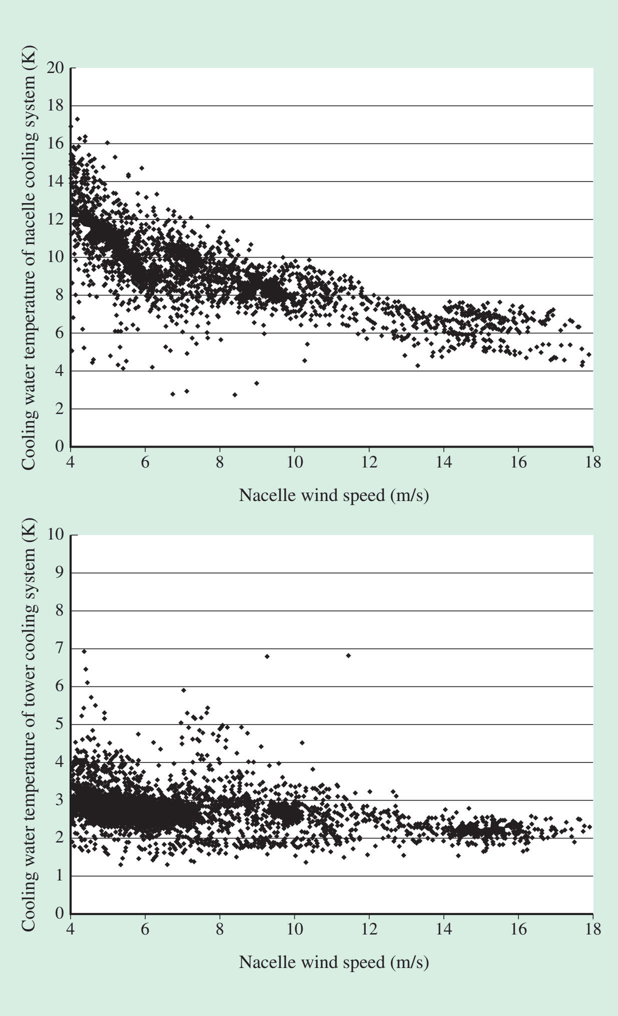


Fig. 6—Correlation between Cooling Water Temperature and Nacelle Wind Speed.
In the nacelle cooling system and tower cooling system, cooling water temperature is low when nacelle wind speed is high, resulting in higher cooling efficiency.

effects such as the equivalently applied centrifugal force, and then multiplied by a conversion factor to calculate the bending moment.

Fig. 7 and Fig. 8 show the flap bend evaluation results while generating power. Fig. 7 shows the average, maximum, minimum, and standard deviation values for 10 minutes of data. Fig. 8 shows the damage equivalent load (DEL). Values labeled 'measured' in the diagrams are actual measurement values, and values labeled 'design' are design values obtained using an aeroelastic analysis software application called Bladed[6]. The values are ratios to the DEL design value at 10 m/s.

DEL was calculated using the following formula.

$$R_{eq} = (\Sigma R_i^m \cdot n_i/n_{eq})^{1/m} \qquad (1)$$

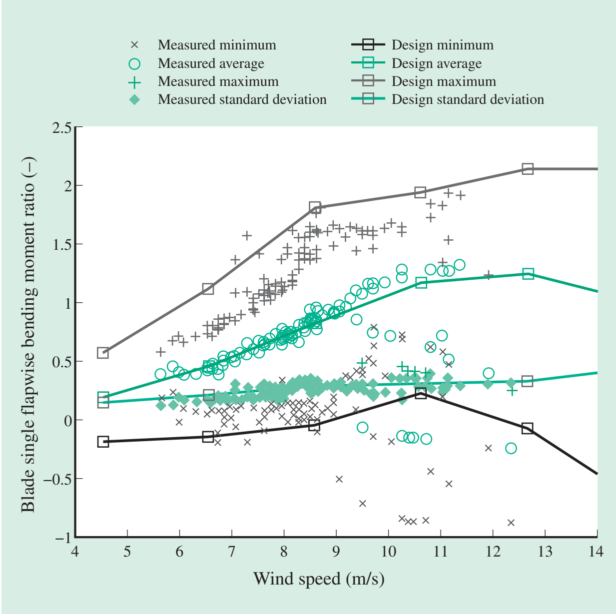


Fig. 7—Statistical Values of Flapwise Bending Moment at Blade Roots.
The graph shows 10 minutes of statistical values for blade flap bend relative to the average wind speed over a 10-minute period.

Where R_{eq} is the DEL, R_i is the load range of the ith bin in the fatigue load spectrum, n_i is the repetition count of the ith bin in the fatigue load spectrum, n_{eq} is the equivalent repetition count (600), and m is the slope of the stress-number of cycles to failure (S-N) curve of the material.

The measured average values and design average values in Fig. 7 are closely matched, indicating that the aeroelastic analysis faithfully reproduced the static behavior of the equipment. The measured maximum values are smaller than the design maximum values, and the measured minimum values larger than the design minimum values, resulting in the fatigue load of Fig. 8 also having smaller measured values than design values. Flap bend DEL is dominant during power generation, indicating that fatigue in parts greatly affected by flap bend is unlikely to be a problem.

VERIFICATION TESTING OF FLOATING SUBSTATION FOR OFFSHORE WIND POWER

Unlike the North Sea in Europe, Japan's coastal waters have few shallow areas, making floaters the best approach to offshore power generation. This chapter describes the Fukushima Floating Offshore Wind Farm Demonstration Project implemented as a

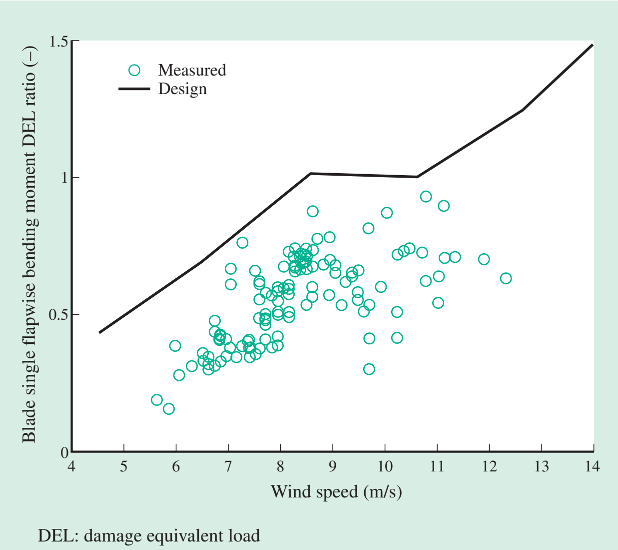


Fig. 8—Flapwise Bending Moment Fatigue Load at Blade Roots.
The graph shows 10 minutes of fatigue equivalent load values for blade flap bend relative to the average wind speed over a 10-minute period.

Fig. 9—Photograph of Exterior of Offshore Substation.
The substation has one 66-kV incoming line and transformer output of 25 MVA. Its equipment is housed within the upper deck. This photograph was taken off the coast of Onahama, Fukushima Prefecture. The substation is shown in the foreground, with a 2-MW Hitachi wind turbine in the background (photo courtesy of the Fukushima Offshore Wind Consortium).

demonstration project in FY2011 by Japan's Agency for Natural Resources and Energy. Fig. 9 shows a photograph of the offshore substation.

Offshore Substation Equipment Vibration Testing

Drawing on the experiences of past major earthquakes, substations produced in recent years are highly seismic-resistant products. Floaters need to withstand normal ocean rolling as well as the extreme rolling produced by typhoons that occur once every few decades. To verify rolling resistance, extensive study was done during the design phase of the Fukushima project, and the performance of switches (66-kV gas insulated switchgears and 24-kV vacuum insulated switchgears) was verified by placing them on vibration generators for testing. Since the main transformer (66 kV, 25 MVA) weighs more than 50 t, there were very few vibration generators that could handle its weight. Its performance was therefore verified by simulating the acceleration produced by rolling by tilting the transformer instead (see Fig. 10).

In addition to rolling, other concerns for ocean-based facilities are rust and damage caused by sea salt. Serviceability is different from land-based facilities. Creating an environment that enables optimum paint refinishing and service work is easy for land-based facilities, but there are limitations for ocean-based facilities that must be considered during design. Although the only equipment actually located outside is the transformer, radiators made of thin sheet material are galvanized or zinc-sprayed to ensure low maintenance.

Verification Testing

Since coming online in October 2013, the project has accumulated nearly two years' worth of performance data. It has experienced several major typhoons, but has continued to operate without problems from rolling or other causes. The effects of salt damage to

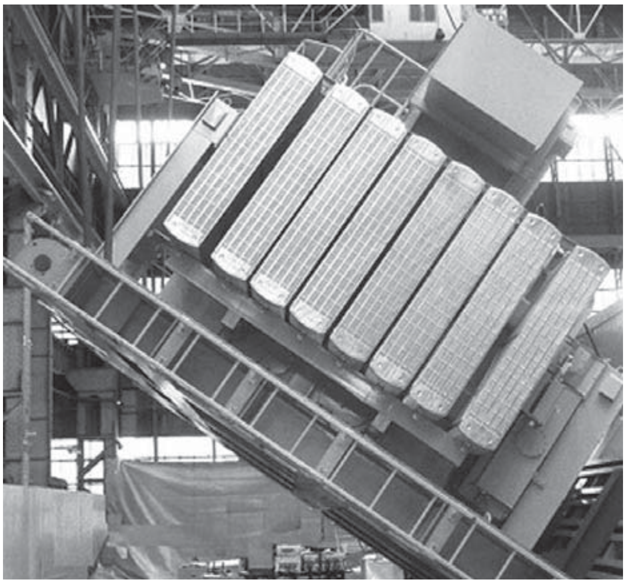


Fig. 10—Transformer Tilt Test.
The photo shows the transformer tilt test done at a test facility in Kokubu Works of Hitachi, Ltd.

the transformer exposed to the outdoor environment are within the expected severity level. Going forward, Hitachi plans to implement cost reduction/design evaluations for the future.

CONCLUSIONS

This article has described the performance/function testing carried out on Hitachi's HTW5.0-126 downwind turbine, the test results, and the development of a floating substation.

In the future, Hitachi will carry out further performance/function testing in areas such as noise, identifying and improving the equipment characteristics. It will also work on the verification of new control methods. These activities will enable Hitachi to offer high-performance/high-reliability equipment to society.

ACKNOWLEDGMENTS

We would like to express our appreciation to the New Energy and Industrial Technology Development Organization (NEDO) for its assistance in the development of the HTW5.0-126 5-MW downwind turbine.

We would also like to express our appreciation to the members of the Fukushima Offshore Wind Consortium for their assistance in the Fukushima Floating Offshore Wind Farm Demonstration Project.

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