Development of 2-MW Downwind Turbine Tailored to Japanese Conditions

Takashi Matsunobu
Tsutomu Hasegawa
Mitsuru Isogawa
Kazuhiko Sato
Moto Futami
Hiroshi Kato

OVERVIEW: Wind turbine systems play a key role in reducing use of fossil fuels and the emission of greenhouse gasses such as carbon dioxide. Turbines used in wind farms for commercial production of electric power need higher reliability, enhanced efficiency, and cost effectiveness. Especially in Japan, there is a surge in demand for systems that can tolerate storm loads, are protected against lightning, do not cause logistical problems, and can produce a stable electricity output. Hitachi and Fuji Heavy Industries Ltd. have developed a 2-MW downwind turbine tailored to Japanese conditions. The first model for commercial production of electric power has successfully been built at Hitachi Chemical Co., Ltd. Kashima Works, about 100 km east of Tokyo, and successfully operated by Wind Power Ibaraki Ltd. The operation has met the design specifications.

INTRODUCTION

THE characteristics required of wind turbines include greater capacity, better reliability, greater efficiency, quick installation, and lower maintenance costs. Demand for wind turbine generation systems is growing strongly because they help reduce carbon dioxide emissions and prevent the greenhouse effect.

Hitachi and Fuji Heavy Industries Ltd. have developed a 2-MW downwind turbine called the "SUBARU 80/2.0." This pitch-regulated

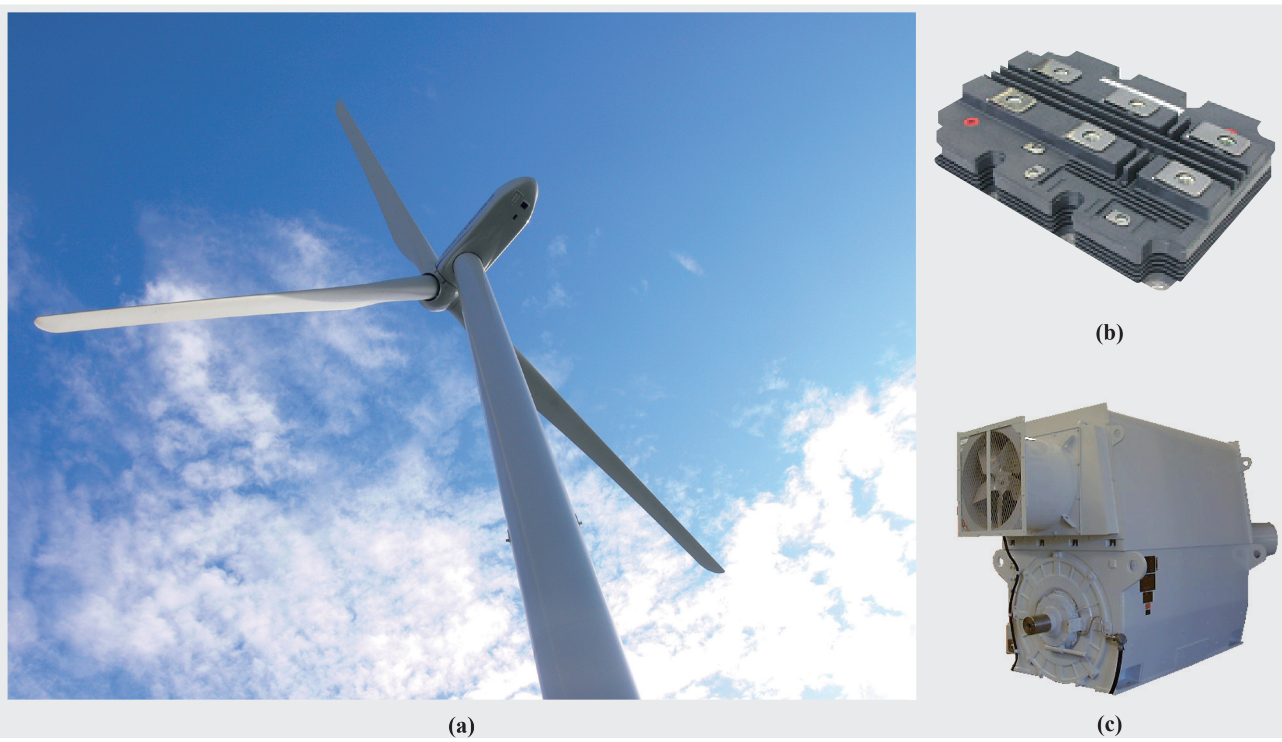


Fig. 1—First SUBARU 80/2.0 2-MW Downwind Turbine to Commence Commercial Production of Electric Power (a), IGBT (b), and Generator (c).
The Hitachi Chemical Co., Ltd. Wind Power Station operated by Wind Power Ibaraki Ltd. (a), an IGBT (insulated gate bipolar transistor) module (b) and a 2,000-kW doubly fed generator (c) are shown.

downwind turbine has active yaw control, a three-blade rotor, gearbox, doubly fed generator, and power conditioning system (see Fig. 1). The 80-m rotor diameter makes possible a high level of efficiency. The nacelle is located at the top of a 60-m or 80-m high tower. The design specifications for the downwind turbine were set at a higher level than required by IEC (International Electrotechnical Commission) regulations. The resulting characteristics (described below) mean the turbine can be constructed and operated under typical Japanese conditions.

(1) Downwind rotor with increased output and stability
(2) Heavy-duty system that satisfies IEC Wind Class 1
(3) Protection against severe positive lightning (95% coverage)
(4) Active power control simplifies connection to the grid.
(5) Easy component transportation through use of a modular nacelle
(6) Light nacelle and easy maintenance

HISTORY OF 2-MW DOWNWIND TURBINE

Hitachi and Fuji Heavy Industries started testing a prototype of the 2-MW downwind turbine system at a demonstration site in 2005. The site at the tip of the Inubo Peninsula faces east toward the Pacific Ocean and is about 100 km east of Tokyo. Subsequent testing used a commercial model.

In 2008, the first 2-MW downwind turbine to be used for commercial production of electric power was delivered to Hitachi Chemical Co., Ltd. Kashima Works. The turbine is sited about 3 km west of the prototype and is operated by Wind Power Ibaraki Ltd.

Both turbines have supplied electric power to a utility company during the one to four years since their delivery.

PERFORMANCE AND EQUIPMENT COMPOSITION

Wind Turbine System

The 2-MW downwind turbine is an HAWT (horizontal-axis wind turbine) with the specifications shown in Table 1. It includes the following components.

Downwind rotor

The 2-MW downwind turbine uses a downwind rotor which means that the turbine is positioned downwind of the tower (see Fig. 2). A downwind turbine configuration has the following advantages because the wind force keeps the turbine in line with the wind direction behind the tower.

(1) The blades do not need to be rigid because a rotor can never hit the tower.
(2) The nacelle naturally aligns itself with the wind direction even during black-out conditions.

TABLE 1. 2-MW Downwind Turbine Specifications
With a blade tip height of 120 m, the commercially produced model will be one of the largest wind turbines in Japan.

Category	Item	Specification
Turbine	Diameter	80 m
	Hub height	80 m
	Rated output	2,000 kW
	Cut-in	4 m/s
	Cut-out	25 m/s
Generator	Type	Doubly-fed
	No. of poles	4
	Frequency	50 Hz or 60 Hz
System	Speed control	Variable velocity
	Output control	Pitch control
	Emergency brake	Pitch control
	Yaw control	Active yaw
Lightning	Protection level	250 kA

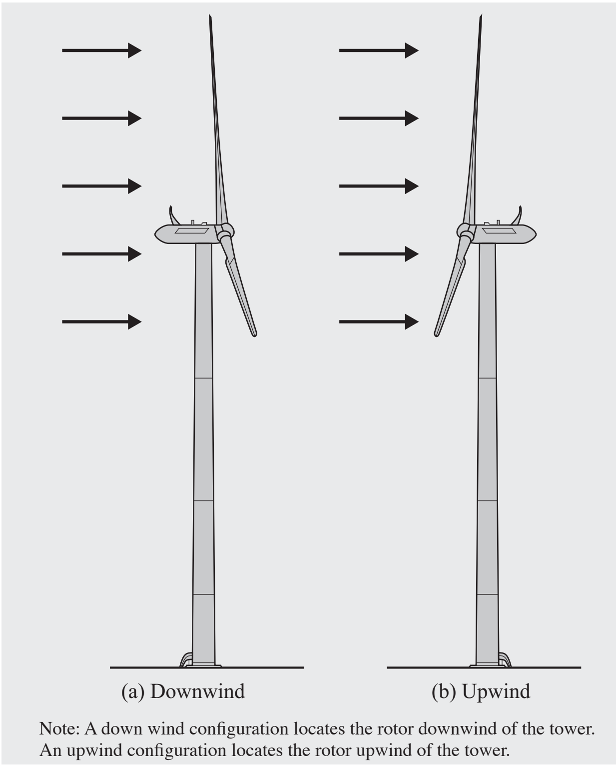


Fig. 2—Comparison between Downwind and Upwind Configurations.
The 2-MW downwind turbine takes advantage of its downwind configuration to obtain high efficiency and stable output.

(3) The rotor orientation aligns with updrafts and this provides high efficiency.

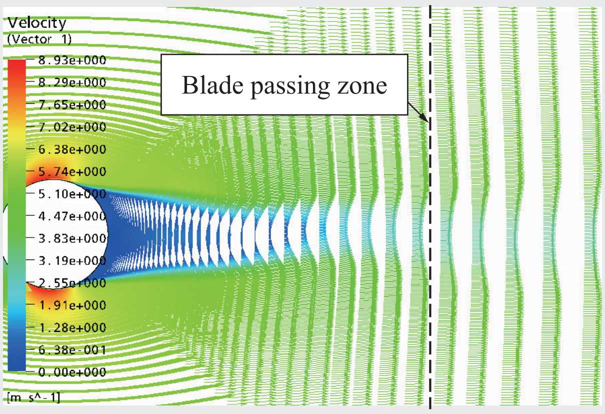
However, a downwind turbine configuration also has the following concerns due to the turbulence produced by the tower.

(1) The tower wake may cause cycle-fatigue in the blades.

(2) Interference between blade and tower may produce low-frequency noise.

Accordingly, use of a downwind turbine configuration requires special design considerations to ensure best use is made of the advantages while also dealing with the concerns.

An advanced aerodynamic design is used to address these issues of blade fatigue and noise caused by the tower wake. Field testing was conducted to demonstrate that the blade can successfully avoid the tower wake. The distance between the blade and tower provides a significant reduction in the overall cycle fatigue behavior of the blades. Fig. 3 shows a three-dimensional analysis used to determine the stress on the blade at a distance from the tower of three times the tower diameter. Although the results show a significant amount of stress, the level is within the design requirements. The testing demonstrated that the turbine successfully met all the environmental and stress requirements.



Note: The wake is the zone of turbulence produced by the tower.

Fig. 3—Tower Wake Analisys [1].
The 2-MW downwind turbine has enough distance between tower and blade to avoid the tower wake.

Hub and blade structure

The hub is mounted on the gearbox and connected by the main shaft which transmits the wind power to the generator. The rotor has an independent pitch control system which uses electrical actuators to keep the blade at the optimum pitch angle.

The blades are made of GFRP (glass fiber reinforced epoxy resin). Two GFRP ribs are encased in two shells. The blades are designed to minimize mechanical losses.

Nacelle

The nacelle (see Fig. 4) contains the main shaft, gearbox, generator, and associated components. The nacelle bedplate has a girder structure. The gearbox is attached to the bedplate and transmits the torque from the main shaft to the generator. A roller bearing is used for the yaw system together with electrical actuators and a hydraulic brake system. The step-up transformer and power conditioning system are not located in the nacelle. This was done to keep the nacelle weight down and to make these components more easily accessible for maintenance.

Fig. 4—Nacelle of 2-MW Downwind Turbine.
The nacelle is designed for light weight and with a streamlined shape to avoid disruption to the wind flow. The wind blows from right to left in the above figure.

Tower structure

The conical tubular-steel tower is made up of four segments to make transportation easier. A door near ground level permits access to the internal components and the nacelle is accessed via ladders or a service lift. The power conditioning system is mounted in the tower base. Bus bars are used to carry the power from the generator in the nacelle to the bottom of the tower. Optical glass fiber cables are used for all control signals to avoid any problems with electromagnetic interference.

Electrical system

An asynchronous 4-pole air-cooled doubly-fed generator with a wound rotor and wound stator

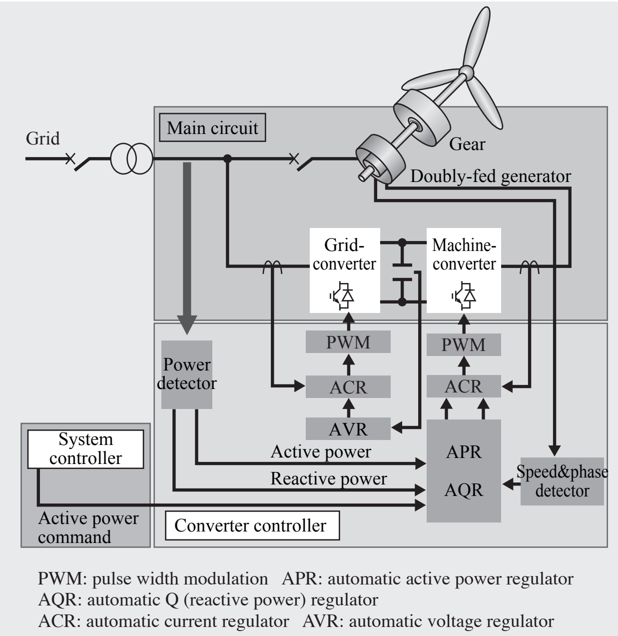


Fig. 5—Configuration of Power Conditioning System.
Active and reactive power control (2) *provides a steady output and easy grid connection.*

is used. The converter system controls the rotor's magnetic field to allow the rotor speed to be varied within a wide speed range. This electrical system can control the turbine power factor within the range 0.95 leading to 0.9 lagging. This is a requirement of the utility company to reduce power fluctuations in the power grid system. Steady variations of the grid are within around +3/-3 Hz. Fig. 5 shows a single-line diagram of the electrical system. The specially designed IGBTs (insulated gate bipolar transistors) allow the generator to have a voltage of 1,400 V which is higher than usual for a wind turbine generator. The higher voltage results in lower losses in the power transmission lines between the nacelle and the converters located at ground level.

Lightning protection

The level of protection against lightning (pass-through energy) on the 2-MW downwind turbine system is ten times higher than stipulated in the IEC61400-24 standard for lightning protection on wind turbine generators. The protection system is designed to cover positive lightning (upward flashes initiating from the ground) which is a common form of lightening in environments such as the Atlantic coast of Norway or the Japan Sea coast of Japan. The lightning protection mechanism used on the 2-MW downwind turbine is as follows.

The blades contain conductors that run from the tip to the bottom. These conductors are connected to receptors in the middle of the blades and to the metal at the tip[3]. The lighting current flows from the blade to the ground through slip rings which transfer the current through the rotating mechanism and act as a bypass circuit to protect the bearings.

A lightning rod is also fitted at the front of the nacelle. This protects the wind sensor and ensures that the lightning current flows to the tower without causing damage. The receptors, metal parts, and lightning rod are all connected to ground through a common interconnecting circuit.

LPZs (lightning protection zones) and thorough shielding is used inside the nacelle and tower structure. All the shields are terminated at a metal box or the tower wall which acts as an extension of the shield. The nacelle acts as a Faraday cage to shield the interior from the electromagnetic radiation generated by external lightning. The LPZs ensure that the wind turbine's control system can withstand any electromagnetic field or lightning current that enters each zone. This approach is based on the IEC 62305 standard.

Logistics and Construction

Since difficult terrain can complicate the logistics of transporting the heavy and bulky major components to the site, a feature of the 2-MW downwind turbine is the use of modular construction (consisting of nacelle, drive-train, and hub modules).

The nacelle and tower can be divided into several sub-components none of which weigh more than 40 tons, the typical carrying capacity of Japanese roads. The light weight of these sub-components make the transportation and installation process comparable to that for a standard 1-MW turbine.

Although the site chosen for the 2-MW downwind turbine did not have difficult terrain and no logistic difficulties with heavy or bulky equipment were experienced when transporting the major components, the site was used to trial the modular construction technique (for the nacelle, drive-train, hub, and rotor). It can be demonstrated that modular construction avoids the expense of upgrading trucks or improving the roading infrastructure. Fig. 6 shows a photograph of a blade being attached to the hub. The space required to set up the rotors is less if this is done at the top of the tower rather than at ground level. A 550-t crawler crane was used to place the major components in position. The crane capacity was less than that typically used for 2-MW class wind turbines.

Fig. 6—Blade Being Attached to Hub at Top of Tower.
Assembling the rotor in the air one blade at a time saves on ground space.

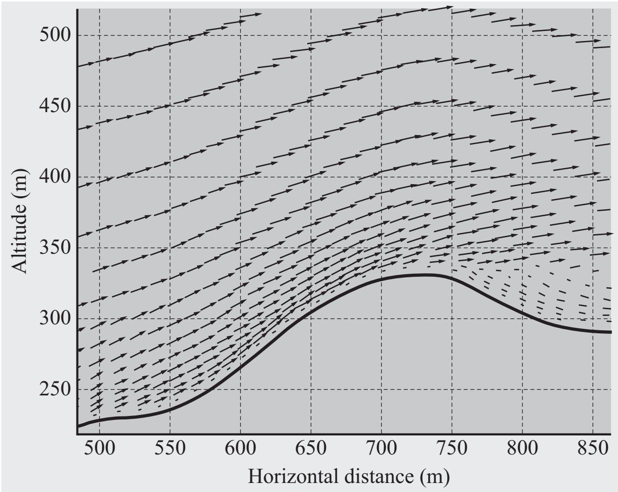


Fig. 7—Airflow over Mountain Slope [4].
A mountain slope or ridgeline often acts to concentrate the wind resulting in an updraft and higher wind speed.

PREDICTION OF DOWNWIND EFFECTS

Complex terrain like that often found on mountainsides in Japan is considered unattractive for wind development and is often excluded when selecting wind turbine installation sites. Complex terrain can cause the wind-flow to be concentrated resulting in updrafts and high wind speeds.

Mountain slopes and ridgelines often act to concentrate the wind flow resulting in updrafts and high wind speeds (see Fig. 7). An upwind turbine with a tilted rotor does not take full advantage of this effect due to misalignment with the wind direction. For downwind turbines, however, this misalignment is smaller and more power can be obtained. Downwind turbines are considered to be the best choice for large wind turbines located on mountainsides.

Because the 2-MW downwind turbine is located on flat terrain and therefore is not subject to updrafts, it was decided that an analysis method should be developed. A number of different approaches were considered and the following formula[4] chosen as being the most accurate.

$$P(V) = \min\left\{P_{Rate}, \left(\frac{\cos(\gamma+\alpha)}{\cos\gamma \times \cos\alpha}\right)^3 \times P_0\right\}$$

Here, P is output power, P_{rate} is rated power, P_0 is power from the power curve, γ is wind inclination and α is the tilt angle of the main shaft (8 degrees for the 2-MW downwind turbine).

For an updraft inclination of +6.0 degrees, a downwind turbine can be expected to produce 7.6% more power than an upwind turbine.

CONCLUSIONS

This article has described the development of a 2-MW downwind turbine system for the commercial production of electric power. The experience gained during the analysis, construction, and commercial operation phases has proved valuable for future designs. Whereas mountainous areas with complex terrain like those found on mountainsides in Japan used to be overlooked and considered unattractive for wind development in the past, this development has solved some of the problems associated with installing wind turbines in mountainous areas. Hitachi and Fuji Heavy Industries Ltd. are aiming to make further improvements in the quality, reliability, and safety of the 2-MW downwind turbine system to encourage the growth of the Japanese wind energy business.

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ABOUT THE AUTHORS

Takashi Matsunobu

Joined Hitachi, Ltd. in 1983, and now works at the Generator System Division, Power & Industrial Systems Division, Power Systems Company. He is currently engaged in the development of wind turbine business.

Tsutom Hasegawa

Joined Hitachi, Ltd. in 1982, and now works at the Wind Turbine Engineering Group, Generator System Division, Power & Industrial Systems Division, Power Systems Company. He is currently engaged in the development of wind turbine business. Mr. Hasegawa is a member of the Institute of Electrical Engineers of Japan (IEEJ).

Mitsuru Isogawa

Joined Hitachi, Ltd. in 1972, and now works at Wind Turbine Engineering Group, Generator System Division, Power & Industrial Systems Division, Power Systems Company. He is currently engaged in the development of wind turbine business. Mr. Isogawa is a member of the IEEJ.

Kazuhiko Sato

Joined Hitachi, Ltd. in 1982, and now works at New Energy Systems Engineering Section, Hitachi Works, Power Systems Company. He is currently engaged in the development of wind turbine systems.

Moto Futami

Joined Hitachi, Ltd. in 1987, and now works at Power Electronics Systems Unit, Hitachi Research Laboratory. He is currently engaged in the development of power electronics systems. Mr. Futami is a member of the IEEJ.

Hiroshi Kato

Joined Fuji Heavy Industries Ltd. in 1985, and now works at Eco-Technologies Company of Fuji Heavy Industries. He is currently engaged in the development of wind turbine systems.