# Power Generation, Distribution and Substation System for Development of Offshore Wind Farms

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*OVERVIEW: With use of renewable energy growing worldwide, wind power generation in particular is expected to play a major role, having a comparatively low per-kilowatt cost. While most wind power generation in Japan to date has been land-based, an expansion is anticipated in the development of offshore sites, which offer more reliable and stronger wind conditions. Hitachi has developed a large 5-MW downwind wind power generation system for the construction of offshore wind farms, and supplies total solutions that extend from generation to power delivery, including substation and transmission systems.*

## INTRODUCTION

RECENT years have seen growing interest in renewable energy in Japan because of its potential to help protect the global environment and provide a domestic source of energy. Prompted by the introduction of feed-in tariffs for renewable energy in July 2012, Japan has seen steady progress on developments in this field, including of wind power generation.

While most of the wind power generation systems currently operating in Japan are land-based, offshore sites are seen as having great potential, with advantages that include stronger wind conditions and being less likely to raise concerns such as noise or impact on the scenery. According to the “Report on FY2010 Study of Potential for Introduction of Renewable Energy”(1) published by the Ministry of the Environment, there is the potential in Japan for the installation of as much as 1,570 GW of offshore wind power. This is roughly eight times the 203.97 GW total installed capacity of Japan’s ten power companies in FY2009(2).

While the construction of an offshore wind farm typically requires a greater investment than a land-based site, a large part of this is due to the foundations being larger and more complex than on land, and also due to the offshore installation work and transmission system, including undersea cable. Accordingly, to improve the economics of offshore wind farms, it is better to increase the output per turbine so that the total number of installed turbines can be reduced. This requires wind power generation systems that are larger than the 2- to 3-MW-class turbines that are considered large by land-based standards.

This article gives an overview of a large 5-MW downwind wind power generation system designed for use in offshore wind farms, and describes substation and distribution systems for such wind farms.

## LARGE 5-MW OFFSHORE WIND POWER GENERATION SYSTEM

### Features of Downwind Wind Power Generation System

Fig. 1 shows the overall dimensions of the large HTW5.0-126 wind power generation system with a rated output of 5 MW that is currently under development. Fig. 2 shows the design power curve and Table 1 lists the main specifications.

Like the existing 2-MW HTW2.0-80 wind power generation system, this new model has a downwind configuration. Most large wind turbines have an

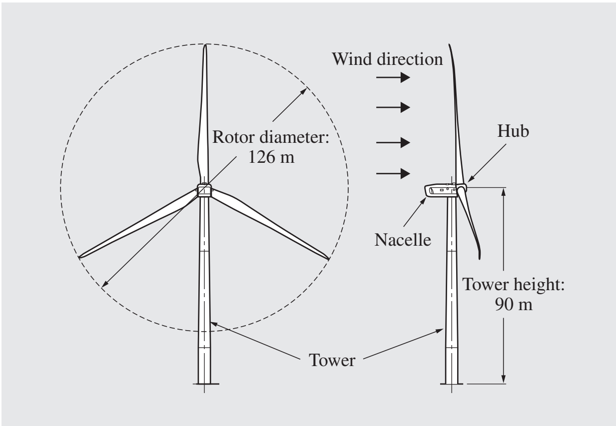


*Fig. 1—Overall Dimensions of HTW5.0-126.*
*The large HTW5.0-126 wind power generation system has a rated capacity of 5 MW.*

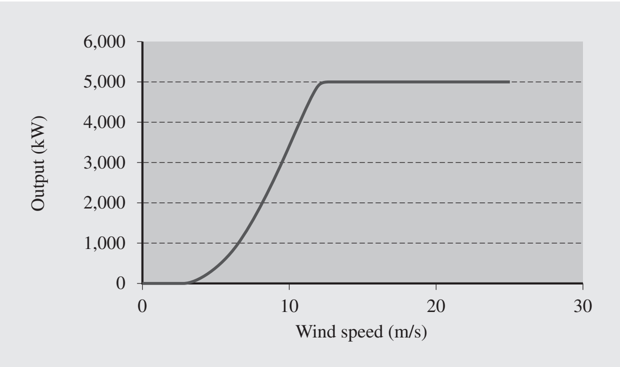


*Fig. 2—Design Power Curve.*
*The design power curve of the HTW5.0-126.*

upwind configuration, meaning the rotor is upwind of the tower. However, in situations such as when an outage caused by a grid fault coincides with a sudden change in wind direction, for example, the overturning moment experienced by a downwind turbine is lower because it can immediately switch to free yaw operation in which the nacelle naturally orients itself along the direction of the wind. This should reduce construction costs by simplifying the turbine foundations throughout the wind farm.

Also, wind turbines are fitted with an anemometer for yaw control. Whereas upwind turbines typically mount this anemometer downwind of the rotor, the ability to have the anemometer upwind of the rotor in a downwind turbine minimizes the influence of blade wake turbulence and reduces loss of generation due to yaw error (see Fig. 3).

Another consequence of having the rotor on the downwind side is that, during strong winds, rising wind speeds tend to increase the clearance between the blades and tower. This is a safety advantage because it reduces the risk of the blades coming into contact with the tower, in contrast to an upwind turbine where higher wind speeds reduce the clearance between the blades and tower (see Fig. 4).

## Equipment Configuration of Large 5-MW Wind Turbine

Fig. 5 shows the equipment layout in the nacelle of the large 5-MW wind turbine. Large wind turbines typically use variable-speed operation in which the speed of rotation is varied to keep the tip speed ratio ($\lambda$) constant with changes in wind speed (see Fig. 6). Because the tip speed ratio for a particular blade shape needs to be kept the same regardless of turbine size, this means that, under the same wind speed conditions, the angular velocity needs to be reduced as the rotor

Table 1. Main Specifications
*Like the 2-MW HTW2.0-80, the HTW5.0-126 has a downwind configuration.*

| | **HTW5.0-126** | **HTW2.0-80 (for reference)** |
|---|---|---|
| Rated output | 5,000 kW | 2,000 kW |
| Rotor orientation | Downwind | Downwind |
| Rotor diameter | 126 m | 80 m |
| Hub height | 90 m | 65 m/80 m |
| Output control | Pitch, variable speed | Pitch, variable speed |
| Yaw control | Active yaw | Active yaw |
| Idling in strong winds | Free yaw | Free yaw |
| Gear ratio | 1:40 (approx.) | 1:100 (approx.) (50 Hz)<br>1:120 (approx.) (60 Hz) |
| Generator | Permanent magnet synchronous generator (36-pole) | Doubly fed induction generator (4-pole) |
| Cut-in wind speed | 4 m/s | 4 m/s |
| Cut-out wind speed | 25 m/s | 25 m/s |
| Wind speed class | S (10 m/s mean annual wind speed) | IIA+ |

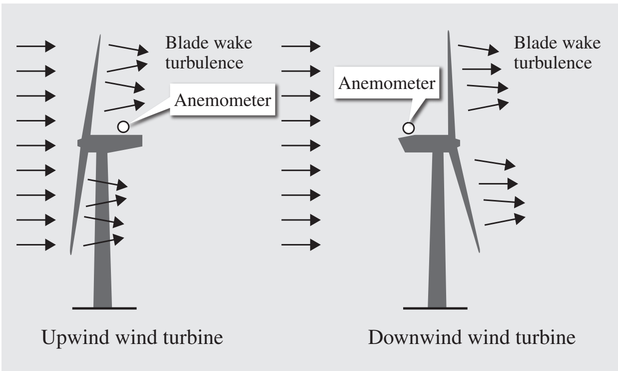


*Fig. 3—Location of Anemometer and Relationship with Blade Wake.*
*Because the anemometer on a downwind wind turbine can be located upwind of the rotor, it suffers less interference due to blade wake turbulence.*

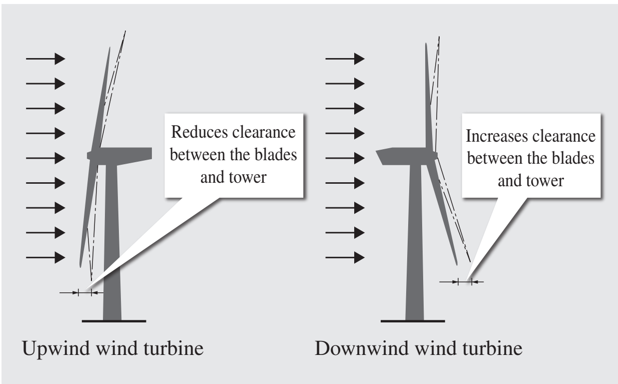


*Fig. 4—Clearance between the Blades and Tower during High Winds.*
*With a downwind configuration, the clearance between the blades and tower increases during high winds, reducing the potential for the blades and tower to come into contact.*

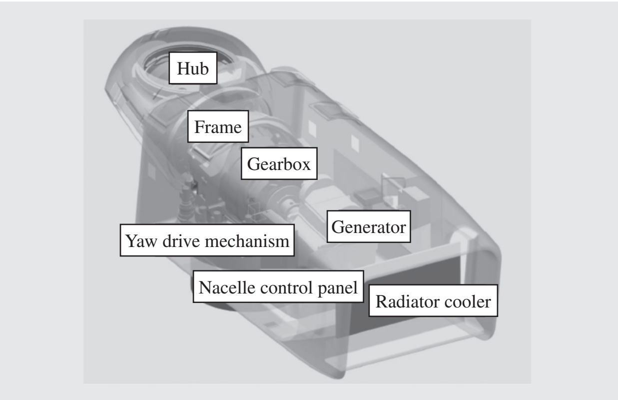


*Fig. 5—Equipment Layout in Nacelle.*
*The equipment inside the large 5-MW wind turbine is laid out as shown.*

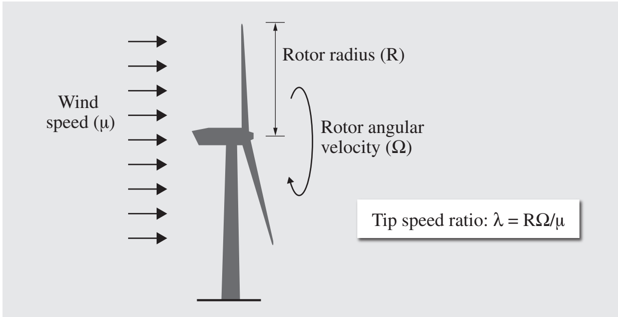


*Fig. 6—Wind Turbine Tip Speed Ratio.*
*Wind turbines typically use variable-speed operation whereby the tip speed ratio (λ) is kept constant as the wind speed varies.*

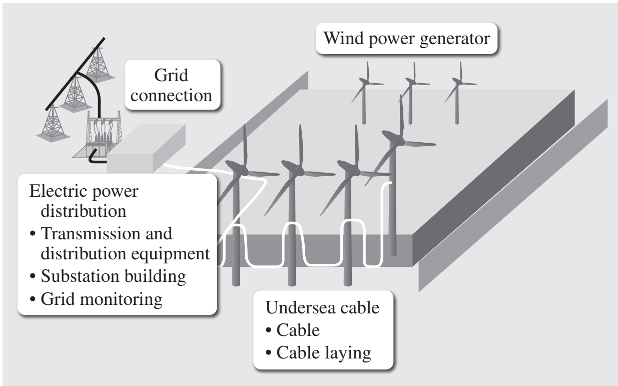


*Fig. 7—Overview of Electric Power Distribution Equipment.*
*The electric power generated by the wind turbines is transmitted to a land-based grid connection substation via array cables and export cables.*

diameter becomes larger[3]. Accordingly, to keep the speed of the input shaft to the generator constant, a higher gear ratio is needed as the rotor diameter becomes larger, increasing the potential for gearbox problems. Hitachi has minimized this potential for gearbox problems by adopting a medium-speed gear drive system that combines a 36-pole permanent magnet synchronous generator with a gearbox that has a gear ratio of no more than about 1:40.

## ELECTRIC POWER DISTRIBUTION AND SUBSTATION EQUIPMENT

Fig. 7 shows the electric power distribution equipment for linking wind turbines to the existing grid that is intended for use with the 5-MW offshore wind power generation system. The electric power generated by the wind turbine is transmitted to an onshore grid connection substation via a power cable that connects to a number of generators (array cable) and a cable that carries the electric power to land (export cable). At the grid connection substation, a transformer steps up the voltage to the grid voltage and the power is supplied to the grid via a connection point. The following sections describe the substation equipment and undersea cable used by this system.

### Substation

Hitachi has many years of multi-faceted experience with ultra-high-voltage switchgear, power system analysis, equipment protection and control, and with static var compensators (SVC), and high-voltage direct current (HVDC) substation equipment. This technology and know-how is available for use in grid connection substations for offshore wind farms. Fig. 8 shows a connection diagram for substation equipment used to connect to the grid. The voltage of the power generated by the wind turbines is stepped up by two transformers and connected to an existing trunk transmission line. As the capacity factor of offshore wind power generators has been estimated at 50% or less[4], a redundant configuration is used so that, if one of the transformers fails, operation can continue using the remaining functional transformer. To improve reliability, an active/backup configuration is also used for the connection to the existing transmission line. In addition to performing grid analyses of voltage fluctuations and other factors for grid connections, detailed protection coordination is also implemented from the grid-side to the wind turbines.

Hitachi is also designing the substation equipment itself to be more compact and place less of a load on the environment. One example is the use of an integrated three-phase bus in 275-kV gas-insulated switchgear (GIS) to reduce both its installation footprint and the amount of sulfur hexafluoride ($SF_6$) insulating gas used. Also, Hitachi's 33-kV circuit breaker (package GIS) uses a T-shaped cable head. A feature of this

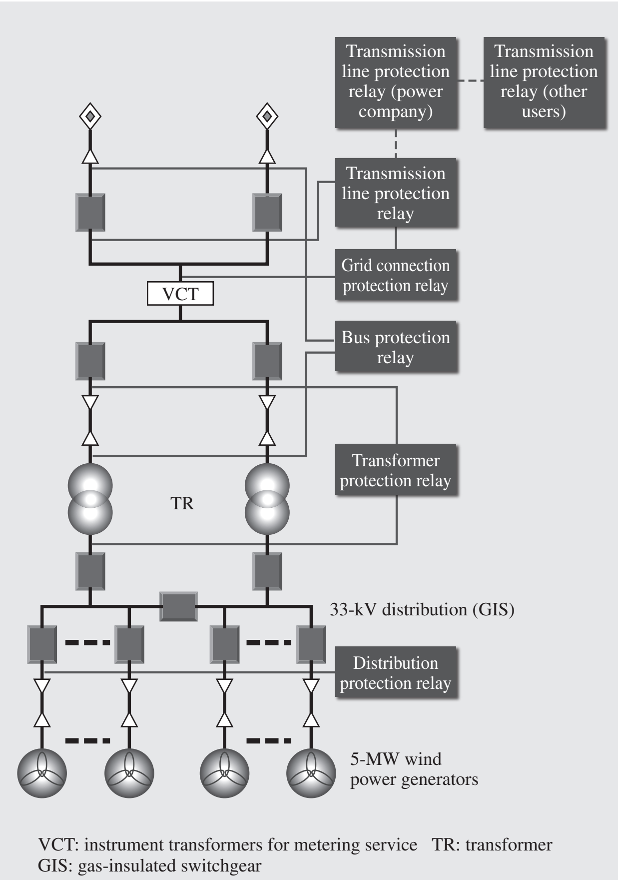


*Fig. 8—Connection Diagram for Substation Equipment for Connection to Grid (Overview).*
*The voltage of the power generated by the wind turbines is stepped up by two transformers and connected to an existing trunk transmission line.*

cable head is that it is designed to allow a test voltage to be applied by externally coupling a test lead to the connection terminal provided for this purpose (which is normally sealed off by a plug). That is, it is possible to perform electrical testing of the equipment and the power cable simply by operating an external disconnecting switch, without needing to change any internal wiring. This eliminates the potential for $SF_6$ gas to escape when making wiring changes.

### Undersea Cable

Because of the need to withstand the tension from the cable-laying ship when laying an undersea cable, and to prevent exterior damage due to currents, fishing equipment, or other impediments, it is common to clad cables in a single or double layer of steel armor with a diameter of 6 mm or more. Whether to use one or two layers of steel armor depends on the environment in which the cable will be laid. In most cases, a single layer is used, with a double layer being adopted in only the case of strong currents, deep locations, or rocky or broken seafloor terrain[(5), (6)].

Although cross-linked polyethylene (XLPE), which has low losses, is widely used as cable insulation in Japan, it has problems with long-term exposure to water such as the formation of water trees. Accordingly, a lead sheath or other layer of metal cladding is often used on undersea cables to keep out water.

Despite this use of metal cladding to protect the cable, cases of damage to undersea cables remain common. The International Council on Large Electric Systems (CIGRE) has estimated the annual incidence at 0.7954 incidents per 100 km, the majority of which are due to fouling by fishing equipment, anchors, and so on[(7)]. Because of the potential for repair of a damaged undersea cable, including manufacturing and laying the replacement cable and restoring the link, to take a long time, measures are needed to prevent cable damage from immediately reducing the utilization of offshore wind farms. Hitachi is actively working to offer such measures, which include adopting a cable-laying method that can bury the cable 0.5 m to 1.5 m below the seafloor to prevent fouling by fishing equipment, and designing the system with a loop configuration in which the undersea cable connects together a number of wind power generation systems so that an alternative transmission path will be available in the event of a failure.

Scouring (erosion of seafloor foundations by currents) can occur around the base of wind turbine foundations, with a scouring depth of as much as 2.5 times the diameter of the foundations having been reported[(8)]. This scouring can leave the undersea cable hanging free and, in the worst case, can lead to a cable break. Accordingly, it is desirable that the design of cable-laying near the wind turbine foundations include consideration of how to prevent this scouring.

## CONCLUSIONS

This article has given an overview of a large 5-MW offshore wind power generation system with a downwind configuration, and described the substation and distribution systems.

In the future, Hitachi intends to proceed with the full-scale deployment of 5-MW wind turbines through the construction and testing of demonstration systems to verify their performance. Hitachi believes that the technologies described in this article can help expand use of offshore wind power generation and also contribute to the development of a domestic source of energy that takes account of the global environment.

## REFERENCES

(1) Ministry of the Environment, “Report on FY2010 Study of Potential for Introduction of Renewable Energy,” Table 4-8, http://www.env.go.jp/earth/report/h23-03/ in Japanese.

(2) T. Ishihara, “Floating Offshore Wind Farm Demonstration Project off Coast of Fukushima,” Journal of Japan Wind Power Association, No. 8, pp. 3–12 (2012) in Japanese.

(3) J. Twidell et al., “Offshore Wind Power,” Kajima Institute Publishing Co., Ltd., p. 17 (2011) in Japanese.

(4) K. Iwamoto, “Offshore Wind Power : Trump Card for Next-generation Energy,” Nikkan Kogyo Shimbun Ltd., pp. 33–234 (Dec. 2012) in Japanese.

(5) K. Iizuka et al., “Update Electric Cable Technology Cable Handbook,” pp. 366–368, Denkishoin (Mar. 1989) in Japanese.

(6) S. Fujii et al., “Development of Power Transmission System for Fukushima FORWARD Project,” Furukawa Electric Journal, No. 131, pp. 44–48 (Feb. 2013) in Japanese.

(7) CIGRE TB379, “Update of service experience of HV underground and submarine cable systems,” Table 30 (2009)

(8) J. Twidell et al., “Offshore Wind Power,” Kajima Institute Publishing Co., Ltd., pp. 252–253 (2011) in Japanese.

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