Mitsubishi High Efficiency Large Capacity Wind Turbines

Takuji Fujikawa
Nobuaki Iwasaki
Yukio Suguro
Yoichi Iwanaga
Masaaki Shibata

Recently, generation of electricity by wind power has been rapidly increasing all over the world as an environment-friendly power generation system, because it makes use of an inexhaustible supply of wind energy, without emitting any carbon dioxide. In the past, development of wind power generation systems has been carried out mainly with the intention of the reduction of the power generation cost, including the equipment construction cost, and also the improvement of the operational reliability. However, in addition to these basic targets, minimization of the influence of variations in output level to the distribution system is the subject of recent study. Attention is now being paid to one possible solution involving use of a variable speed wind turbine that is capable of effectively reducing changes in output level by absorbing variations in wind energy as inertial energy. Mitsubishi Heavy Industries, Ltd. (MHI) has developed a new variable speed wind turbine, MWT-S series, incorporating a permanent magnet synchronous generator made by Mitsubishi Electric Corporation, the first system of this kind in the world, and installed it at the Tappi Wind Park of Tohoku Electric Power Co., Inc., for verification test in July 2000. From the results of the verification tests performed jointly with Tohoku Electric Power Co., the characteristics of the variable speed wind turbine, including (1) reduction in output power variations, (2) reduction in rush current, (3) reduction in operating noise and (4) less maintenance, have been duly verified. For further improvement of the cost-effectiveness and reliability of wind power generation, MHI started the operation of a 600 kW synchronous generator type wind turbine in April 2002 and is now developing a 1 000 kW high-efficiency induction type, covering a low wind speed range, and also a 2 000 kW large capacity synchronous generator type wind turbine. These new turbines are expected to be in operation by the end of 2002.

1. Introduction

In the wake of the upsurge in global environmental protection consciousness and reorganization of the energy supply system, wind power generation plants using environment-friendly, non-depletable wind energy are being constructed in many places around the world. Also in Japan, wind power generation is one of the most promising solutions among new energy development projects. The Japanese Government has raised the national target for the introduction of wind power generation to 3 million kilowatts by 2010, also with the intention of increasing the self-sufficiency rate of primary energy.

As of January 2002, the wind power plants already constructed around the world have a capacity to supply 23 270 MW of electricity in total. Considering that it is estimated that it will increase to 58 000 MW toward 2005, construction of new wind power plants will rapidly increase.

In view of effective use of land and advantages of large-scale equipment, construction of large-capacity wind turbines is rapidly increasing with the progress in wind turbine technology. Wind turbines with output of 600 to 1 000 kW per turbine are currently dominant, while those with output of about 500 kW were the largest only a few years ago. Recently, wind turbines with an output of 2 000 kW or more have been developed and put into commercial operation.

MHI manufactured 40 kW wind turbine in 1980, 300 kW one in 1982, and delivered 500 kW one to the New Energy and Industrial Technology Development Organization (NEDO) in 1996, and then developed a 1 000 kW (1 MW) wind turbine for Shukutsu Wind Power Plant in Muroran city in 1999. MHI is now working to develop a 2 000 kW (2 MW) wind turbine.

For more flexible output control for the benefit of and compatibility with the interconnected operation system, installation of variable-speed wind turbines has also been examined. MHI and Mitsubishi Electric Corporation have jointly developed a 300 kW-class variable speed gearless permanent magnet synchronous wind turbine and have installed it in Tappi Wind Park of Tohoku Electric Power Co., Inc., where verification studies have been carried out with this electric company since July 2000. Commercial operation of a newly developed 600 kW synchronous generator type wind turbine was started in April 2002.

Besides, MHI are also developing a 1 000 kW (1 MW) high efficiency wind turbine to meet the need

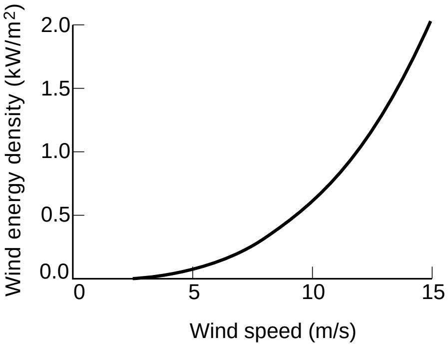

Fig. 1 Wind energy density

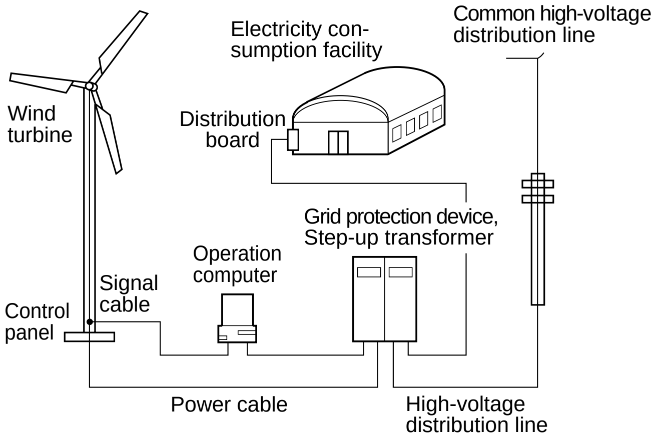

Fig. 2 Composition of a typical wind power generation system

Fig. 3 General view of large-capacity wind turbines

for operation in a low wind speed range and, in parallel, a 2 000 kW large capacity synchronous generator type wind turbine to meet a future need for the construction of offshore wind power plants.

The following are the details of the technology for wind energy utilization and the progress made by MHI with the development of high efficiency, large capacity wind turbines, and the trend of the manufacture of greater capacity wind turbines in future.

2. Utilization of wind energy

In wind power generation, wind energy is used efficiently as a force to turn rotor blades and operate a generator of a wind turbine.

When the mass of air is m and the velocity of wind is V, the kinetic energy of the wind is expressed as:

Kinetic energy of wind = $1/2mV^2$

Given this equation, the kinetic energy of wind passing through a wind turbine which has a blade swept area A (m^2) at a velocity V (m/s) in a unit time (s), that is wind energy P (W), is expressed by the following equation when air density is ρ (kg/m^3):

Wind energy $P = 1/2\ (\rho AV)V^2 = 1/2\rho AV^2$

Hence, wind energy varies directly as cube of wind velocity.

When wind energy acting on a unit swept area of rotor blade is represented by wind energy density P_0 and when the air density ρ is 1.225 kg/m^3 at 1 atm and 15°C on land in Japan, the wind energy density P_0 is as shown in **Fig. 1**.

In practical operation, the theoretical upper limit of usable wind energy (Betz's limit) is 59.3 % of the wind energy density P_0, because wind speed varies locally due to the resistance of the wind turbine itself. In addition, because of the mechanical loss, the ratio of wind energy finally available for wind turbine output (wind turbine energy coefficient) is only a little above 30% of P_0 for the current models of small capacity wind turbines and a little above 40% for large capacity turbines.

3. Composition of wind power generation system

The composition of a typical large capacity wind power generation system is described here. As **Fig. 2** illustrates, power cable coming from the wind turbines are connected to high-voltage distribution lines via a step-up transformer. Signal cables from the wind turbines are connected to an operation control computer. And, a distribution board is installed as required near the electricity consumption facility.

Fig. 3 illustrates a general view of large-capacity wind turbines that were delivered by MHI to Shukutsu Wind Power Plant in Muroran city; a 490 kW wind turbine is seen on the left and a 1 000 kW (1 MW) on the right. The 1 000 kW (1 MW) wind turbine has rotor blades of about 57 meters in diameter and the main shaft of the rotor blades (hub) is located a height of 60 meters from the level of the foundation, that is comparable to a jumbo jet.

Among the power generation technologies utilizing natural energies, the technology for wind power generation has been properly developed in spite of the limitations on the cost reduction when compared with hydraulic power generation. The large-capacity wind turbines of today have been developed as a result of years of experience in the use of wind energy, in the following ways:

- Before the seventeenth century, windmills were used in irrigation and grain milling in European

Fig. 4 Tehachapi wind farm in Cal., USA

Fig. 5 Tappi Wind Park of Tohoku Electric Power Co., Inc.

Table 1 Features of modern wind turbines

1. Application of aerodynamics → for effective use of wind energy
2. Application of new materials → Use of FRP and alloy steels for large-size structure
3. Use of the above for power generation → for increase of degree of freedom from limits set by geographical conditions and for large-scale power generation
4. Application of the latest technique → Full span pitch control and automatic yaw control

countries, but the use of Dutch type windmills decreased rapidly after the Industrial Revolution.

- In the late 1880s, some researchers started to study the feasibility of wind power generation as a means of using alternative energy resources, but their efforts were not fruitful in those days.
- However, in the wake of the energy crisis of the 1970s and the problem of harmful acid rain, technologies for wind power generation have been rapidly improved by applying advanced methods such as listed in **Table1**. These technologies are now being rapidly refined, with construction of wind power plants of greater capacity to increase cost-effectiveness, also with Government aid.

4. Progress of development of the MHI large-capacity wind turbines

MHI, the only Japanese manufacturer which supplies large-capacity wind turbines, has developed its current large-capacity models based on its years of experience in the manufacture of various wind turbines, as described below.

Following its construction of an experimental 40 kW small-size wind turbine at its Nagasaki Shipyard and Machinery Works, Kouyagi Plant in 1980, MHI continued research and development step by step toward to the completion of large-capacity wind turbines. In 1982, MHI delivered the first commercial 300 kW wind turbine to the China Wind Power Plant in Tonaki-jima Island of Kyushu Electric Power Co., Inc., acquiring in the verification process much information and know-how about the design of wind turbines for commercial use. Subsequently, MHI has developed a 250 kW FRP blade upwind turbine as a mass production model. Up to the present, MHI has manufactured more than 800 units of this MWT-250 wind turbine. In particular, it is notable that 660 units of this model are in long operation commercially at Tehachapi, California, USA, which is the world's largest wind farm, and is equipped with wind turbines of only this model (**Fig. 4**).

In 1991, the NEDO started a development project for a large-capacity wind power generation system. In this project, MHI carried out the work from design to installation of a 500 kW wind turbine, which was completed in October 1996 at the operation site at Tappi-misaki, Aomori Prefecture (**Fig. 5**). Through the operation of the wind turbine constructed there, the influence of complicated topography on the efficiency and reliability of wind turbine operation has been clarified.

The first model of the MWT-450, which succeeded the MWT-250 as a mass-production turbine, was delivered to Winkra Energie, Germany in March 1996. For this wind turbine, Germanischer Lloyd (GLWind), a type certification organization certifying the reliability of design technique, has granted official site certification to a non-European manufacturer for the first time.

To meet the need for wind turbines providing higher output in overseas markets, MHI applied its proven design technique and developed a 600 kW-class wind turbine model, the MWT-600, in 1998. Following the first delivery of 131 units of this model to the USA in 1999, more than 260 units are now in operation for commercial power generation. In 2001, for the MWT-600 Mk among the MHI's 600 kW-class wind turbine models, GLWind granted the official design certification "Wind turbine Class IIA" for the first time to a Japanese model.

As European wind turbine manufacturers have been putting their 1 MW or larger turbines to practical application, MHI started to develop a 1 MW wind turbine in 1998. This 1 MW wind turbine, the first of

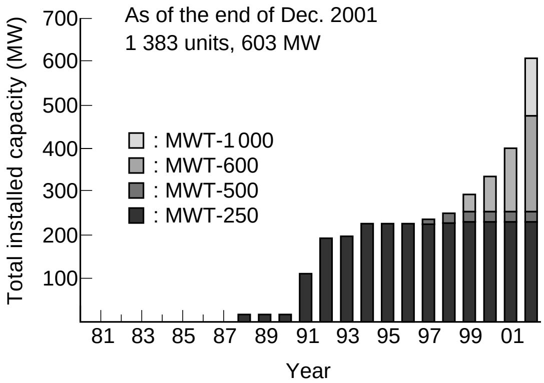

Fig. 6 Record of orders received/delivered by MHI

its class in Japan at that time, was completed and installed in March 1999 and is operating satisfactorily. Lately, MHI has received a big order (130 units) from customers in the USA for 1 MW wind turbines. GLWind granted the official design certification "Wind turbine Class IA" for this model in August 2002. As of the end of December 2001, the total orders for wind turbines received and delivered by MHI amount to 1 383 units with a combined output of 603 MW (**Fig. 6**).

Furthermore, to meet the need for a system that is compatible with interconnected operation, MHI and Mitsubishi Electric Corporation jointly developed a 300 kW-class variable speed gearless permanent magnet synchronous generator wind turbine in July 2002. **Fig. 7** shows the progress of development of MHI's large-capacity wind turbines.

5. The latest concerns in large-capacity wind turbine development

The following are the main items due to be examined for the development of a large-capacity wind turbine.

Table 2 Framework for wind turbine design

(1) Conceptual design for wind turbine
(2) Study of efficiency and blade design
(3) Wind condition simulation study
(4) Examination of static and dynamic strength of blades, rotor head, main shaft, gearing, generator, safety devices, control system, tower, foundation structure, etc.
(5) Establishment of proper maintenance practice to ensure a service life of wind turbines of more than 20 years

Table 3 Fundamental specifications for synchronous generator wind turbines

Type	MWT-300S	MWT-600S	MWT-2000S*
Rated output (kW)	300	600	2 000
Rotor blade diameter (m)	30	45	75
Revolutions (rpm)	16 to 46	10 to 34	8 to 24
Rated wind speed (m/s)	14.5	13.0	13.0
Cut-in wind speed (m/s)	2.5	2.5	2.5
Cut-out wind speed (m/s)	25.0	25.0	25.0
Record of delivery (unit)	7	1	-
Total output (kW)	2 050	600	-

*Scheduled to start commercial operation in 2002)

5.1 Design framework

Table 2 shows the items to be examined for designing a wind turbine.

5.2 Basic specifications and features of MWT-2000S

MHI is now developing the MWT-2000S synchronous type wind turbine. The technical specifications and overall dimensions of the MWT-2000S are shown in **Table 3** and **Fig. 8**, for comparison with other smaller models. This new model under development has the features detailed below.

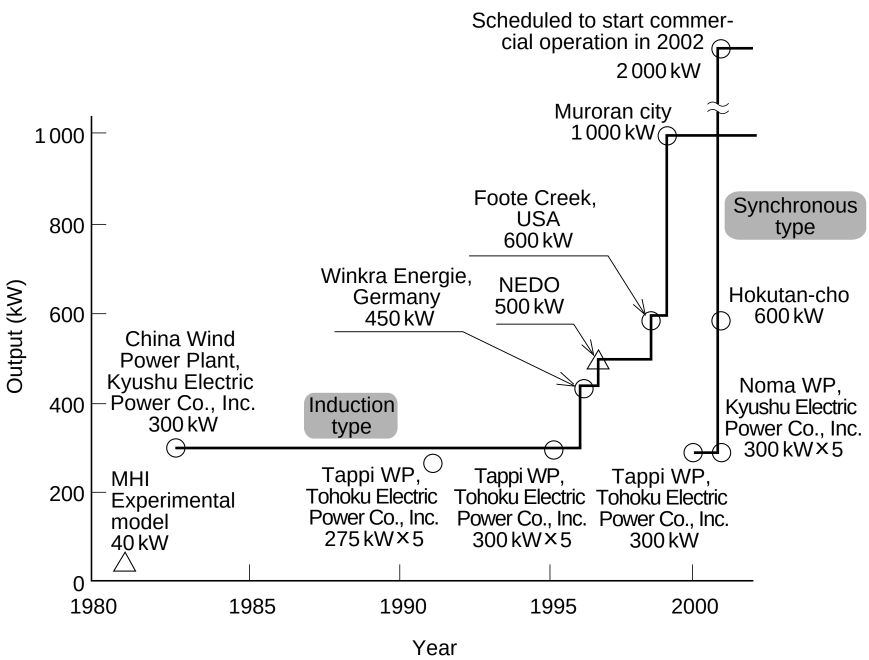

Fig. 7 Development of MHI large-capacity wind turbines

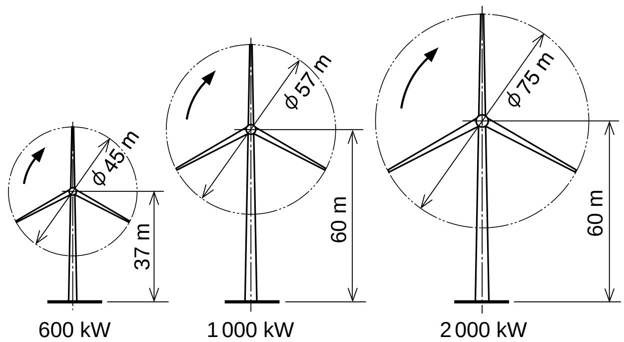

Fig. 8 Overall dimensions of typical large-capacity wind turbines

Its rotor consists of three blades made of glass fiber reinforced plastic (GFRP) and has a diameter of 75 meters. Rated wind speed is 13 m/s, and cut-in and cut-out wind speeds (average of ten minute measurements) are 2.5 m/s and 25 m/s, respectively. The rotating speed of the rotor can be controlled to very between 8 and 24 rpm. The output regulation system is based on variable pitch control and a pulse width modulation (PWM) system, where an electric motor built into the rotor head optimizes the blade pitch angle according to changes of wind speed. Wind energy received by the blades is transmitted to the rotor head, main shaft and finally to the generator. A permanent magnet multipolar synchronous generator is used to generate power and an AC-DC-AC conversion method is used to regulate the output for interconnected operation.

The typical technical features of the MWT-2000S are as follows:

(1) Highly reliable construction based on principle design data which have been verified satisfactorily by field operation of 300 to 1 000 kW-class wind turbines,

(2) Sound from blades is minimized by sharpening the contour of each blade toward the tip, and mechanical sound is also reduced by more than 2 dB(A) by use of a gearless transmission system and soundproof mounting for the generator,

(3) High aerodynamic efficiency is obtained by increasing the thickness of the blade root portion by 30 to 40 %,

(4) Large-sized, light-weight rotor blades (made of GFRP) have sufficient strength to withstand strong winds even in typhoon conditions,

(5) PMW system using a large power transistor limits the rush current at the grid connection and regulates the output variations (from −3% to +3%),

(6) Variable speed permanent magnet multipolar synchronous generator wind turbine improves the power generating efficiency in a low wind speed range by 5% on average, and

(7) The gearless transmission system and motor-driven blade pitch angle control minimize

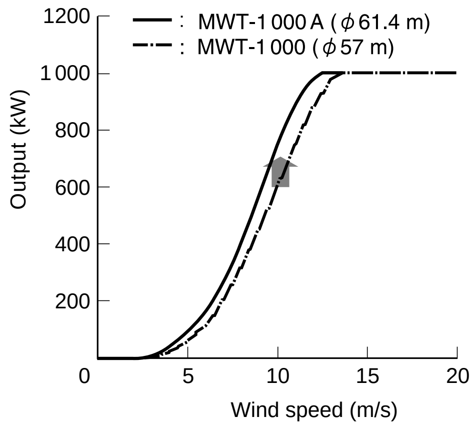

Fig. 9 Output curve of new 1 000 kW wind turbine

hydraulic components, considerably reducing maintenance work.

5.3 Course of development and outline of high-efficiency MWT-1000A wind turbine

The MWT-1000A wind turbine, which is now being diligently developed for low wind speed applications, is the successor to the well field-proven high-efficiency MWT-1000 wind turbine in the basic specifications and overall dimensions. Particularly, a new longer blade design has been adopted for the MWT-1000A to improve its efficiency for operation in a low wind speed range.

The development of this turbine was started originally to meet the needs for wind power generation in low wind speed regions in the USA, but this project has now also been directed to the domestic market, following the recent increase in wind power generation projects for local low wind regions.

Fig. 9 shows the output power curves of the MWT-1000A and a conventional 1 000 kW wind turbine, indicating that the output power of the MWT-1000A exceeds the other by more than 25 % at a wind speed of 10 m/s.

6. Trend in the construction of larger capacity wind turbines

In the above section, MHI's activities related to the development of large-capacity wind turbines were described; however, the world's largest wind turbines of today are capable of generating more than 2 MW of electricity, and considering this trend, MHI has also started to study the construction of an advanced 5 MW-class wind turbine. In pursuance of this end, it becomes necessary to establish the technique to minimize the influence of variations in wind speed on the output, as well as the improvement of cost-efficiency with the increase of wind turbine output.

MHI wishes to make a breakthrough in the new age of wind power generation by tackling the below mentioned various technical subjects, as itemized in

Table 4 Subjects for technical development of wind power generation

For wind turbine development:
(1) Shaping of highly efficient rotor blades
(2) Large-capacity wind turbine
(3) Ease of maintenance
(4) Formation of wind turbine complex (wind farm) consisting of a number of and/or grouped turbines for increase of output capacity and smoothening of output at high level
(5) Reasonable method for forming offshore wind turbine complex (wind farm)
(6) Simple, reliable efficiency assessment methods
(7) Multipolar synchronous type high-voltage generator

For power distribution lines:
(1) Efficient turbine operation with joint use of storage batteries
(2) Hybrid operation with other power sources
(3) Optimization of interconnected operation
(4) Utilization of system for multipurpose operation
(5) Direct-current power transmission

Table 4, including the related technologies:

(1) Construction of a high-efficiency, large-capacity wind turbine which has smoothening effects to provide stable output at all times,
(2) Ease of maintenance,
(3) Optimization of auxiliary equipment arrangement, including that for offshore power generating plant,
(4) Establishment of a reliability assessment method for wind turbines aiming at more economic operation, and
(5) Improvement of interconnected operation at wind farms. For this improvement, countermeasures against variations in output frequency and voltage and higher harmonics must also be taken into account. To smoothen the load in interconnected operation, joint use of storage battery and flywheel type electric power storage system will be required. For large-scale interconnected operation, it will probably become necessary to include many units of variable-speed wind turbine or, where necessary, use a hybrid system with diesel engines, and use the power for adjustment or backup power from some other source within the same system.

Up to the present time, MHI has proved the practicality of some of the above-mentioned operations at its verification facilities. The details of the effects of such advanced operation will be reported in due course.

7. Conclusion

The course of the development of large-capacity wind turbines made by MHI up to the present has been described in this report, and it is estimated that the size and capacity of wind turbines will increase steadily in the future. More large-scale wind farms will be constructed, first in on-land areas where wind conditions are relatively favorable, and then this will be followed by the construction of offshore wind farms. In the course of these developments, it will also be important to utilize the type certification system and refine the interconnection operation technique and the technique to regulate the interconnected operation for load smoothening.

Today, wind power generation is set to grow rapidly throughout the world, and, under the circumstances, MHI will continue to put its efforts into the development of wind power generation technology, and supply its high-efficiency wind turbines in the hope of contributing to society.

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Takuji Fujikawa
Power Systems Headquarters

Nobuaki Iwasaki
Power Systems Headquarters

Yukio Suguro
Nagasaki Shipyard & Machinery Works

Yoichi Iwanaga
Nagasaki Shipyard & Machinery Works

Masaaki Shibata
Nagasaki Research & Development Center, Technical Headquarters