Connecting Wind Power Generation to a Power System

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1. Introduction

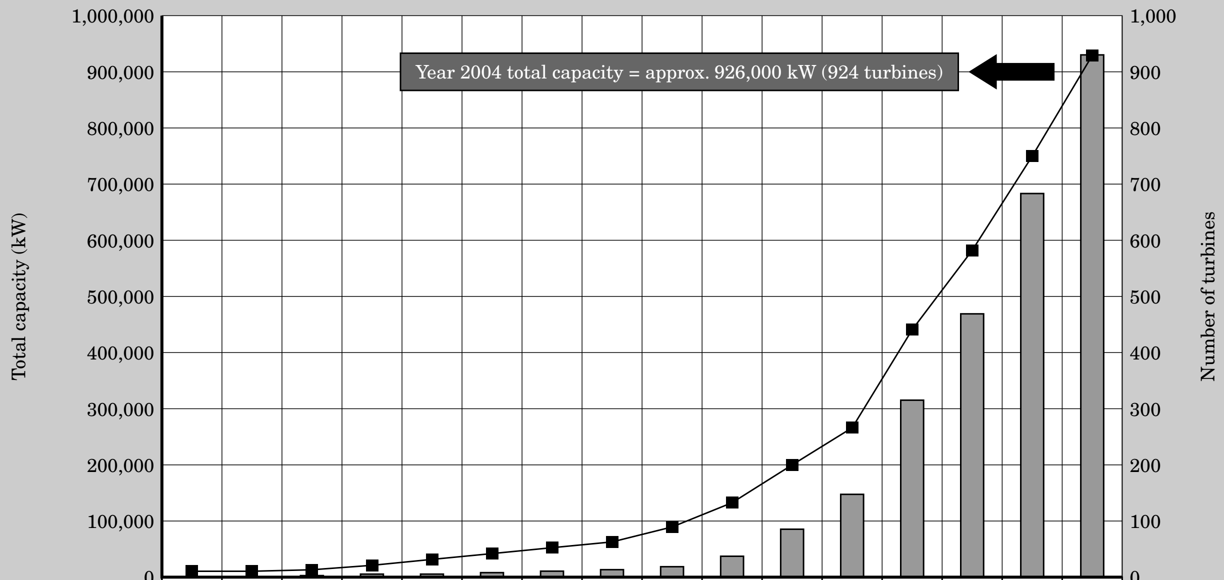
Wind power generation uses a natural energy source, and is increasingly being employed because of its low impact on the environment. However, it is difficult to control wind generated power in a planned way, and as the capacity of wind power generating equipment connected to a power system increases, the power quality (stability of voltage and frequency) may become difficult to maintain. The necessary countermeasure is a wind power output stabilizing apparatus that charges a battery system with the constantly fluctuating generated power and then discharges that battery system to smooth the electric power at points where the wind power plant is connect to the power system.

This paper discusses Fuji Electric's involvement with wind power generation and describes power stabilization apparatuses for a wind power generation system.

1.1 Japanese domestic trends of wind power generation

Figure 1 shows the history of the introduction of wind power generation in Japan. Wind power generation use has been increasing rapidly since 2000 due to the Wind Power Generation Field Test Business Subsidy System and the New Energy Introduction Countermeasure Subsidy System implemented by the Japanese government since 1995, and the expanded offerings of wind power available from electric power companies and available for purchase for industrial use. As of the end of March 2005, wind power generation in Japan has reached approximately 926 MW, from 924 turbines, and this is approximately 1/3 of the targeted level (of which the targeted introduction of wind power generation is 3 GW by

Fig.1 Introduction of wind power generation in Japan



	to 1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Total capacity (kW)	1,215	1,015	2,541	3,474	4,973	7,580	10,421	13,712	21,538	37,822	82,637	143,744	312,757	464,210	680,665	926,575
Number of turbines	9	9	14	23	33	44	54	66	89	127	198	259	434	576	742	924

Source : Website of NEDO Technology Development Organization (as of the end of March 2005)

2010) of new energy introduction in Japan.

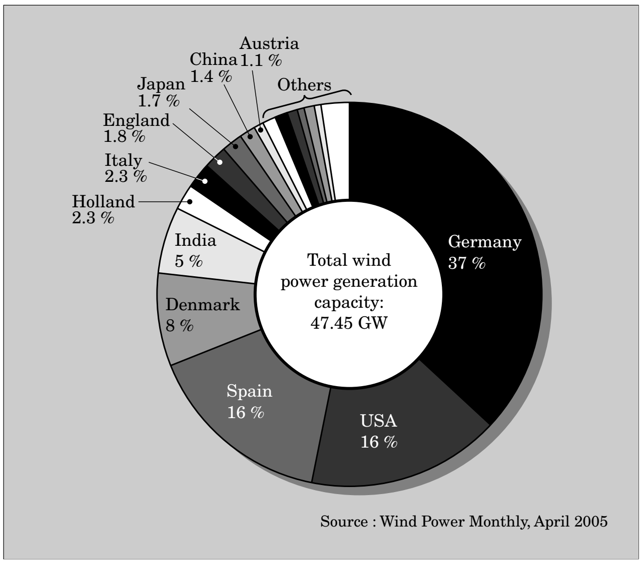
Assuming that the average output per turbine is 1 MW, it will be necessary to construct 2,000 new turbines during the next 5 years. However, this exposes problems involving the connections to a power system, and some countermeasures will be needed to achieve the targeted level of wind power use. For this reason, a group consisting of the Japanese Ministry of Economy, Trade and Industry, academic experts, electric power companies, wind power generation companies, and the like, has established a Subcommittee for Connecting Wind Power Generation to Power Systems of the New Energy Task Force of the Advisory Committee on Natural Resources and Energy, and issued an interim report (proposal) on July 27, 2004. Additionally, on June 23, 2005 the results of a review of measures incorporated in the interim report were announced. The parties concerned continue to study methods of implementing specific measures in order to reach the 2010 targeted level of wind power generation.

1.2 Global wind power generation

Figure 2 shows a comparison of the wind power generation per country.

As of the end of March 2005, the total global wind power generation capacity is approximately 47.45 GW. Germany is ranked first, and in a single year constructs more than 3 GW which is the targeted level for Japan in the 2010. As mentioned above, the introduction of wind power generation has been increasing rapidly in Japan since 2000. Since 2004, Japan has been ranked among the top ten countries for wind power generation, however, its levels of wind power generation are still too low to enter into the top five. The reason for the somewhat low ranking is, in addition to the difference of policy from Europe and the United States, because flat land is scarce in Japan, wind turbulence is significant, areas having favorable wind conditions are concentrated in Hokkaido, Northern Honshu, and Kyushu, and protection against tyhoons and lightening is required.

Fig.2 Wind power generation per country



2. Fuji Electric's Efforts Involving Wind Power Generation

Having an abundance of experience with products in the fields of power generation, substation and system control, and based on its plant management capability and power system analysis skills, Fuji Electric is actively involved in the development of wind power generation systems. Fuji's major accomplishments in this field are discussed below.

Fuji Electric has delivered grid-interconnection facilities to Japan's first full-fledged wind power generation plant (three 100 kW turbines) located in Tachikawa Town in Yamagata Prefecture in 1993, to Japan's first full-fledged Wind Farm (twenty 1,000 kW turbines) at the Tomamae Green Hill Wind Park of Eurus Energy Co. Tomamae in 1999, and to Japan's largest capacity, the Iwaya Wind Farm, (twenty-five 1,300 kW turbines) of Eurus Energy Iwaya Co. in 2001. Including these record-setting wind power plants in Japan, as of 2004, Fuji Electric has delivered grid-interconnection facilities for wind power generating equipment comprising a total output of 163,150 kW and consisting of 106 turbines.

Moreover, in 2003, Fuji Electric built a plant, including grid-interconnection facilities, at the Shimane Prefecture Bureau of Enterprise Oki-Oominesan Wind Power Plant (three 600 kW turbines) ordered by Iwatani International Corporation. For the Oominesan Wind Power Plant, it was postulated that because the plant is located on an island and system capacity is small, the power fluctuation due to changing wind speed and direction would exceed the allowable frequency fluctuation of the power system. As a countermeasure, Fuji Electric also delivered the world's first super high-speed flywheel power stabilizer for stabilizing the amount of fluctuation in output power from the wind power plant per unit time. For this wind power generating system, Fuji Electric and the Shimane Prefecture Bureau of Enterprise were awarded the "New Energy Chairman's Award," in 2003.

Furthermore, in December 2003, Fuji Electric Systems founded Win Power Corporation, a 100 % subsidiary company that engages in development at suitable sites, detailed surveys of wind conditions, environmental investigations, system design, etc., and has completed a full turn-key job for the Nishime Wind Power Plant (one 1,250 kW turbine and one 600 kW turbine).

Based on these accomplishments, Fuji Electric is confident of its ability to supply and satisfy each wind power generating company with an entire wind power system, not just the grid-interconnection facilities.

The Nishime Wind Power Plant has been generating wind power favorably since March 2005.

3. Challenges and their Countermeasures for Connection to a Power System

The power generated by a wind turbine is proportional to the cube of the wind speed, and therefore even a slight fluctuation in wind speed results in a large fluctuation in generated wind power. Moreover, wind speed fluctuates randomly with respect to both cycle and magnitude, and the increased fluctuation in generated power due to increased adoption of wind power may invite power fluctuation and frequency fluctuation in a power system and result in a degradation of the power quality.

The fluctuation in voltage may be addressed with local measures such as by maintaining the operating power factor of the wind power turbine to be the same as for other power station and substation equipment, or by installing a var compensator. The fluctuation in frequency, however, is a system-wide problem.

The abovementioned Subcommittee for Connecting Wind Power Generation has provided the following specific measures for stabilizing the frequency.

(1) Construction of a wind energy forecast system base on wind forecasts
(2) Study of disconnection of wind power and wind energy, output control method
(3) Output smoothing of wind power generation by installing power storing equipment
(4) Use of connecting lines between electric power companies

Furthermore, the Japanese Ministry of Economy, Trade and Industry is beginning to provide assistance and to investigate and study technical aspects relating to the implementation of specific measures.

Frequency fluctuation causes and countermeasures are described below, with particular focus on power stabilizing equipment.

3.1 Causes of frequency fluctuation

Frequency fluctuation is a problem that spans the entire power system and is caused by an imbalance between the total power generated by power generating equipment connected to the power system and the consumed power. Power companies control the power generated at power plants so that the generated power is always in balance with the constantly fluctuating consumed power. Figure 3 illustrates this concept.

(1) Small load fluctuation

A governor-free (an automatic control function provided in the speed regulator of a hydro or thermal power plant) function is used to respond to small load fluctuations.

(2) Short cycle fluctuation

An LFC (at a central dispatching center, output control for a hydro or thermal power plant according to deviation in frequency) function is used to respond to short cycle fluctuations.

Fig.3 Frequency control in response to fluctuation in demand

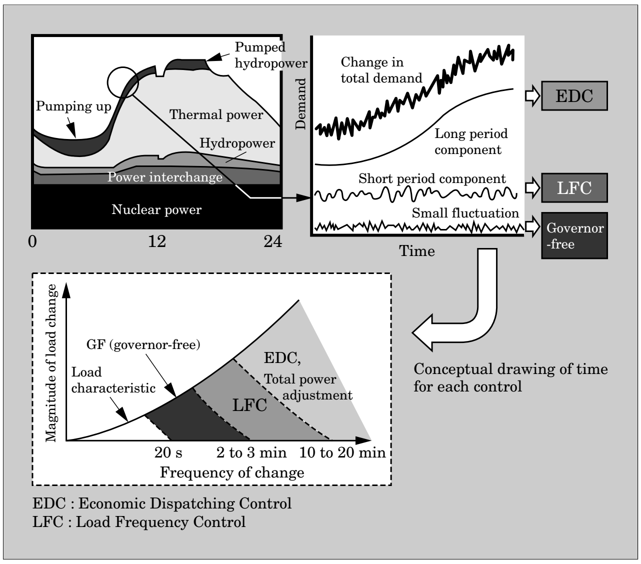
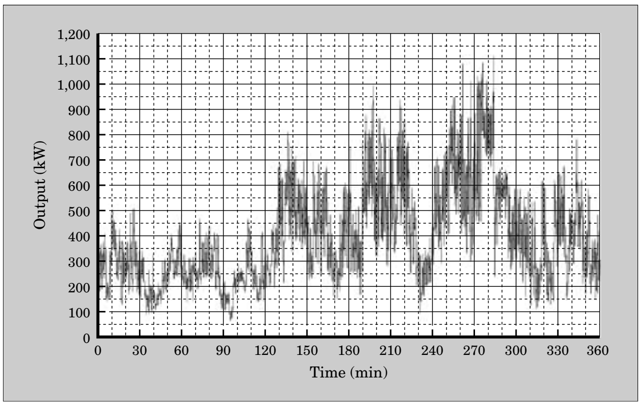


Fig.4 Example of power generation fluctuation in variable speed machine



(3) Long cycle fluctuation

An EDC (at a central dispatching center, output control for a hydro or thermal power plant, including operating and stopping control based on supply-demand estimation) function is used to respond to long cycle fluctuations.

3.2 Fluctuation in power generation of a wind power system

Figure 4 shows an example of the power generation fluctuation of a wind power turbine. It can be seen that fluctuations in wind speed and direction result in random combinations of power fluctuations having cycles of several tens of seconds, cycles of several minutes, cycles of several tens of minutes, and cycles of several hours. As a method to suppress the effect of wind speed fluctuation, variable speed machines have been used to absorb the fluctuation by changing the rotating speed rather than the generated power output, however, fluctuations having cycles of greater than several seconds cannot be absorbed due to limitations in the variable speed range. In other words, in the case of a fixed speed machine, a fluctuation component having a cycle of several seconds will be added.

Cases in which the fluctuation in wind turbine generated power and the load fluctuation (fluctuation in power consumption) cancel each other out present no problems. In the worst case scenario, however, both fluctuating values add together, the capacity of governor-free and LFC frequency control become insufficient, and the frequency may not be maintainable within the targeted range for power system operation. This is a problem in cases where a wind power turbine is installed in an area such as an island where the power system has a small capacity, but is also a problem in power systems of large capacity when many wind power turbines having a capacity that exceeds a certain percentage of the power system capacity are introduced into a concentrated area.

Furthermore, if the wind reaches speeds in excess of 20 to 25 m/s due to a typhoon or the like, the wind turbine will cutout (stop). However, because the power generated by a wind turbine will decrease from its rated value to zero in a short time, problems may arise in the dynamic and transient stability of the power system.

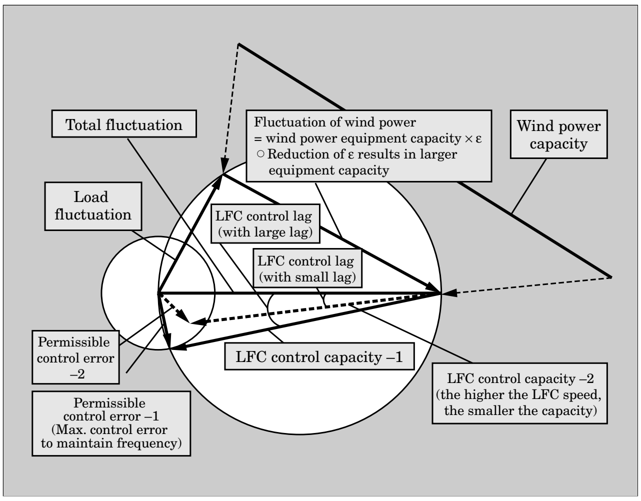
3.3 Measures to suppress frequency fluctuation (active power fluctuation)

Figure 5 shows the relationship between LFC control capacity (quantity and response speed) of the electric power companies, load fluctuation, and allowable fluctuation in wind power generation.

As shown in Fig. 5, the following four methods are available as measures to increase the amount of generated wind power.

(1) Increase the LFC control capacity
(2) Reduce the LFC control lag

Fig.5 Relationship between fluctuation suppression of load / wind power generation and LFC control



(3) Reduce the load fluctuation
(4) Reduce the fluctuation ratio (ε) of wind power

However, measures (1) and (2) are determined by the configuration of each electric company's equipment, and it is difficult to modify or upgrade the equipment configuration within a short period of time for the purpose of wind power generation. Moreover, measure (3) involves the fluctuation in power consumption by the end-user, and suppression of this consumption is not possible.

Thus, in order to increase the amount of generated wind power, the LFC control capacity or the governor-free control capacity must be used to maintain the amount of fluctuation in wind power generation to the allowable level of fluctuation or lower. This control is realized with a power stabilizer that charges a power storage apparatus with the constantly fluctuating generated power and also discharges the power storage apparatus in order to smooth the power at points of connection between the wind power plant and a power system.

In an isolated power system such as on an island, electric power is supplied mainly with diesel power generating equipment. A diesel power generator is capable of output control, in approximately one minute, from the maximum output to the minimum output, and also capable of absorbing and controlling fluctuations in the power generated by a wind power turbine and fluctuations in the power consumed, for which the fluctuation cycles are relatively short. However, frequent output control potentially has a deleterious effect on the service life of diesel power generating equipment, and there is a limit to which governor sensitivity can be increased. Thus, in an isolated and weak power system such as on an island, it is necessary to suppress the small fluctuating components of wind power having a cycle of several minutes or less and residing in the governor-free area of Fig. 3.

On the other hand, in a bulk power system, mainly due to a generated power control that also controls the starting and stopping of a thermal power plant, fluctuations in the power consumed and fluctuations in the power generated by wind power generating equipment are absorbed and a balance between the power generated and consumed is maintained in order to keep the frequency at its rated value. However, the generated power output control speed of a thermal power plant is slower than that of a diesel or hydropower plant, and a dozen to several tens of minutes are required and there are limits to the minimum output and controllable output.

Therefore, when connecting multiple pieces (a large capacity) of wind power generating equipment to a bulk power system, in addition to suppressing the load fluctuation in the governor-free frequency area, it is also necessary to suppress short cycle fluctuations in the LFC area, i.e., generated power fluctuations having cycle lengths of several tens of minutes or less must be suppressed. Figure 6 shows an example of the output controllability rates for various types of power generating equipment.

A detailed description is omitted in this paper, but as shown in Fig. 3, demand is low at night, and therefore fewer power plants operate using EDC. For this reason, the controllability of power systems is also decreasing, and in order to maintain the night-time fluctuation at a level comparable to the allowable fluctuation in day-time wind power generation, it may be necessary in some cases to install a power storage apparatus having a large smoothing capability or to stop the wind power turbine.

3.4 Types and features of power storage apparatuses

It has previously been mentioned that combination with some sort of power storage apparatus is needed when connecting wind power generation equipment to a power system, and Fig. 7 shows the relationship between the practical maximum power and storage capacity of various types of power storage apparatus.

Fig.6 Output controllability rates of power generating equipment

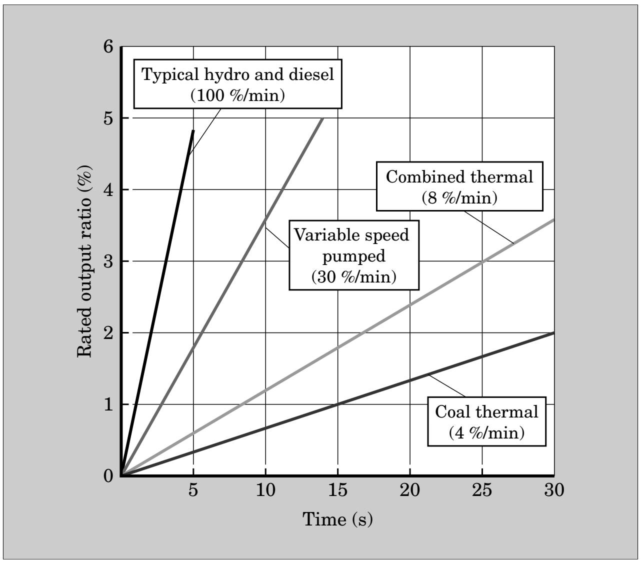
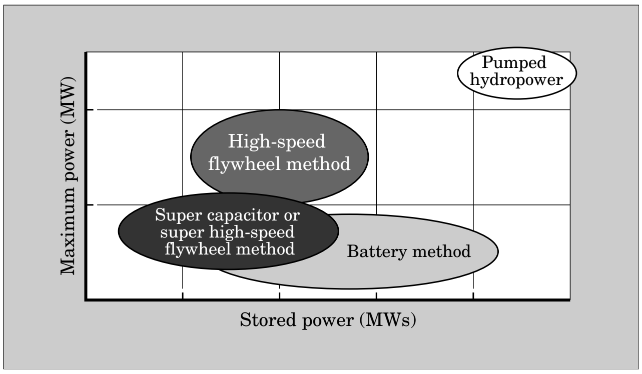


Fig.7 Maximum power and storage capacity of power storage facility



Typical methods for storing power are described below.

(1) Electric energy (various storage batteries, electric double-layer capacitors) method

Storage batteries are static devices, and storage batteries can be freely arranged to achieve the required storage capacity. However, because there is a limit to the number of times these batteries can be charged and discharged at a high cycle rate, they are therefore well suited for suppressing the short cycle and long cycle components shown in Fig. 3. Moreover, in order to use storage batteries to suppress small fluctuations having a high cycle rate, it is necessary to lengthen the service life of the storage battery by increasing the kWh capacity and considering the depth of discharge.

The New Energy and Industrial Department Organization (NEDO Technical Development Organization), an independent administrative agency, is performing verification testing of a wind power plant output leveling system that takes into account the suppression of long cycle fluctuations. The types of storage batteries being used in this testing are redox flow batteries, sodium sulfur (NaS) batteries and lead batteries, and nickel hydride batteries are also expected to be used in the future.

Moreover, because electric double-layer capacitors, which store electric power by ionic transfer without a chemical reaction, require no auxiliary equipment, are highly efficient, and have a long service life for full charge-discharge cycling, their future use is anticipated. Because the amount of energy stored per unit volume is similar to that of the super high-speed flywheel (to be described later), and electric double-layer capacitors are well suited for suppressing small fluctuating components having a rapid fluctuation cycle speed.

(2) Kinetic energy (flywheel) method

There are two flywheel methods, the high-speed flywheel method and the super high-speed flywheel method. The energy storage capacity of a rotating body is proportional to the square of its rotating speed. A super high-speed flywheel has a rated rotational speed at the order of 40,000 min^{-1}, more than 10 times of the speed for a high-speed flywheel, and thus this method achieves more than 100 times the energy storage on a rotating body of the same mass.

This method enables the external dimensions of the power generator to reduce, and has the characteristics of high responsiveness, high efficiency, and almost no limitation on the number of full charge-discharge cycles. However, because energy storage capacity is limited, this method is best suited for suppressing small fluctuating components.

Moreover, the amount of stored energy can be ascertained correctly by detecting the rotating speed, and therefore by using a suitable control method, the kWh capacity of the power stabilizing apparatus may be reduced.

3.5 Power stabilizing apparatus for wind power plant

Here, a power stabilizing apparatus that uses a method of electric energy or kinetic energy is described. Figure 8 shows an example configuration of a power stabilizing apparatus and Table 1 lists the types and features of suitable power storage apparatuses.

This method uses a bidirectional inverter and therefore the phase angles of the input and output current can be controlled. Accordingly, both active and reactive power can be controlled simultaneously, and when connecting a wind power system to a power system, this method also provides functionality that combats the other problem of voltage fluctuation.

A portion of the actual operational results of a super high-speed flywheel power stabilizing apparatus is described below. The response speed, fluctuation cycle to be controlled, required maximum power, required amount of power, and the like are the same as in the case when using another power storage means such as storage batteries or an electric double-layer capacitor.

(1) Indicial response with the super high-speed flywheel method

Figure 9 shows an example of the active power indicial response of the super high-speed flywheel method. This power stabilizing apparatus aims to also control the fluctuating cycles of small fluctuating components, and therefore a first-order lag time constant of several hundred milliseconds or less is desired for the response speed. In the indicial response test results, including the lag time of the active power converter, the first-order lag time constant was approximately 220 ms, and the first-order lag time constant of the reactive power control circuit was 38 ms.

(2) Active power fluctuation suppression with the super high-speed flywheel method

By optimizing the setting value of the control constant of the system controller, we are verifying that the frequency region of energy absorbed or discharged (active power fluctuation cycle) by the super high-speed flywheel can be changed arbitrarily. Based on the relationship with maximum output, power storage capacity, and the like, in cases where control is applied only to small fluctuating components, it is desired that the response region of the power stabilizing apparatus be set to the fluctuation cycle of approximately 10 to 100 seconds. Moreover, by increasing the maximum output and power storage capacity, small cycle compo-

Fig.8 Example configuration of power stabilizing apparatus

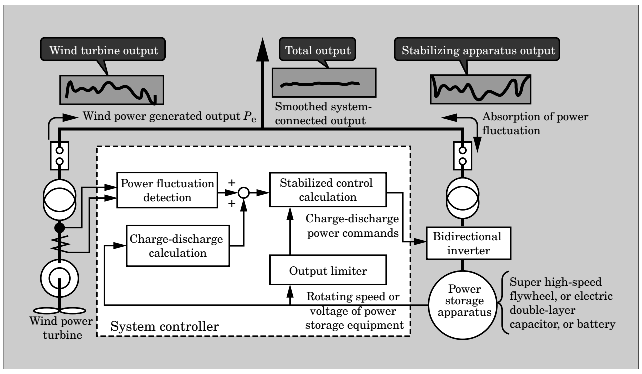


Fig.9 Example of active power indicial response

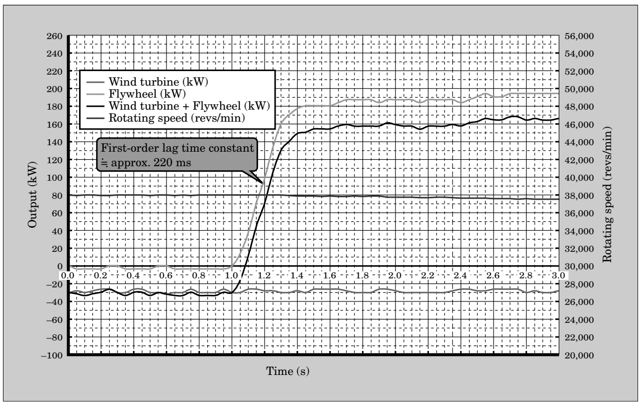


Table 1 Types and features of power storage apparatuses

	Super high-speed flywheel (FFW-300S)		Electric double-layer capacitor (Super capacitor)		Secondary battery (lead, NaS, redox flow)	
Electricity storing method	Good	Kinetic energy	Excellent	Physical ionic transfer (direct charging and discharging with electricity)	Good	Chemical reaction
Ascertainment of quantity of electricity stored	Excellent	Rotating speed (proportional to square of rotating speed)	Excellent	Voltage (proportional to square)	OK	Voltage (non-linear: accurate ascertainment is difficult)
Max. power	Good	Determined by inverter capacity (series-parallel connection with power storage apparatus)	Good	Determined by inverter capacity (series-parallel connection with power storage apparatus)	Good	Determined by inverter capacity (series-parallel connection with power storage apparatus)
Response speed	Good	100 ms or less	Excellent	10 ms or less	OK	1,000 ms or less
Repeat frequency (service life)	Excellent	Short cycle repeatable (no deterioration of characteristics)	Good	Short cycle repeatable (some deterioration of characteristics)	Poor	Difficult to repeat short cycles (deterioration of characteristics)
Auxiliary equipment	OK	Converter for flywheel, vacuum pump, chiller (cooler)	Good	Cooling fan	OK	Lead battery: None Other batteries: Circulation pump, heater, etc.

nents can also be subjected to control, and in this case it is desired that the response region of the power stabilizing apparatus be set to the fluctuation cycle of approximately 10 to 1,000 seconds.

Figure 10 shows an example of the characteristics of power fluctuation suppression of a super high-speed flywheel power stabilizing apparatus that aims to suppress small fluctuation components on an island. The power generated by a wind power turbine has cycles ranging from several seconds to several minutes, and although fluctuation of active power is accepted in the 100 kW to 300 kW range, it can be seen that the super high-speed flywheel power stabilizing apparatus decreases the above value to less than 100 kW.

Situated on an island, this power generating facility is a diesel generator having a total capacity of 31,000 kW. In 2000, the maximum demand was 24,900 kW, the minimum demand at night was 8,500 kW and the minimum demand during the day was 12,400 kW. Three 600 kW wind power turbines are connected to the power system, and a super high-speed flywheel power stabilizing apparatus, having an active power suppression range of ±0 to 200 kW, a power storage capacity of ±9,000 kWs, and a reactive power suppression range of ±0 to 200 kvar, is used to suppress the fluctuation of active power to the rated value or less within several minutes and to also

Fig.10 Characteristics of power fluctuation suppression

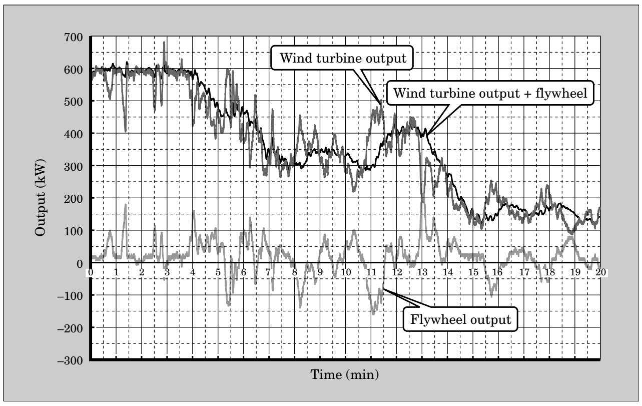


Fig.11 Power fluctuations with and without flywheel energy storage

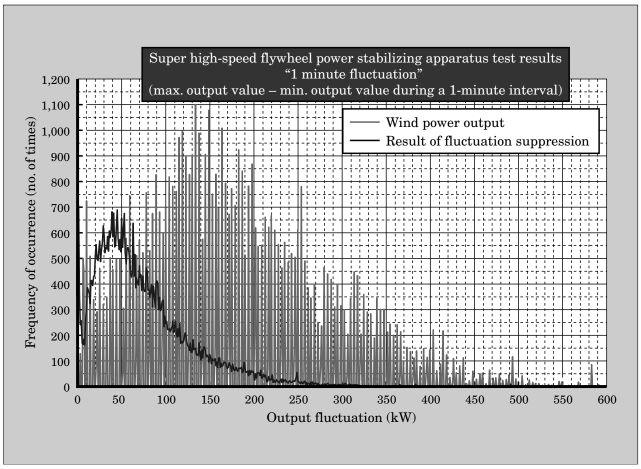
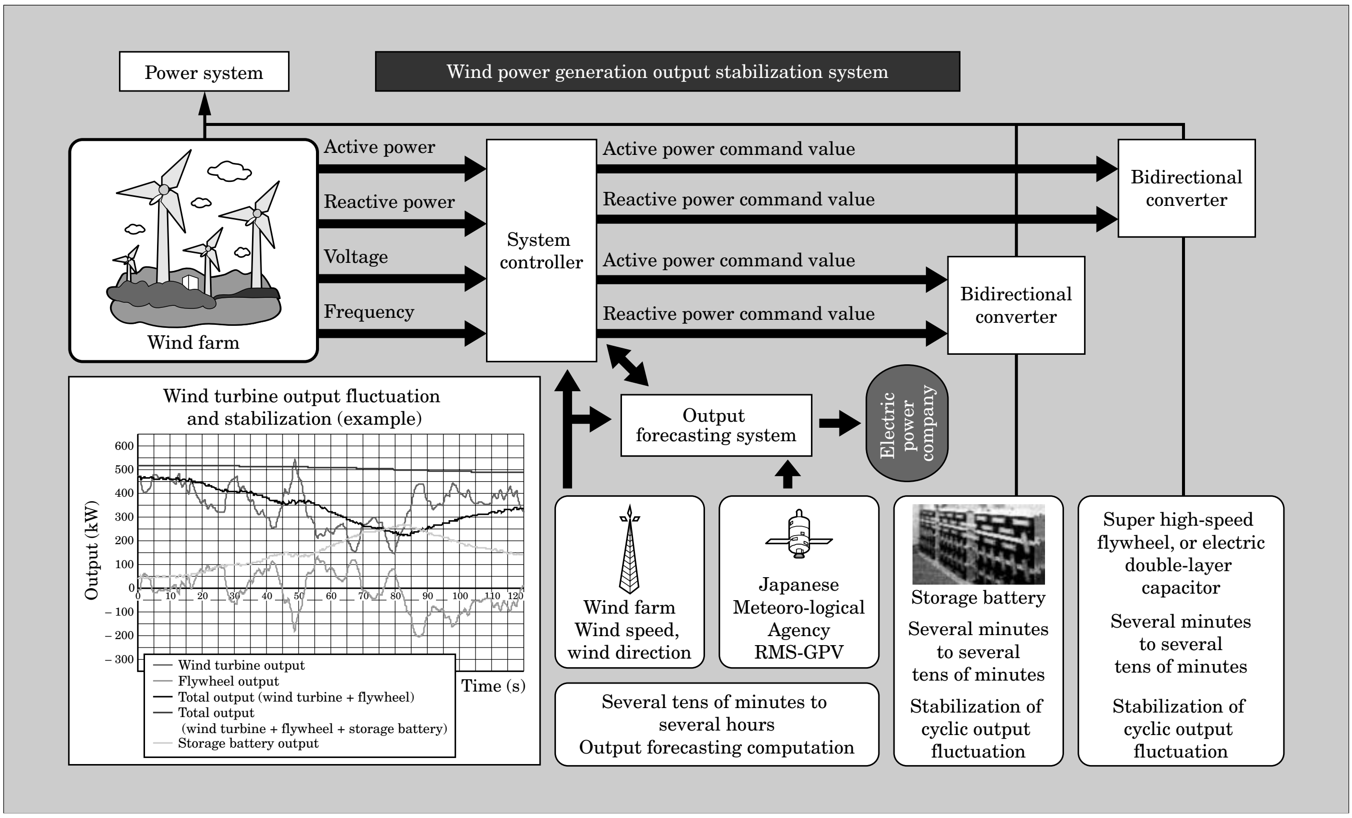


Fig.12 Example hybrid system configuration



suppress the voltage fluctuation to the rated value or less.

The control constant is optimized so that the super high-speed flywheel maintains the rotating speed (amount of energy storage) at the rated value or less, and suppresses the fluctuation in active power to the rated value or less.

Figure 11 shows the fluctuation [(maximum value) – (minimum value)] of generated power in one-minute intervals, the frequency of occurrence, and the results of fluctuation suppression when a power stabilizing apparatus is provided. From the results of the power stabilizing apparatus, it can be seen that the frequency of fluctuations of 100 kW or greater has been reduced dramatically.

3.6 Hybrid power stabilization system

The super high-speed flywheel power stabilizing apparatus for wind power generating equipment that was introduced in section 3.5 is a system well suited for suppressing the power fluctuation of short cycle components and small fluctuation components. Similarly, an electric double-layer capacitor power stabilizing apparatus can also be applied to suppress power fluctuation in this area.

Furthermore, to manage long cycle components and to respond to weather forecasting, a hybrid power stabilization system consisting of various power storage apparatuses is effective.

Natural Resources and Energy Agency and NEDO are already moving ahead with investigation and research of weather forecasting. Figure 12 shows an example configuration of a hybrid system.

4. Conclusion

Wind power generation contributes greatly to combating environmental problems such as global warming, however, due to power system connection constraints in order to maintain the power quality, and restrictions on the parties involved with construction and operation, there is a high hurdle to achieving the level of wind power introduction targeted by the Japanese government. Thus, in order to reach the targeted level of 3.0 GW by 2010, the Subcommittee for Connecting Wind Power Generation to Power Systems vows to disclose a variety of countermeasures, work to ascertain the implementation status of the countermeasures, and as necessary, draft and promote additional countermeasures.

Fuji Electric will strive to improve the performance and reliability of wind power generation systems, to satisfy each wind power generating company and electric power company, and through cooperation with organizations and committees involved in wind power generation, intends to be actively engaged in the steady advancement of wind power generation.

Moreover, in order to reduce the life cycle cost of power stabilizing apparatuses, Fuji Electric will continue to research the selection and combination of power storage apparatuses suited to a particular application, and continue to advance the research, development and demonstration of various types of control methods in order to reduce the kW capacity and the kWh capacity to the minimum required levels.

The authors respectfully request continued cooperation and guidance from all concerned parties.