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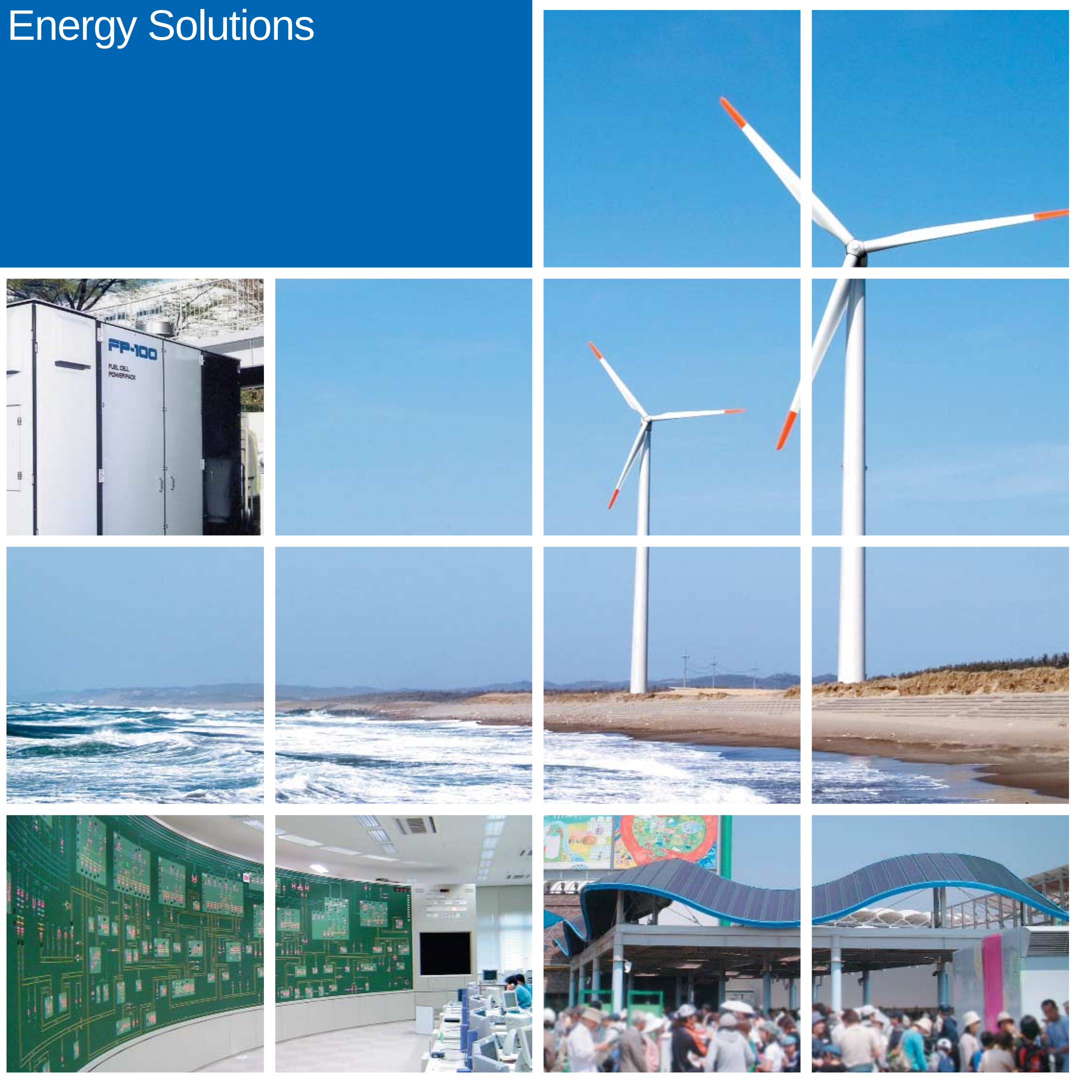
FUJI ELECTRIC REVIEW

3

2006 VOL.52

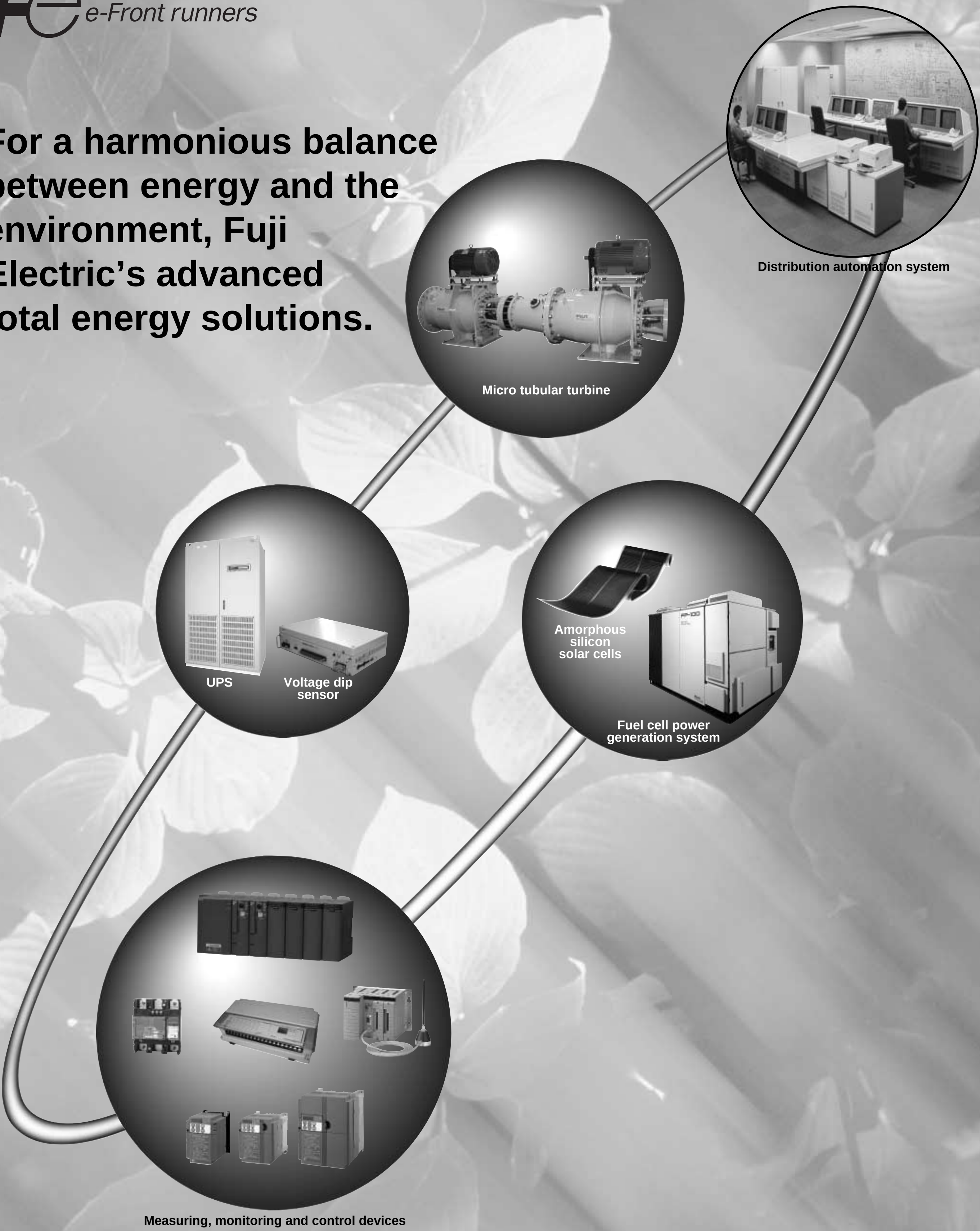
Energy Solutions



Fuji Electric Group

e-Front runners

For a harmonious balance between energy and the environment, Fuji Electric’s advanced total energy solutions.



Fuji Electric is working to develop total energy solutions realizing coexistence of existing large-scale energy systems and distributed energy systems such as new energy, covering for a sequential energy cycle of generation, distribution and consumption.

Fuji Electric’s Energy Solutions

FUJI ELECTRIC
REVIEW

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Energy Solutions

CONTENTS

Cover photo:

The severity of global environment-related issues is intensifying. Consequently, there is an urgent need for applications of natural energy such as wind power and solar energy, the utilization of hydrogen energy by using fuel cells or the like, the efficiency transport and supply of energy to areas of demand, non-wasteful utilization of energy that has been supplied, and other measures concerning the introduction and use of various types of new energy.

From among the above-described energy solutions provided by Fuji Electric, the cover photo depicts wind power generation, film-type solar cells, phosphoric acid fuel cells, and a power monitoring and control system that contributes to the high reliability and efficiency distribution of electric power.

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Overview of Fuji Electric's Energy Solutions

Kazuhiro Ohashi

1. Introduction

In response to the increasing severity of global warming, acid rain, ozone layer depletion, destruction of tropical rainforests, desertification and other such environmental problems of a global-scale that are not limited by national borders, the Kyoto Protocol took effect in February 2005. Japan has announced a "Basic Energy Plan," a medium and long-range energy policy that emphasizes energy security, environmental suitability and the application of free market principles, and which calls for the introduction of alternative (oil-free) energy sources and energy saving, and the introduction of free market principals to the energy field as typified by the opening of an exchange for electric power transactions.

Fuji Electric established a "Basic environmental protection policy" in 1992, and has acquired ISO14001 certification, promoted energy saving in manufacturing processes, deployed a zero emissions plan based on strict implementation of the "3 Rs" (reduce, reuse and recycle), and has advanced the protection and preservation of the global environment by providing solutions in the fields of energy, electric power distribution,

Fig.1 Changes in the environment and Fuji Electric's energy solutions

		Item	Start (To 2000 / 2001 to 2005 / 2006 and beyond)
Application		Outline of measures to combat global warming ▼	2001 to 2005
Application		Renewable portfolio standard (RPS) measure concerning use of new energy by power companies ▼	2001 to 2005
Application		Energy savings law revised ▼	2001 to 2005
Application		Basic energy plan ▼	2001 to 2005
Application		▼ Kyoto Protocol (COP3) effective	2001 to 2005
Fuji Electric's energy solutions	Energy saving ESCO	Energy saving devices (highly efficient transformers, inverters, etc.)	To 2000
		Energy measurement systems (EcoPASSION, PowerSATELITE)	To 2000
		Guaranteed saving ESCO	2001 to 2005
		Shared saving ESCO	2001 to 2005
	New energy	Phosphoric acid fuel cell	To 2000
		Microtubular water turbine	2001 to 2005
		Equipment for connecting wind power plant to a power system	To 2000
		Wind power generating system, wind power business	2001 to 2005
		Amorphous silicon solar cells	2001 to 2005
		Power stabilizing system	2001 to 2005
	Energy management	Spectrum PowerCC	2001 to 2005
		Forecasting techniques, optimizing techniques	2001 to 2005
	Power metering network	Power metering for transaction-use, automatic metering system	To 2000
		Pulse meter adapted to network	To 2000
	Computer technology	Neural network forecasting, optimization	To 2000
		SCADA	To 2000
		Control component compatible with IP technology	2001 to 2005
		System analysis simulator, various simulation models	To 2000
	Maintenance technology	Preventative maintenance, various tools	To 2000
		24-hour call center service	To 2000

water treatment, industry and transportation, information, lifestyle, and the like.

In the energy field, Fuji Electric has responded to global environmental problems, and contributed to ensuring energy security and reducing energy cost with energy solutions that combine technologies for energy saving, ESCO (energy service company), new energy, energy management systems, power quality improvement, maintenance, environmental preservation and the like. Figure 1 lists environmental changes and Fuji Electric's involvement with energy solutions. An overview of Fuji Electric's energy solutions is presented below.

2. Current Status and Future Outlook for Energy Solutions

In October 2003 the Basic Energy Plan was approved at a Japanese government cabinet meeting and reported during a session of the Japanese parliament. The basic policy of this plan relating to power demand can be summarized as follows.

(1) Measures relating to energy supply and demand
- (a) Support for research and development that would not be undertaken sufficiently if left solely to market forces
- (b) Official regulations for ensuring profit and safety for the entire population

(2) Measures to counteract energy demand
- (a) Creation of a resource-saving economic and social structure
- (b) Load leveling

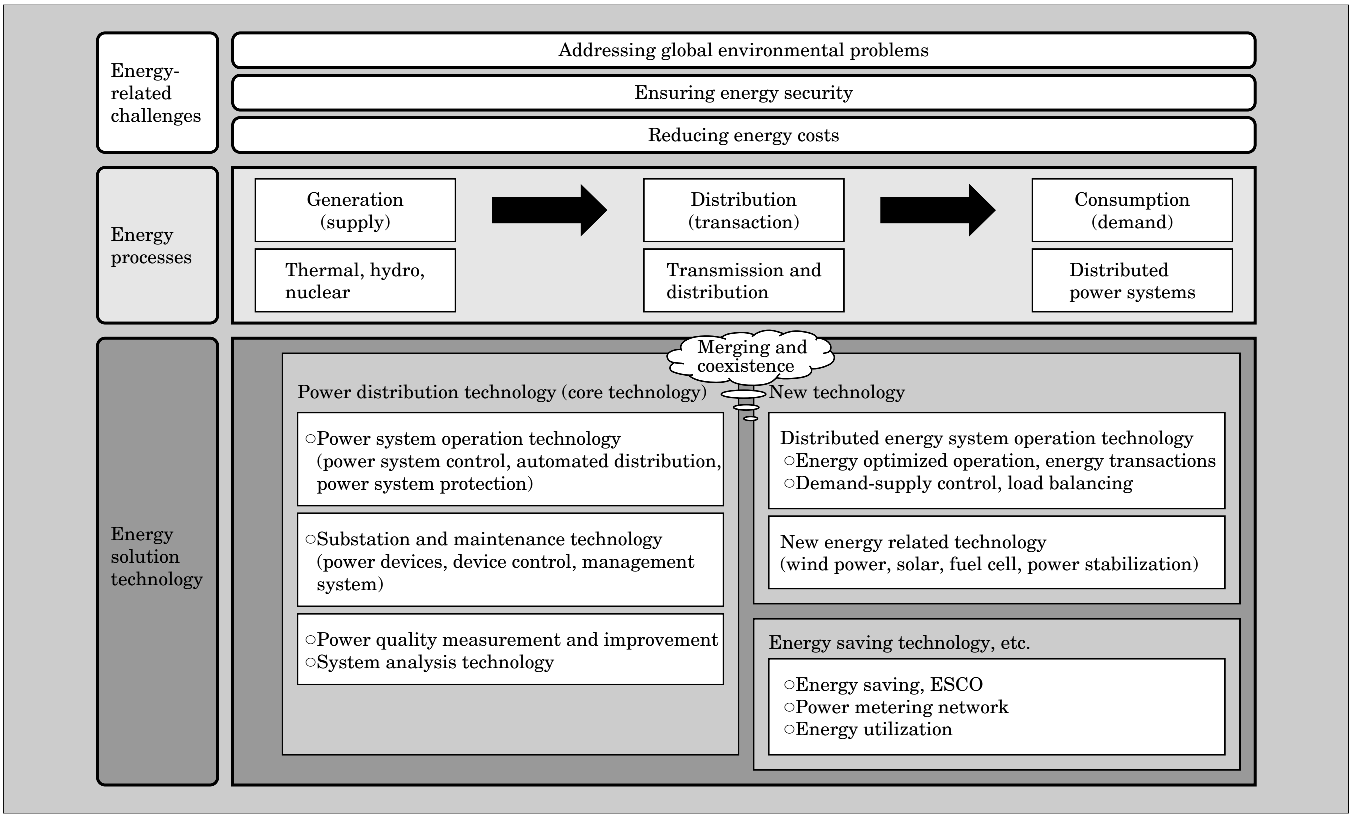
(3) Development and introduction of various types of energy
- (a) Development, introduction and use of nuclear power: Promotion of nuclear power as a key power source, with a guarantee of safety as the major precondition
- (b) Development, introduction and use of new energy: Contribute to improved energy self-sufficiency and efforts to combat global warming; expected to be implemented as distributed energy systems

This plan, based on new energy and nuclear power generation in the medium and long-term, and using distributed-type new energy power sources, ensures energy security and environmental suitability. The future challenge for energy systems is to create a network in which a distributed energy system that uses new energy, for example, can coexist with a large-scale existing energy system based on nuclear power generation.

Issues involving environmental considerations, regulations and technology will be clarified and these measures advanced, but solutions to the following technology-related issues are essential.

- ○ Technology that supports energy conservation and energy management for the consumer; ESCO-based support
- ○ Device technology for new energy such as fuel

Fig.2 Fuji Electric's energy solution technologies



cells, solar power generation, wind power generation, and micro hydropower generation; System interconnection technology
- ○ Power quality measurement, status monitoring, control technology, power system analysis technology, and stabilization control technology to prevent a degradation of power quality caused by distributed power sources
- ○ Operation and control technology, including a storage system for distributed energy, so that an existing large-scale energy system and a distributed energy system can coexist
- ○ Technology for constructing a virtual micro-grid system based on IT (information technology)
- ○ Energy management technology having functions for controlling the supply-demand balance of generated and consumed energy including heat, and for supporting exchange transactions

To resolve the above technology-related issues, as can be seen in Fig. 2, Fuji Electric aims to establish a system placing "power distribution" technology as its core technology for the energy cycle sequence of generation, distribution and consumption. Fuji Electric is working to develop customer-oriented total energy solutions that combine energy saving, ESCO, power metering network, and system maintenance technology, by promoting the restructuring of energy solution technologies so that existing large-scale energy systems can coexist with distributed energy systems that use new energy or the like.

3. Fuji Electric's Efforts

Table 1 shows an overview of Fuji Electric's energy solution technology and main products and services. The main examples of Fuji Electric's involvement include supply-demand control systems that include local energy systems (micro-grids) and ESCO service, wind power generation equipment that includes power output stabilizing equipment, a wind power business, and lightweight and flexible film-substrate amorphous silicon solar cells. In addition, by participating in national projects and cooperating with external institutions, including joint research between industry, academia and national research institutes and joint development overseas (in China), Fuji Electric is also committed to the development of new technologies and products. Fuji Electric's various solution technologies are described below.

3.1 Energy saving, ESCO solutions

Energy saving measures help to combat global warming by reducing the final consumption of energy and thus suppressing the generation of carbon dioxide (CO_2) caused by energy consumption, and together with the introduction of new energy, are important environmental measures. As disclosed in the concept of the "Law Concerning the Rationalization of Energy Usage" (also known as the Energy Saving Law), energy savings measures are used to rationalize the usage of energy by eliminating waste and increasing the efficiency of energy usage. Because energy saving based only on economizing and self-restraint is not sustainable and has limited effectiveness, basic measures that include a reassessment of the entire system are needed in order to realize effective energy saving without sacrificing productivity and comfort. For this purpose, ingenuity, ideas and specialized knowledge are needed.

Table 1 Energy solution technology and products

Segment	Description	Product or service
Energy saving ESCO	Consulting and implementation of measures concerning the reduction of customer's energy costs	○ Energy saving measurement ○ Energy saving consulting ○ ESCO with inverter ○ ESCO with CHP (combined heat and power)
New energy	Supply of equipment for using new energy and renewable energy Provision of engineering services	○ Wind power generation, Wind power generation business ○ Solar power generation ○ Micro hydropower ○ Fuel cell (biomass power generation)
Energy management Distributed energy system	Assessment of customer's energy utilization status, Rationalization of use and procurement Solutions for optimization, Provision of services	○ Power quality measurement ○ Equipment for power quality improvement ○ Energy management, optimal operation ○ Generator control ○ Energy exchange transaction support ○ System analysis technology
Power metering network	Supply of equipment relating to power metering, Provision of solutions	○ Power metering ○ Automated metering system ○ Automated metering terminal
Computer technology	Supply of equipment for highly reliable energy distribution Provision of solutions and services	○ Power monitoring system ○ Automated distribution system ○ Information sharing system ○ Tele-control, tele-meter ○ Protective relay
Maintenance technology	Energy equipment maintenance, Operation outsourcing, Provision of preventative maintenance services	○ Maintenance network ○ Call center ○ Operation, procurement, maintenance outsourcing

Having developed highly efficient equipment and energy-saving equipment, and having been actively involved in energy saving engineering that applies various plant control technologies, Fuji Electric has provided a wide range of energy solutions. In particular, Fuji Electric has focused on further improving energy saving technology such as by increasing the effectiveness of ESCO businesses for local governmental office buildings, and by creating a BEMS (building energy management system) that utilizes measurement and control technology. In the future, Fuji Electric intends to continue to contribute to all sorts of energy saving measures.

3.2 New energy solutions

From early on, Fuji Electric worked to develop the technology for fuel cells and amorphous silicon solar cells, and has accumulated much experience through its involvement with new energy and renewable energy such as wind power, micro hydropower, wave power, and geothermal power.

At present, Fuji Electric has increased the cell life from 40,000 to 60,000 hours of the phosphoric acid fuel cell only commercially available in Japan, and has introduced a 100 kW model to the market. Furthermore, in order to expand the range of applications, Fuji is strongly promoting the development of a model equipped with a hydrogen supply function and the development of home-use proton-exchange membrane fuel cells.

Introduced to the market is October 2004, the film-substrate amorphous silicon solar cell has the advantages of flexibility and light weight, and has been attracting attention as product that expands the possibilities for solar cells. Additionally, this solar cell has a shorter energy payback time (the interval during which the energy expended for manufacture is generated and recovered by the product itself) and lower impact on the environment during manufacture than a conventional crystalline-type solar cell. Figure 3 shows the appearance of a flexible, film-substrate amorphous silicon solar cell module.

Fig.3 Film substrate-type amorphous silicon solar cell module

Aiming to decrease the initial cost and running cost associated with wind power generation, the output per turbine is being increased and large-scale wind farms are being promoted. However, planned output control is difficult to implement for wind power generation, and the connection of a wind power plant to an electric power system may be subject to many restrictions. Fuji Electric also provides power stabilizing equipment that leverages the power station and substation using monitoring and control technology and system analysis technology for which Fuji has an abundance of experience, and is working to merge wind power generating systems with existing electric power systems.

3.3 Distributed energy system

Natural energy power generation such as wind power generation and solar power generation is unstable because its output is affected by natural conditions, and has limited connectability to an electric power system due to concern about frequency and voltage stability. Of the various distributed energy systems that have been proposed to minimize the impact on an electric power system when connecting distributed power sources that include natural energy generation, the micro-grid is attracting the most attention.

A micro-grid is an onsite self-sufficient power supply system that receives power from distributed power sources such as CHP, solar cell power generation and wind power generation installed within a certain area where several end-users are located and maintains a balance between energy supply and demand within the grid. A micro-grid requires supply-demand balancing control in order to stabilize the power flow at points of connection to a larger electric power system. Fuji Electric is advancing the construction of a distributed energy system by integrating a wide range of technologies such as generator and inverter device technology, measurement and information processing technology, system monitoring, control and protection technology, and power system stabilizing technology.

3.4 Energy management (Spectrum PowerCC *1)

Fuji Electric is promoting the application of "Spectrum PowerCC," an energy management system ideally suited for comprehensive supply and demand control for the energy and heat that is generated and consumed.

Spectrum PowerCC is a standard software package that incorporates SCADA (supervisory control and data acquisition) and other standard functions such as load forecasting, power generation planning and generator control, engineering tools, various standards that facilitate the linking of data, and the latest IT

*1: Spectrum PowerCC is a trademark of German Siemens AG.

(information technology) such as Windows*2 and Web software. Further, a system running on the Spectrum PowerCC platform and that leverages the technology and know-how cultivated with conventional power monitoring and control systems, for example, by combining that technology and know-how with one of Fuji Electric's proprietary applications such as market transaction support on the end-user side for power exchange transactions, is being promoted as an energy management system suitable for the Japanese market.

3.5 Power metering network system

Efforts to introduce power metering (legal meters for transactions involving electric fees) and an automated meter system for processing that metered data are already underway, and nearly all bulk customers of 500 kW or greater have installed such systems. With the advancement of retail electricity liberalization, high voltage customers rapidly have increased need for such systems and their rate of installation is accelerating. Moreover, typical low-voltage customers are planning to install such systems in some regions where meter reading is inconvenient, and there is increasing need for ON/OFF switching on the load side of the power supply.

Fuji Electric is working to achieve widespread use of network systems through developing electronic power meters provided with a current loop-type communications functionality, and communications terminals and the like that connect power meters to an upper-level network.

3.6 Computer technology

Previously, monitoring and control systems for the large-scale energy systems that form the power system infrastructure were configured so as to collectively monitor and control a local area. In the power distribution field, however, greater importance is being placed on increasing business efficiency and equipment downsizing, monitoring and control systems are becoming more streamlined, and there is increasing demand for information sharing, mutual backup, and more sophisticated business functions among systems distributed over a wide area.

Fuji Electric is developing technology for the construction of a wide-area monitoring and control system that incorporates these types of horizontal integration. Additionally, equipment that utilizes IP (Internet protocol) network technology is being developed for the protection and control equipment and telecontrol equipment directly linked to onsite devices. Systems that do not need to be concerned with the location of computer installations can now be constructed. These technologies can also be applied to a distributed energy system.

On the other hand, under these circumstances, it has also become important to reassess maintenance and preservation tasks in order to use energy more efficiently and to prolong the service life of equipment, and Fuji Electric is moving ahead with the development of applications that employ predictive technology based on neural networks and the deployment of maintenance technology that supports the more efficient operation of equipment. Moreover, Fuji Electric is also developing functions for enhanced information security whereby, instead of relying simply on a user ID and password, authority for an operation area and scope of work is granted based on authentication and an operator security level obtained from an IC card.

3.7 Maintenance technology

Following the revision of Japan's "Electric Utility Law" in 1995, safety regulations for electric equipment were reassessed with greater emphasis on corporate responsibility, and optimal maintenance planning is desired for improved reliability and economic reasons.

Fuji Electric provides support tools for predictive maintenance based on residual service life diagnostic techniques, remote diagnosis, long-term maintenance planning optimization and the like, and is promoting a life cycle service featuring a call center that operates 24 hours per day, 365 days per year.

4. Conclusion

The formation of a sustainable recycling-oriented society is an important challenge.

Fuji Electric intends to continue to concentrate its collective technical expertise and strive to achieve a harmonious coexistence between energy and the environment.

With the publication of this special issue, we wish to express our gratitude to all concerned parties throughout the world and to respectfully request continued guidance and support.

*2: Windows is a registered trademark of US-based Microsoft Corp.

Technology for Distributed Energy Systems

Eijiro Ibaragi
Tomohiro Suzuki
Shinsuke Nii

1. Introduction

In response to the heightened awareness of global environmental problems, the use of renewable energy and natural energy is being promoted, but such sources of power are typically associated with a high cost of power generation and they also have stability-related problems since the quantity of power generated is strongly influenced by natural conditions, and there is also a limit to the capacity that can be connected while maintaining the power quality of an existing system.

Meanwhile, the power quality in Japan is the highest in the world, but the cost is high and is one factor for the overseas expansion (hollowing out of Japanese domestic industry) of global corporations that compete among an international community. Under these circumstances, liberalization is being promoted to apply market economic principles to the consumable product of electric power, and some positive results have been achieved.

A distributed energy system has been proposed as a means for responding to environmental problems while effectively leveraging the application of market principles. A distributed energy system is a configured from a distributed power source that includes new energy power generation, a load (consumers), an energy storage apparatus, a monitoring and control system, and the like. A distributed energy system adjusts the balance between the supply and demand of energy in order to realize a stable supply of power.

This paper discussed the trends and Fuji Electric's efforts concerning distributed energy systems.

2. Various Concepts Relating to Distributed Energy Systems

The social infrastructure in Japan has been supported by an assumption of highly reliable and high quality electric power, and high reliability and quality are becoming even more crucial nowadays with the recent advances in electronics and information technology and the advent of an information-based society whereby a power outage would have an much larger impact on our lifestyle and security than in the past. Meanwhile, the response to environmental problems as described above and the introduction of market principles to the power industry are vigorously being advanced as demanded by society, and there is also demand for an environmentally-friendly and low-cost power supply that maintains the quality of electric power. These types of societal demands are common to every nation in the world, and various trials are being implemented throughout the world in order to find solutions to these demands.

A virtual power plant is a system that performs general management and control via a communications network, and in order to utilize efficiently the emergency generators that are legally required at factories and hospitals, the system operates an emergency generator to supply power at times such as when demand is high, or in the case of a surplus, to sell power to reduce the upkeep costs for the customer. Virtual power plants are being commercialized by software companies in the USA as a novel business model for a plant that contributes to the stability of a regional system.

A power park is a trial system that supplies power in different grades of quality in a limited region whereby the power quality is modified and power is supplied according to the needs of a load. This system installs a distributed generator of relatively large capacity in the existing distribution system, and via a power quality control center, modifies and supplies power priced differently according to the quality.

FRIENDS (flexible reliable and intelligent electrical energy delivery system) is being studied in Japan as a new type of electric power energy distribution system capable of responding to the various requirements subsequent to the easing of regulations. FRIENDS aims to utilize a large number of distributed power sources and power storage equipment in order to realize a highly reliable power supply and energy savings, and to leverage the use of a multi-functional information network in order to realize sophisticated user services. With FRIENDS, a QCC (quality control center) that controls the power quality between a distribution substation and user is installed to supply

Fig.1 FRIENDS conceptual diagram

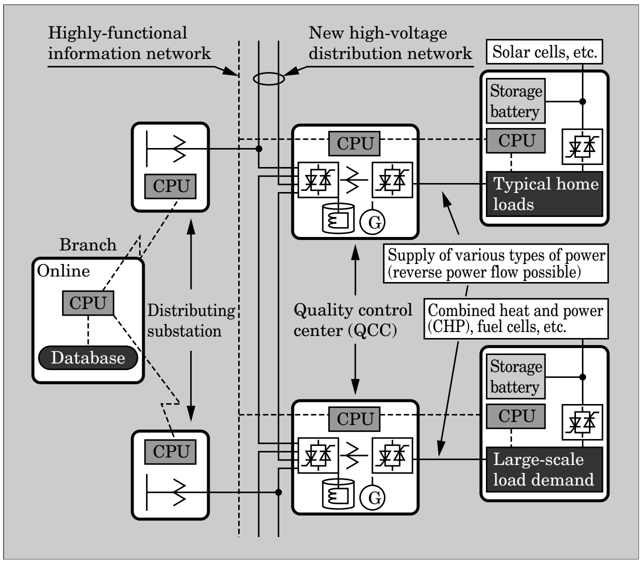


Table 1 Technical challenges concerning construction of distributed energy systems

Category	System connectivity	System			Device
		Planning	Measure-ment	Protection and control	
Steady-state	Ancillary service Isolated operation detection	Power source (capacity, type, combina-tion) Power storage equipment (capacity, type, installation location) Connection point	Regular measure-ments (items, precision, sampling time)	Control of supply-demand balance Output stabiliza-tion control	Response speed Efficiency Durability
Emergency	Emergency power inter-change	Backup power source DSM	Waveform measure-ment (recording time, precision, sampling time)	Emergency control Relay protection method	Operable range

power of multi-level quality. Moreover, by using a powerful information and communications network between the power supplier and user, with transferring information relating to the supply of power and providing power information to the customer, various multi-purpose information and communications services are supplied. (See Fig. 1.)

A micro-grid is an online-type power supply system in which distributed power sources such as combined heat and power (CHP) generators, solar cells, and wind power turbines are installed in a particular region in order to provide power self-sufficiently to that region. Micro-grid is connected to the grid at one or two points, but controlling the supply-demand balance within a grid, the power flow is stabilized and switching between isolated operation and parallel operation can be accomplished with ease. Configurations in which a micro-grid is connected to an existing power system and is supplied power in the case of emergency, and a system that performs load and source leveling by connected together several micro-grids have been proposed to stabilize micro-grid operation.

In Japan, the research of these types of distributed energy systems are being advanced mainly by the New Energy and Industrial Technology Development Organization (NEDO), demonstrative project on grid-interconnection of clustered photovoltaic power generation systems, demonstrative project of regional power grids with various new energies, and demonstrative project on new power network systems are ongoing.

3. Technical Challenges Concerning Distributed Energy Systems

Table 1 lists the major technical challenges that the construction of distributed energy systems faces. These challenges are categorized as device-specific challenges concerning the devices used to configure a network, network configuration-related challenges, and system connectivity-related challenges. Moreover, each of these challenges is described for steady-state and emergency conditions.

Device-specific challenges include improvement of the load regulation speed, efficiency, and durability. Another challenge is improvement of the capability to maintain operation of the devices in an excessive state during an emergency.

When constructing a system, there are challenges relating to the methods of planning, system monitoring, and control and protection. Planning-related challenges involve the technique for combining the types and capacities of best-suited power sources, the method for determining the specifications of the power storage equipment, the technique for arranging various devices within a system, etc. System monitoring-related challenges include the monitoring of various items during steady-state and emergency operation, degree of precision required, data sampling frequency, and the configuration of a system that includes a communication method to realize the monitoring. Control and protection-related challenges involve the technology for stabilizing unstable outputs and the control technology for maintaining a balance between supply and demand within a network.

System connectivity-related challenges include a determination of the quantity of interchange power to be received from the system, and a method for ensuring supplementary power in the case of an emergency. The services received from a system change according to the reliability of the network and the method of system operation during an emergency, and the technology for configuring an economical system is also a challenge.

Of the technology for constructing distributed energy systems, this paper describes the network measurement and information processing technology, supply-demand balancing control, stabilization control, and metering system that relate to the shaded portion of Table 1. Moreover, power quality management for distribution systems is expected to become a challenge for the future, and a wide area PQ (power quality) measuring system is introduced as one example of a countermeasure.

4. Fuji Electric's Distributed Energy System Technology

4.1 Measuring and signal processing technology

Figure 2 shows an example configuration of a supply-demand balancing system. Measurement and control terminals are installed onsite and connected by a network to a monitoring and control center. At the monitoring center, a data server aggregates information from each terminal, and a monitoring and control PC implements load forecasting, optimal operation planning and supply-demand balancing control. Figure 3 shows the appearance of a measurement and control terminal.

These multi-functional and low-cost measurement and control terminals have the following features.

(1) Switchable voltage and current settings for each channel
(2) Ability to monitor various physical quantities such as the amount of electricity and heat, weather information, and the like from a single server
(3) Ability to transfer analog and digital I/O control signals to a PC via a TCP/IP (transmission control protocol/Internet protocol) connection
(4) Demand monitoring and warning function
(5) Waveform recording that is initiated by an external trigger or when a measured value exceeds a threshold value
(6) Ability to measure multiple points simultaneously by using GPS (global positioning system) time synchronization
(7) Equipped with various communication interfaces

In a supply-demand balancing system, measured information is used as data for realizing a 5-minute supply-demand balancing system (to be described later), and for next day load forecasting and optimal operation planning.

In a supply-demand balancing system, the measuring equipment transmits RMS value-converted data at regular time intervals to a control center. The objective of supply-demand balance control can be achieved by measuring such data as the voltage, current, power and reactive power, and measuring weather conditions for forecasting the next day demand. However, in order to prevent a decrease in power quality in a distributed energy system, in addition to the usual power monitoring, data must also be measured to verify the power quality. Table 2 lists an example of the items that are measured in a distributed energy system. Moreover, in addition to normally measured data, transient measurements are also needed to determine the cause of trouble and the responsibility of general electric power suppliers in the case of a fault. With a waveform recording function having a large-capacity memory and a function for multi-point simultaneous measurement with GPS time synchronization, measurement and control terminals are able to assess fault phenomena and to identify fault points, and can also be used for such applications.

Data is usually collected at 1-minute intervals by the server, and 1-minute short-cycle data collection is also necessary for the short-time supply-balance control required by a distributed energy system that includes natural power generation.

The transmission of data between an onsite termi-

Fig.2 Example configuration of supply-demand balancing system

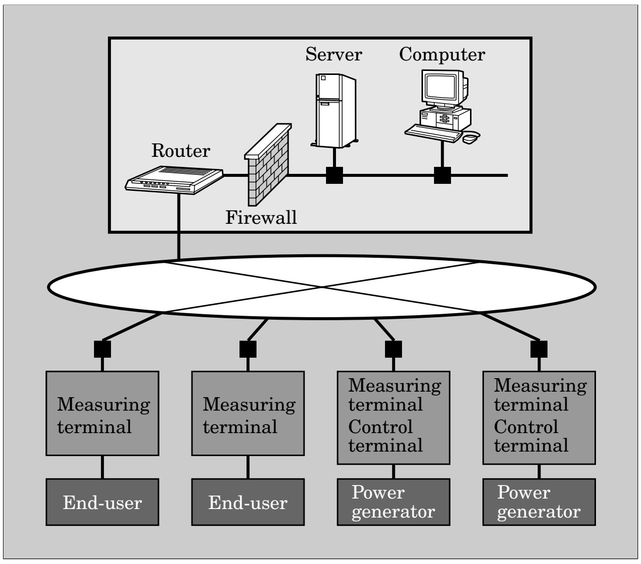


Fig.3 Appearance of measurement and control terminal

Table 2 Measurement items in a distributed energy system (example)

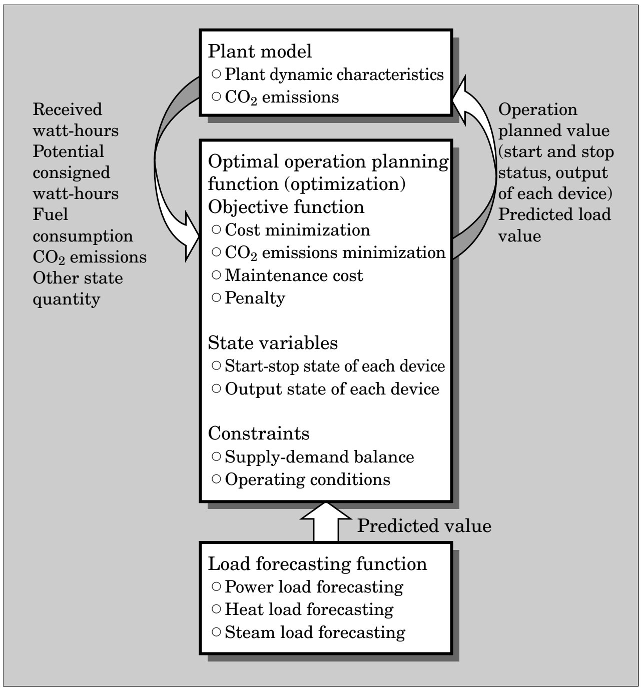
Measurement item		Type	Measurement point		Purpose		
			Each load point, power generating point	Power receiving point, line	Forecasting, optimization	Supply-demand control	Power quality
Active power	P		◎	◎	◎	◎	◎
Reactive power	Q		◎	◎	◎		◎
Voltage	V	3-phase RMS value	◎	◎	◎	◎	◎
	v	Instantaneous value	○	○			○
Current	I	3-phase RMS value	◎	◎	◎	◎	◎
	i	Instantaneous value	○	○			○
Frequency	f		◎	◎			◎
High-frequency voltage	$V_{(nf)}$	(content)	◎	◎			◎
Flicker	ΔV_{10}	10 Hz data	◎	◎			◎
Thermal flow			◎		◎		◎
Thermal temperature			◎		◎		◎
Air temperature			◎		◎		
Solar radiation			◎		◎		
Wind velocity			◎		◎		

◎: Normal data, ○: Transient data

nal and the monitoring and control system may be implemented over a dedicated LAN (local area network) such as a fiber optic network, or by using a WAN (wide area network). A dedicated LAN is highly secure and realizes high-speed communications, but its expensive construction and maintenance costs are disadvantages, and the economic feasibility of a LAN in a microgrid is an issue.

In the cases where a WAN is utilized, various services are available, including dial-up connections, mobile communications such as a cell phone, or always-on Internet services such as ADSL (asymmetric digital subscriber line), ISDN (integrated services digital network), and FTTH (fiber to the home) that utilize public communications networks. Generally, with this type of service, costs rise when the security and/or communication speed is increased, and therefore, the communication method must be selected as suitable for the desired objective, after careful comparison of the cost associated with the communication specifications.

Fig.4 Forecasting function and optimizing control function



4.2 Stabilizing control

A distributed energy system, established in a local area or a demand area, must be configured so as to suppress the impact on the power system. Supply-demand balancing control system is capable of maintaining a balance between supply and demand, and control that uses power storage equipment to stabilize the output of new energy are applicable.

4.2.1 Supply-demand balancing control

Supply-demand balancing control equalizes the watt-hours generated and consumed within a fixed constant or certain time interval. The 30-minute supply-demand balancing control implemented by PPS (power producer and supplier) companies aims to allow PPS companies having a stable output power plant to fulfill their power supply contracts. On the other hand, the supply-demand balancing in a distributed power supply network aims to prevent unstable distributed power sources from affecting existing electric power company power sources. Accordingly, supply-demand balancing should control with shorter time intervals, and more accurate forecasting and optimized operation technique than in the case of PPS supply-demand balancing. (See Fig. 4.)

In an optimized operation plan, unstable power generating equipment for natural energy such as solar energy and wind power sources is combined optimally with adjustable power and heat source equipment such as power CHP, storage batteries, steam boilers and heat-storage equipment, and also externally procured power so as to maintain the supply-demand balance for electricity and thermal energy respectively. Specifically, first, in order to establish the supply-demand balance, a predictive technique such as a structured neural network or Kalman filtering is used. With prior numeric results and weather predictions, the power load, thermal load, and solar and wind power generation are forecast for preset time intervals (of every 30 minutes or so). Next, the supply-demand balance computed from the power and thermal forecasts, and the resulting cost from operating constraints, marginal output, and load fluctuations of the equipment are determined. Along with this, the operating state and quantity for power generation, thermal supply, electric power storage, thermal energy and externally procured power are allocated so as to minimize an evaluation index for the operating cost and/or to minimize carbon dioxide (CO_2) emissions.

The supply-demand balancing function operates, stops and allocates the output of the generator according to a cost-minimizing operation rule set with the optimized operation plan, and performs online control using an iterative prediction and smoothing algorithm such as Kalman filtering.

4.2.2 Stabilization of natural energy power generation

There is a large fluctuation in the output power generated from natural energy such as solar energy or wind power, and technology to suppress the fluctuation in output from such distributed power sources is needed. In particular, by using power storage equipment, the technology for suppressing output fluctuation at the distributed power source side can be applied not only for control at the power generating side, but can also be deployed in the future to stabilize system connection points in a micro-grid. Using flywheels, secondary batteries and other power storage equipment, Fuji Electric is developing stabilization technology for the output of generated power, and is working to achieve the practical usage of natural energy.

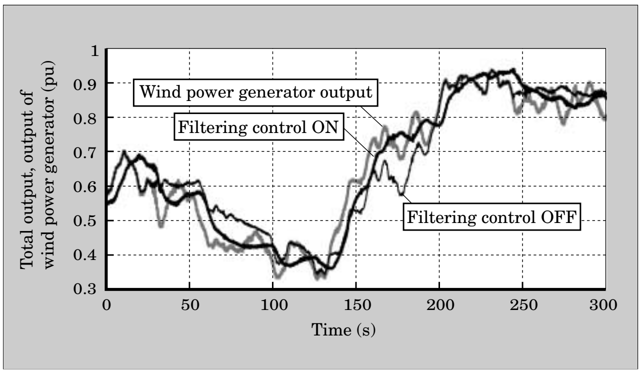
To enable the installation of wind power generating equipment in systems on weak power systems such as a remote island or a distance terminal, a power stabilizing system has been built to absorb the electric power fluctuation that accompanies fluctuation in wind power or the like. In island Okinoshima in Shimane Prefecture, a wind power generating system having the world's first super-high speed fly wheel power stabilizer is installed, and Shimane Prefecture and Fuji Electric received a New Energy Foundation Chairman Award.

Technical considerations for planning the power stabilization of power storage equipment are described as follows.

(1) Determination of the storage capacity
(2) Specification of the stabilized the power fluctuation cycle
(3) Verification methodology

In the case where power storage equipment is used to stabilize the fluctuation in power output at a system connection point, the targeted fluctuation cycle component is detected from among the various fluctuation cycles contained in the wind power fluctuation, and the power storage compensates by absorbing a reverse phase of that fluctuation component. At this time, the power storage equipment of limited capacity is repeatedly discharged and charged, and limiting must be applied appropriately so that the maximum storage capacity is not exceeded, or if the maximum has been exceeded, so that a shock will not be imparted to the system.

Fig.5 Effectiveness of filter control for power storage equipment



The measured output fluctuation in generated wind power and a comparison of the effect of the filtering control (variable smoothing constant) of the output fluctuation detector of the power storage equipment are shown in Fig. 5. As can be seen, when the filtering control was OFF, due to an attempt to suppress excessive long-cycle fluctuation, the storage capacity was exceeded and as a result the overall goal of suppressing wind power fluctuation could not be achieved.

4.3 Metering system

In a distributed energy system, the metering and billing of supplied energy must be implemented fairly and efficiently within the system.

A distributed energy system must internally meter the quantities of electric and thermal energy, fuels such as natural gas and hydrogen, and various other quantities such as the backup power supplied.

Table 3 lists a summary of the metered items in a distributed energy system.

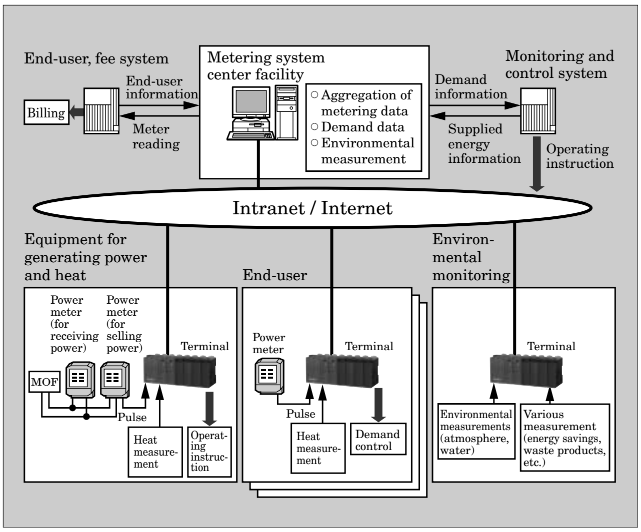
The construction of a metering system is essential for the fair and efficient implementation of metering and billing in a distributed energy system. Figure 6 shows an overview of a metering system. A terminal detects service pulses from each meter, and a central system reads the meters remotely via a communications network, so that the meter-reading task can also be implemented efficiently.

Figure 7 shows an example of the appearance of a metering terminal installed at the site of an end-user. The programmable controller of the terminal enables

Table 3 Example of metered items in a distributed energy system

Category	Item		Metered item
Billing	Electric power	Sale of electric power to the own customers	Electric watt-hours, power, reactive power
		Generated electric power	Electric watt-hours
		Sale of surplus electric power to the electric company	Electric watt-hours
	Heat	Steam	Temperature, pressure, flow rate
		Hot water	Temperature, flow rate
		Cold water	Temperature, flow rate
Deliveries	Fuel	Gas	Flow rate (pressure)
		Heavy fuel, light fuel	Mass
		Hydrogen	Flow rate, pressure
Distribution	Consigned power transfer		Electric watt-hours
Other	Evaluation of energy savings		Electric watt-hours, CO_2 conversion
	Environmental measurements		Atmosphere, water content, soil
	Metering of waste products		Type, volume
	Various services		Number of times used, time duration, etc.

Fig.6 Overview of metering system



autonomous control such as demand control and off-peak operation.

4.4 Wide area power quality measuring system

The introduction of distributed power sources has advantages, but also invites concern about the potential degradation of power quality when the distributed power sources are connected to a power system. The establishment of a suitable technology for this purpose is an important theme for future development. In particular, the presence of power generating companies at the end-user side make it difficult to identify sources of failure and to ascertain responsibility, and therefore, continuous monitoring of the system status and recording of information is necessary. A wide area

Fig.7 Appearance of metering terminal

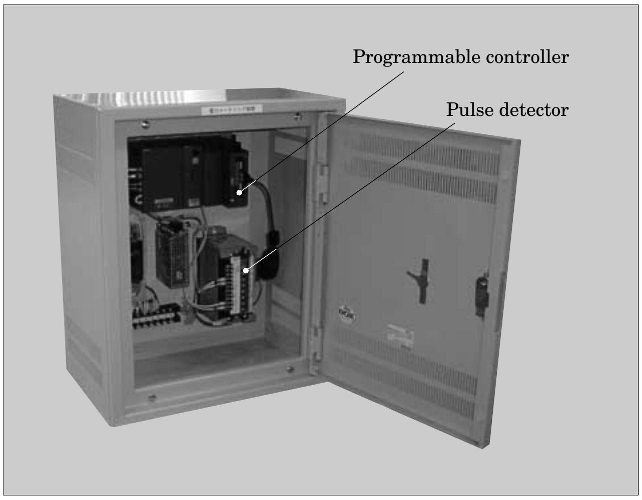
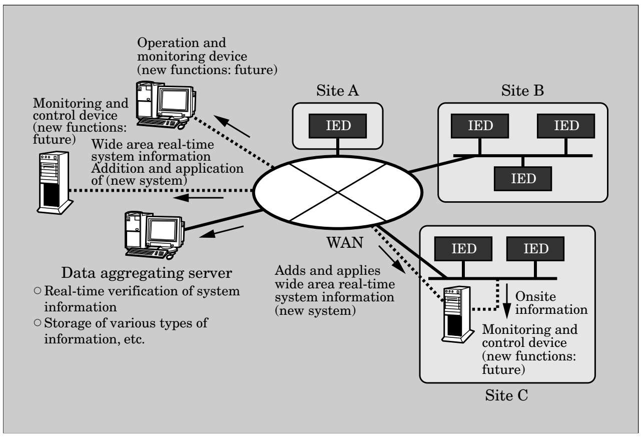


Table 4 Functions of a wide area power quality measuring system

Item	Function
Status assessment	Identification of extended range of voltage drop or the like at time of system fault Ascertainment of failure source at time of failure
Optimal operation	Real-time measurement of system trends and load status. Used for optimal operation and load forecasting.
Fault recovery	Based on the real-time status of the voltage and current, and device information at the time of a system fault, real-time monitoring is carried out to evaluate a faulty section, assess the behavior of the protection system, and determine whether suitable system recovery should be carried out.

Fig.8 Overview of a wide area power quality measuring system



power quality measuring system (wide area PQ measuring system) solves various problems during system operation by realizing a system with measuring terminals (IED: intelligent electrical devices) distributed at multiple points in a wide area system to collect system information in real-time. Table 4 lists the functions of the wide area PQ measuring system, and Fig. 8 shows an overview of the system configuration.

The wide area PQ measuring system is configured from onsite IEDs, communication circuits and a data-aggregating server. In the future, using information from the wide area PQ measuring system, a monitoring and control function may possibly be added. Data-aggregating IEDs are installed onsite at the facility to be measured, and a data-aggregating server operates via a power communications network or WAN to collect and analyze the basic IED data of the value of each V, I, V_0 and I_0 vector (magnitude and phase), for a total of 8 channels (per IED unit). The data aggregation is performed in real-time with 100 ms sampling, and each IED can use a GPS antenna to take synchronous measurements with ±10 μs precision.

5. Example of a Distributed Energy System

The Kyoto eco-energy project (KEEP) is presented below as an example of a distributed energy system. NEDO is commissioning the research of concentrated regions of new energy plants, whereby the fluctuating power sources of wind power and solar energy are combined appropriately with new energy, and a system for controlling these energy sources is constructed. Within the region of this practical study, a new energy-based distributed energy supply system, constructed at an appropriate cost, supplies stable power and heat without any large impact on the connecting power system, and the quality, cost and other data of the supplied power is aggregated and analyzed. Because there are different forms of supplied electrical power, two other projects, in addition to KEEP, are currently underway. KEEP is being implemented in Kyotango City located in the center of the Tango Peninsula in the Northern part of Kyoto Prefecture. The seven participating entities are Fuji Electric, Kyoto Prefecture, Kyotango City, Amita Company, Obayashi Corporation, Nissin Electric Corporation and Nomura Re-

Fig.9 Overall outline of the Kyoto eco-energy project

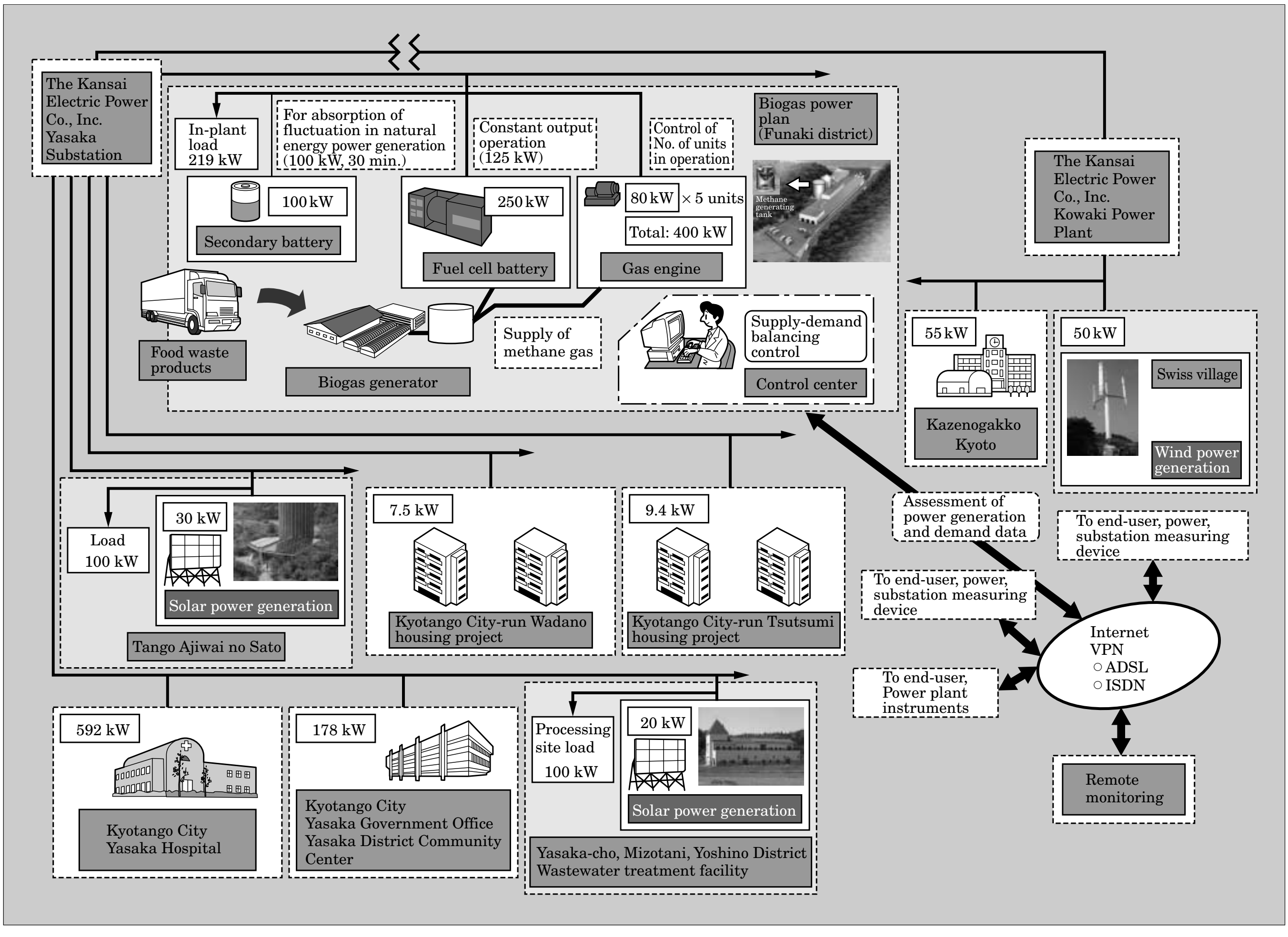


Table 5 List of equipment installed for the Kyoto eco-energy project

Installation site	Device	Generated power output (kW)	Thermal output (MJ/h)
Biogas power plant	Biogas generator	–	–
	Gas engine-type power generator	80 × 5	2,243 (max.)
	Fuel cell	250	308 (max.)
	Secondary battery (lead storage battery + bi-directional inverter)	100	–
	Measuring equipment	–	–
Control center (inside the biogas power plant)	Server	–	–
	PC	–	–
	Firewall, etc.	–	–
Swiss Village (Taikoyama)	Wind power generator (vertical axis wind turbine)	50	–
	Measuring equipment	–	–
Tango Ajiwai no Sato	Solar power generator (hybrid)	30	–
	Measuring equipment	–	–
Wastewater treatment facility	Solar power generator (polycrystalline)	20	–
	Measuring equipment	–	–
Each end-user	Measuring equipment for each end-user	–	–

search Institute. Fuji Electric is responsible for the construction and overall research of a supply-demand balancing system.

In this practical study, a "virtual micro-grid" is formed, via a typical power company's power network, between selected existing end-users and the wind power generation and solar power generation equipment to be introduced, biogas power generation (gas engine-type generator and fuel cell) equipment, and secondary battery energy supply equipment. Within this virtual micro-grid, a supply-demand balancing system is constructed, and power quality and the like must be verified.

This practical study intends to find solutions for the following research challenges.

(1) To ensure a supply-demand balance in response to the fluctuation in power generated from new energy and a constantly fluctuating load, using a power generating facility requiring no power transformation such as a gas engine-type generator or the like

(2) To provide a stable supply of power and heat while implementing supply-demand control that combines new energy equipment (distributed power sources) having differing characteristics

(3) To ensure the same level of power quality as from a typical electric company, using the power quality evaluation items (power outage, voltage fluctuation, frequency fluctuation, etc.)

(4) To analyze the economic efficiency of the overall system by categorizing and analyzing the necessary expenses associated with wind power, solar power, and biogas power generation facilities

Figure 9 shows the power generating facility of this practical study and an overview includes the end-user, and Table 5 lists the equipment that has been installed for KEEP.

At the control center that Fuji Electric oversees, fluctuations in generated wind power, solar power and the like, and the constantly changing load fluctuations are absorbed by controlling the output of a biogas power generator and secondary batteries to achieve a balance between supply and demand.

At each facility, measuring equipment is installed as a system for measuring online the load power consumed by each end-user and the amount of power generated from natural energy. The measured data is transmitted via a general-purpose public line (ADSL or ISDN) and aggregated at a control center in a biogas power plant. The control to balance supply and demand is implemented by combining fuel cells (constant operation), gas engine-type generators (control of the number of units and control of the output setting value) and secondary batteries (short-cycle power generation and load fluctuation absorption control) in the biogas power plant.

In order to reduce the degree of impact on the power system, the control targets 5-minute supply-demand balancing, and aims to achieve 5-minute balancing with an 8 % tolerance by the end of 2005, and with the greater accuracy of the future, 5-minute balancing with 3 % tolerance by the end of 2007.

Moreover, the biogas residue from a food plant is supplied as raw fuel to a gas engine-type power generator and fuel cells in the biogas power plant. Fuel cells are fundamental power sources that generate a constant quantity of electric power, and the quantity of generated power is adjusted according to the demand by controlling the number of gas engine-type generators that operate. Furthermore, hot water collected from the power generator is slated to be used for heating a methane fermentation tank, and for supplying hot water and heat to the control room.

In this practical study, the investigative work and research necessary for the management of raw material procurement is also carried out, including an investigation of raw materials (items, content, properties, quantity, frequency of occurrence, etc.), experimental methane fermentation test of raw material samples, and the like in order to realize the stable and highly efficient of generation of power from biogas.

Additionally, power generating facilities using solar cells having different characteristics have been installed at two locations, and a wind power generating facility has been installed that uses a wind direction-independent vertical axis wind turbine capable of converting with high efficiency the complex fluctuation in wind power unique to a mountain area.

Each facility is presently starting operation so that full-scale research can begin in December 2005. Using actual equipment at facilities for generating power from new energy and the like, a supply-demand balancing system capable of providing a stable supply of electric power based on regional and system characteristics will be developed, and the quality, practicality, versatility and economic efficiency of the power supply system will be evaluated. Furthermore, by utilizing heat from the installed equipment and so on, we aim to achieve good results in order to further the use of new energy.

6. Conclusion

New energy power generation is anticipated as a means for ensuring energy security and combating global warming, but from the perspective of the power system, new energy is an unstable power source that is difficult to handle. Distributed energy systems are attracting attention as a way to compensate for these disadvantages.

This paper has described the micro-grid type of distributed energy system in which Fuji Electric is involved. Distributed energy systems have the potential to open a new era for power systems, but many technical challenges remain. The construction of a distributed energy system requires many types of technology, in addition to that described herein, and these technologies can be integrated to construct a system. Fuji Electric intends to continue pursuing the realization of distributed energy systems.

Current Status and Future Trends of Amorphous Silicon Solar Cells

Masahiro Sakurai
Toshiaki Sakai

1. Introduction

The Kyoto Protocol for preventing global warming was adopted at the Conference of Parties III (COP3) of The United Nations Framework Convention on Climate Change held in Kyoto, Japan in December 1997. This Protocol established numerical targets for reducing greenhouse gas emissions in 2010 for each of the participating industrialized countries. In February 2005, the Kyoto Protocol was enacted and full-scale efforts began to reduce carbon dioxide (CO_2) emissions, and subsequent efforts to introduce new energy having a low impact on the environment are expected to become invigorated.

Among the types of new energy, photovoltaic power generation systems emit no CO_2 while generating power, and their widespread use is highly anticipated. The Japanese government is promoting adoption of new energy by adopting:

(1) measures involving power generation (① expanded adoption by the public sector, and ② technical development to promote lower cost, higher efficiency, etc.)

(2) measures involving heat (① comprehensive plans for local governments to introduce new forms of energy, ② promotion of the Biomass Nippon Total Strategy, and ③ promotion of the introduction of biomass-derived fuel as transportation fuel, etc.)

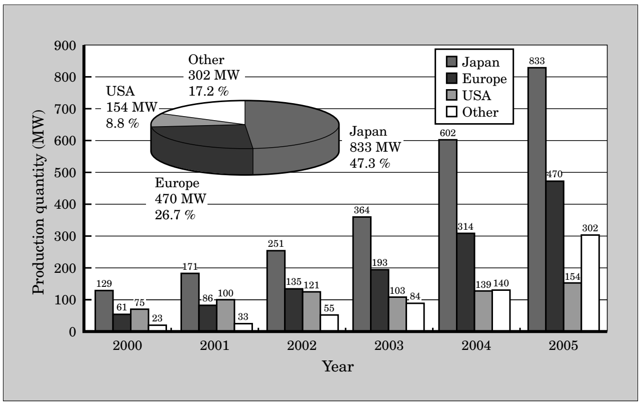
and other measures in order to achieve the projected level of adoption of new energy in 2010 as established by the Investigative Committee on Natural Resources and Energy.

In particular, to achieve the goal of photovoltaic power generation of 4,820 MW by the year 2010, various assisting businesses (such as the Program for Infrastructural Development of Introduction of Residential PV System and Field Test Project on Photovoltaic Power Generation System for Industrial and Other Applications) and preferential governmental policies have accelerated the introduction of photovoltaic power generation. Moreover, the New Energy and Industrial Department Organization (NEDO Technical Development Organization), an independent administrative agency, has developed the "Photovoltaic Power Generation Roadmap for Year 2030 (PV2030)" which is a long-term strategy for technical development from 2004 through 2030. Here, it is assumed that by the 2030, photovoltaic power generation will provide approximately one-half of the electric power for household-use (approximately 100 GW as a photovoltaic power generating system), and therefore, technical innovation and system use have been studied in order to improve economic efficiency and to expand applicability.

Meanwhile, the production of solar cells has increased dramatically since 1997, and the produced capacity of 288 MW in 2000 has undergone a more than 6.1-fold increase to 1,759 MW by 2005. Japan accounts for 833 MW or approximately 47 % of the total production quantity. Figure 1 shows the share of total solar cell production by country. Of the solar cells produced in 2005, crystalline silicon (Si) solar cells accounted for 84 %, and thin film Si accounted for approximately 14 %, but due to the problem of depletion of Si raw material, the share of amorphous silicon (a-Si) and CIS (copper-indium-selenium) solar cells is expected to increase.

Fuji Electric began research and development on a-Si solar cells in 1978. In 1980, Fuji successfully developed and sold the world's first commercial solar cells for use in calculators. Since 1980, Fuji has been contracted to perform research under the Sunshine Program administrated by the Agency of Industrial Science and Technology that belongs to the Japanese

Fig.1 Solar cell production share (data from 2006 PV News)



Ministry of International Trade and Industry, and has developed a-Si solar cells that provide electric power. In 1993, Fuji Electric was the first in the world to achieve a 9 % conversion efficiency with a large-area a-Si solar cell (30 cm × 40 cm) that uses a glass substrate.

The commercialization of a-Si solar cells, however, would involve the batch processing of solar cells having glass substrates, and problems arise involving the long manufacturing time, substrate conveyance and handling when processing large quantities of large-area substrates (estimated to be approximately 1 m^2) with a vacuum apparatus, and therefore these solar cells were poorly suited for mass production. Consequently, based on previously acquired technical expertise, Fuji Electric began developing a manufacturing process capable of simultaneously achieving high productivity and low cost since 1994, and as of October 2004 has been selling a newly developed a-Si solar cell having a plastic film substrate.

2. a-Si Solar Cell with Film Substrate

2.1 Structure of cell having plastic film substrate

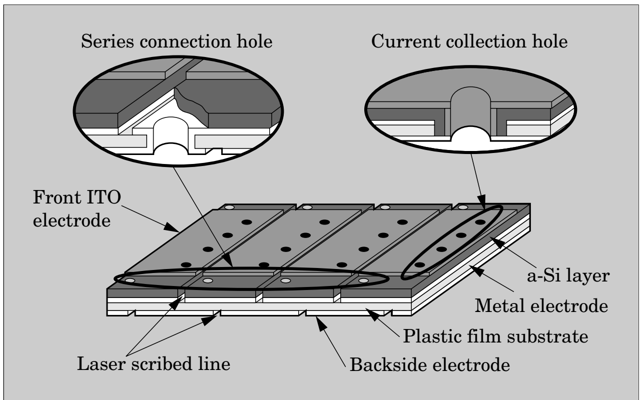
The greatest advantage in using a flexible substrate such as plastic film is that a roll-to-roll process can be utilized. By placing an entire roll of the substrate in the vacuum apparatus, problems relating to substrate conveyance can be avoided and automation simplified, thereby enabling the configuration of processes suitable for large-scale mass-production.

Plastic film is electrically non-conductive and therefore can be used to fabricate integrated series-connected structures, however, because it has a low heat resistance characteristic, there are problems such as significant expansion and shrinkage of the substrate, and connective structures and processes require innovative designs. Fuji Electric manufactures solar cells using a special film having a high heat resistance characteristic as the plastic substrate material, and then forms metal electrodes, an a-Si layer and front ITO electrodes on top of the plastic film substrate.

Fuji Electric has developed a novel solar cell structure known as SCAF (series-connection through apertures formed on film). In order to connect adjacent cells in series, holes for series connections are formed on the edges of a module, and metal electrodes formed on both surfaces of the plastic film substrate are connected via these holes to enable series connections. Figure 2 shows the series-connection structure of Fuji Electric's a-Si solar cell.

A SCAF-structure film-substrate cell is subdivided into several rectangular solar cells known as unit cells. So that the module output voltage is at a practical voltage level, it necessary to connect these unit cells in series, and a series-connection structure was realized by connecting metal electrodes of adjacent unit cells via the series connection holes provided in the film substrate. With the SCAF structure, due to the formation of several current collector holes having high resistance, the electric current generated by the unit cells avoids generating a voltage loss at the front ITO electrodes and instead flows to the metal electrodes having low resistance, and this current flow is also connected via series connection holes formed at the cell edge to the metal electrodes of adjacent unit cells. This structure enables the number of series connections to be changed by modifying the pattern, and enables a single solar cell to be capable of providing a voltage level suitable for the particular application.

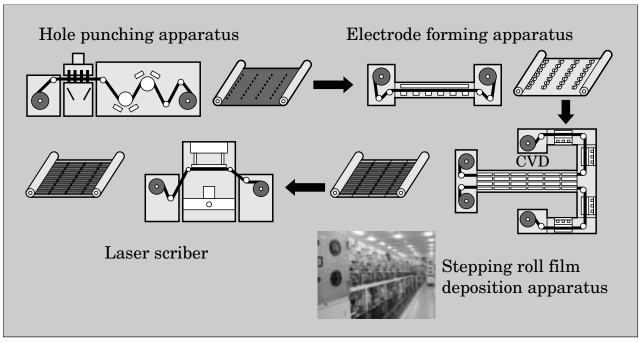
Fig.2 SCAF series-connection structure



2.2 Manufacturing process technology

The SCAF structure solar cell manufacturing process is based on a roll-to-roll processing method. The process consists of the steps of: ① using a substrate pre-processing apparatus to form holes in a roll-shaped film substrate by a mechanical punching method, ② using a sputtering method and an electrode forming apparatus to form metal electrodes on the film, and ③ using a stepping-roll method with a layer forming apparatus to fabricate sequentially an a-Si layer (plasma CVD: chemical vapor deposition method), front ITO electrodes (sputtering method), and backside electrodes (sputtering method). Multiple layer formation chambers are contained within a single vacuum container, and step ③ is devised such that, by stepping the substrate and then stopping the substrate inside a layer formation chamber, each layer formation cham-

Fig.3 SCAF-structure a-Si solar cell manufacturing process



ber can operate as an independent chamber.

Figure 3 shows the process for manufacturing a SCAF-structure a-Si solar cell and the appearance of a stepping roll layer forming apparatus.

3. Application to a Photovoltaic Generation System

3.1 Advantages of film-type solar cell modules

Solar cell modules that use a SCAF-structure cell with a plastic film substrate have the following advantages.

(1) Lightweight: A film-type solar cell weighs 1 kg/m^2, which is less than 1/10th the weight of a conventional solar cell.

(2) Flexibility: The structure, which does not use glass, can be installed even on curved surfaces, and has excellent designability.

(3) High output voltage: The use of an original series-connection structure makes it possible to obtain easily a high output voltage to which an inverter may be connected directly.

Consequently, all external connections between solar cells can be implemented as parallel connections, and there is no risk of incorrect wiring occurring during the fabrication of an array with series and parallel connections when using a crystalline module, and thus, system reliability is improved.

The solar cells developed by Fuji Electric are a-Si/a-SiGe tandem-type solar cells, based on a-Si technology, and have the following advantages compared to crystalline Si solar cells.

(1) Large annual power generation: a-Si solar cells have a small temperature coefficient and therefore the decrease in their summertime efficiency is also small. At the same rated capacity, the annual power generation is approximately 10 % larger than a crystalline Si solar cell (according to Fuji Electric's in-house comparative data).

(2) Low consumption of energy during manufacture: Compared to conventional crystalline Si solar cells, a-Si solar cells consume only a small amount of energy during manufacture, and are environmentally friendly.

Figure 4 shows the results of a field test of Fuji Electric's a-Si/a-SiGe tandem solar cells in the Yokosuka area of Japan. In the figure, efficiency is shown as the ratio of power generation in the case where it is assumed that the solar cell operates with the energy conversion efficiency of standard conditions, compared

Fig.4 a-Si solar cell field test results

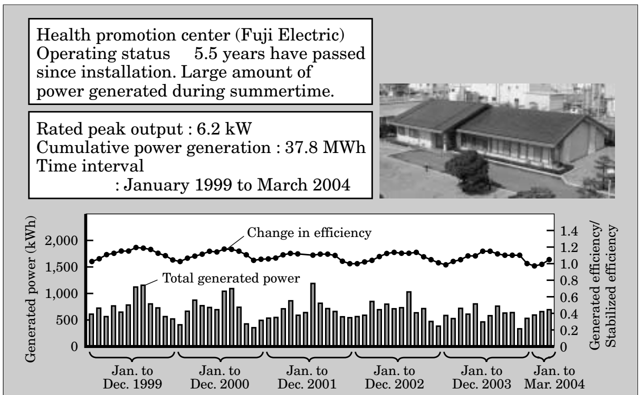


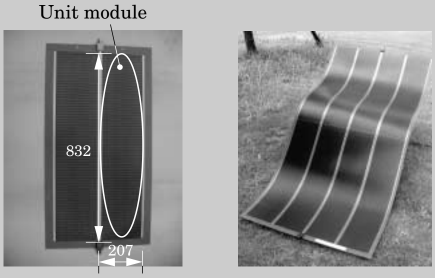
Fig.5 Metal-integrated PV module and its specifications

Ideally suited for a gymnasium or other building having an arched roof.

		Metal-integrated type
Rated peak power		96 W
Rated peak output voltage		320 V DC
Rated peak output current		0.3 A
Rated open circuit voltage		435 V DC
Rated short circuit current		0.35 A
External dimensions		525×3,881×13 (mm)
Peak system voltage		600 V
Mass	(including 0.8 t steel plate)	16 kg
	(module only)	2 kg

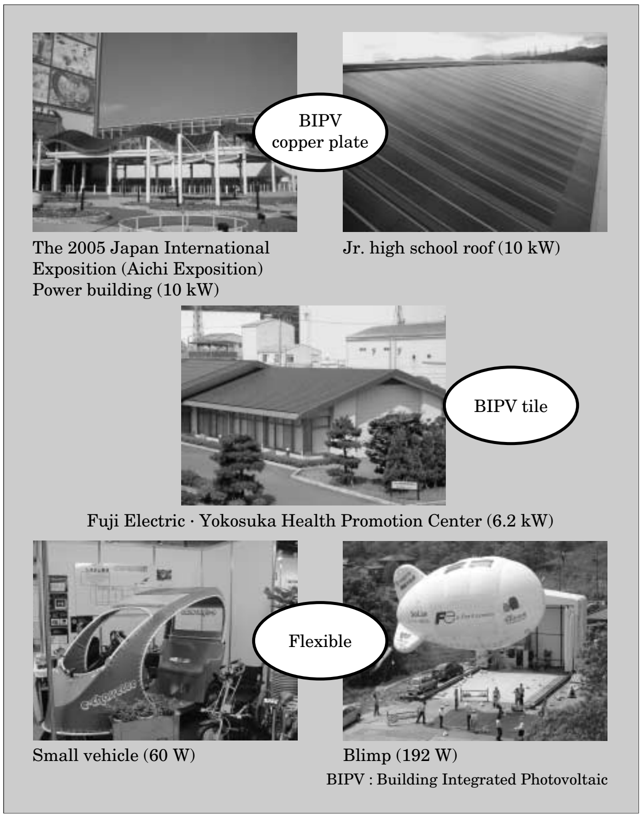
Fig.6 Flexible a-Si solar cell module and its specifications

	Unit module	2 parallel	2 series, 2 parallel	4 series, 2 parallel
Rated peak output	12 W	24 W	48 W	96 W
Rated peak output voltage	80 V DC	80 V DC	160 V DC	320 V DC
Rated peak output current	0.15 A	0.3 A	0.3 A	0.3 A
Rated open circuit voltage	108.8 V DC	108.8 V DC	217.5 V DC	435 V DC
Rated short circuit current	0.175 A	0.35 A	0.35 A	0.35 A
External dimensions (provisional)	250×935 (mm)	460×935 (mm)	460×1,770 (mm)	460×3,440 (mm)
Mass	260 g	460 g	0.82 kg	1.6 kg
Module structure	ETFE/EVA/cell/EVA/ETFE (overall thickness is approx. 1 mm) Pin height : 13 mm			



2 parallel 24 W 4 series, 2 parallel 96 W [(2 series, 2 parallel 48 W) × 2]

Fig.7 Example installations



to the power generation in the actual roof environment. Additionally, the stabilized efficiency shown in Fig. 4 is the value when the solar cell is exposed to light several times every 48 hours and the range of fluctuation of efficiency at that time is within 2 %.

3.2 Product form

Fuji Electric has been selling metal-integrated PV (photovoltaic) modules and film-type solar cells since October 2004.

(1) Metal-integrated PV module

Previously, most of the commercially available building-integrated PV modules had been covered with glass. Glass covered building-integrated modules have a heavy weight per unit area, and when installed at high elevations as roofing material, their size has been restricted due to safety considerations. Targeting application to buildings, and especially the rooftops of public and industrial buildings, for which large demand is anticipated, Fuji Electric has developed a lightweight metal-integrated PV module constructed from a film-type PV module laminated directly to a steel plate.

The metal-integrated PV module has a weight, not including the steel plate, of approximately 1 kg/m^2, and has a total weight, including the steel plate, of approximately 4 to 8 kg/m^2, which is approximately half that of the conventional stationary-type PV module. Therefore, when solar cells are to be installed, there is no need to drastically redesign the load resistance of the structure, and further, since construction can be carried out in the same manner as a usual metal roof, a well-designed metal roof with attached solar cells can be realized at low cost. Figure 5 shows the appearance of metal-integrated PV modules and lists the specifications.

(2) Flexible film solar cell

Modules suitable for curved surfaces because they use a flexible plastic film as the substrate and do not use constraining members such as a glass cover or a frame can also be installed. Application and development is being advanced in fields such as buildings where the visual design is important, or power supplies for electronic devices where lightweight is desired. Additionally, as a PV module suitable for many applications, including power supplies for energy-saving devices, independent power supplies, emergency power supplies, etc., Fuji Electric has also developed a film-type PV module capable of parallel and series connections and consisting of unit sub-modules of 12 W each. Figure 6 shows the appearance of a flexible a-Si Solar Cell module and lists its specifications.

3.3 Example installations

Figure 7 shows example installations that leverage the advantages of metal-integrated a-Si PV modules and flexible a-Si PV modules.

4. Conclusion

The production of solar cells continues to grow at an annual rate of greater than 50 %, and the cumulative produced capacity is predicted to reach 4.82 GW by 2010 and 34 GW by 2020. The market size is expected to reach 1 trillion yen by 2020. In the future, a large gain in market share is forecast for thin film solar cells, and under these favorable market conditions, Fuji Electric has begun selling two types of PV modules that use flexible a-Si solar cells having a thin film substrate. Fuji Electric intends to continue its R&D efforts in order to reduce cost and boost efficiency, and to advance the development of new applications that leverage the lightweight, flexibility and other advantages of flexible a-Si solar cells.

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Present Status of Fuel Cells and Outlook for Development

Yoshimi Horiuchi
Hideo Nishigaki
Kenichi Kuroda

1. Introduction

With the Kyoto Protocol taking effect in February 2005, Japan has also been required to make a full-out effort to reduce emissions of CO_2, a greenhouse effect gas. According to the Kyoto Protocol Detailed Program enacted by the Japanese Cabinet in April 2005, the use of fuel cells is predicted to provide approximately 2,200 MW of power by 2010, of which approximately 1,000 MW will be for industrial use. Under these circumstances, Fuji Electric will continue to promote its 100 kW phosphoric acid fuel cells (hereafter referred to as PAFC) that is currently on the market, and aiming to achieve greater market penetration, intends to move ahead with development to reduce cost and expand the range of applications of PAFC. Moreover, since 1989, Fuji Electric has also used technology acquired during PAFC development to develop polymer electrolyte fuel cells (hereafter referred to as PEFC). This paper discusses the present status of PAFC technology, the status of hydrogen supply system development to expand the range of the PAFC applications, and the development status of PEFC technology.

2. Status of Introduction of PAFC Technology

2.1 Delivery record and overview of onsite operation per application

The delivery record of commercial-type fuel cells and their cumulative operating times are listed in Table 1. The first commercial-type PAFC began shipping in 1998, and has been delivered to hospitals, supermarkets, hotels, office buildings, and the like. These fuel cells continue to operate successfully and some have achieved more than 56,000 hours of cumulative operating time. Additionally, a low-cost second commercial-type began shipping in 2001 and this model has achieved more than 30,000 hours of cumulative operating time, while realizing low cost and highly reliable operation. Both the first and second commercial types have a utilization rate of more than 95 %, and realize a high level of durability and reliability.

Table 1 Introduction of commercial-type fuel cells

	Used in	Date delivered	Fuel	Operating time (h)
1st commercial-type fuel cell	Hospital	August 1998	City gas	44,265
	Hotel	March 1999	City gas	56,637
	Commercial institution	March 1999	City gas	Operation ended
	University	April 2000	City gas	41,687
	Office	March 2001	City gas	38,230
	Office	March 2001	City gas	39,541
	Office	July 2000	City gas	42,666
	Office	July 2000	City gas	44,638
	Methane fermentation plant	January 2001	Biogas	Operation ended
2nd commercial-type fuel cell	Training institute	December 2001	City gas	30,311
	Sewer processing plant	March 2002	Biogas	29,780
	Sewer processing plant	March 2002	Biogas	30,080
	Hospital	July 2003	City gas	19,851
	College	October 2003	City gas	11,650
	Exhibition institution	November 2003	City gas	14,666
	Office	January 2004	City gas	13,296
	Hospital	March 2004	City gas	10,557

(October 19, 2005)

An increasing number of fuel cell models have achieved the targeted service life of 40,000 hours (approximately 5 years), and as shown in Table 2, more than 11 models, including the pre-commercial prototypes, have achieved this level of service. In the future, assuming that the operation of these commercial types continues favorably, more and more fuel cell models will surpass 40,000 hours of operation, and by overhauling these models (by replacing their fuel cell stack and apparatus for reforming), an increasing number of fuel cells will achieve even longer service lives.

2.2 Future plans to introduce fuel cells

Based on the success with commercial fuel cells that operate for 40,000 hours, Fuji Electric has improved the fuel cell stack and the reforming apparatus, and since 2005 has been shipping fuel cells capable of operation for 60,000 hours. Scheduled shipments include 1 unit for exhibition, 2 units for use in a hospital, and 4 units for use at a sewer processing plant. Increasing the service life to 60,000 hours (approximately 7.5 years) results in less frequent overhaul work and decreases the equipment recovery cost.

In order to promote more widespread use of fuel cells, Fuji Electric plans to publicize the track record to date of high reliability, and to lower costs further. On the other hand, the range of PAFC applications has expanded because, in addition to city gas, PAFCs can also use renewable energy such as digester gas and biogas.

3. Hydrogen Supply System Using Stationary Fuel Cells

Working to expand the range of fuel cell applications, Fuji Electric has successfully used biogas obtained from fermented raw garbage and sewage digester gas, in addition to city gas, as raw fuel for PAFC. A hydrogen supply system using stationary fuel cells is capable of CHP (combined heat power) while simultaneously producing and supplying highly pure hydrogen, and development of such systems is being advanced to expand the applicable range of fuel cells even further.

3.1 System overview

A hydrogen supply system using stationary fuel cells, such as the 100 kW phosphoric acid fuel cell power generator manufactured and sold by Fuji Electric outputs a portion of the hydrogen-rich reformed gas that is the fuel for power generation, and using a compressor and PSA (pressure swing adsorption), produces highly pure hydrogen of at least 99.99 % purity. In other words, the system generates electrical power and produces highly pure hydrogen.

Table 2 PAFC units having cumulative operating time of at least 40,000 hours

Cumulative operating time (h)	No. of units
40,000 to less than 45,000	9
45,000 to less than 50,000	0
50,000 or greater	2
Total	11

Development of this system was commissioned by Tokyo Gas Co., Ltd, and Fuji Electric designed and manufactured a phosphoric acid fuel cell power generator and a reformer outlet gas cooler (also functioning as a buffer tank) for removing excess moisture from the reformed gas that is output, and is also responsible for control of the entire system. Figure 1 shows the skeletal structure of the system.

3.2 Development overview

Development of this system began in the latter half of 2003, aiming for a product launch date in 2006.

(1) 2003: Assessment and implementation of basic design

Under the condition of not requiring changes to the main equipment of an existing fuel cell system, we assessed the quantity of reformed gas that could be output to the power generator. As the results of this basic assessment, the relation between the output flow rate of reformed gas and the generated power output are shown in Fig. 2.

Fig.1 Configuration of hydrogen supply system using stationary fuel cells

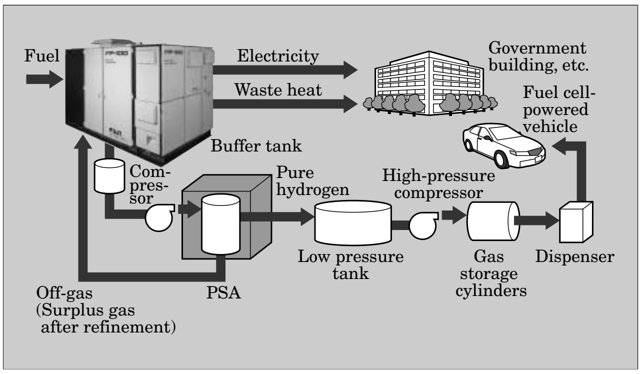
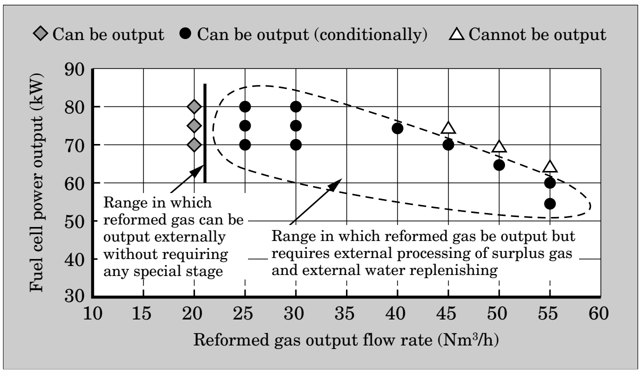


Fig.2 Reformed gas output flow rate



(2) 2004: Detailed design and modification of existing equipment

We modified existing equipment for the purpose of outputting reformed gas, and designed, manufactured and installed a reformer outlet gas cooler and a control system.

(3) 2005: Assessment of commercial equipment specs

We assessed commercial specifications based on the results of verification testing and experimental results.

Based on the assessment of the basic design, the goal was established to develop small capacity (8.5 Nm^3/h) and large capacity (20 Nm^3/h) systems capable of producing and supplying highly pure hydrogen. The corresponding capacities of these systems are as follows.

Small capacity supply: Capable of supplying sufficient hydrogen for 5 fuel cell-powered vehicles per day (1 bus per day)

Large capacity supply: Capable of supplying sufficient hydrogen for 12 fuel cell-powered vehicles per day (2 to 3 buses per day)

The hydrogen production and supply capabilities of 8.5 Nm^3/h and 20 Nm^3/h correspond to reformed gas output quantities of 20 Nm^3/h and 50 Nm^3/h, respectively.

3.3 Anticipated effects

In the near future, the arrival of an era in which hydrogen is used as a fuel is highly anticipated. At that time, it is predicted that highly pure hydrogen will be produced and supplied at low cost to end-users. Recent development efforts aim to serve as a bridge to that era of full-scale usage of hydrogen fuel, and the following types of effects are anticipated.

(1) Even in cases where the production and supply of highly pure hydrogen is not needed, the system can operate as a CHP plant and contribute, as a constantly high-efficiency system, to reducing the load on the environment.

(2) During late night hours and other times when the power load decreases, the excess capacity for producing reformed gas can be used to produce hydrogen, thereby contributing to an improved utilization rate of the equipment.

(3) Because both electric power and heat can be supplied, economical operation is anticipated, with a low-cost hydrogen supply provided even during the initial introduction stage and permitting early recovery of invested capital.

(4) By installing and using stationary fuel cells as CHP equipment before introducing them into fuel cell-powered vehicles, at the future time when fuel cell-powered vehicles are eventually introduced, an additional hydrogen supply system part may be installed to provide the necessary hydrogen supply.

4. PEFC Development

Fuji Electric became involved in the development of a polymer electrolyte fuel cell stack in 1989, and since 2002, has been advancing the development of a 1 kW-class polymer electrolyte fuel cell system. Using first and second prototypes, a stationary home-use system was demonstrated and its problems identified, optimal capacity was assessed, and basic data was accumulated and evaluated so as to implement successive improvements. The operating status of a third PEFC prototype created in 2004, the operating status of PEFC verification testing in Mie Prefecture (known as the PEFC field testing in Mie Prefecture), and an overview of a fourth PEFC prototype developed in 2005 are described below.

4.1 Operating status of third PEFC prototype

The method of manufacturing the MEA (membrane electrode assembly) for the PEFC stack has been optimized, and a cell of improved durability and reliability has been used in this third generation prototype. Figure 3 shows the operating status of the third PEFC prototype, and Fig. 4 shows the operating status (as of July 2005) of an evaluation-use PEFC stack having the same specifications as the third PEFC prototype. The third PEFC prototype has accumulated 5,500 hours of operation as a power generator. The

Fig.3 Operating status of third PEFC prototype stack for evaluation

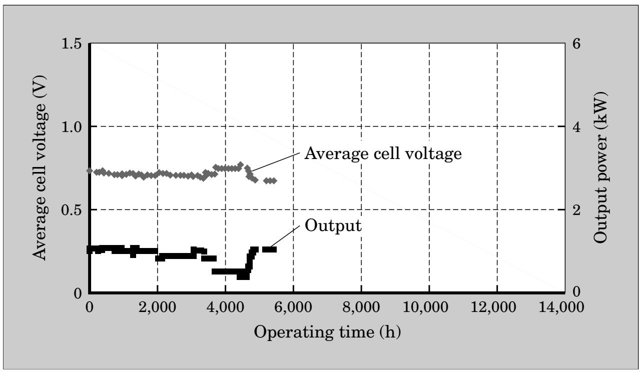
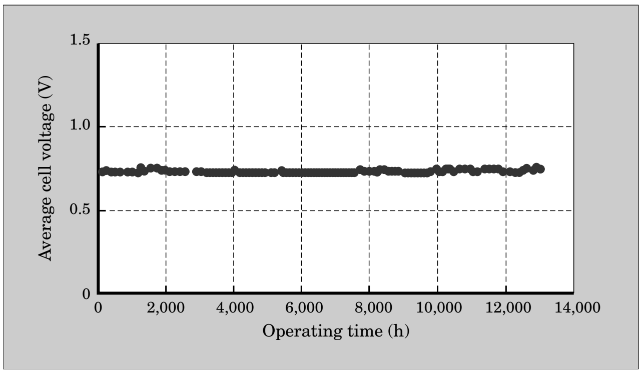


Fig.4 Operating status of PEFC prototype stack for evaluation



PEFC stack, having operated for 12,700 hours, surpassed the targeted value (showing a voltage drop of not more than 2 μV/h), and verified the improved effect of the cells.

4.2 Operating status of Mie prefecture field-test PEFCs

Receiving assistance from the Fuel Cell Verification Testing Business run by Mie Prefecture, as well as Yokkaichi City and Suzuka City of Mie Prefecture, PEFC field tests were begun in April 2005 at the two sites of Yokkaichi City and Suzuka City.

Figure 5 shows an onsite installation in Yokkaichi City, and Fig. 6 shows an installation in Suzuka City. The Yokkaichi City field-test PEFC is installed at a convenience store (the Takahama-cho, Yokkaichi City branch of the “Family Mart” convenience store chain) and the hot water generated is supplied to a local home-visit bathing service. The Suzuka City field-test PEFC is installed at a typical home (the official residence of the Suzuka National College of Technology), and is used to supply electricity and hot water to the residence. Figures. 7 and 8 show the operating status at Yokkaichi City and at Suzuka City, respectively. As of September 30, 2005, the respective operating times are approximately 3,600 hours and

Fig.5 Onsite installation of field-test PEFC in Yokkaichi City

Fig.6 Onsite installation of field-test PEFC in Suzuka City

Fig.7 Operating status of PEFC field test in Yokkaichi City

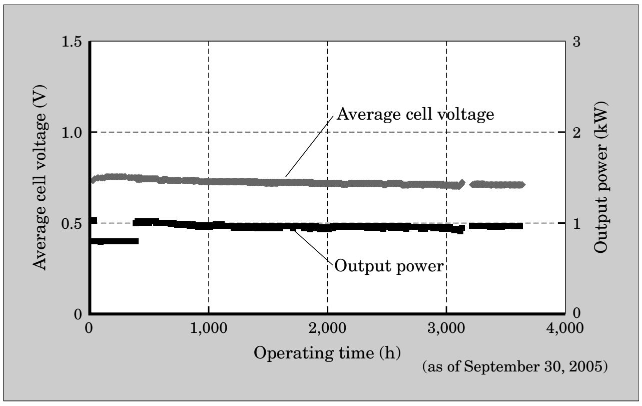


Fig.8 Operating status of PEFC field test in Suzuka City

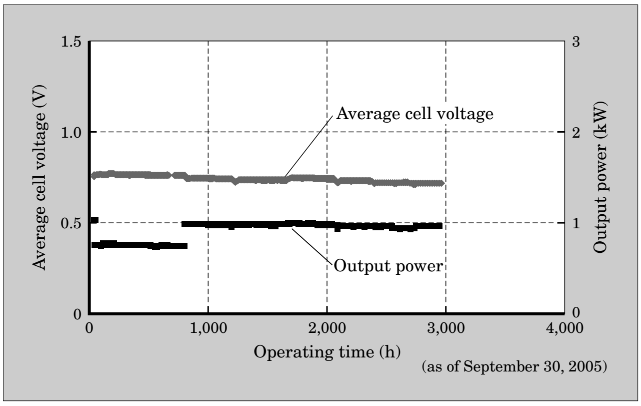
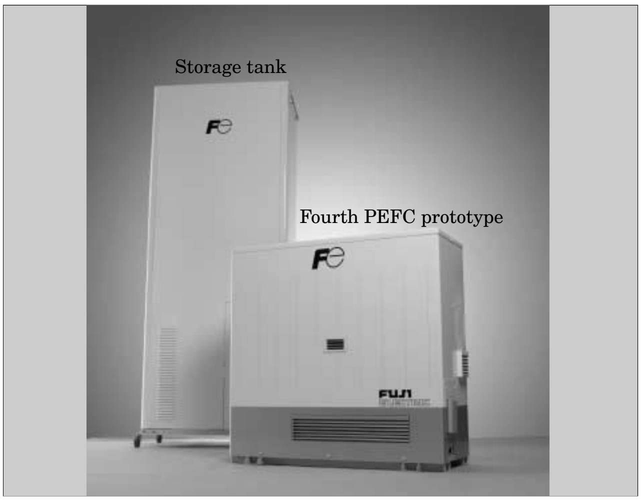


Table 3 Specifications of fourth PEFC prototype

Output power	1 kW (AC power transmitting side)
Electrical connection	1 phase, 3 wires 200 V AC
Electrical efficiency	35 % (for rated output, LHV)
Thermal output	Approx. 60°C
Heat recovery	51 % (for rated output, LHV)
Fuel	City gas (13 A)
Operation	Fully automatic
Main dimensions (width, height, depth)	910×895×360 (mm)

Fig.9 Appearance of fourth PEFC prototype



3,000 hours.

4.3 Development status of fourth PEFC prototype

At present, Fuji Electric is moving ahead with production and evaluation of a fourth PEFC prototype stack that aims to realize a dramatic reduction in cost. The basic specifications and the appearance of the fourth prototype are shown in Table 3 and Fig. 9, respectively. The specifications aim to improve the power generating efficiency and the overall thermal efficiency, while eliminating the need for nitrogen for purging during start up and shut down. In the future, Fuji Electric plans to initiate an internal evaluation of the fourth PEFC prototype, and then to verify its reliability and durability during continuous operation and start-stop operation. Fuji Electric also intends to advance development that enhances durability and targets mass production, and to accelerate PEFC commercialization.

5. Conclusion

Hydrogen is an energy-yielding substance that does not emit carbon dioxide when used, and because it can be produced from non-fossil fuels, hydrogen-derived energy is also preferred from the standpoint of energy security. In order to realize a hydrogen fuel-using society, the early widespread adoption of the key technology of fuel cells desired. To contribute to the advent of this hydrogen fuel-using society, Fuji Electric intends to position fuel cells as a key component in the energy and environment fields, and to strive to expand the usage of phosphoric acid fuel cells and to strengthen efforts to develop polymer electrolyte fuel cells.

The authors wish to thank the relevant organizations and each user for their guidance and cooperation thus far, and requests their continued understanding and support in the future.

Connecting Wind Power Generation to a Power System

Kenji Yago
Kazuaki Koshi

1. Introduction

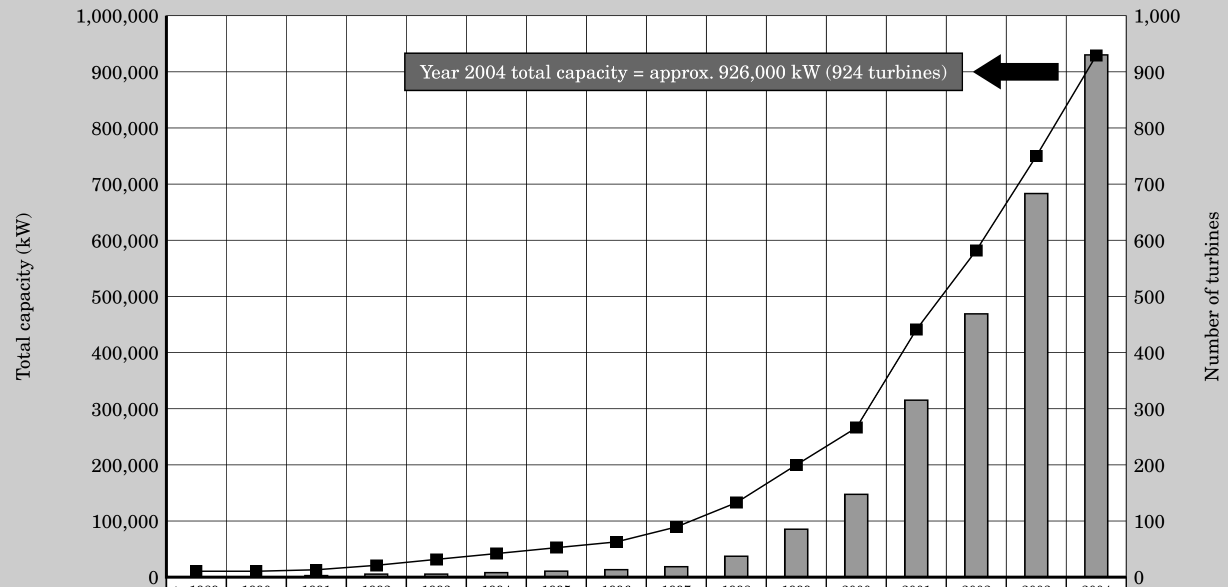
Wind power generation uses a natural energy source, and is increasingly being employed because of its low impact on the environment. However, it is difficult to control wind generated power in a planned way, and as the capacity of wind power generating equipment connected to a power system increases, 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.

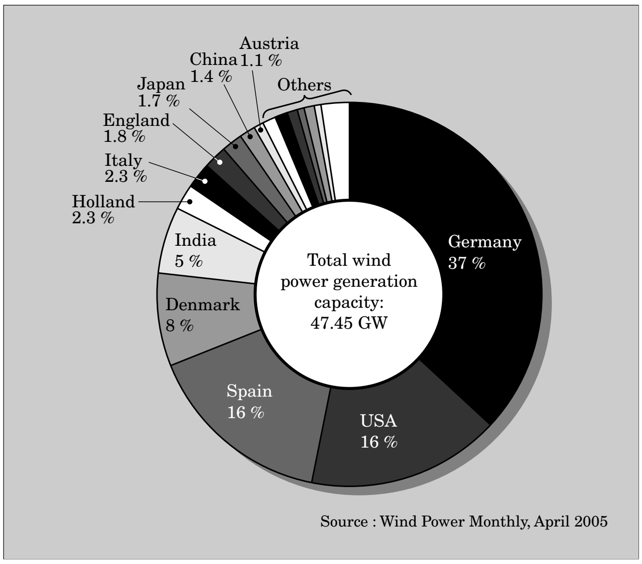
Assuming that the average output per turbine is 1 MW, it will be necessary to construct 2,000 new turbines during the next 5 years. However, this exposes problems involving the connections to a power system, and some countermeasures will be needed to achieve the targeted level of wind power use. For 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.

(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.

Fig.3 Frequency control in response to fluctuation in demand

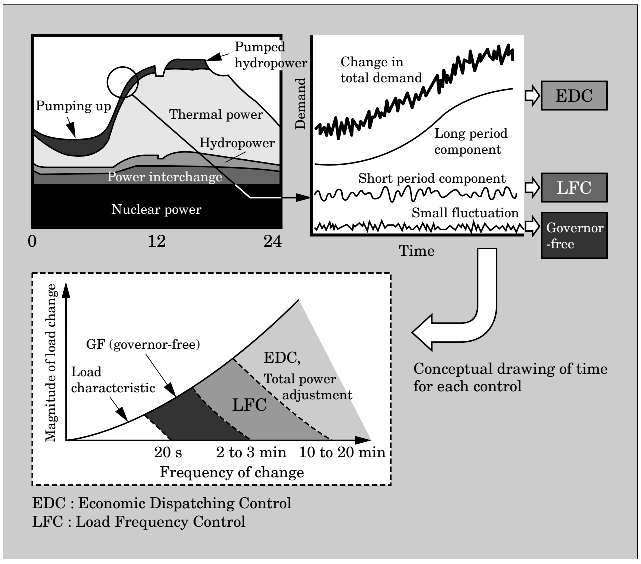
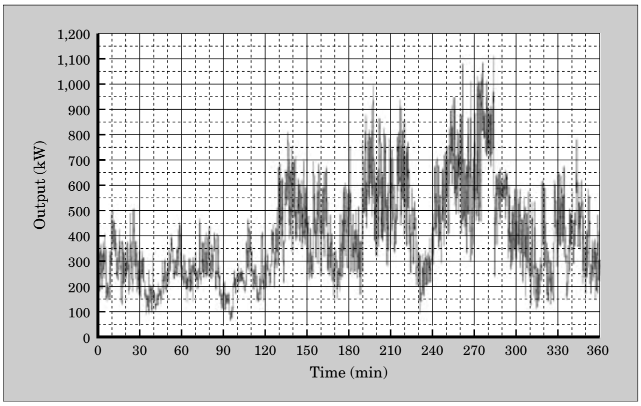


Fig.4 Example of power generation fluctuation in variable speed machine



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.

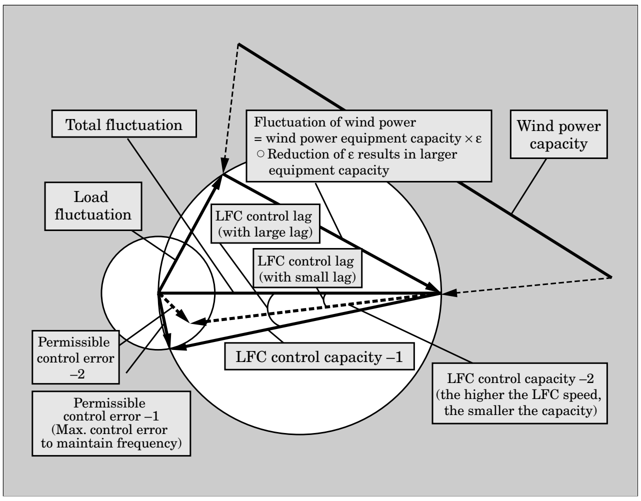
3.3 Measures to suppress frequency fluctuation (active power fluctuation)

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

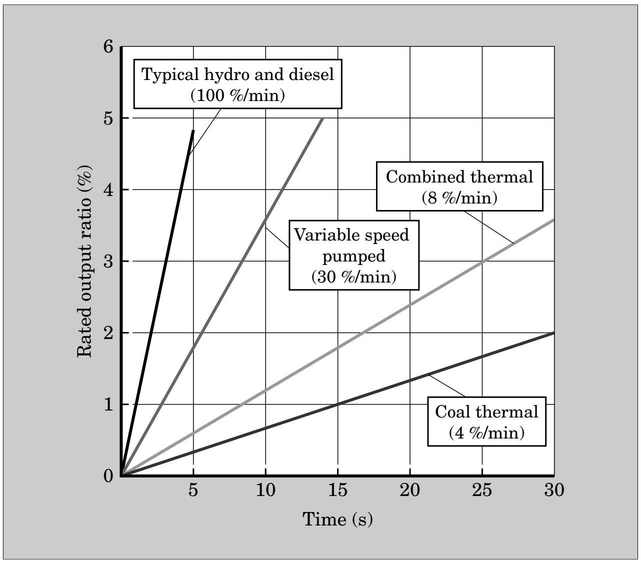
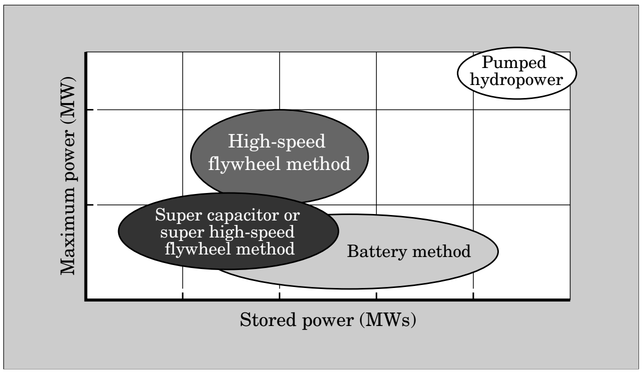


Fig.7 Maximum power and storage capacity of power storage facility



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

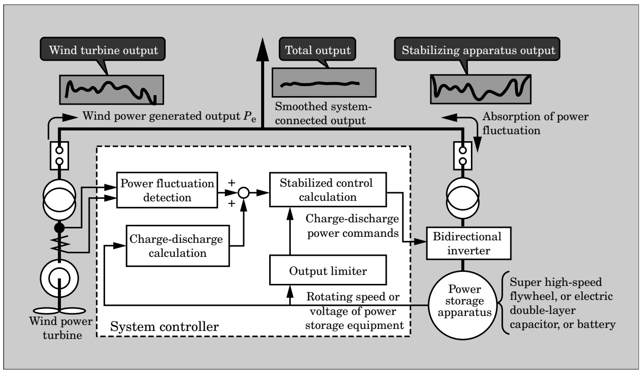


Fig.9 Example of active power indicial response

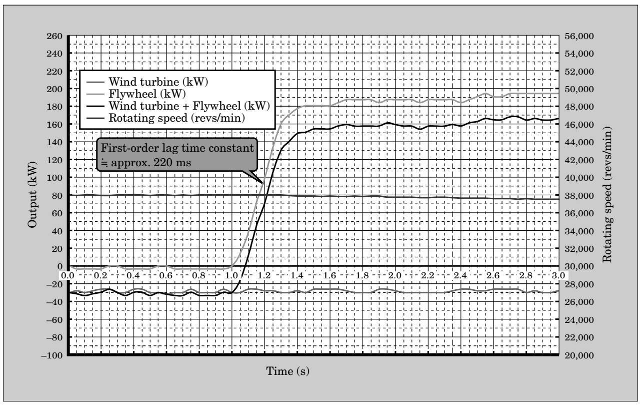


Table 1 Types and features of power storage apparatuses

	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

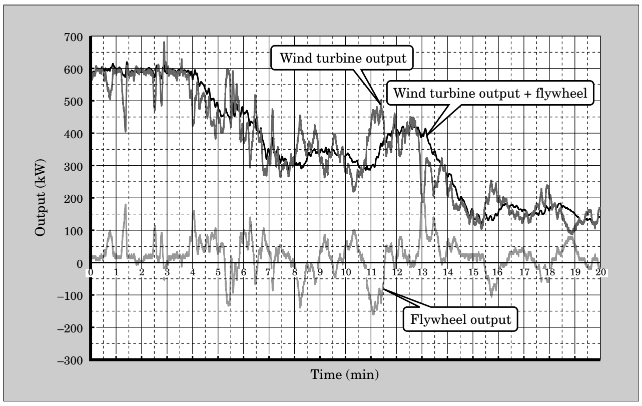


Fig.11 Power fluctuations with and without flywheel energy storage

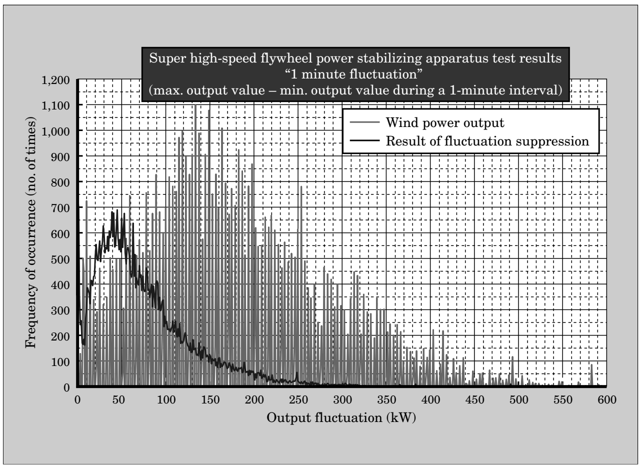
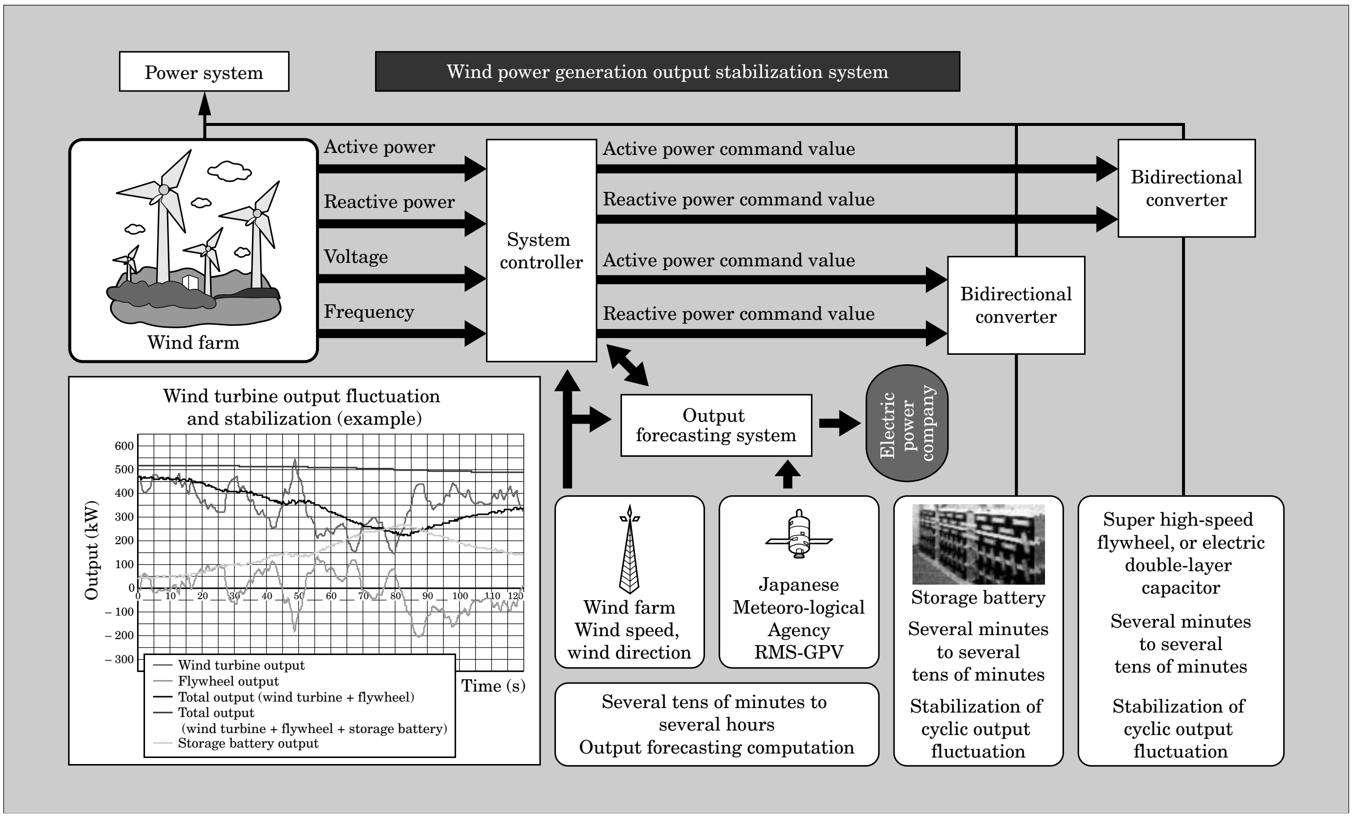


Fig.12 Example hybrid system configuration



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

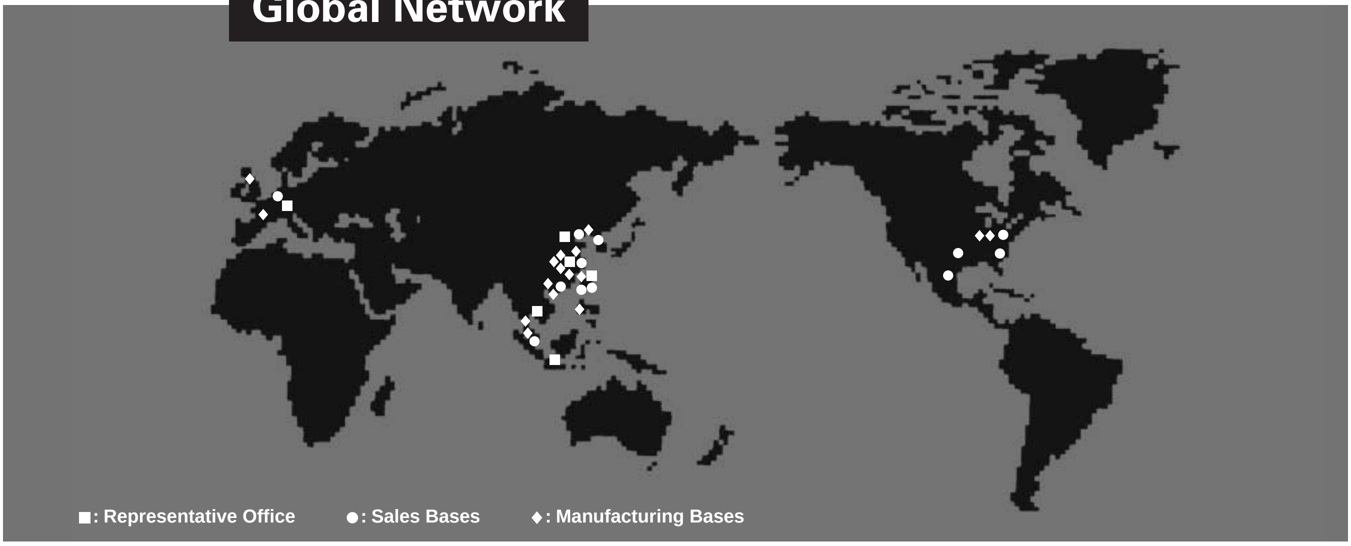
Wind power generation contributes greatly to combating environmental problems such as global warming, however, due to power system connection constraints in order to maintain the power quality, and restrictions on the parties involved with construction and operation, there is a high hurdle to achieving 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.

Global Network



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