Technology for Distributed Energy Systems

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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

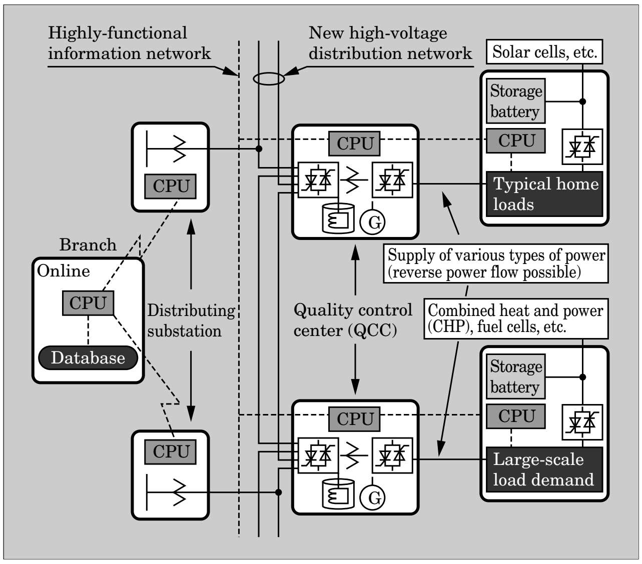
The social infrastructure in Japan has been supported by an assumption of highly reliable and high quality electric power, and high reliability and quality are becoming even more crucial nowadays with the recent advances in electronics and information technology and the advent of an information-based 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



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

Table 1 Technical challenges concerning construction of distributed energy systems

Category	System connectivity	System			Device
		Planning	Measurement	Protection and control	
Steady-state	Ancillary service Isolated operation detection	Power source (capacity, type, combination) Power storage equipment (capacity, type, installation location) Connection point	Regular measurements (items, precision, sampling time)	Control of supply-demand balance Output stabilization control	Response speed Efficiency Durability
Emergency	Emergency power interchange	Backup power source DSM	Waveform measurement (recording time, precision, sampling time)	Emergency control Relay protection method	Operable range

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

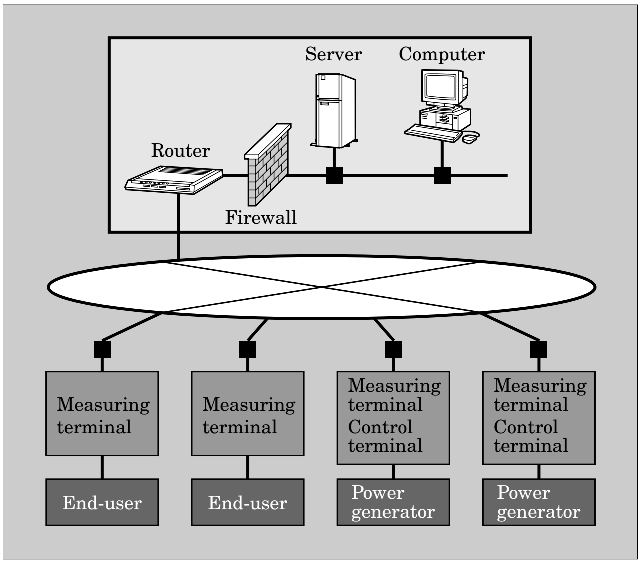


Fig.3 Appearance of measurement and control terminal

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

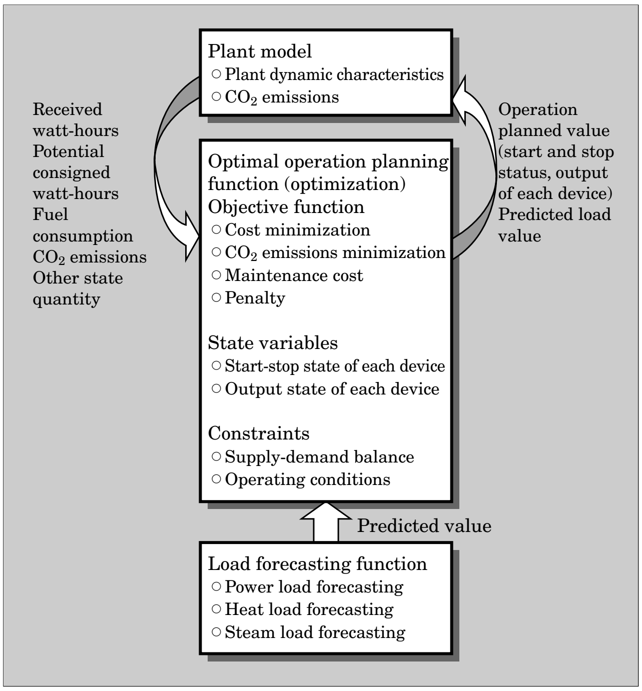
Measurement item		Type	Measurement point		Purpose		
			Each load point, power generating point	Power receiving point, line	Forecasting, optimization	Supply-demand control	Power quality
Active power	P		◎	◎	◎	◎	◎
Reactive power	Q		◎	◎	◎		◎
Voltage	V	3-phase RMS value	◎	◎	◎	◎	◎
	v	Instantaneous value	○	○			○
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.

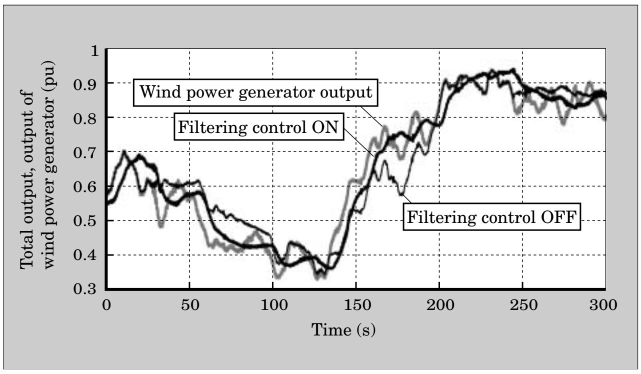
To enable the installation of wind power generating equipment in systems on weak power systems such as a remote island or a distance terminal, a power stabilizing system has been built to absorb the electric power fluctuation that accompanies fluctuation in wind power or the like. In island Okinoshima 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.

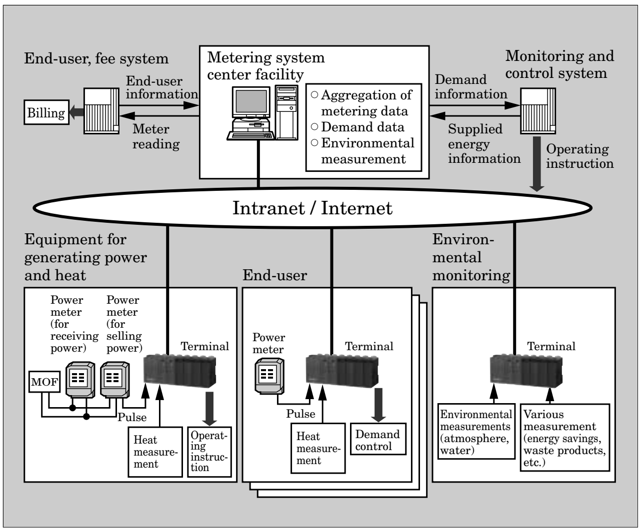
The construction of a metering system is essential for the fair and efficient implementation of metering and billing in a distributed energy system. Figure 6 shows an overview of a metering system. A terminal detects service pulses from each meter, and a central system reads the meters remotely via a 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.

Fig.7 Appearance of metering terminal

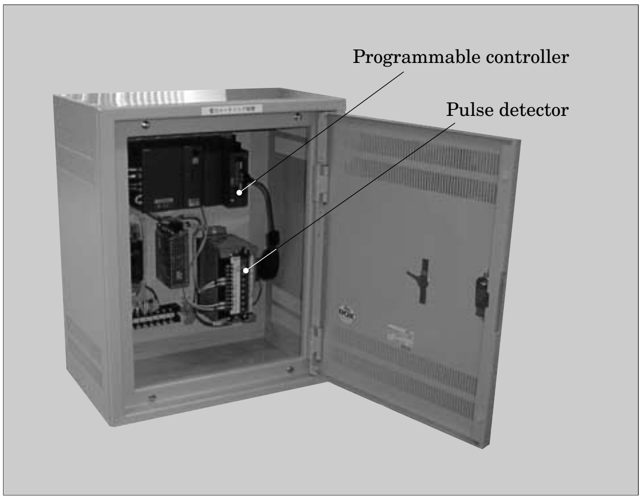
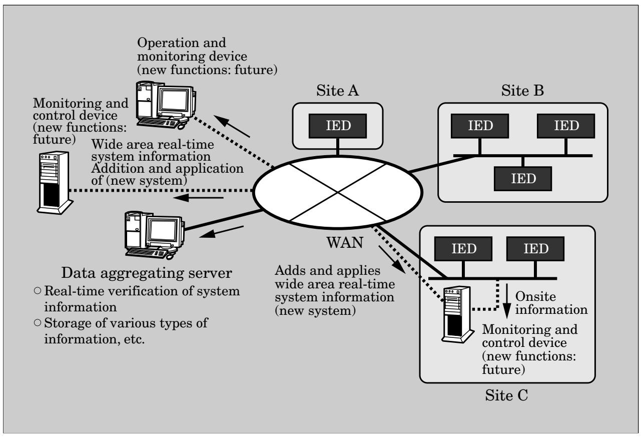


Table 4 Functions of a wide area power quality measuring system

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



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 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

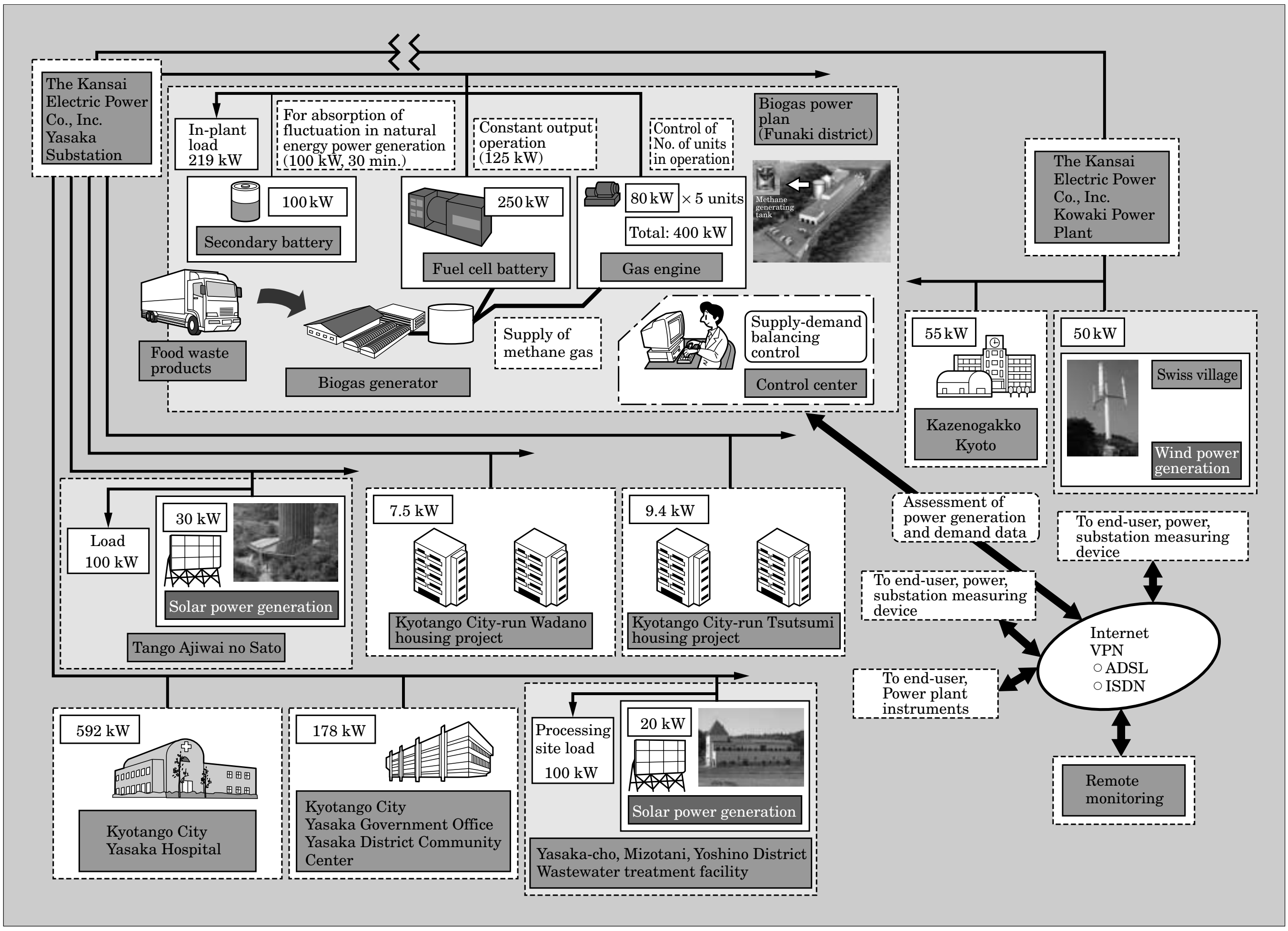


Table 5 List of equipment installed for the Kyoto eco-energy project

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.