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Energy Creation and Social Infrastructure Solutions Contributing to Creation of Sustainable Societies

Fuji Electric

Innovating Energy Technology

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Cover Photo

(clockwise from the upper left and in the center):

Power conditioning equipment for Minami-Hayakita Substation, Variable impedance type SVC, Panoramic view of Units 5 and 6 of Lahendong Geothermal Power Plant, Panoramic view of Kamikita Rokkasho Photovoltaic Power Plant (Photo courtesy of Shin Mutsu Ogawara Inc.)

Energy Creation and Social Infrastructure Solutions Contributing to Creation of Sustainable Societies

Further use of renewable energies is required to reduce CO_2 emissions to create sustainable societies. To meet the request, Fuji Electric has provided power generation solutions and power system stabilization solutions based on making full use of power electronics technology, and they are becoming more and more important.

This special issue introduces Fuji Electric's efforts for energy creation and social infrastructure solutions and its latest technologies and products, which contribute to the creation of responsible and sustainable societies through innovation in energy and environmental technology.

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OGIMOTO, Kazuhiko*

To deal with global warming issues, it is necessary to save energy, promote electrification and utilize low-carbon power sources, and power systems are undergoing significant changes. Renewable energy sources, especially photovoltaic and wind power generation, are expected to be introduced in earnest in many countries and regions. This first took place in Europe and other countries and regions with some political support. In Japan, the use of photovoltaic power generation dramatically increased after the Great East Japan Earthquake due to an extremely advantageous purchase price based on the Feed-in Tariff Scheme. In the Kyushu area, where the largest capacity of photovoltaic power generation is deployed in Japan, approximately 7 GW of photovoltaic power has been introduced against a maximum demand of 16 GW, which far exceeds the percentage of cases in Germany as a single-source renewable energy generation. At one o'clock on May 4, 2016, 66% of the power demand there was covered by photovoltaic power generation.

The output of photovoltaic and wind power generation varies unpredictably depending on the weather. For this reason, using these renewable energy sources more will make supply and demand balancing difficult in operating power systems, hindering stable supply and demand operations every day, hour, minute and second. In this situation, the importance of being able to balance supply and demand, or the capability to make adjustments to supply or demand to strike a balance, has started being globally recognized recently. While a supply-demand balancing capability has always been required, its insufficiency has been emerging due to the increased variability and uncertainty arising from renewable energy and the decreased operational capacity of thermal and other power generation, which conventionally provided the balancing capability.

The need for a supply-demand balancing capability is like the need for oxygen. It is essential for sustaining human life and that of other living things, but we seldom feel the need for oxygen because of its abundance on earth. However, it becomes obvious when people go underwater or into outer space, and oxygen must be secured at a cost. Likewise, a supply-demand balancing capability has always been necessary, but its need has grown along with the increase in variability and uncertainty in supply and demand operations due to the increased output of photovoltaic and wind power generation. Accordingly, securing this capability at a cost by dealing in the market is gaining importance.

To do this, conventional power sources such as thermal and pumped storage power generation are often used first. Possible measures for ensuring greater capability include controlling the output of photovoltaic and wind power generation and sophisticating and enhancing tie line operations, in addition to the much-talked-about power storage and demand regulation. These not only require enhancement and sophistication of the relevant equipment and infrastructure but also they involve increased power loss and power usage limitation. However, they provide a balancing capability and hence new value in power systems.

As the insufficiency of the supply-demand balancing capability has become evident, on-going system improvements have been made to elaborate the wholesale power markets and ancillary service markets in Western countries. In California in the United States, for the purpose of dealing with the variations in and uncertainty of renewable energy, an initiative has been launched by actual dealing in the market to utilize the numerous resources on the customer side through aggregation, in addition to introducing storage batteries in advance. Meanwhile, wholesale power market prices are on the decline in Germany and other countries, and negative prices occur in some time periods. This trend indicates that the value of power, which has been measured in kWh, is making a transition to a supply-demand balancing capability.

Generation of new value points to the necessity of developing, introducing and disseminating new technologies so as to create that value. Power systems require supply and demand balancing in various time domains, ranging from instantaneous balancing to equalization of the demand and supply variation in one day, and adjustment between different seasons. This is because there are changes in the demand and supply structure of the respective power systems and differing capabilities of power grids. There is a global demand

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to create a new power system featuring low cost and high stability by accurately identifying the new value (need) to develop and disseminate technologies.

For the formulation of the Long-term Energy Supply and Demand Outlook approved in 2015, the Power Generation Cost Verification Working Group made a comparison of power generation costs (in yen/kWh) between different types of power sources. At the same time, a certain level of understanding was obtained about the importance of the so-called supply-demand balancing capability, referred to as the “system cost” or “system constraint”. To find a stable and economical solution to future power needs and in turn energy problems including global environment issues, we believe that we can shape the future of Japan, which has energy resource constraints, by recognizing the new value and the strengths and weaknesses of the respective technologies and combining them. We look forward to the earnest activities of researchers, engineers, business managers and all other people involved in the development of policies and systems for making the most of technologies.

Energy Creation and Social Infrastructure Solutions: Current Status and Future Outlook

FUJIWARA, Masahiro*

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1. Introduction

The global demand for electric power is predicted to increase continuously at an annual rate of 1.9% in non-member countries of the Organization for Economic Cooperation and Development (OECD) and at 0.6% even in OECD member countries where demand has already become saturated. From a global perspective, it is necessary to address the unstable trend of oil prices and the mitigation of emission of CO_2 and other global greenhouse gases based on the “Paris Agreement” effectuated in fall 2016. In Japan, there are issues that must be addressed, such as reliable implementation of electricity reform, working on the measures for “Long-term Energy Supply and Demand Outlook” formulated in 2015, the revision of the “Feed-in Tariff (FIT) Scheme for renewable energy,” and the full liberalization of retail trade in gas from April 2017. In order to address these issues, Fuji Electric is committed to improving the comprehensive economy of its customers by providing higher operation efficiency and maintainability. In the area of energy creation, we have been working on technology development and commercialization in the fields of thermal power generation, geothermal power generation, nuclear power generation, photovoltaic power generation, wind power generation and fuel cells.

Social infrastructure solutions are connected to supporting people’s life and economic activities. The conventional solutions have been developed with the aim of creating a comfortable and effective system. On the other hand, the experience of accidents that resulted from aging facilities and several earthquake disasters have caused urgent demand for addressing new evaluation measures such as intrinsic safety, environmental performance and resilience.

Fuji Electric has set “through our innovation in energy and environment technology, we contribute to the creation of responsible and sustainable societies” in its management policies and has been carrying out constant innovation in a wide variety of energy and environmental technologies. For energy creation and social infrastructure solutions, in particular, we continue daily activities with the slogan of “maximized environmental performance, efficiency, economic benefits, value, and innovation” as we carry out our business operations. This paper introduces Fuji Electric’s current efforts toward energy creation and social infrastructure solutions in its representative fields and describes the current status and future outlook.

2. Thermal Power Generation Field

Outside Japan, there are strong needs for thermal power generation in Taiwan, South Korea, Southeast Asia and some parts of Africa, which have strong electricity demand. In Japan, there is some need for thermal power generation against the background of a problem with restarting nuclear power plants, biomass power generation*[1] in response to FIT, and securing power source by power producers and suppliers.

While improving the economy of thermal power generation, Fuji Electric has reduced environmental load and significantly improved efficiency to help its customers create values. Specifically, we have offered stable and reliable technologies, for example, high temperature and high pressure steam operation, small- to medium-capacity turbines applicable to reheating process, compact steam turbines, and reduction of the number of casings. By using these technologies and know-how effectively, Fuji Electric is currently involved in many projects such as in-

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***1: Biomass power generation**

Biomass means organic resources derived from plants or animals. Biomass power generation uses these resources as fuel for thermal power generation to generate power. Biomass can be made from wastes or cultivated plants. When used as fuel, it is dried or processed into the form of chips or pellets.

land-type large gas turbine combined-cycle power generation, ultra supercritical pressure thermal power generation*2 and biomass power generation. We are proceeding with design, manufacturing and construction as we aim for on-schedule completion. We are willing to make efforts in technology innovation and engineering ability improvement now and in the future so that we can meet the requests from our customers inside and outside Japan.

As for after-sales service, Fuji Electric has provided not only simple periodic repairs and rehabilitation but has also been working on improving efficiency and operations by actively applying the latest technologies. Our preventive maintenance has been effective for making a considerable improvement to availability through the application of various diagnosis technologies. We have been contributing to the effort of minimizing the downtime of power plants by strengthening our overseas service bases (the Americas, Taiwan, South Korea, Southeast Asia and the Middle and Near East) as well as by developing on-site maintenance and repair techniques. Furthermore, the Plant Operation Support Center established in the Kawasaki area remotely monitors the operation of plants located inside and outside Japan to provide effective advice from the aspect of operation and maintenance. Fuji Electric will make active suggestions for services while meeting various needs of its customers also in the future.

3. Geothermal Power Generation Field

Geothermal power generation including hot spring power generation has been appreciated anew inside and outside Japan as a renewable energy source that ensures a stable power supply that is independent of the weather and other natural conditions. Geothermal sources applicable for flash cycle power generation*3 have been already used for power plant operation or under planning or development. On the other hand, binary cycle power generation*4 that can utilize low-grade heat sources has great potential in the future. It seems only a matter of time until binary cycle generation surpasses flash cycle generation in terms of the scale of new plants built in a year.

Construction of geothermal power plants is still planned in countries that are aggressively working on geothermal power generation, such as Indonesia, the Philippines, Mexico, Italy, Iceland and Kenya. In Japan, the Long-term Energy Supply and Demand Outlook includes a plan for tripling the percentage of geothermal power generation by 2030. Moreover, as support from the government, financial assistance is available from the Japan Oil, Gas and Metals National Corporation (JOGMEC) for risky attempts to explore geothermal sources or drill wells, which has led to many plans currently being implemented.

As a global top manufacturer in the geothermal power generation field, Fuji Electric has been continuing technology development to improve the economy and operation efficiency and the corrosion resistance, reliability and maintainability of equipment. For after-sales service, as is the case in the thermal power generation field, we have been expanding our service bases and menus and actively making suggestions about services to ensure safe, stable and economical operation of the plants of our customers.

As for flash cycle power generation, Fuji Electric has completed 4 plants in Indonesia and is building plants or manufacturing equipment intended for Iceland, Mexico and the Philippines (refer to “Units 5 and 6 at Lahendong Geothermal Power Plant and Units 3 and 4 at Ulubelu Geothermal Power Plant in Indonesia” on page 12). As for binary cycle power generation, we completed constructing the largest-scale plant in Japan with 5 MW capacity using a substitute for chlorofluorocarbons as the working fluid in March 2017. In addition, we are manufacturing equipment for another plant of the same capacity using normal pentane as the working fluid. We are also entering the hot spring power generation field.

4. Nuclear Power Field

In the Long-term Energy Supply and Demand

***2: Ultra supercritical pressure thermal power generation**

Supercritical pressure power generation is a method for highly efficient power generation conducted under high temperature and high pressure conditions exceeding the critical pressure of water in order to reduce the thermal energy required for water vaporization. The temperature and pressure are increased stepwise to improve power generation efficiency. The condition where the pressure reaches 24.1 MPa or more and the temperature exceeds 566°C is called ultra supercritical pressure power generation.

***3: Flash cycle power generation**

This is a power generation method used when the steam coming from the production well contains much hot water. Only steam is extracted with a steam-water separator and then used to turn the steam turbine directly.

***4: Binary cycle power generation**

This is a power generation method used when steam or hot water at relatively low temperature is used as a heat source. Pentane or another low-boiling-point working fluid is heated to create high-pressure steam which is used to turn the turbine. This method is suitable for low-grade (low-temperature) heat sources that cannot be applied to flash cycle power generation.

Outlook, nuclear power generation is positioned as a power supply covering 20% to 22% of Japan's demand in 2030. However the basic premise is to ensure safety, and the mandatory requirement for restarting plants or continuing construction is to satisfy the new regulatory standards laid down based on the lessons learned from the accident at Fukushima Daiichi Nuclear Power Station. As a result, the decommissioning of 12 reactors has already been decided. Thirty-seven reactors are waiting to be restarted and 5 reactors have been restarted as of the end of 2016 (see Fig. 1).

With the Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF) positioned at the center, earnest efforts are currently being made nationwide to fulfill the decommission plan. These include measures against contaminated water, and technology development and equipment design to remove fuel debris. At the same time, the nuclear fuel cycle has also been promoted seriously to reprocess used fuel and use the collected mixture of uranium and plutonium peacefully and effectively. The nuclear power field requires continuous solution technologies at the moment from both aspects of the efforts toward restarting and decommissioning of nuclear power plants.

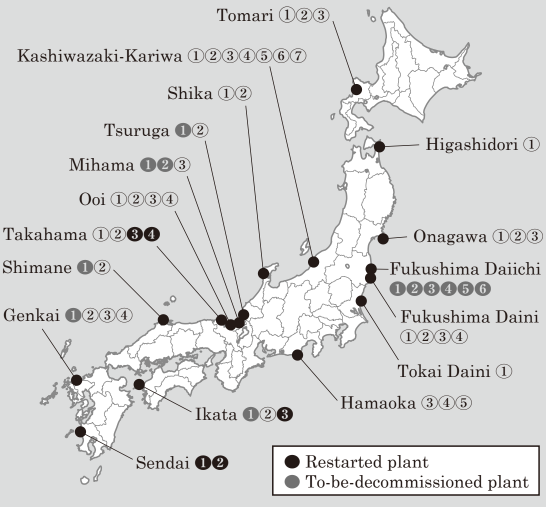
In order to enable safe treatment, disposal and storage of the radioactive wastes generated in the process of operation and decommission of nuclear power facilities, Fuji Electric has been proceeding with research and development of solidification technology. It has been doing this by utilizing geopolymer materials that have various superior properties in partnership with Amec Foster Wheeler plc in the United Kingdom. Furthermore, we have provided technologies and products that satisfy the new regulatory standards concerning mixed oxide fuel (MOX fuel) manufacturing facilities, remote handling equipment and seismic-resistant switchboards to contribute to the nuclear fuel cycle. (refer to "Seismic-Resistant Switchboards Conforming to New Regulatory Standards Concerning Commercial Nuclear Reactors" on page 18).

5. Photovoltaic Power Generation Field

Since the FIT scheme was introduced in Japan in 2012, the capacity of the equipment that has been approved so far have totaled 80 GW; however, the capacity of the equipment that has started operation remain 30 GW. Among the equipment that has not yet started operation, the total capacity of 49 kW or less low-voltage interconnection power generation equipment is 17.5 GW and that of 2 MW or more extra-high-voltage interconnection power generation equipment is 23.8 GW. This shows the polarized market between small-scale and large-scale equipment (see Fig. 2).

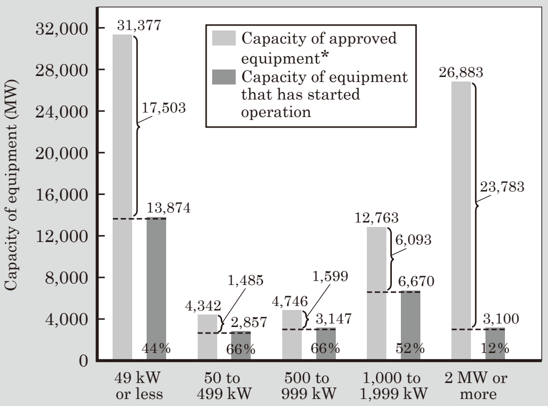
Fuji Electric covers the equipment capacity of 500 kW or more to meet market needs by taking advantage of the know-how in its system components such as power conditioning sub-systems (PCSs) and extra-high-voltage substation equipment as well as in engineering, procurement and construction (EPC, full turn-key solution including site development). The total capacity of the delivered PCSs is 1,800 MW and the total capacity of the deliveries based on EPC is 400 MW including plants under construction.

The most recent issues in this field are as follows: cost savings for ensuring profits despite the reduction in the FIT purchase price, and power system stabilization that becomes necessary with the



(Source: "Current condition of nuclear power generation," The 38th meeting of Japan Atomic Energy Commission, Document 3-1, Federation of Electric Power Companies of Japan, December 1, 2016)

Fig.1 Operating status of nuclear power plants in Japan



(Source: Equipment introduction situation document from METI website "Learn About Reusable Energies")
* Equipment approved by July 2016

Fig.2 Capacity of photovoltaic power generation equipment approved by July 2016 and capacity of equipment that has started operation among them (by capacity) increased introduction of renewable energies. In order to surely resolve these issues, Fuji Electric has developed and provided PCSs and power system stabilization systems that have achieved high performance and low price (refer to “Kamikita Rokkasho Photovoltaic Power Plant with Capacity of 71 MW DC / 51 MW AC” on page 23).

As for a high-performance, low-cost PCS, our flagship product, a 1-MW outdoor type, is scheduled to be released in October 2017.

We have also developed a new, low-cost power stabilization system by adding large-capacity storage batteries to the conventional one, and it is slated for delivery to several plants. The introduction of this system made it possible to reduce the capacity of the storage battery. This led to a synergy with a reduction in the price of storage batteries to ensure the business feasibility of several projects which had been facing tough conditions.

6. Wind Power Generation Field

Wind power generation has also gained benefit from FIT, and it is expected to be introduced further. Facilities of 7.5 MW or more, however, are mandatory to undergo an environmental assessment that takes about 3 years, so that full-scale construction of large-scale wind farms started in FY2016. Although the purchase price for photovoltaic power generation has decreased greatly, the price for wind power generation has been kept at 22 yen/kWh. Some photovoltaic power generation operators have been making a move to shift to wind power generation as a new investment destination. For the time being, there are expected to be more players planning to introduce wind power.

Fuji Electric has also been providing EPC for several megawatt power plants and has been committed to the engineering of grid connection system and power stabilization system as well as on the sales of system components.

Hokkaido and Tohoku are well known to have many sites where wind conditions are suitable for wind power generation. In the area having a power transmission network with relatively small capacity, there is a challenge of power quality affected by output fluctuations due to a change in the wind conditions. For example, Hokkaido Electric Power Co., Inc. released “Technology requirement for the output fluctuation mitigation measures for wind power generation equipment” in FY2016. It requests operators to install storage batteries or take other measures in new wind power plants to be built so as to keep output fluctuations within the level that will not affect the frequency adjustment of electric power systems.

Fuji Electric put a power stabilization system into practical applications by combining a storage battery and PCS for optimum control and started delivery. This system suppresses the output fluctuation in wind power plants and stabilizes the voltage and frequency within a required value range by charging and discharging the storage battery properly (see Fig. 3).


Fig.3 Power conditioning sub-system for power stabilization system

This system has already been delivered to many customers not only within the territory of Tohoku Electric Power Co., Inc. but also to remote Japanese islands and the Galapagos Islands (refer to “Power Stabilization System with Lead-Acid Batteries and Lithium-Ion Batteries for Galapagos Islands” on page 48).

We will work on the EPC for wind power generation equipment in earnest by setting the power stabilization system at the core and adding our know-how acquired in the EPC for photovoltaic power generation equipment.

7. Fuel Cell Field

Fuel cells can use various types of fuels as long as it contains some material that can generate hydrogen through a chemical reaction. Many practical applications use city gas, LPG, biogas such as sewage digestion gas, and even hydrogen.

Fuel cells are characterized by their high power generation efficiency in spite of their small capacity, emissions containing almost no NO_X, SO_X or other air pollutants, and being low-noise, low-vibration power generating equipment with good environmental properties. They are thus suitable for distributed power sources. When their exhaust heat is recovered and used for a cogeneration system, they can be an excellent power supply with a total efficiency reaching 90%.

Fuel cells can be divided into several types depending on the electrolyte used, including a phosphoric acid fuel cell (PAFC), polymer electrolyte fuel cell (PEFC), molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC). Since the operating temperature and power generation efficiency vary depending on the type, suitable applications are also different (see Table 1).

Fuji Electric started the development of PAFCs in 1973 and has conducted field tests on over 90 units with up to 5-MW capacity for various outputs and applications with support from the government and in partnership with electric power companies and gas companies. By taking advantage of the knowledge acquired from there, we started the delivery of a 100-kW on-site type commercial unit in 1998 and have delivered 75 units around the world by 2016 (see Table 2). The longest cumulative operation time per unit exceeded 124,000 hours (about 15 years). This proves high equipment reliability and an excellent after-sales service system.

Fuji Electric is currently working on enhancing functionality, expanding applications and reducing price in order to promote the prevalence of PAFCs. We plan to expand the sales of PAFCs centered on the following points: in Japan, grid independent power supply for emergency and the application to biogas power generation*5 that is applicable to FIT; and outside Japan, a fire prevention system that creates a low-oxygen atmosphere in the entire target space by using exhaust gas. Moreover, we are striving to develop an SOFC for next-generation high-efficiency cogeneration systems (refer to "Status of Development and Sales Strategy of Fuel Cell Systems" on page 30).

Table 1 Types and applications of fuel cells

Type	Phosphoric acid (PAFC)	Polymer electrolyte (PEFC)	Molten carbonate (MCFC)	Solid oxide (SOFC)
Operating temperature	190 °C to 200 °C	70 °C to 90 °C	600 °C to 700 °C	700 °C to 1,000 °C
Power generation efficiency	40% to 45%	35% to 40%	45% to 50%	45% to 60%
Major application	Commercial use	Home use, automotive use	Commercial use	Commercial use, home use

Table 2 Delivery destinations of commercial PAFC units (as of December 2016)

Destination		Number of units
In Japan	Office building	6
	Training center, exhibition facility	5
	University, government building	8
	Hospital, hotel	8
	Factory	8
	Sewage treatment facility	28
	Verification test	1
Outside Japan (Germany, South Korea, the United States. and South Africa)		11
Total		75

8. Power Distribution Field

At the Great East Japan Earthquake, long blackouts and planned outages revealed the vulnerability of the power distribution. Consequently, the government and municipalities have been promoting various measures to improve energy security. The introduction of FIT, in particular, has led to a significant increase in the construction of power plants using renewable energies, primarily photovoltaic power. As a result, the issue of power system stabilization has come to the surface. Specifically, there are issues of power system frequency affected by the unstable output of photovoltaic power generation or wind power generation, and of voltage in distribution lines affected by the reverse power flow from distributed power sources.

At the same time, several measures have been promoted such as the freeze on electricity rates, stable supply of power, and increased opportunity for new power providers to enter through the electricity system reform. The Organization for Cross-regional Coordination of Transmission Operators, JAPAN was established in 2015 and the full liberalization of electricity retail trade started from 2016. Further reforms will advance in the future including the abolishment of price control and the separation of power generation and transmission.

The demonstration of a virtual power plant (VPP) is being conducted (see Fig. 4). This is a cluster energy management system (CEMS) developed to be a new stable power supply system.

Timely introduction of various frameworks has been considered as new electric power trading markets, including "an hour-ahead market," "a real-time market," "a capacity market" and "a negawatt market" (see Fig. 5).

At the community level, community energy supply service operations are being planned and established with the aim of local generation for local consumption and for job creation. On the side of utility customers including companies, new energy systems are being developed for minimizing energy costs or in the business continuity plans (BCPs) designed for reducing the loss in business property to a minimum at times of natural disaster.

***5: Biogas power generation**

Biogas refers to gases produced from organic resources such as garbage or sludge through the use of anaerobic microorganisms. Biogas power generation is a method for using such gases to generate power.

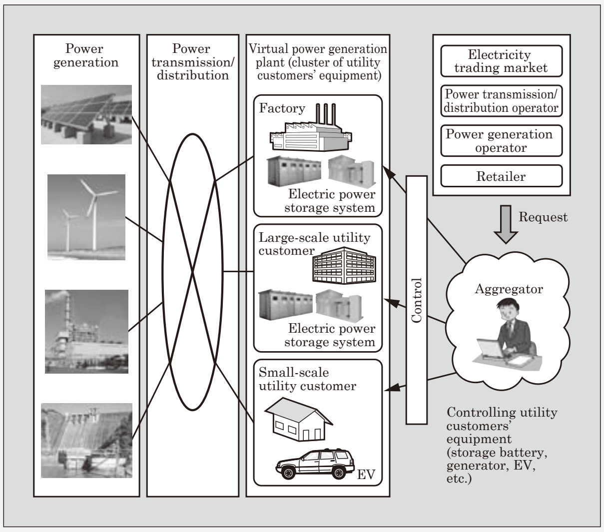


Fig.4 Illustration of virtual power plant demonstration

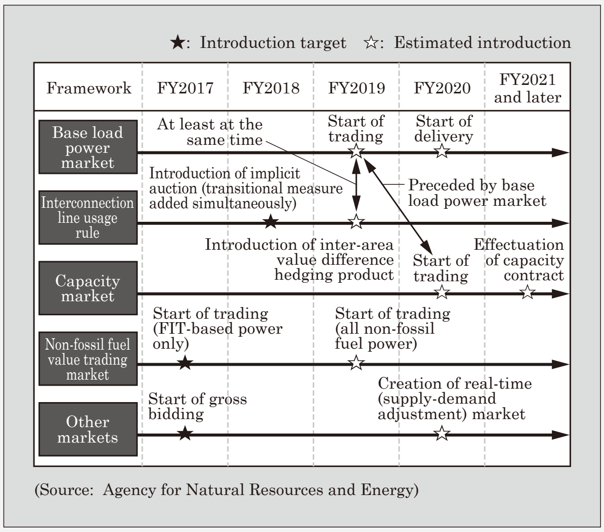


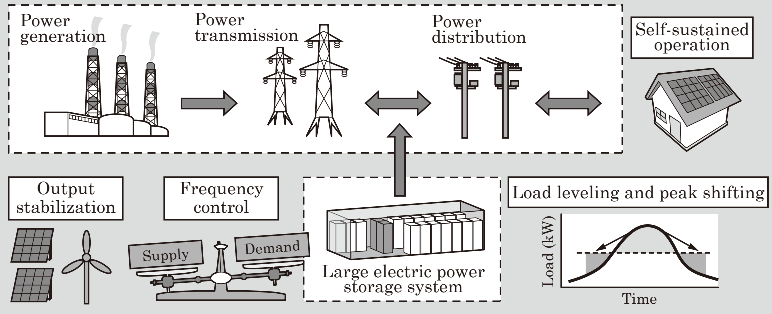
Fig.5 Future outlook in electric power trading market (introduction target and estimated introduction)

Fuji Electric is willing to certainly meet the various needs of its customers by applying the knowledge acquired through various demonstration projects and the results of its independent development as well as by adding information and communication technology (ICT) to the technologies and products related to monitoring, operation and control of power generation equipment and electric distribution facilities. For example, we have developed a computer system for ensuring optimal power system operation, a large electric power storage system designed for power system stabilization and for peak shifting on the demand side, and a static var compensator (SVC) for keeping the power system voltage within the specified value. These systems and equipment have been released onto the market in a timely manner. Introduction examples are shown below.

Figure 6 shows the applications of Fuji Electric's electric power storage system. It achieves all of the storage battery control functions in the figure through a combination of appropriate PCSs and control systems for various needs.

Power storage systems for power system operators such as electric power companies tends to grow in scale and their capacities often increase to several tens of MWh. Fuji Electric delivered a redox flow battery control system to the Minami-Hayakita Substation of Hokkaido Electric Power Co., Inc. in 2015. This system optimally controls the multiple storage banks of the battery system (15 MW, 60 MWh) manufactured by Sumitomo Electric Industries, Ltd. (see Fig. 7). Storage batteries are normally characterized by fast response and easy scalability. They also have advantages of a shorter lead time and less limitation on installation sites compared with pumped storage power generation that has been used conventionally for peak shifting. Consequently, they are expected to be further introduced in the future (refer to "Large-Scale Power Conditioning System for Grid Storage Battery System with Redox Flow Battery Having World's Highest Capacity Class of 60 MWh" on page 41).

As a method for controlling the voltage of the distribution system, Fuji Electric uses an SVC that has no limitation on the number of operations instead of a step voltage regulator (SVR) that is mostly used in present systems although its num-



Customer	Needs	Function
Power system operator	○ Equipment availability improvement through load adjustment ○ Stabilization of power system frequency	○ Peak shifting ○ Frequency control
Electric utility provider	○ Adjustment ability ○ Negawatt support ○ Balancing within planned value range	○ External output adjustment ○ Schedule control
Renewable energy provider	○ Output stabilization ○ Avoidance of power generation suppression	○ Stabilization control ○ Peak shifting
Utility customer (factory, large facility, etc.)	○ Power cost reduction ○ BCP	○ Peak shifting ○ Isolated operation

Fig.6 Applications of electric power storage system in electric power system

Fig.7 Large electric power storage system of Minami-Hayakita Substation

ber of operations is limited. SVCs are divided into 2 types, switching converter type or variable impedance type, depending on the method of generating reactive power. The variable impedance type distribution SVC was developed in partnership with Tohoku Electric Power Co., Inc. The step-less, continuous control has been enabled through the use of a variable inductor. The structure without a cooling fan has made it possible to create a smaller and lighter SVC with higher reliability compared with conventional SVCs. As a result, this SVC can be mounted on a utility pole. In the "Demonstration Project on Next-Generation Power Grid Construction for Distributed Energy" of the New Energy and Industrial Technology Development Organization (NEDO), we are currently developing a next-generation SVC that will achieve higher performance, smaller size and lighter weight and can be mounted on a single utility pole using silicon carbide (SiC) modules. Fuji Electric will provide the product together with computing systems for monitoring control to contribute to maintaining the voltage of an entire distribution system (refer to "Distribution Static Var Compensators and Static Synchronous Compensators for Suppressing Voltage Fluctuation" on page 36).

9. Water Environment Field

It is mandatory to treat industrial wastewater from factories and offices properly and thoroughly according to stringent water quality regulations based on the Water Pollution Prevention Act and more stringent standards specified in ordinances of local governments. Consequently, new construction or extension of a factory requires its wastewater treatment equipment to be improved (see Fig. 8). Water quality regulations continue to become more stringent year by year. Companies are facing a challenge to strictly observe these wastewater standards while reducing running costs.

Fig.8 Wastewater treatment facility

For example, in the food and beverage industry, the demand for instant food or retort food is increasing and various types of beverages are released for people in a wide age range. Companies are required to increase production or production items and change manufacturing processes. This leads to a variation in the amount and quality of wastewater, which makes wastewater treatment control difficult. In terms of considering the surrounding environment and improving the work environment, companies and organizations are also required to prevent foul odors such as those emanated from ammonia or hydrogen sulfide. Since most of the wastewater from food and beverage factories is highly concentrated organic wastewater, they are often processed with biological treatment, as typified by a standard activated sludge method. To use this method for a case where the amount of wastewater increases or their quality changes, companies are compelled to take measures involving significant capital investment, such as reinforcing the treatment capacity or adding pre- and post-treatment facilities that may require civil engineering work.

Fuji Electric has developed a new wastewater treatment solution by using *Bacillus**6 that can reduce the treatment cost and prevent odor simultaneously. This solution uses a specific species of *Bacillus* that can degrade organic material efficiently. We combined it with a special activator which we developed through advanced analysis of genes and enzymes to maximize the degradation ability of the *Bacillus* (see Fig. 9).

This new wastewater treatment solution does not require large-scale capital investment and performs excellently to prevent odors while reducing running costs. In more specific terms, this solution is characterized by the ability to not only degrade highly concentrated organic material in a short time but also prevent the generation of excess sludge, which is one type of industrial waste. The cost for sludge disposal can be reduced by 20% to 40% com-

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6: *Bacillus

Refer to "Supplemental Explanation" on page 60.

Fig.9 *Bacillus* inoculum and activator

pared with conventional methods while odors can be reduced to the level of the lower detection limit or less. Moreover, the power for operating the aeration blower can also be reduced by 10% to 40% compared with conventional methods because the species is a facultative anaerobe.

In joint research with Utsunomiya University, Fuji Electric has advanced the application of *Bacillus* to develop a sludge-less wastewater treatment system that can dramatically reduce the initial investment and running costs for new construction or extension of wastewater treatment equipment. This system is based on a combination of *Bacillus* and the magnetically activated sludge method of Utsunomiya University, allowing simultaneous reduction of initial investment, running costs and installation space. For example, the system uses a magnetic separator shown in Fig. 10 for solid-liquid separation in biological treatment, so that it can shrink the capacity of a biological treatment tank to a half or a third compared with conventional methods. A settlement tank is also unnecessary, and thus the construction cost (initial investment) can be saved significantly. Moreover, *Bacillus* promote biological autoxidation so that excess sludge is reduced to zero. This eliminates the need for a sludge dehydrator required for sludge disposal as well as for the costs for chemicals, electric power and disposal, resulting in significant reduction also in running costs (refer to “New Wastewater Treatment Solution Using *Bacillus*” on page 54).

Fig.10 Sludge-less wastewater treatment system (magnetic separator)

10. Postscript

This paper introduced Fuji Electric’s current efforts toward energy creation and social infrastructure solutions in its representative fields and described the current status and future outlook. In addition to these, various efforts have been also made such as for the hydroelectric power generation field in collaboration with Voith Hydro GmbH & Co. KG in Germany, electricity smart meters that have the top market share in Japan, and sanitization and operation software packages for government offices.

Fuji Electric is determined to work on technological innovation and service improvement also in the future to help its customers create value by focusing on, listening to and working together with customers. We will also provide safe, secure and environment-friendly energy creation and social infrastructure solutions and continue to make large contributions to the creation of sustainable societies.

Units 5 and 6 at Lahendong Geothermal Power Plant and Units 3 and 4 at Ulubelu Geothermal Power Plant in Indonesia

MURAKAMI, Takashi* TAKAMIYA, Atsushi*

ABSTRACT

Indonesia has been promoting geothermal development as a measure to overcome its increasingly serious power shortage. Fuji Electric has long been committed to geothermal power generation, which has low CO_2 emissions and provides an eco-friendly and stable power supply independent of weather conditions. We possess a large number of technologies in this field. We emphasize the relationship with partners and work to shorten the construction period by applying various ideas and making efforts based on our experience and track record for promoting an engineering, procurement and construction (EPC) project. Units 5 and 6 at the Lahendong Geothermal Power Plant and Units 3 and 4 at the Ulubelu Geothermal Power Plant started commercial service up to 3 months ahead of the initial schedule, helping to improve the electricity situation in Indonesia.

1. Introduction

Along with hydraulic, photovoltaic and wind power generation, geothermal power generation using geothermal resources, which are renewable energy sources, emits considerably less CO_2 emissions than power generation based on fossil fuels. It has been attracting global attention in terms of reducing CO_2 emissions.

Fuji Electric has delivered major equipment for geothermal power plants with a capacity exceeding 2,900 MW inside and outside Japan and maintained a market share of about 40% in the world for the last 10 years (see Fig. 1). This is the result of customers' comprehensive evaluation of Fuji Electric's technologies for solving problems specific to geothermal power plants such as corrosion and scale, as well as its abilities to carry out projects, including shortening of work periods, as an engineering, procurement and construction (EPC) contractor. We have experience constructing a triple-flash geothermal power plant in New Zealand that has the largest capacity in the world. We have also obtained a good reputation for technologies specific to geothermal power plants, such as measures against silica precipitation and the selection of turbine blade material.

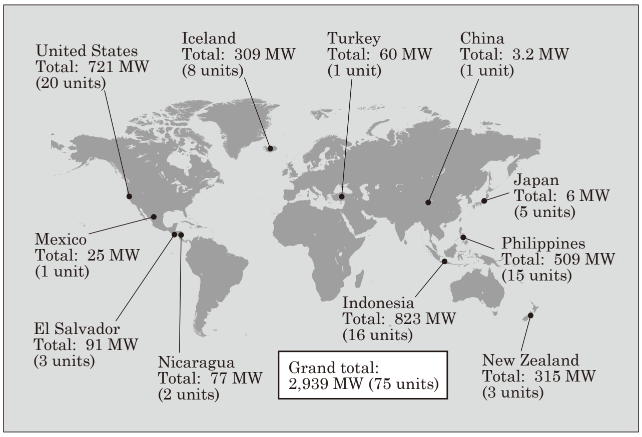

Fig.1 Fuji Electric's achievements in delivery of geothermal power generation equipment

Indonesia has been promoting geothermal development as a measure to overcome its increasingly serious power shortage. Units 5 and 6 of Lahendong Geothermal Power Plant and Unit 3 of Ulubelu Geothermal Power Plant, to which Fuji Electric delivered major equipment, started commercial operation ahead of their initial schedules. The construction work for Unit 4 of Ulubelu Geothermal Power Plant has been continuing smoothly and we aim to complete it in April 2017.

This paper describes an overview of these geothermal power plants and our efforts toward shortening work periods.

2. Geothermal Power Generation in Indonesia

Indonesia is a key country in the Association of Southeast Asian Nations (ASEAN), abundantly endowed with natural resources and a labor force, and is expected to continue seeing significant growth also in the future.

Although the demand for electric power in Indonesia has tended to increase significantly in recent years, the power development plan has rather failed to keep up with the situation (see Fig. 2(1), (2)). The electrification ratio is still low at around 70% and power shortage is so serious that planned outages are performed. There are demands for the construction of new power

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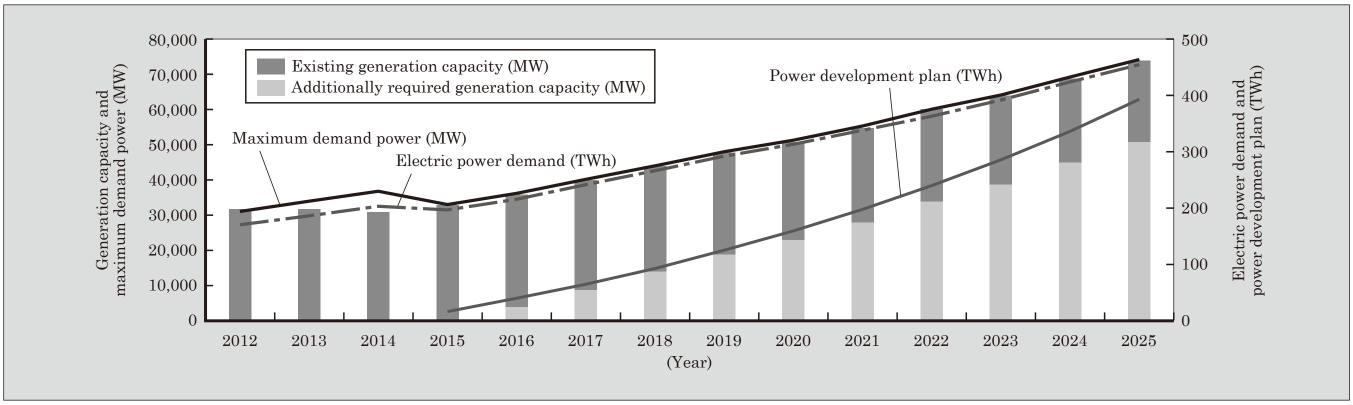

Fig.2 Electric power demand prediction and development plan in Indonesia

plants as well as for the reinforcement of transmission networks.

On the other hand, the total capacity of the geothermal power generation facilities in Indonesia is the world's third largest after the United States and the Philippines, and a power of about 1,340 MW was generated from geothermal energy as of 2015. Although the country's geothermal resource potential is estimated to be 29,000 MW, which is the second largest in the world, the utilization ratio remains at around 5% (see Fig. 3).

Considering such background, the Ministry of Energy and Mineral Resources of Indonesia has set a goal of expanding the power supply from geothermal power plants and increasing the total electrical power capacity based on geothermal energy to 9,500 MW in the country(3).

By capitalizing on its expertise and experience in the geothermal power generation equipment field, Fuji Electric has delivered 3 generators and 16 units (turbine and generator) of geothermal power generation equipment in Indonesia. The total capacity of geothermal power generation equipment delivered by Fuji Electric has reached about 823 MW. In FY2014, Fuji Electric obtained an order for a project of 2 units, namely Units 5 and 6 of Lahendong Geothermal Power Plant and a project of 2 units, namely Units 3 and 4 of Ulubelu Geothermal Power Plant (see Fig. 4).

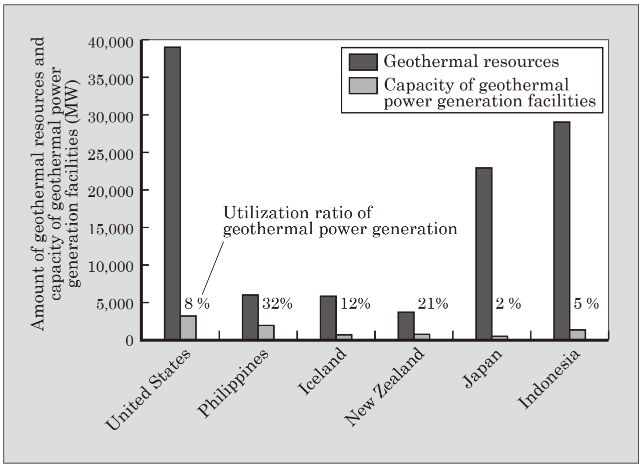

Fig.3 Comparison of utilization ratio of geothermal power generation in major countries

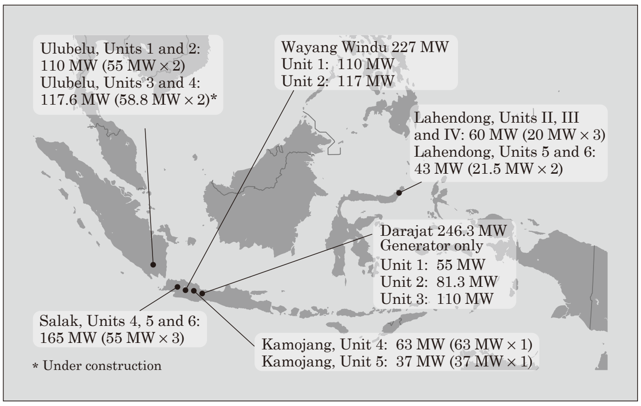

Fig.4 Fuji Electric's achievements in delivery of geothermal power generation facilities in Indonesia

For both projects, Fuji Electric proposed high-quality and high-performance equipment in short delivery time, which were highly rated by the client; and we won the orders among increasingly fierce competition in the geothermal power generation market. While Unit 4 of Ulubelu Geothermal Power Plant is under construction, Units 5 and 6 of Lahendong Geothermal Power Plant and Unit 3 of Ulubelu Geothermal Power Plant have already started commercial operation up to 3 months ahead of the original project schedule.

The construction and commissioning of Unit 4 of Ulubelu Geothermal Power Plant are proceeding smoothly, and we aim to start commercial operation in April 2017.

3. Units 5 and 6 of Lahendong Geothermal Power Plant

3.1 Project overview

Units 5 and 6 of Lahendong Geothermal Power Plant were constructed in the mountains about 800 m above sea level in Talikuran village, Tompaso District, Minahasa Province on Sulawesi Island, which is an island located at almost the center of Indonesia. The place is about an hour and 20 minutes by car from Manado, the capital city of North Sulawesi Province located at the north end of Sulawesi Island. The generation capacity is 40 MW at the sending end as net electric power output (20 MW × 2 units). In the nearby village of Lahendong, existing Units II to IV of Lahendong Geothermal Power Plant have been operating commercially. All of these units were delivered by Fuji Electric (see Fig. 5).

This project was ordered by PT Pertamina Geothermal Energy on December 1, 2014 as an EPC contract including civil engineering and installation, with Sumitomo Corporation specified as a prime contractor. Fuji Electric closed a contract with Sumitomo Corporation to deliver the major equipment of the power plant including geothermal steam turbines and generators that constitute the main part and condensers. A steam-above-ground system (SAGS) and some other equipment were delivered by PT Rekayasa Industri, a leading engineering company in Indonesia.

Figure 6 shows a panoramic view of Units 5 and 6 of Lahendong Geothermal Power Plant and Fig. 7 is the external appearance of the turbine and generator of Unit 5.

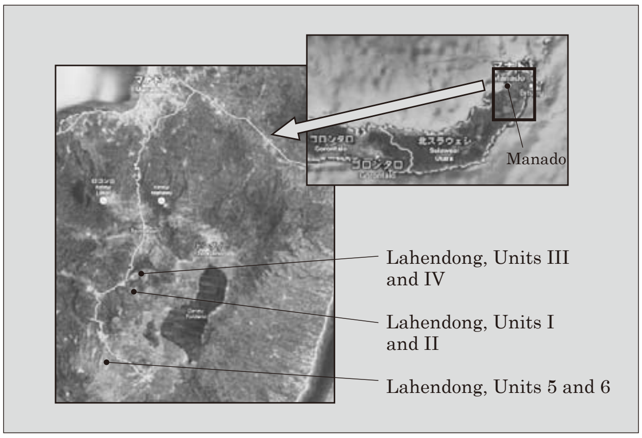

Fig.5 Location of Lahendong Geothermal Power Plant

Fig.6 Panoramic view of Units 5 and 6 of Lahendong Geothermal Power Plant (Unit 5 on the right)

Fig.7 Turbine and generator of Unit 5 of Lahendong Geothermal Power Plant

3.2 Project characteristics

This project employs axial exhaust flow turbines that have low exhaust loss. The condensers are a compact direct-contact type with built-in gas cooling zones. In order to shorten the construction period, the turbines and generators are designed and manufactured in the skid-mount style*1 and shipped from Japan.

The ratio of noncondensable gas components to the geothermal steam is 1% (weight %). For gas extraction equipment used to extract this noncondensable gas component from the condenser, we adopted a hybrid system of a steam ejector and a vacuum pump. The gas extraction equipment consists of 3 units in total: 2 units operating at 50% capacity (regular use) and one unit operating at 50% capacity (backup). The cooling tower has a tower body structure made of FRP and consists of 3 cells. The hotwell pumps are designed as 2 units operating at 50% capacity. This power generation equipment is provided with a run-back function to lower the output setting instantaneously when one hotwell pump stops and operate by limiting the amount of cooling water sent to the condenser to 50%.

The distributed control system (DCS) includes automatic turbine activation equipment so that the plant can be started automatically with the push of a button from opening the main steam stop valve to 100% rated output.

Table 1 shows the major specifications of the turbine and generator.

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*1: Skid-mount style: A style of unit in which a steam turbine and a generator are provided as a package. Since the equipment can be shipped, transported and installed as a package, on-site assembly is unnecessary, and this greatly contributes to shortening the construction period on the site.

Table 1 Major specifications of turbine and generator of Units 5 and 6 of Lahendong Geothermal Power Plant

Item		Specification
Turbine	Type	Single-cylinder, single-flow, axial exhaust, reactionary condensing turbine
	Sending end output	20,000 kW
	Inlet pressure	8.0 bar (absolute pressure)
	Inlet temperature	170.2 °C
	Condenser vacuum	0.075 bar (absolute pressure)
Generator	Type	Air-cooled turbo generator
	Capacity	25,300 kVA
	Voltage, frequency	11 kV, 50 Hz
	Power-factor	0.85 (lagging)

4. Units 3 and 4 of Ulubelu Geothermal Power Plant

4.1 Project overview

Units 3 and 4 of Ulubelu Geothermal Power Plant are constructed about 800 m above sea level in the mountains in Ulubelu District, Tanggamus Regency, Lampung Province at the south end of Sumatra Island. The generation capacity is 110 MW at the sending end as net electric power output (55 MW × 2 units). They are located next to existing Units 1 and 2 of Ulubelu Geothermal Power Plant which uses equipment delivered by Fuji Electric and started operation in 2012 (see Fig. 8).

Sumatra Island is expected to have the largest geothermal resource potential in Indonesia, and Ulubelu is an area where geothermal development was started ahead of other areas in the island.

Fuji Electric has been promoting the project in cooperation with Sumitomo Corporation and PT Rekayasa Industri. Unit 3 of Ulubelu Geothermal Power Plant already started commercial operation in July 2016 and Unit 4 is being constructed with the aim of completion in April 2017. The electric power generated in this station is supplied to the Lampung area via the Indonesian government-owned electric power company, (PT. PLN), and it is making a great contribution toward eliminating the chronic power shortage in the area.

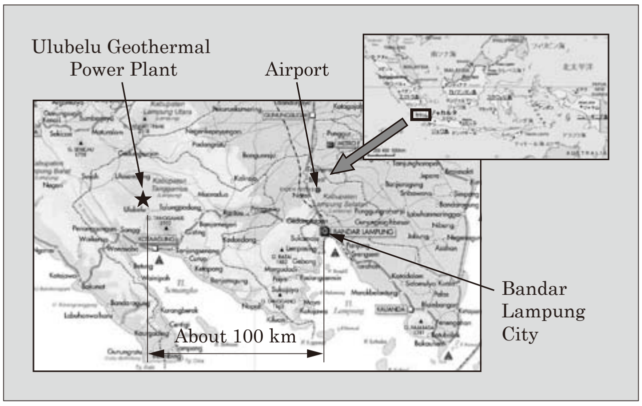

Fig.8 Location of Ulubelu Geothermal Power Plant

Fig.9 Panoramic view of Units 3 and 4 of Ulubelu Geothermal Power Plant

Fig.10 Turbine and generator of Unit 3 of Ulubelu Geothermal Power Plant

Figure 9 shows a panoramic view of Units 3 and 4 of Ulubelu Geothermal Power Plant and Fig. 10 shows the external appearance of the turbine and generator of Unit 3.

Units 3 and 4 of Ulubelu Geothermal Power Plant are positioned as one of the renewable energy development projects promoted by the Indonesian government under a presidential decree. The project is funded by a loan from the World Bank and has been attracting a lot of attention in Indonesia.

4.2 Project characteristics

A hot water high temperature liquid-dominated geothermal resource (2-phase fluid), which consists mainly of liquid water underground, is collected from multiple production wells to the production well pads through transport pipelines and then separated into steam and geothermal brine by a steam separator. The steam is sent to the power plant after its pressure

Table 2 Major specifications of turbine and generator of Units 3 and 4 of Ulubelu Geothermal Power Plant

Item		Specification
Turbine	Type	Single-cylinder, double-flow, downward exhaust, reactionary condensing turbine
	Sending end output	55,000 kW
	Inlet pressure	7.6 bar (absolute pressure)
	Inlet temperature	168.0 °C
	Condenser vacuum	0.08 bar (absolute pressure)
Generator	Type	Air-cooled turbo generator
	Capacity	70,000 kVA
	Voltage, frequency	11 kV, 50 Hz
	Power factor	0.85 (lagging)

and flow are regulated, and the geothermal brine is returned to the underground through a reinjection well. The total length of these transport pipelines reaches 30 km or longer. The separated steam is controlled at a constant pressure by the vent equipment located in the power plant. After the steam scrubber of the power plant removes moisture from it, the steam is sent to the steam turbine.

The major equipment of the power plant includes reactionary condensing steam turbines with downward exhaust, totally enclosed air-cooled generators, direct contact condensers, large electric motors and turbine generator control devices. These were manufactured by Fuji Electric and the steam separators, steam scrubber, electrical equipment, FRP pipes and cables were procured in Indonesia.

The overall layout of the power plant was restricted by the site area and terrain. We made a plan to arrange Unit 3 and Unit 4 east and west and placed the cooling tower on the hill in the north, the turbine building and electrical room in the center, and the switching station in the south.

Table 2 shows the major specifications of the turbine and generator.

5. Points to Note on Implementation of Geothermal Power Generation Project

5.1 Cooperation with partners

As the consortium leader, Sumitomo Corporation assumed the role primarily in general commercial affairs, insurance service and shipping operations, conducted coordination and negotiations with PT Pertamina Geothermal Energy, and supported PT Rekayasa Industri and Fuji Electric.

PT Rekayasa Industri has been the sole operator serving the on-site portion by handling the SAGS, electrical equipment and site construction. It also took the initiative to ensure compliance with Indonesian laws and regulations and coordinate with local communities.

Sumitomo Corporation, PT Rekayasa Industri and Fuji Electric have been working together in many order negotiations and project implementations in the construction of geothermal power generation facilities in Indonesia for over 10 years and have developed an ideal partnership bringing a synergy effect.

5.2 Improvement of client satisfaction

Fuji Electric designs equipment by considering the life cycle with the emphasis on operation and maintainability. In terms of improving client satisfaction, we optimized the layout of the power plants based on maintenance and management, considered the accessibility to the equipment, and reflected the requests from the client regarding operability and other factors as much as possible in both the engineering stage and site construction stage.

5.3 Shorter project delivery

In recent years, the construction period for geothermal power plants has become shorter than that of the past cases. For Unit 5 of Lahendong Geothermal Power Plant, the client requested a work period of 22 months. This is one month shorter than the period of 23 months requested for Unit 5 of Kamojang Geothermal Power Plant, which is a power plant of the same scale also delivered by Fuji Electric and which is already in commercial operation. The contracted work period for Unit 3 of Ulubelu Geothermal Power Plant was 23 months. The client requested a 5-month reduction from the 28 months taken for constructing Unit 1 of Ulubelu Geothermal Power Plant, which is already in commercial operation in the area. Fuji Electric met these requests for work period shortening by planning the arrangement of gas extraction equipment by itself to optimize overall layout and downsize the power plant. It also designed the turbine, generator and chemical equipment as a package to reduce the amount of materials required for site construction.

In the initial stage of the project, we coordinated the construction and commissioning processes in detail with PT Rekayasa Industri. During the construction of the project, we planned the delivery of equipment and materials according to the processes agreed on with PT Rekayasa Industri to prevent any delay in the site construction. In the engineering stage, it is important to exchange engineering data smoothly. We set the deadline for this exchange with PT Rekayasa Industri in advance and followed the schedule to promptly accomplish the equipment specifications and a detailed design of civil engineering and construction. We actively had meetings with PT Pertamina Geothermal Energy in both Indonesia and Japan to determine the design principles and solve pending issues.

These activities have led to the promotion of core engineering in the initial stage of the project, making it possible to deliver equipment and carry out construction in accordance with the plan.

As a result, Unit 5 and Unit 6 of Lahendong Geothermal Power Plant and Unit 3 of Ulubelu Geothermal Power Plant started commercial operation about one month, 3 months and 3 weeks ahead of the initially planned schedules respectively. The construction work for Unit 4 of Ulubelu Geothermal Power Plant has been progressing smoothly.

6. Postscript

This paper described Units 5 and 6 of Lahendong Geothermal Power Plant and Units 3 and 4 of Ulubelu Geothermal Power Plant.

Constructing geothermal power plants in Indonesia in the future is expected to become more difficult due to geographical conditions and environmental considerations. Fuji Electric aims to contribute in both aspects of the environment and energy by making the most of its experience and achievements.

Furthermore, by utilizing our expertise based on a number of achievements, we are determined to promote further development of geothermal power generation as a renewable energy source that generates fewer CO_2 emissions, is environmentally friendly and ensures stable power supply independent of the weather conditions.

In closing, we should mention the considerable cooperation we received from our client, PT Pertamina Geothermal Energy, and Sumitomo Corporation and PT Rekayasa Industri in the construction of these geothermal power plants. We would like to express our deep appreciation for their cooperation.

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Seismic-Resistant Switchboards Conforming to New Regulatory Standards Concerning Commercial Nuclear Reactors

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ABSTRACT

Nuclear power plants and other nuclear-related facilities are required to have a certain level of seismic capacity according to the importance of their equipment. After the Great East Japan Earthquake, the nuclear regulatory standards have been revised and demand a greater seismic capacity of related equipment. To meet the demand, Fuji Electric has been developing high-rigidity seismic-resistant switchboards that conform to the new regulatory standards. We evaluated the rigidity with natural frequency analysis and verified that dynamic components can retain their functions with vibration testing. The results show that we would achieve a target natural frequency of 30 Hz or more.

1. Introduction

Switchboards play a major role in ensuring safety in nuclear power plants and other nuclear-related facilities. They are required to prevent the main body from breakage and the internal electrical components from malfunction by ground acceleration during an earthquake. In general, the higher the natural frequency of a switchboard, the more the acceleration caused in the switchboard, and its internal electrical components during an earthquake (response acceleration) can be reduced. Since switchboards are equipment important to safety, they are designed to ensure seismic capacity by having a highly rigid structure with substantially higher natural frequencies than those of the buildings in which they are installed.

After the Great East Japan Earthquake in 2011, switchboards used in commercial nuclear power plants have been required to have higher seismic capacity, and the demand for seismic-resistant switchboards has been escalating. Fuji Electric has a track record of delivering seismic-resistant switchboards for laboratories mainly for the Japan Atomic Energy Agency. We have also been working on the development of seismic-resistant switchboards that can be used in commercial nuclear power plants. The challenges were as follows: For use in laboratories, it was only necessary to design a rigid structure with a natural frequency of 20 Hz or higher. Commercial nuclear power plants, however, may require natural frequencies of 30 Hz or higher and so the structure should be designed to satisfy this.

In the "New Regulatory Requirements for Commercial Nuclear Power Reactors" revised in July 2013 (new regulatory standards), the scale of the earthquake that needs to be assumed at the time of design was reconsidered to require the facilities to have a structure that can endure a stronger seismic force (acceleration applied to the switchboard) than before.

This paper describes the seismic-resistant switchboards that we have developed to conform to the new regulatory standards.

2. Seismic Design

In conventional seismic design, the reference values of the earthquake resistance for seismic-resistant switchboards were specified as a horizontal acceleration of 1 G and vertical acceleration of 0.5 G, which are sufficiently higher than the design seismic force. After the Great East Japan Earthquake, the reference ground motion used for seismic design was changed, and switchboards have been required to have a higher seismic capacity. The maximum values of the design seismic force, which are varies depending on the region because the ground condition of the installation site should be considered, were changed to a horizontal acceleration of 3 G and vertical acceleration of 2 G.

It has been said that 20 Hz or higher is sufficient for the natural frequency of the seismic-resistant switchboard. We, however, set the development target at 30 Hz or higher because this value may be required in some regions.

The seismic design conditions are as follows:

(a) Natural frequency: 30 Hz or higher
(b) Anti-acceleration: 3 G or higher in horizontal direction, 2 G or higher in vertical direction

Figure 1 shows the development process of the seismic-resistant switchboard. The switchboard development process is divided into 3 phases: Rigid structure design, verification of dynamic component ability to re-

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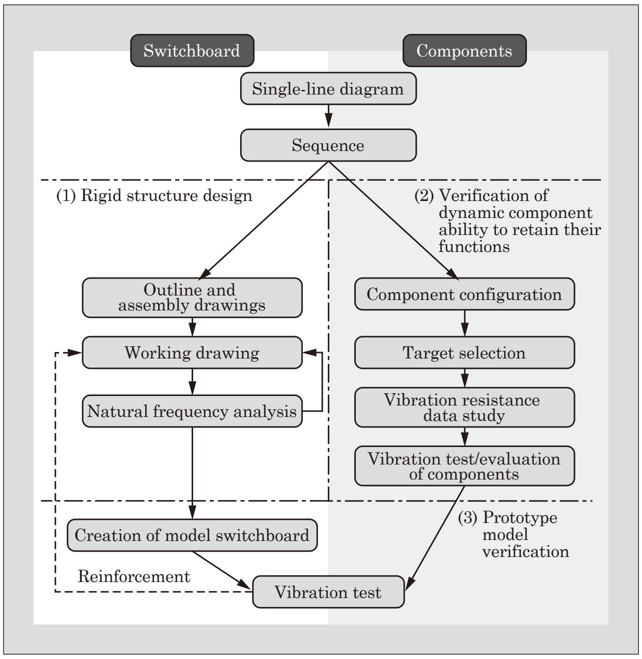


Fig.1 Development process of seismic-resistant switchboards

tain their functions, and prototype model verification.

(1) Rigid structure design

This phase analyzes the natural frequency of the switchboard based on the working drawing. To meet the target of the natural frequency of the panel, the structure design is changed by adding beams, changing the wall thickness, and doing other corrections.

(2) Verification of dynamic component ability to retain their functions

Among the internal components of the switchboard, dynamic components with moving parts (such as circuit breakers, protective relays, auxiliary relays and timers) must retain their functions even in the event of an earthquake. Such ability, however, cannot be verified from structure analysis. Consequently, this phase actually shakes each component separately for evaluation and determines the acceleration up to which the component can retain its functions. As for draw-out type components that are not completely secured, a vibration test is performed under the condition simulating the actual securing method to determine the acceleration up to which the component can retain its functions.

(3) Prototype model verification

To verify the result of structure design obtained in (1), this phase creates an actual-size model of a high-voltage switchboard for seismic resistance verification and performs a vibration test to verify its natural frequency. Then, the internal components evaluated in (2) are mounted in the switchboard, and their health is checked by verifying their functions under vibration.

3. Improving Seismic Capacity of High-Voltage Switchboard

3.1 Design of seismic-resistant switchboards

A high-voltage switchboard is equipment for distributing supplied power according to the specifications of load equipment. It consists of circuit breakers, protective relays, auxiliary relays, transformers, current transformers, and other devices.

The high-voltage switchboard used for the prototype has 2 vacuum circuit breakers (VCBs) stacked vertically and is designed to provide a commonly used rated current of 1,200 A or 2,000 A and breaking capacity of 40 kA. It employs the "F-MPC60B" digital multifunction relay, which is a commonly used protective relay for power applications. Table 1 shows the major specifications.

This high-voltage switchboard is equipped with shutters for the main circuit disconnection sections of draw-out type circuit breakers or other components.

Table 1 Major specifications of high-voltage switchboard

Item		Specification
High-voltage switchboard	Model	JEM-1425 MWG
	Rated voltage, number of phases	7.2 kV, 3-phase 3-wire
	Rated frequency	50/60 Hz
	Rated bus current	3,000 A
	Rated short-time withstand current	40 kA, 2 s
	Rated insulation voltage	Power frequency withstand voltage: 22 kV, 1 minute Lightning impulse withstand voltage: 60 kV
	Dimensions	W1,000 × D2,600 × H2,300 (mm)
Vacuum circuit breaker (VCB)	Rated operating voltage	100/200 V AC, 100/125 V DC
	Rated breaking capacity	40 kA
	Rated current	1,200 A, 2,000 A
	Closing system	Motor-spring stored energy

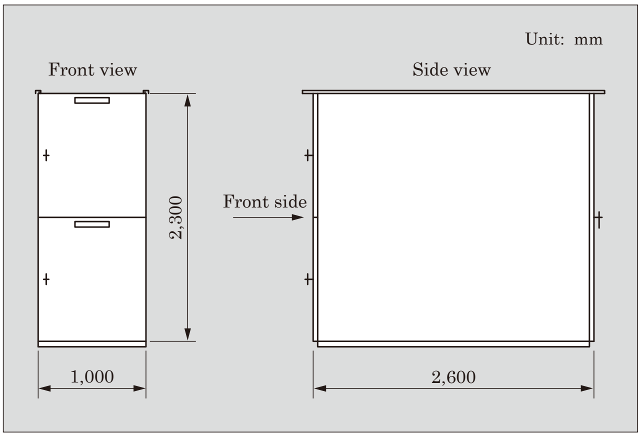


Fig.2 Outline drawing of high-voltage switchboard for seismic resistance verification

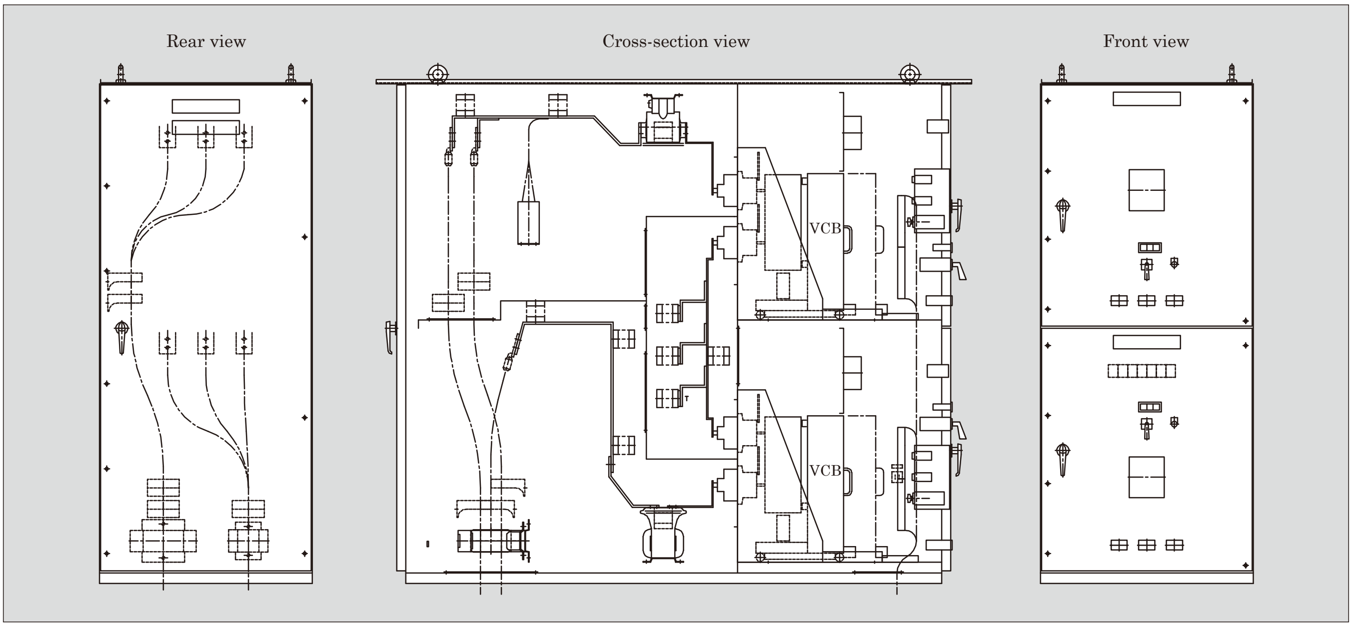


Fig.3 Assembly drawing of high-voltage switchboard for seismic resistance verification

After the circuit is disconnected and the circuit breaker is drawn out to the test position, the shutter closes automatically and covers the main circuit live section to improve safety during inspection. Auxiliary components for the main circuit (voltage transformers, grounded type voltage transformers, arresters) are mounted on transfer wagons, enabling for easy replacement and mounting space saving. On the other hand, some structural measures are needed to ensure that such a structure designed for maintainability to allow easy replacement of a vacuum circuit breaker and other components will not lead to a weakness in terms of seismic capacity. To meet the requirement, the switchboard frames and components are designed to make surface contact so as to suppress the vibration of the components and ensure seismic capacity. A clamp mechanism is adopted to enable easy securing and drawing in/out operation. The vacuum circuit breakers provide sufficient seismic capacity in both the operating position and test position. Figure 2 and Figure 3 respectively show the outline drawing and assembly drawing of the high-voltage switchboard for seismic resistance verification.

3.2 Natural frequency analysis

Based on the design drawing of the seismic design switchboard, the natural frequency was analyzed with NX NASTRAN structure analysis software. Figure 4 shows the analysis results. The result indicated that the entire housing starts shaking at 36.7 Hz, which proves that its natural frequency satisfies the seismic design requirements.

3.3 Producing high-voltage switchboard for seismic resistance verification

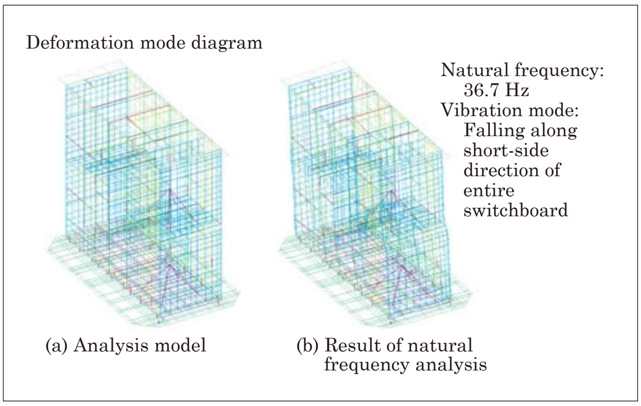


Fig.4 Result of natural frequency analysis

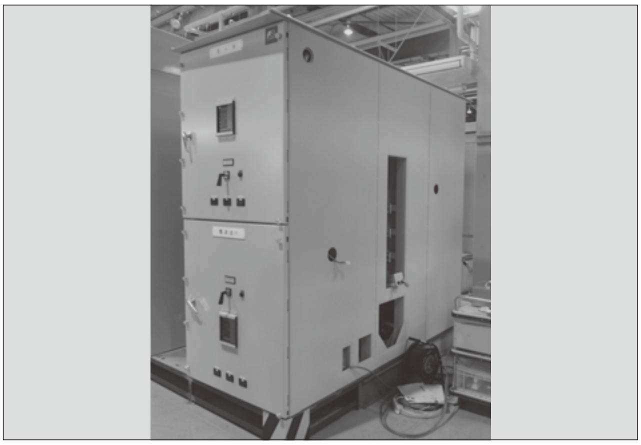


Fig.5 High-voltage switchboard for seismic resistance verification

Figure 5 shows the external appearance of the high-voltage switchboard for seismic resistance verification. In order to improve seismic capacity, the framework was built with square pipes (vertical posts and ceiling, total of 8 frames) that were joined to the side panels to increase rigidity. Moreover, in order to ensure a natural frequency of 30 Hz or higher, the connection between the base frame and switchboard was reinforced.

3.4 Vibration test

We conducted a vibration test for the purpose of verifying the seismic capacity of the high-voltage switchboard. Figure 6 shows the states of the switchboard secured on a shaker table and of the components mounted inside the switchboard.

We attached accelerometers to the switchboard housing and major internal components and measure response acceleration during vibration to determine its natural frequencies and anti-acceleration. At an input acceleration of 100 Gal*[1] (sine wave), the range between 5 and 50 Hz was swept at a rate of 0.1 Hz/s and the natural frequency was measured in 3 directions of horizontal and vertical. Figure 7 shows the magnification factor of an accelerometer that was mounted on the switchboard frame plotted against the frequency in the horizontal (depth) direction. They were evaluated using the measured value of the accelerometer mounted on the shaker table as a reference. The frequency at which the magnification factor is highest is the natural frequency. The measured natural frequency of this switchboard housing was approximately 37 Hz, which shows good agreement with the value obtained through analysis.

Furthermore, the natural frequencies were estimated to exceed 30 Hz in all directions.


(a) Switchboard secured on shaker table


(b) Components mounted inside switchboard

Fig.6 States of vibration testing

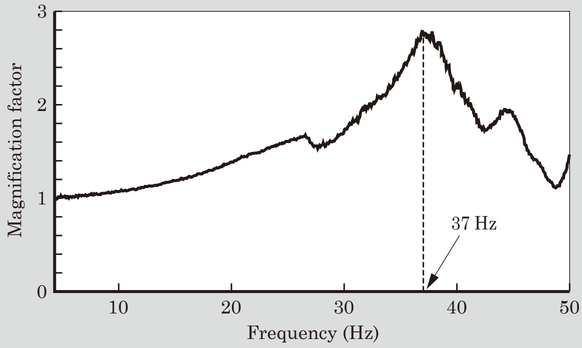
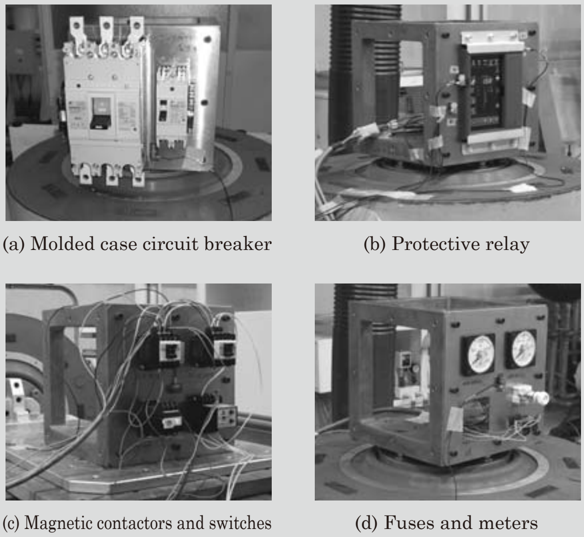


Fig.7 Result of vibration testing

4. Improving Seismic Capacity of Low-Voltage Switchboard and Its Components

The development of low-voltage switchboards, such as power centers and control centers, have also been promoted based on the same design conditions and steps as the high-voltage switchboards to ensure seismic capacity.

In addition, we have determined the acceleration rate up to which each component can retain its functions by conducting vibration tests for each component individually, as well as for components being mounted in a switchboard. Figure 8 shows the states of vibration testing of individual components.


(a) Molded case circuit breaker (b) Protective relay

(c) Magnetic contactors and switches (d) Fuses and meters

Fig.8 States of vibration testing of individual components

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*1: Gal: Unit of acceleration. 1 Gal = 0.01 m/s²

For some components such as molded case circuit breakers (MCCBs), protective relays and auxiliary relays, the same models are used in both high-voltage and low-voltage switchboards. We designated representative types for such components and evaluated them separately to confirm their seismic capacity.

5. Postscript

This paper described seismic-resistant switchboards conforming to the new regulatory standards concerning commercial nuclear reactors. We started the development of seismic-resistant switchboards conforming to the new regulatory standards with studies concerning high-voltage switchboards, such as internal component evaluation, seismic analysis and stress analysis. This was followed by studies concerning low-voltage switchboards, such as seismic analysis, verification using a model switchboard, and checking the critical acceleration of the components.

We created a prototype high-voltage switchboard in actual size and conducted vibration testing. The result showed there was a prospect of achieving the target natural frequency of 30 Hz. This completed the development of the series of switchboards from high voltage to low voltage that offer the seismic capacity required in the new regulatory standards or other criteria.

Fuji Electric is committed to improving safety in nuclear power plants and other nuclear-related facilities by supplying these seismic-resistant switchboards both now and in the future.

Kamikita Rokkasho Photovoltaic Power Plant with Capacity of 71 MW DC / 51 MW AC

SHIRINASHIHAMA, Ritsuho* HONDA, Daisuke* KUBOZONO, Takaharu*

ABSTRACT

Fuji Electric has developed high-efficiency power conditioning sub-systems (PCSs) and has a number of track records in delivering them to photovoltaic power plants. We won an engineering, procurement and construction (EPC) contract for Kamikita Rokkasho Photovoltaic Power Plant with a capacity of 71 MW DC / 51 MW AC and completed the delivery in January 2017. The output is converted to 51 MW AC with fifty-one 1,000-kW PCSs, boosted to 154 kV with an electric substation facility, and then transmitted to the power grid of Tohoku Electric Power Co., Inc. We conducted a general function test in November 2016 and verified that the plant has the specified functionality and performance required of a power plant. In February 2017, the plant started operations to sell electric power to Tohoku Electric Power Co., Inc. for 20 years.

1. Introduction

The Kamikita Rokkasho Photovoltaic Power Plant operated by Mirai Power (Kamikita Rokkasho) Corporation (a special-purpose company) owned by Sojitz Corporation commenced operations in February 2017. This is a large-scale photovoltaic power plant with an overall capacity of 51 MW AC. It uses 263,172 photovoltaic modules (PV Modules) with a generation capacity of 71 MW DC that are arranged on the approximately 150-hectare land owned by Shin Mutsu Ogawara Inc. in Rokkasho Village, Kamikita District, Aomori Prefecture. Fuji Electric won the engineering, procurement and construction (EPC) contract for the power plant. The construction was completely smoothly and accident-free over a period ranging from November 2013 to January 2017. In February 2017, the power plant started operations to sell electric power to Tohoku Electric Power Co., Inc. At the start of operations, the power plant was Japan's 4th largest photovoltaic power plant with respect to capacity*[1].

In this paper, we will describe the power plant construction and equipment installation of the Kamikita Rokkasho Photovoltaic Power Plant.

2. Overview of Kamikita Rokkasho Photovoltaic Power Plant

Fig.1 Panoramic view of Kamikita Rokkasho Photovoltaic Power Plant (Photo courtesy of Shin Mutsu Ogawara Inc.)

In the Kamikita Rokkasho Photovoltaic Power Plant, a village road traverses in the east-west direction through the central part of the power plant site (see Fig. 1). On the northern side of the village road, 19 power conditioning sub-systems (PCSs) are installed on approximately 50 hectares of land, and the southern side, 32 PCS units are installed on approximately 100 hectares of land. The output of the 71-MW DC photovoltaic cells is converted to an output of 51 MW AC by fifty-one 1,000-kW PCSs made by Fuji Electric, boosted to 154 kV by substation equipment made by Fuji Electric, and then transmitted to the transmission lines of Tohoku Electric Power Co., Inc. Figure 2 shows the configuration of the overall system.

The power plant is expected to sell 65,930 MWh of power per year. This is equivalent to the yearly energy consumption of 18,400 standard households. It also corresponds to a yearly CO_2 reduction of 35,200 t-CO_2.

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*1: Japan's 4th largest photovoltaic power plant: Investigated by Fuji Electric (As of February 2017)

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* Power & Social Infrastructure Business Group, Fuji Electric Co., Ltd.

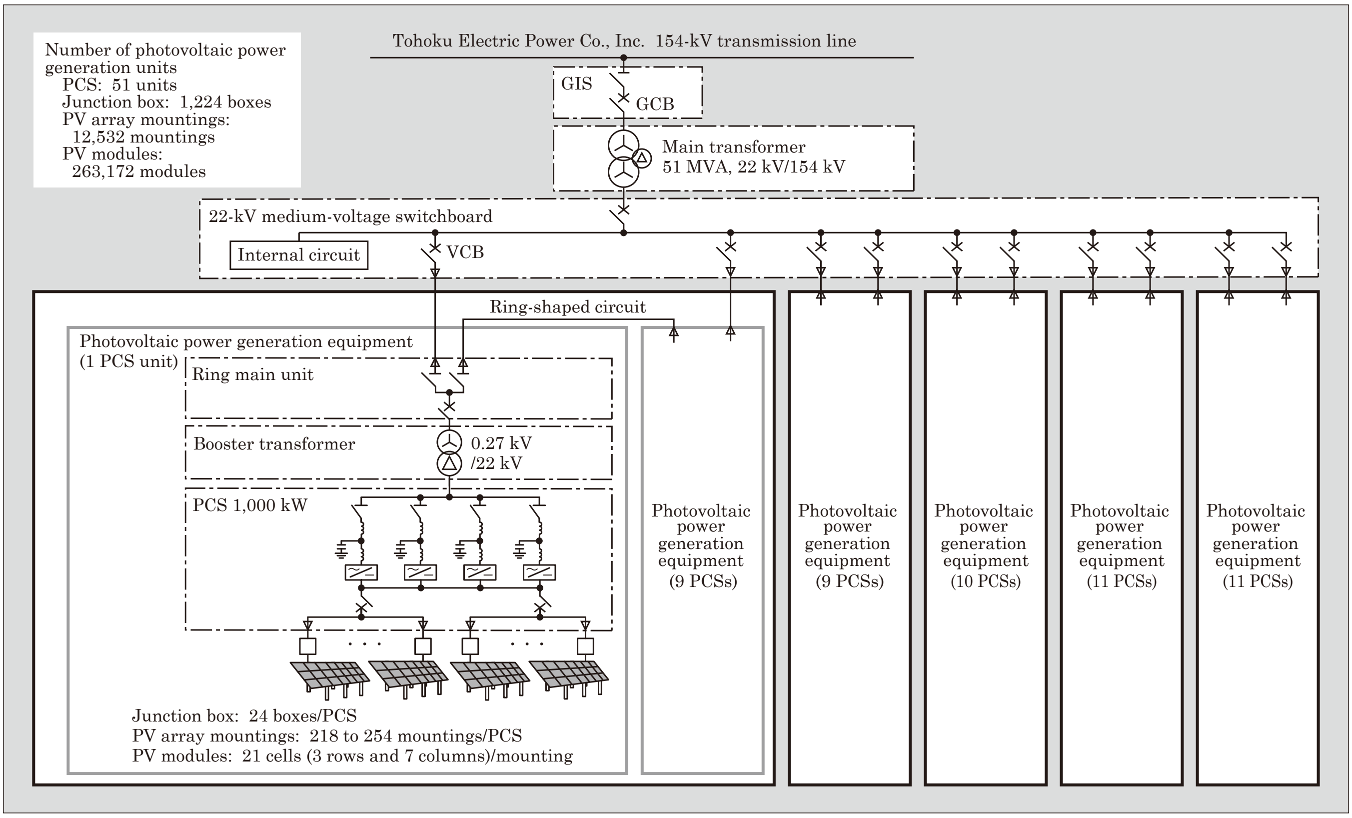

Fig.2 Overall system configuration diagram

Table 1 Main stages of construction of Kamikita Rokkasho Photovoltaic Power Plant

No.	Year / month Type of work	2013			2014												2015												2016												2017		
		10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3
I	Civil engineering work		▼ Start of construction			Winter work stoppage												Winter work stoppage												Winter work stoppage							★ Power receiving		★ Power system interconnection (All PCSs)			▼ Start of operation	
(1)	Tree felling, uprooting, and land preparation work		■	■				■	■	■	■	■	■																														
(2)	PV array foundation construction										■	■	■	■	■	■				■	■	■																					
(3)	PV array and module assembly work											■	■	■	■	■				■	■	■	■	■	■	■	■	■															
(4)	On-site road and fence construction											■	■	■	■	■																											
(5)	Equipment foundation construction													■	■	■				■	■	■																					
II	Electrical work																																										
(1)	PV array periphery construction													■	■	■				■	■	■	■	■	■	■	■	■				■	■	■									
(2)	PV site equipment installation work																						■	■	■	■	■	■															
(3)	High-voltage trunk construction																					■	■	■	■	■	■	■															
(4)	Interconnection substation equipment construction																						■	■	■	■	■																
III	154-kV conduction path construction																			■	■	■	■	■	■	■	■	■															
IV	On-site test adjustment																															■	■	■	■	■	■	■	■				
V	General test adjustment																																							■	■		

3. Construction of Power Plant

Table 1 shows the main stages of the construction of the power plant. The construction of the Kamikita Rokkasho Photovoltaic Power Plant spanned 3 years and 3 months, starting in November 2013 and completing the commissioning tests at the end of January 2017. It should also be noted that actual construction only took 2 years and 6 months because snowfall prohibited construction work for a total of 9 months during winter seasons.

The construction of the power plant started with tree felling and uprooting, and prepared roadways and land for the construction work. After this, we constructed the mountings for the PV modules and performed the foundation construction, wiring work, and commissioning tests of the equipment such as the PCSs to complete the delivery.

3.1 Installation work of PV array mountings and PCSs

We used a pile foundation for the mountings for the PV array and laid 6 H-section steel in approximately 4.1 m with the ground form of the land being remained. The installation state of the PV array mounts is shown in Fig. 3. The PV array mounts [W 11,540 × D2,616 × H2,710 (mm)] are able to mount a total of 21 PV modules in the form of a matrix with 3 rows and 7 columns. Furthermore, a total of 12,532 PV array mounts were installed on the work site. The PV array mounts were installed in consideration of winter snowfall. As a result, the PV modules were installed at a mounting angle of 30° with a minimum ground clearance of 1.2 m. The intervals between the PV array mounts in the north-south direction are 5.0 m on level ground, in consideration of the low altitude of the sun in the winter. Since the arrangement makes use of the topography, the intervals have been arranged narrowly on the southern slope, but widely on the northern slope.

The PCSs and their accompanying booster transformers and peripheral devices (ring main units) have been installed at 51 locations on the site. Their foundation structures have a height of 1.0 m or more above the ground in consideration of snowfall. Figure 4 shows the installation state of the PCS, booster transformer and ring main unit.

3.2 Electrical work

Nine to eleven PCSs are connected in a ring shape with 22 kV cables of a total of 5 circuits, which are laid using underground piping. The total length of the underground piping spans approximately 20 km, and it took 12 months to lay the cable. Between the northern and southern land, we installed the underground piping and laid the cable by excavating under the village road using a jacking method.


(a) Front


(b) Back

Fig.3 Installation state of PV array mounts

Fig.4 Installation state of PCS, booster transformer and ring main unit

3.3 154-kV transmission line construction and substation construction

Embedded cables instead of transmission towers are used for 154-kV transmission lines in consideration of the impact on the wind turbines installed in the vicinity of the power plant. Electricity is fed from a 154-kV transmission tower of Tohoku Electric Power Co., Inc. to the nearby gate-type steel structure via overhead lines and then to the substation equipment of the power plant through the underground piping. We reclaimed and dug the adjacent slope for a distance of approximately 500 m and installed the underground piping to lay the cables.

The main equipment of the 154-kV substation consists of a gas-insulated switchgear (GIS), main transformer and 22-kV medium-voltage switchgear, which had a total weight of about 140 t. Foundation work was implemented and each piece of equipment installed after the quality of the ground was improved to ensure withstand of this load.

4. Photovoltaic Power Generation Equipment

The photovoltaic power generation equipment consists of PV modules, junction boxes, PCSs, booster transformers and ring main units. This equipment uses the PV modules to feed DC power into the PCSs, and then transmits the power after converting it to an AC output.

4.1 PV modules and junction boxes

Table 2 shows the main specifications of the PV module and junction box. The power plant uses mono-

Table 2 Main specifications of PV module and junction box

(a) PV module

Item		Specifications and characteristics
Basic specs	Cell type	Monocrystalline silicon
	Cell usage amount	60
	Module dimensions	Long-side 1,640 × short-side 1,000 × thickness 35 (mm)
	Maximum load capacity	5,400 Pa (positive load)*1, 2,400 Pa (negative load) *2
	Weight	16.8 kg
	Front cover material	Strengthened glass
	Back cover material	Backsheet
	Frame material	Anodized aluminum alloy
	Frame color	Aluminum alloy base color
	Module delivery quantity	263,172
	Manufacturer	LG Electronics (Korea)
Electrical characteristics	Maximum power ($P_{\max}$)	270 W
	Module efficiency	16.50%
	Maximum power voltage (V_{pm})	31.50 V
	Maximum power current (I_{pm})	8.58 A
	Open-circuit voltage (V_{oc})	38.50 V
	Short-circuit current (I_{sc})	9.17 A
	$P_{\max}$ temperature coefficient	−0.430%/°C
	V_{oc} temperature coefficient	−0.310%/°C
	I_{sc} temperature coefficient	0.040%/°C
	System max. voltage	1,000 V
	Test conditions (STC)	Cell temperature 25 °C, AM 1.5 *3, irradiation amount 1,000 W/m^2

*1: Positive load refers to the load received from the front of the module.
*2: Negative load refers to the load received from the back of the module.
*3: AM (Air Mass) 1.5 means the average solar spectrum on the earth at the latitude in the vicinity of Japan, and refers to a distance that has traveled through the atmosphere at 1.5 times perpendicular incidence.

(b) Junction box

Item		Specifications/characteristics
Basic specs	Installation location	Outdoor
	Ambient temperature	−25 °C to +40 °C
	Dimensions	W800 × D300 × H900 (mm)
	Outer cover protective structure	IP44
	Main circuit conductor	1,500-V cable WL2
	External connection	Terminal block system
	Number of deliveries	1,224
Electrical specs	Rated operational voltage	1,000 V DC
	Rated insulation voltage	1,200 V DC
	Input string circuit	11 circuits
	Rated bus current	110 A
	String circuit protection	Fuse protection (15 A)
	Main switch	MCCB
	Surge protection	SPD

Table 3 Main specifications of PCS

Item		Specifications
Series name		PVI1000-3/1000
Rated output		1,000 kW
Insulation method		Transformerless method
Electrical specs (DC input)	DC input voltage range	0 to 1,000 V
	Operating voltage range	450 to 950 V
	MPPT Range	460 to 850 V
	DC input branches *1	24
Electrical specs (AC output)	Rated output capacity	1,000 kW
	Rated output voltage	270 V −10% to +12%
	Rated frequency	50/60 Hz ±5%
	Number of output phases	$3\phi 3$ W non-grounded compatibility
	Rated output current	2,138 A
	Output power factor *2	>0.99 (At rated output)
	Output current distortion rate (general) *3	<5% (At rated output)
	Output current distortion rate (each order)	<3% (At rated output)
	Equipment max. efficiency	98.5%
	Equipment efficiency (EURO efficiency)	98.2%
	Overload capacity	100% continuously
	Noise	70 dB or less
Grid connection	Grid protection	OV, UV, OF, UF
	Single operation detection system (passive) *4	Voltage phase jump detection
	Single operation detection system (active) *4	Reactive power fluctuation system
	Voltage boost and suppression function	Reactive current compensation and active current output suppression
	FRT	JEAC 9701 compliant
Cubicle structure	Installation method *5	Outdoor self-standing type
	Compatibility IP *6	IP54
	System method	Substation system
	Cable pulling	Bottom
	Cooling system	Forced air cooling
Dimensions	PCS unit	W3,500 × D2,300 × H2,800 (mm)
	Substation	W6,050 × D2,400 × H2,800 (mm)
Weight	PCS unit	7,000 kg
	Substation	12,500 kg
Environment conditions	Storage temperature	−20 °C to +50 °C
	Operation temperature *7	−20 °C to +40 °C
	Relative humidity *8	15% to 95%
	Altitude	2,000 m or less
Standard compliance		IEC 62109-1, JIS, JEM, JEC
Communication method		RS-485, MODBUS *9, TCP

*1: Option *2: Excluding single operation Q output *3: At output 1/8 to rated *4: Not used *5: Salt resistant specs *6: Powder-snow countermeasure specs *7: Cold region specs *8: No condensation *9: Trademark or registered trademark of Schneider Automation, Inc.

crystalline silicon PV modules with a maximum output of 270 W per module. Twenty-one PV modules arranged in 3 rows and 7 columns make up an array, which are mounted on each mounting, and output 5.67 kW DC according to the PCS having an input of 1,000 V. A junction box aggregates the power of 8 to 11 arrays and produces outputs of 45.4 to 62.4 kW. The DC outputs of 24 junction boxes are aggregated and input to a PCS. The number of inputs for arrays of a PCS can be less than that of the conventional PCS with a low-voltage input of 750 V by at least 30%, and this contributes to decreasing construction costs.

4.2 PCS, booster transformer and ring main unit

The PCS converts the 1,000 V DC input from the 24 junction boxes into 270 V AC, thus providing a maximum power output of 1,000 kW AC. The PCS is a 3-level inverter system consisting of Japan's largest single unit capacity of 1,000 kW and also achieves the industry's highest conversion efficiency of 98.5% (EURO 98.2%). In addition, adopting an outdoor air cooling system eliminates the need for an air conditioner of a container storage PCS, thus enabling us to reduce auxiliary power loss during operation(1).

The DC input of the PCS utilizes a 24-branch type, and it is no longer necessary to use collection boxes that were traditionally mounted to a 4-branch type. Furthermore, mounting a current detector (DCCT) to each 24-branch DC input allows the users to measure and monitor DC input current.

The use of a multiplex transmission system (RS-485, optical communication) has also made it possible to monitor the operation data of the PCSs via a host monitoring system installed in the vicinity of the substation. In addition, the PCSs can be remotely started and stopped from the monitoring system.

After the outputs of PCS are boosted to 22 kV by the booster transformer (capacity of 1,000 kVA), they are aggregated to the 22-kV medium-voltage switchgear of the substation via the ring main unit. The main specifications of the PCS are shown in Table 3.

5. High-Voltage Substation and Grid Connection Equipment

The external appearance of 154-kV gate-type steel structure and substation is shown in Fig. 5. The power outputs from the PCSs are aggregated to the 22-kV medium-voltage switchgear, boosted by the main transformer from the 22 kV to a transmission line voltage of 154 kV, and then interconnected to the transmission lines of Tohoku Electric Power Co., Inc. via the GIS.

The 22-kV medium-voltage switchgears are composed of 10 vacuum circuit breakers (VCBs) according to the circuit of the ring main unit. They also come equipped with a function for cutting off the relevant circuit when a failure of transmission lines occur in the premises.

The main transformer utilizes an oil-immersed self-cooling transformer, the capacity of which is equal to a total of 100% output of 51 PCSs.

The power plant uses a 154-kV gas circuit breaker (GCB) for the interconnection with the power system. The GCB cuts off the power plant from the power system when a failure occurs in the high-voltage substation or transmission lines. The breaking capacity of the GCB is 25 kA, 5 cycles. The responsibility demarcation point with Tohoku Electric Power Co., Inc. is the jumper line connecting part of the interconnecting transmission tower.

(a) 154-kV gate-type steel structure

(b) Substation equipment (GIS, main transformer)

Fig.5 154-kV gate-type steel structure and substation

6. Protective Equipment, Monitoring and Control Equipment, and Auxiliary Equipment

The high-voltage substation, power plant monitoring equipment and protective equipment for the 154-kV interconnection lines are installed inside a container package in the vicinity of the substation.

Since the transmission lines of Tohoku Electric Power Co., Inc., which interconnect the Kamikita Rokkasho Photovoltaic Power Plant, also interconnect the wind power plants of other business operators, PCM protective equipment has been installed as protective equipment for the power grid as specified by Tohoku Electric Power Co., Inc. The power plant detects failures in the transmission lines between substations and wind power plants and performs parallel off*2.

The monitoring equipment of the power plant collects the main data of the PCSs and has functionality for displaying power system states, measurement values, trends and daily and monthly reports. It uses a system capable of measuring the current of the

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*2: Parallel off: Disconnection of power generation equipment from the grid

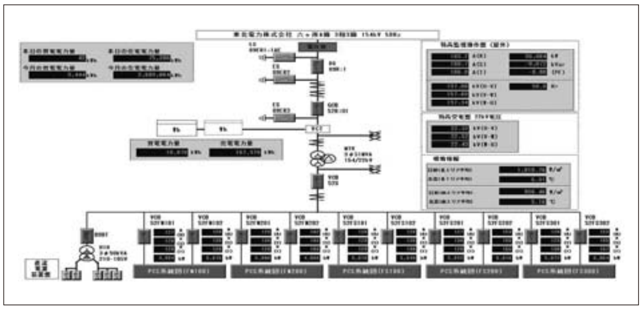

Fig.6 Power system diagram monitoring screen of monitoring equipment

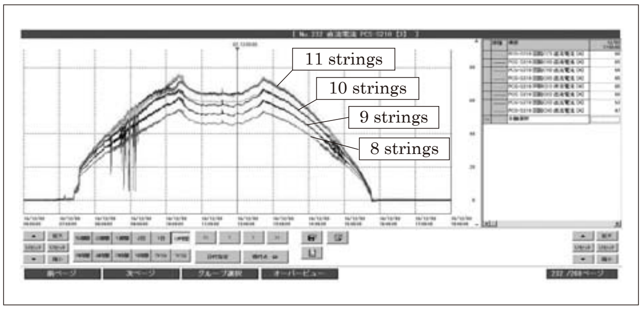

Fig.7 Current value trend screen for 24-branch circuits of PCS

24-branch circuit on the DC side of a PCS, and it can automatically determine differences in current for each branch from the trend data of the current values to display deviations. A single circuit of the 24-branch circuit corresponds to a single connection on the junction box, and this functionality enables the early detection of string fuse blow-out points inside the junction box.

Figure 6 shows the power system diagram monitoring screen for the monitoring equipment and Fig. 7 shows the current value trend screen for the 24-branch circuit of the PCS.

In order to protect against theft of the PV modules and cable, the power plant utilizes the special equipment of a security company to perform 24-hour security monitoring of the surrounding fence and gates of the power plant.

7. General Functionality Test and Performance Approval Test

In November 2016, we performed a general functionality test that included a general interlock test, control power loss test, load cut-off test and load test. We were able to confirm that the power plant possessed the required functionality and performance. We confirmed that the PCSs output a maximum power of 51 MW, and are capable of transmitting the power to the 154-kV grid.

We implemented an evaluation for power generation performance by comparing the estimated amount of electric power with the actual output. The estimated amount of electric power was calculated from the solar radiation and temperature data obtained from the 10 pyranometers and 10 thermometers installed in the power plant based on the method for estimating generated electric power stipulated by JIS C 8907. The actual output used the output values of the electric power meters for sale. The performance approval test was performed in an environment that solar radiation is 300 W/m^2 or more per hour consistently, temperature is 30 °C or less, and the surface of the modules has no adhered snow or dirt. The results of the test confirmed that the power amount for sale was between 101.6% and 113.2% of the estimated amount of electric power, while also satisfying the prescribed power generation performance. Figure 8 shows the results of the performance approval test.

Fuji Electric has completed the delivery of the power plant by the end of January 2017 after passing the pre-use self-inspection and safety management inspection.

Approval test data

12/3	Entire power plant				
Time	Solar radiation (Wh/m^2)	Temperature (°C)	Sales amount of electric power (MWh)	Estimated amount of electric power (MWh)	Ratio (Sale/Estimated)
0:00	0.0	5.3	0.0	0.0	0.0%
1:00	0.0	5.3	0.0	0.0	0.0%
2:00	0.0	5.3	0.0	0.0	0.0%
3:00	0.0	5.3	0.0	0.0	0.0%
4:00	0.0	5.3	0.0	0.0	0.0%
5:00	0.0	5.3	0.0	0.0	0.0%
6:00	4.8	5.2	0.0	0.3	0.0%
7:00	203.7	5.5	7.8	12.0	65.1%
8:00	457.5	6.3	28.3	26.5	106.8%
9:00	661.0	7.2	42.0	37.2	113.2%
10:00	782.1	8.1	49.2	43.5	113.1%
11:00	820.3	8.7	50.0	45.2	110.6%
12:00	776.3	9.0	48.0	42.8	112.1%
13:00	643.0	8.8	39.6	36.1	109.5%
14:00	440.9	8.1	25.7	25.3	101.6%
15:00	146.3	7.2	4.5	8.7	51.7%
16:00	0.2	5.9	0.0	0.0	0.0%
17:00	0.0	5.3	0.0	0.0	0.0%
18:00	0.0	3.9	0.0	0.0	0.0%
19:00	0.0	1.4	0.0	0.0	0.0%
20:00	0.0	−0.1	0.0	0.0	0.0%
21:00	0.0	−2.3	0.0	0.0	0.0%
22:00	0.0	−2.7	0.0	0.0	0.0%
23:00	0.0	−1.7	0.0	0.0	0.0%
Total generated power per day (MWh)			295.1	277.6	106.3%

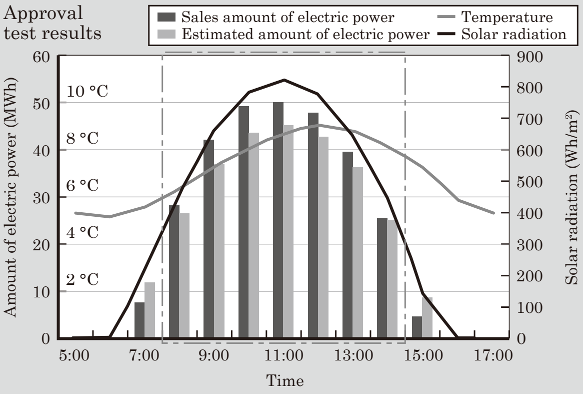

Fig.8 Performance approval test results

8. Postscript

We described the power plant and equipment construction of the Kamikita Rokkasho Photovoltaic Power Plant, which has a capacity of 71 MW DC/51 MW AC.

Recently the construction of photovoltaic power plants has been sluggish due to the review of the "Feed-in Tariff (FIT) Scheme for renewable energy," but in the future, it is expected that there will be a growth in large-scale photovoltaic power plants in order to meet the needs of output fluctuation relaxation measures and grid voltage fluctuation measures. Storage battery equipped PCS and power system fluctuation suppression type PCS are greatly contributing to the expansion of renewable energies, while taking full advantage of Fuji Electric's PCS technology.

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Status of Development and Sales Strategy of Fuel Cell Systems

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ABSTRACT

Fuji Electric has been working to improve the functions of phosphoric acid fuel cells (PAFCs) and expand their applications. For the Japanese market, we are mainly offering models that have grid independent power supply mode for emergency and models that generate electricity from biogas. For the market outside Japan, we are providing the PAFCs for fire-prevention equipment that utilizes low oxygen concentration exhaust emitted from a fuel cell system. We have also been developing solid oxide fuel cells (SOFCs) for next-generation, high-efficiency cogeneration systems. We are designing, manufacturing and evaluating the performance of them to aim for a electric power generation efficiency exceeding 50%.

1. Introduction

In July 2015, the Agency for Natural Resources and Energy announced in its "Long-term Energy Supply and Demand Outlook" that it expects there to be an increase in the adoption of cogeneration systems that include fuel cells. This expectation was caused by a result of the need for comprehensive energy savings from the viewpoint of achieving a safe, stable, economically efficient, and environmentally compatible energy supply. Compared to other cogeneration systems, fuel cells have a number of advantages such as making it possible to use a variety of fuels, providing high power generating efficiency even at small capacities, contributing to reduced running costs and CO_2 emissions, and excelling in environmental friendliness. Among the different kinds of fuel cells, phosphoric acid fuel cells (PAFCs) have a proven track record of long-term commercial usage with a lifetime of 124,000 hours (about 15 years) or longer, making them a practical choice as a small- and medium-scale cogeneration system. In addition, solid oxide fuel cells (SOFCs) provide even greater power generating efficiency than PAFCs, and for this reason, they are expected to become a practical choice for business applications in the near future.

Fuji Electric started selling its 100-kW PAFCs in 1998. We have streamlined the procurement, manufacturing and engineering processes for PAFCs so that they are used especially for the cogeneration system with a power generating capacity of 100 kW of small- and medium-scale facilities bearing high energy costs. From 2010, our endeavors to improve the life expectancy and installability of fuel cell units facilitated the development and sales launch of our cold-climate compatible "FP-100i" PAFC as an all-in-one package that integrates peripheral equipment (see Fig. 1).

Fig.1 Phosphoric acid fuel cell "FP-100i"

In this paper, we will focus on the specifications and application development of the FP-100i, while also describing our SOFC, which is currently under development as a highly-efficient next-generation cogeneration system(1).

2. "FP-100i" Specifications and Optional Functionality

Table 1 shows the main specifications of the FP-100i. Taking advantage of our strength for developing reforming systems, we have developed new models that use such fuels as city gas, for which supply infrastructure has already been built, and biogas (digestion gas), which is regarded as an up-and-coming renewable energy. Furthermore, we have also added a model to our line-up that is capable of generating power with hydrogen as a highly expectant contributor to next-generation infrastructure. The model has achieved a

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* Power & Social Infrastructure Business Group, Fuji Electric Co., Ltd.

Table 1 Main specifications of “FP-100i”

Item	Specifications		
Fuel	City gas	Biogas	Pure hydrogen
Output	105 kW (Power generation end)		
Output voltage/ frequency	210 V/50 Hz or 60 Hz		
Power generation efficiency (LHV)*	42%	40%	48%
Heat output	123 kW	116 kW	99 kW
Total efficiency (LHV)	91%	84%	93%
Exhaust gas	NOx: less than 5 ppm SOx, dust: less than detection limit		NOx, SOx, dust: None
Dimensions	W2.2 × D5.5 × H3.4 (m)		
Weight	14 t		13.5 t

*LHV: When a unit amount of fuel adiabatically and completely combusted under a specific state, and the combusted gas is cooled until it reaches its original temperature, the dissipated heat is called "Heating value." Heating values are classified as either higher heating value (HHV), which contains the latent heat of water vapor, and lower heating value (LHV), which does not contain the latent heat of water vapor.

Table 2 Option line-up for “FP-100i”

Standard compliance	Fuel	Function				Remarks
		Cogeneration	Grid independent power supply	Fuel switching	Low oxygen air supply	
JIS compliance	City gas	○	–	–	–	
		○	○	○	–	Disaster response type
	Digestion gas	○	–	–	–	
	Pure hydrogen	○	–	–	–	
CE compliance	Natural gas	○	–	–	–	
		○	–	–	○	Fire prevention response type
	Pure hydrogen	○	–	–	–	

high power generation efficiency of 48%.

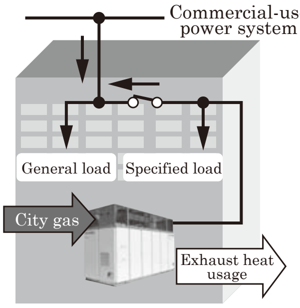
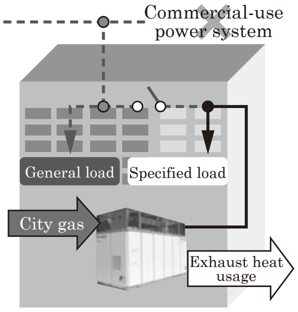
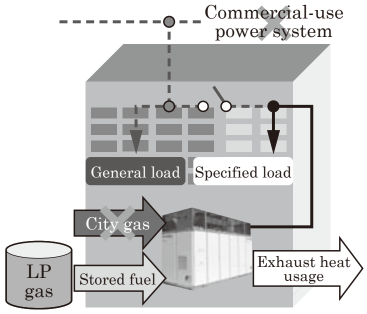
In addition to applications as cogeneration systems, we are also offering optional functions, including the disaster response mode, in which the FP-100i can independently supply electricity by using LP gas as backup, and the fire prevention mode, in which it can supply clean low-concentration oxygen air. Table 2 shows the main option line-up for the FP-100i.

3. Examples of Deliveries and Installations in Japan

The adoption of cogeneration systems in Japan saw its peak in 2004 and since then began to decrease due to high fuel prices. However, ever since the Great East Japan Earthquake in March 2011, there has been a growing interest in energy security, resulting in increased adoption. Fuji Electric has developed a model with a grid independent power supply mode for emergencies in order to ensure power supply to critical loads by instantly switching to LP gas when there is a power or city gas outage. This model has been delivered to hospitals and public facilities since these are places of major importance during times of emergency.

Table 3 shows the activation of operation switching during disasters is shown schematically. This model usually operates while connected to a commercial power system. If a power failure occurs, FP-100i can automatically performs parallel off*[1] from the power system, once moves to the standby operation mode, and can start isolated operation approximately 30 seconds after detection of the power failure. Standby operation mode refers to an operation mode in which the fuel cell generates power continuously and solely, and the generated power is consumed inside the power gen-

Table 3 Operation switching during disasters

State	During ordinary use	During power outage	During power outage + city gas stoppage
Switching operation	Grid interconnection operation	Parallels off from the power system and supply power to a specified load	Parallels off from the power system, change fuel, and supply power to a specified load
Output	105 kW	100 kVA	70 kVA
Fuel	City gas	City gas	LP gas (3 hours per 50-kg cylinder)
Operation	Grid interconnection operation	Isolated operation	Isolated operation
Power supply range			

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[1] Parallel off: Disconnection of power generation equipment from power systems

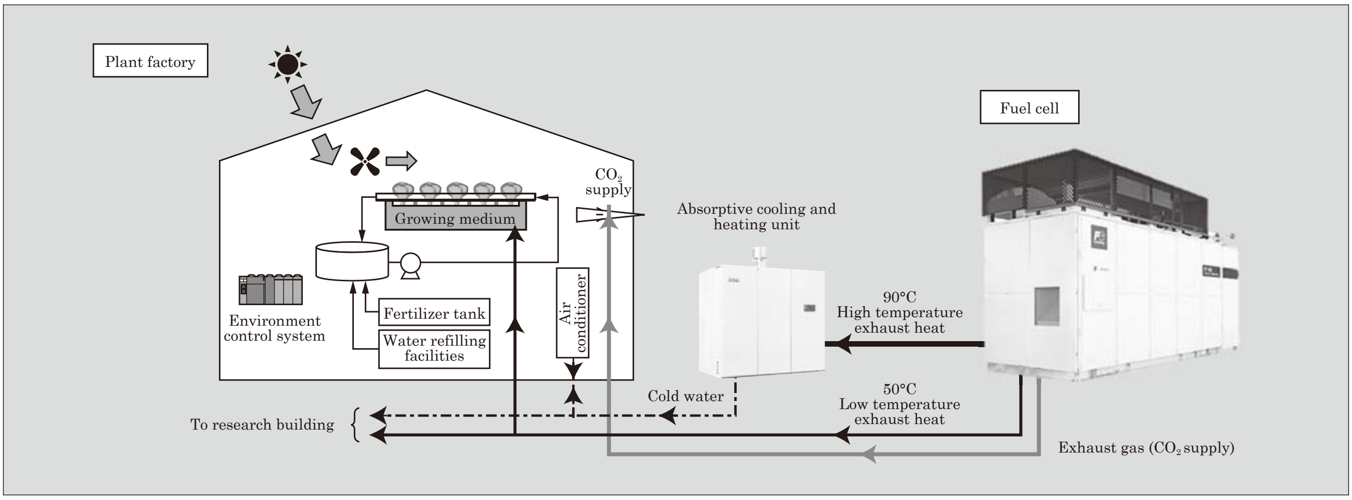

Fig.2 Cogeneration system and supply of CO$_2$ to plant factory inside Tokyo Factory

Fig.3 Fuel cell facilities installed in Tokyo Factory

erating equipment of the fuel cell. When the fuel cell is connected to a load in a state of isolated operation, sequential turn-on can be made for rotating machines, which may cause in-rush current, by using the overcurrent protection function, load protection function and limiter function. When the city gas supply is stopped, the LP gas operation with 50-kg cylinder can supply electricity for approximately 3 hours, although the output is limited to 70 kVA.

In FY2015, we installed fuel cell facilities in Fuji Electric's Tokyo Factory. The facilities are capable of not only supplying electricity and heat during normal operations, but also independently supply critical loads with power by utilizing photovoltaic cells and storage batteries in case of emergency. Furthermore, we have made use of the clean emissions of the fuel cells in a new application. A portion of the emissions, which have a high CO$_2$ concentration approximately 150 times the atmosphere, is being supplied it to the annexed plant factory experiment facility to control the plant growing environment (see Fig. 2 and Fig. 3).

In addition, we have been advancing in the use of the fuel cells in a sewage treatment facility following the enactment of the "Feed-in Tariff (FIT) Scheme for renewable energy" in July 2012. When generating power using carbon neutral sewage digestion gas, we can sell the generated power for 20 years at the rate of 39 JPY per 1 kWh. Compared to other types of power generating devices of the same scale, highly efficient power generation fuel cells are capable of generating more power, and thus the installation of the fuel cells have been increasing in number due to the advantages during the life cycle. In FY2014, we delivered a total of 10 units to 4 locations, and in FY2015, we delivered 8 units to one location. We expect the number of inquiries regarding fuel cells to continue to increase in the future.

4. Examples of Deliveries and Installations for Markets Outside Japan

In markets outside Japan, the installation of commercial-use fuel cells has been advancing ahead of household-use fuel cells. Fuji Electric began making shipments to the markets outside Japan in 2010. Up until now, we have delivered a total of 11 units to 4 countries, which include Germany, South Korea, the United States and South Africa.

Germany has decided to stop all of its 17 nuclear power plants by 2022. However, the introduction of renewable energy sources, such as photovoltaic power generation, wind power generation and biogas power generation, has brought about power system instability problems. As a means of mitigating these problems, it is expected that cogeneration systems will play an important role because they can easily adjust the output. Fuji Electric has also devised a new form of added value for cogeneration systems by implementing a method for applying the clean low oxygen air emitted from fuel cells to fire prevention systems that work by reducing the oxygen concentration indoors. These systems have been gaining popularity in Germany, and we have already started delivering them for use in warehouses and data centers. Unlike engine generators that generate power through combustion of fuel and air, fuel cells generate electricity by an electrochemical reaction of fuel and air that are separated by an electrolyte. Fuel cells only selectively consume oxygen in the air during the power generation process and discharge air with a low oxygen concentration that does not contain harmful flue gas. The low oxygen partial pressure located at high altitudes several thousands of meters up not only prevents building materials and paper from igniting, but also has no immediate impact on the human body. As shown in Fig. 4, compared to systems that reduce oxygen concentrations indoors that have conventionally used membrane separation and adsorptive separation to make and supply nitrogen from the air, we have achieved a highly efficient system configuration that suppresses compressor energy consumption (running costs), noise and vibration, while providing a high degree of environmental friendliness. Figure 5 shows the installation state of our demonstration system in Germany.

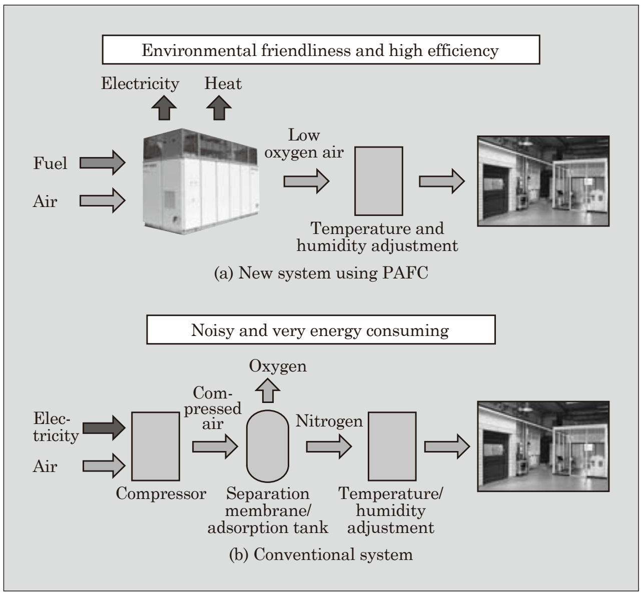

Fig.4 Comparison of systems that reduce oxygen concentration indoors

Fig.5 Fire prevention demonstration system installed in Wismar, Germany

In January 2016, we acquired N$_2$telligence GmbH, which had expanded our sales of low oxygen fire prevention systems in Germany as our business partner. By taking advantage of its patent and sales network, we will enjoy accelerated sales growth both in Germany and throughout Europe. In order to sell products in the EU, it is necessary to fulfill CE marking obligations. Since Fuel cell facilities are a type of chemical plant that consists of machinery and electrical equipment, they are subject to a wide range of EU directives. Although there was no precedent of Japanese made fuel cells fulfilling CE mark compliance, we took various measures including the modification of devices to acquire compliance certification from a third-party certificate authority. In addition, we also obtained compliance certification via a third-party certificate authority with regard to Germany's VDE 4105 system interconnection standard.

In Germany, a low calorie gas that contains about 10% nitrogen is used in many regions as a city gas. A fuel processing device converts the fuel gas into a gas that contains a large amount of hydrogen inside the fuel cell, and after this it is supplied to the fuel cell unit to enable power generation. Conventionally, whenever the fuel processing device used a fuel gas that contains a large amount of nitrogen, it would generate ammonia as by-product, which is harmful to the fuel cell unit. We have developed a fuel processing device that convert fuel gas including nitrogen into hydrogen-rich fuel gas without producing ammonia by making such improvements as using new catalyst. In the future, we expect that our fuel cells will become more popular in regions that utilize low calorie gas.

In South Korea, a growing demand for commercial-use fuel cells is being facilitated by the government policies, including the "Renewable Portfolio Standard" (RPS) and the obligations of adopting renewable energy for new buildings. Fuji Electric began to ship the fuel cells to South Korea in 2014 and has delivered them to commercial buildings and data centers.

South Africa, which is expected to experience growth as one of the BRICS, has been suffering from severe power shortages due to the deterioration of power generation facilities. Businesses have been actively installing in-house power generation equipment as a means of protecting themselves. In 2014, Fuji Electric delivered a fuel cell to an office building in South Africa. During normal hours, electricity is transmitted to the building via its interconnected system, but during planned power outages, the fuel cell unit makes use of its grid independent power supply mode to provide critical loads with electricity.

Fuji Electric has developed an Internet cloud-based remote monitoring system and maintenance system for fuel cells installed overseas, enabling us to monitor the equipment conditions and update the software from Japan (see Fig. 6). The systems makes

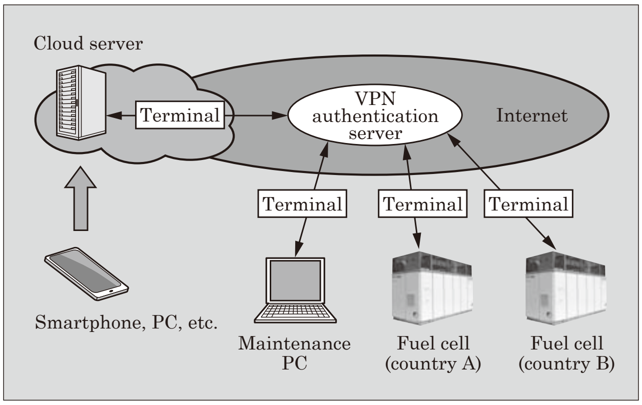

Fig.6 Cloud-based fuel cell remote monitoring system and maintenance system

it possible to simultaneously save operation data to a cloud server while also remotely updating the fuel cell software from a maintenance PC. Therefore, it is possible to view the operation data anywhere anytime by simply logging into the cloud server from a mobile terminal. Using this system is useful to stabilize the operation of the fuel cells.

5. Solid Oxide Fuel Cells (SOFCs)

In addition to PAFCs, we have been advancing the development of SOFCs (see Fig. 7). SOFCs are best characterized for their high power generation efficiency, and we have been aiming for a commercial-use cogeneration system with a capacity of several tens of kW based on the target specifications of the demonstration unit as shown in Table 4. We have been developing this unit under the support of the New Energy and Industrial Technology Development Organization (NEDO) since FY2014. Total efficiency when using all of the recovered heat is close to that of PAFCs, but the electric output ratio is higher than the heat. Therefore, it is capable of economic and efficient operation even when installed at sites where there is not much heat usage.

Table 4 Target specifications of SOFC demonstration unit

Item	Target specifications
Power generation output	50 kW class
Power generation efficiency (LHV)	50% or more
Exhaust heat recovery efficiency (LHV)	30% or more (hot water output)
Total efficiency	80% or more
Device dimensions	W5.0 × D2.2 × H2.8 (m)

In FY2014 to FY2015, we worked on the development of elemental technologies such as normal-pressure type fuel cell modules, and during FY2016 to FY2017, we advanced in the design, manufacture and performance evaluation of the demonstration unit for our cogeneration system. Figure 8 shows the equipment configuration of the SOFC that we are currently developing. The system uses an internal reforming cell stack. As a result, it has a simple configuration with only a few main pieces of equipment including a desulfurizer, fuel cell module, exhaust heat recovery unit and anode gas circulation blower. By circulating the exhaust gas (anode gas) on the fuel side of the fuel cell module, the water produced by the fuel cell reaction is circulated, and this, in turn, supplies the steam needed for the reforming reaction of the fuel gas. By doing this, we have aimed to achieve the self-sustained operation of water, thus eliminating the need to replenish the water externally while the unit is operating. In addition, this has made it possible to increase the utilization factor of the fuel for the entire system and also achieve a high power generation efficiency. The self-sustained operation of water is necessary for extending the interval between maintenance work for and suppressing maintenance costs of a water processing device, and as a result, this technology is vital for achieving practicality. Furthermore, we continue to pursue development so as to achieve high power generation efficiency through an optimized design for the fuel cell module, high efficiency via the adoption of a 3-level inverter, and an equipment layout design for the inside of the package that is based on a 3D model thermo-fluid analysis.

Fig.7 External appearance of SOFC demonstration unit

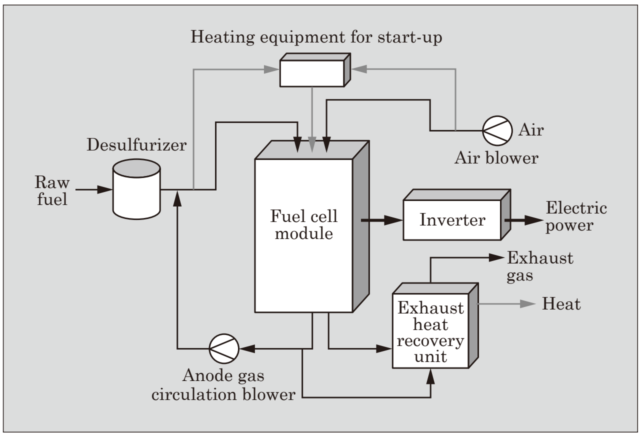

Fig.8 Equipment configuration of SOFC

6. Postscript

We will expand the sales of PAFCs by making the most of their added values, including power supply security functions and fire prevention functions that supply air with a low oxygen concentration, as well as their advantages that they can use a wide range of fuels, such as biogas and hydrogen. In addition to PAFCs, highly efficient power generating SOFCs are also starting to appear on the market for general cogeneration systems.

We are making use of our cultivated fuel cell technologies as we aim to take advantage of their features in the development and expanded adoption of various applications not only in Japan, but also throughout the world so that we can contribute to mitigating global warming, protecting the environment and achieving a sustainable society.

References

(1) Koshi, K. et al. Development of Fuel Cells Adapted to Meet New Needs. FUJI ELECTRIC REVIEW. 2013, vol.59, no.2, p.135-139.

Distribution Static Var Compensators and Static Synchronous Compensators for Suppressing Voltage Fluctuation

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ABSTRACT

The rapidly expanding introduction of photovoltaic power systems in recent years may cause problems such as a voltage rise in distribution lines. To solve the voltage problems in distribution systems, Fuji Electric has developed static var compensators (SVCs) and static synchronous compensators (STATCOMs), which control voltage with reactive power. Fuji Electric's SVCs offer a simple equipment configuration without the need for a harmonic filter. We confirmed the effect of suppressing a voltage rise by conducting a field test within the territory of Tohoku Electric Power Co., Inc. The distribution STATCOMs are compact and lightweight devices that use SiC devices to achieve single-pole tower mounting with natural air cooling by taking advantage of these low power dissipation characteristics.

1. Introduction

Photovoltaic power systems have been introduced rapidly in recent years following the implementation of the "Feed-in Tariff (FIT) Scheme for renewable energy." On the other hand, a photovoltaic power system is an unstable power supply because its output fluctuates depending on the weather conditions. Consequently, this increased introduction will cause problems such as voltage rises in the distribution line. The conventional voltage control employed automatic step voltage regulators (SVRs) in the distribution line to keep the voltage within the proper range. It was difficult to use SVRs for handling irregular and rapid voltage fluctuations due to the use of stepwise voltage control through tap switching and time delay.

In order to stabilize the voltage in distribution systems, Fuji Electric provides static var compensators (SVCs) for distribution systems, which control voltage with reactive power. This paper describes the configuration and features of these distribution SVCs.

2. Features of Distribution SVCs

2.1 Differences between SVR and SVC

Figure 1 shows the concept of voltage regulation using an SVR and an SVC.

An SVR, mainly used in the conventional voltage control, is series-connection equipment, and it regulates voltage by switching the tap of a transformer. When the tap is switched, the voltage after the point at which the SVR is installed is changed uniformly. Under the SVR-based voltage control, the voltage and let-through current at the installation point of the SVR are measured and then the tap is operated to achieve the target voltage. Since the control is based on tap operation, the voltage is regulated in steps such as 100-V increments/decrements as shown in Fig. 1 (a).

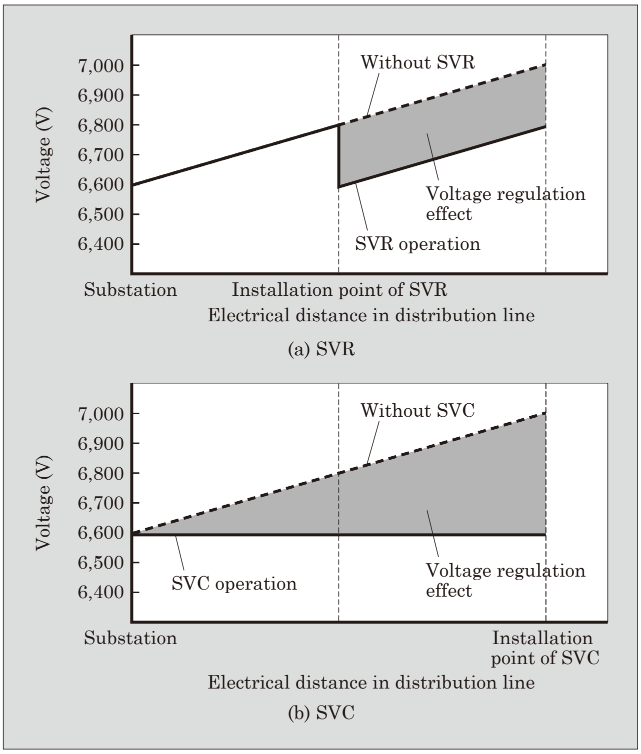

Fig.1 Conceptual diagram of voltage regulation

On the other hand, an SVC is parallel-connection equipment that regulates voltage by supplying reactive power to the system. The relationship between the inductance X and reactive power Q between the installation point of the SVC and the substation can be calculated approximately with the following formula:

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$$\Delta V=\frac{X\cdot Q}{V}\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(1)$$

ΔV: Voltage regulation range (V)
X: Inductance between the substation and the installation point of the SVC (Ω)
Q: Reactive power (var)
V: Voltage of the system (V)

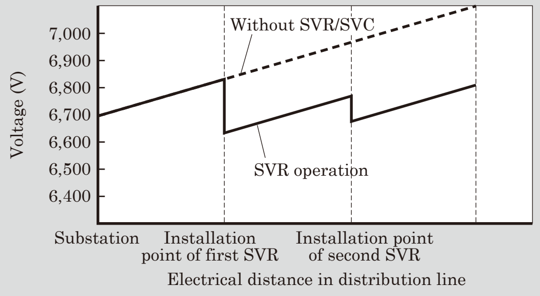
The SVC-based voltage control outputs the necessary reactive power according to the difference between the voltage measured at the installation point of the SVC and the target voltage. Since an SVC can provide continuously variable output of reactive power, the voltage regulation range changes continuously as shown in Fig. 1 (b).

An SVC can regulate voltage more effectively when it is installed at the point where the inductance from the substation becomes large, or a point far from the substation, than the case when it is installed at a point near the substation. When a voltage at a point far from the substation is abnormally risen by a power source such as photovoltaic power system, voltage regulation using an SVC is thus advantageous. Moreover, when an SVR is used to handle rapid voltage fluctuations caused by photovoltaic power systems, the number of mechanical tap operations of the SVR increases, and this may result in the SVR needing to be replaced earlier. When an SVC is used to control rapid voltage fluctuations, the replacement cycle remains the same because no mechanical operation is involved.

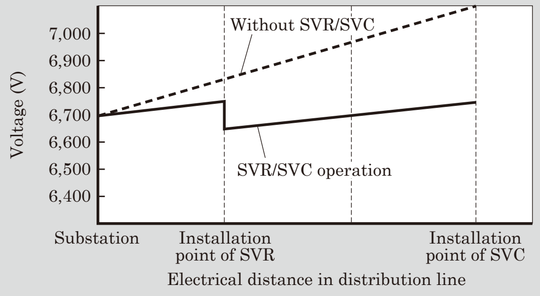
In view of the characteristics of SVRs and SVCs, installing an SVR on the substation side and an SVC on the terminal side of the distribution line is the best way to exploit their advantages. Figure 2 shows the concept of regulating voltage with 2 SVRs and with one SVR and one SVC.

In Fig. 2 (a), where 2 SVRs are used for voltage regulation, the voltage rises at the terminal. On the other hand, in Fig. 2 (b), the combination of an SVR and an SVC can prevent voltage rises across the power system. It is especially noteworthy that the voltage rise at the terminal is suppressed with control by the SVC and the voltage rise on the substation side is suppressed with control by the SVR. In this way, using existing SVRs and SVCs in coordination can keep the voltage across the system healthy.

SVCs are divided into 2 types. One is variable impedance type SVCs, which generate reactive power by controlling an electric current flowing into a reactor. The other is switching converter type SVCs or static synchronous compensators, which generate reactive power by using a self-turn-off power switching element to generate a current or voltage of the desired phase. The following sections describe the variable impedance type and switching converter type SVCs being developed by Fuji Electric.



(a) Combination of 2 SVRs



(b) Combination of one SVR and one SVC

Fig.2 Graphs illustrating concept of voltage regulation using multiple units

2.2 Variable impedance type SVCs

Typical variable impedance type distribution SVCs are a thyristor controlled reactor (TCR) type, which uses a thyristor to directly switch and control the current flowing into a reactor. This type requires a harmonic filter to directly turn on/off the current flowing into the reactor with the thyristor. To meet this requirement, in joint research with Tohoku Electric Power Co., Inc., Fuji Electric has developed a new type of variable impedance type distribution SVC using a variable inductor to which magnetic flux control technology has been applied. This type can use direct current to control the current flowing into a reactor. This eliminates a harmonic filter and allows for an SVC with simpler equipment configuration compared with conventional SVCs.

Figure 3 shows the basic principle of the new variable impedance type distribution SVC. The principle is different from that of conventional variable impedance type distribution SVCs. The magnetic core has AC winding and control winding. When a direct current passes through the control winding, magnetic saturation occurs and effective magnetic permeability decreases. Based on this principle, controlling the magnetic flux density to change the magnetic permeability makes it possible to control the effective inductance and regulate the reactive power flowing into the system. The main circuit is only comprised of an iron core and windings, which allows for a configuration ensuring high reliability for high resistance against surges.

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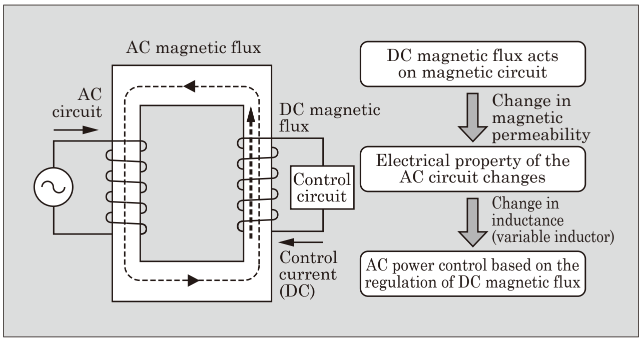


Fig.3 Basic principle of variable impedance type distribution SVC

Fig.4 Variable impedance type distribution SVC

Table 1 Specifications of variable impedance type distribution SVC

Item	Specification
Rated capacity	300 kVA
Variable capacity	0 to 300 kvar (lagging)
Rated voltage	6,600 V
Frequency	50/60 Hz
Cooling system	Natural cooling
Mass	4,000 kg or less
Dimensions	W2,500 × D1,500 × H2,000 (mm)
Main circuit	Variable inductor (without harmonic filter)

Since a direct current is used as the control current for regulating the reactive power output, the configuration of the control circuit and software algorithm can also be simplified.

Figure 4 shows the external appearance of the developed variable impedance type distribution SVC, and Table 1 shows its specifications.

2.3 Configuration of distribution static synchronous compensators

A distribution static synchronous compensator regulates voltage by using a self-turn-off power switching element to regulate reactive power. Conventional distribution static synchronous compensators use a silicon (Si) semiconductor. It was difficult to ensure a high withstand voltage and high-frequency switching, and there were limitations on the reduction of loss and acoustic noises. Accordingly, cooling fans were indispensable for the conventional products, which led to poor maintainability and the mounting on a utility pole required a 2-pole structure.

As a countermeasures, Fuji Electric is developing an SVC by applying silicon carbide (SiC) devices instead of Si devices as power semiconductors in order to achieve a distribution static synchronous compensator that does not require a cooling fan. SiC is a semiconductor material that allows higher withstand voltage and higher frequency switching than Si. At present, SiC power semiconductors of 3.3 kV, 200 A have been developed and applied. Figure 5 shows the circuit of the developed distribution static synchronous compensator, and Table 2 shows its specifications.

This distribution static synchronous compensator consists of a 3-level inverter and an interconnection transformer, and the inverter has employed a SiC module consisting of a 3.3-kV SiC metal-oxide-semiconductor field-effect transistor (MOSFET) and a SiC Schottky barrier diode (SBD). Thermal analysis of this configuration has shown there are prospects for achieving natural air cooling without the need for a cooling fan.

Applying SiC devices has made it possible to re-

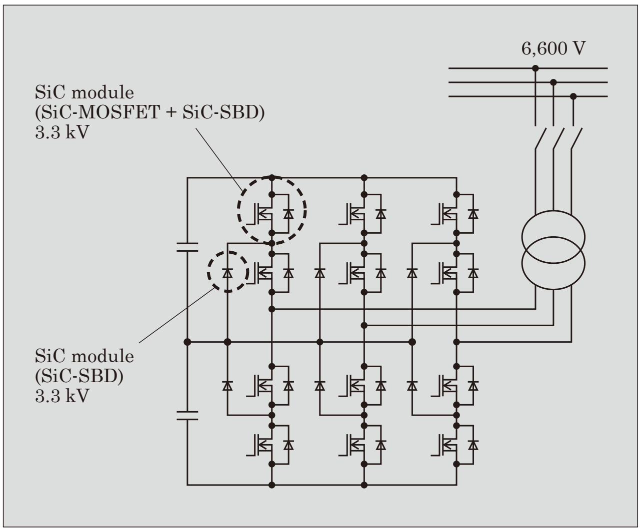


Fig.5 Circuit of distribution static synchronous compensator

Table 2 Specifications of distribution static synchronous compensator

Item	Specification
Rated capacity	300 kVA
Variable capacity	0 to 300 kvar (lagging, leading)
Rated voltage	6,600 V
Frequency	50/60 Hz
Cooling system	Natural cooling
Mass	1,800 kg or less (60 Hz)
Dimensions	W1,300 × D1,000 × H2,500 (mm) max.
Main circuit	Transformer and inverter

duce the weight of the distribution static synchronous compensator compared with variable impedance type distribution SVCs, resulting in a mass and volume that enable single-pole mounting.

A verification test is scheduled to take place at the Akagi Testing Center of the Central Research Institute of Electric Power Industry in FY2017 and a demonstration test is scheduled in the territory of an electric power company in FY2018.

Developing this distribution static synchronous compensator was made possible through the "Demonstration Project on Next-Generation Power Grid Construction test for Distributed Energy" of the New Energy and Industrial Technology Development Organization (NEDO).

3. SVC Operation in Distribution System

In order to confirm the operation of voltage regulation using the new variable impedance type distribution SVC, Fuji Electric is conducting a field test with the cooperation of Tohoku Electric Power Co., Inc. in the actual distribution lines in the territory of Tohoku Electric Power Co., Inc. Figure 6 shows the system diagram of the field test, and Fig. 7 shows the installation status.

Figure 8 and Table 3 show the result of the field test. Figure 8 shows an example of voltage fluctuations a day before and after the installation date of the variable impedance type distribution SVC. In this case, the variable impedance type distribution SVC is controlled in such a way that, when the upper limit voltage (6,700 V) is exceeded, reactive power is output to suppress the voltage rise. Before the variable impedance type distribution SVC was installed, the system showed a high voltage on average and the voltage temporarily exceeded 6,800 V. The maximum and average voltages decreased after the installation, showing the SVC's ability to suppress a voltage rise. The effect of suppressing rapid voltage fluctuations can also be recognized.

In addition, the number of daily activations of SVR-2 in the system decreased after the variable impedance type distribution SVC was installed. In gen-

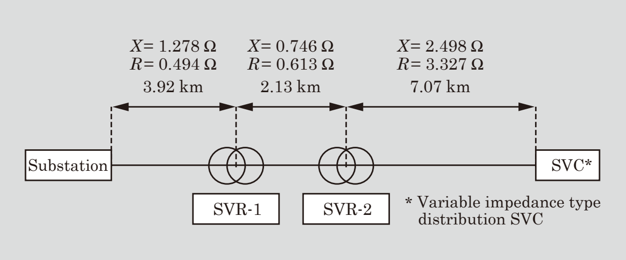
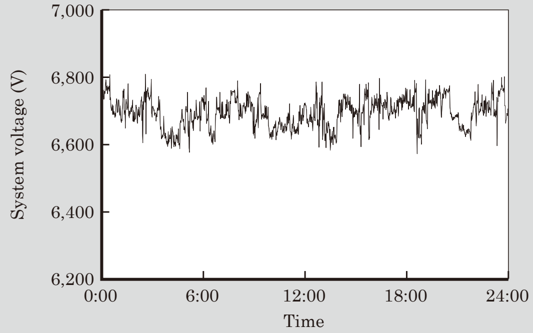
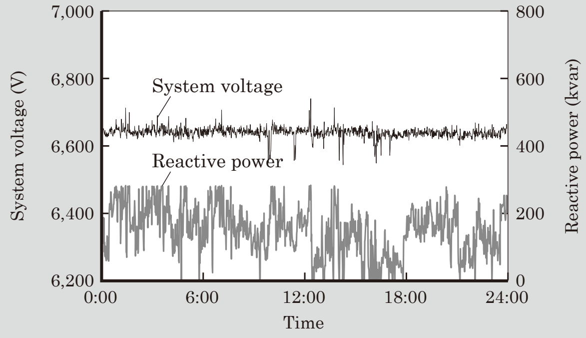


Fig.6 System diagram of field test

Fig.7 Variable impedance type distribution SVC in field test



(a) Before installation of variable impedance type distribution SVC



(b) After installation of variable impedance type distribution SVC

Fig.8 Example of field test result

Table 3 Field test result

Item	Test result	
	Before installation	After installation
Average voltage	6,680 V	6,639 V
Maximum voltage	6,838 V	6,740 V
Minimum voltage	6,512 V	6,543 V
Rate of voltage remaining within the control range*[1]	72.9%	99.9%
Average reactive electric energy	–	146 kvar
Maximum voltage change*[2]	210 V	120 V
No. of SVR-2 activations	15	5

*1: Percentage of the period in which the voltage remains within the control range from 6,350 to 6,720 V when one day is assumed to be 100%.

*2: Maximum absolute value of the difference between the present voltage data and the data of one minute before eral, when an SVC and an SVR are installed in one system, their controls may interfere with each other, producing a hunting phenomenon that increases the number of SVR activations or causing a problem where the control is done by the SVC only and the SVR does not operate. The hunting and other problems, however, can be prevented by optimally controlling and setting the SVC according to the installation position and setting values. This field test showed a satisfactory result without problems such as increased SVR activations, confirming the ability of cooperative control using the SVR and variable impedance type distribution SVC. The greater introduction of photovoltaic power systems will create a problem regarding output fluctuations. This test has proved that this configuration can effectively suppress the increased SVR activations that result from the fluctuations.

4. Postscript

This paper described our distribution SVCs about a voltage regulation method, as well as the principles and configurations of variable impedance type and switching converter types. In the field test of the variable impedance type distribution SVC, we confirmed the effect of suppressing voltage rises. We believe that SVCs help to solve the problem of voltage fluctuations in distribution systems caused by photovoltaic power systems.

Fuji Electric will continue to develop distribution SVCs to provide equipment that help increase the introduction of photovoltaic power systems and other renewable energy facilities.

In closing, we would like to express our deep gratitude to Tohoku Electric Power Co., Inc. for the great deal of guidance and cooperation in the development, design and verification test of variable impedance type distribution SVC. We also wish to thank the parties concerned in the “Demonstration Project on Next-Generation Power Grid Construction for Distributed Energy” of the New Energy and Industrial Technology Development Organization (NEDO) for the great deal of guidance they gave us in the development and design of static synchronous compensators.

Large-Scale Power Conditioning System for Grid Storage Battery System with Redox Flow Battery Having World's Highest Capacity Class of 60 MWh

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ABSTRACT

Fuji Electric received an order from Sumitomo Electric Industries, Ltd. for a large-scale power conditioning system consisting of power conditioning equipment (2.5 MVA × 13 banks) and storage-bank control panels, which are part of a power system stabilization demonstration facility using a redox flow battery system having the world's highest capacity class of 60 MWh. We delivered the system to the Minami-Hayakita Substation of Hokkaido Electric Power Co., Inc. The power conditioning equipment is capable of governor-free equivalent control for quick charging and discharging in accordance with the frequency fluctuation in the power system, remote control from the central load dispatching center, and supplementary discharge control depending on the battery status. The bank controller panels control the statuses of as many as 65 power conditioning sub-systems to achieve large-scale and high-speed parallel operation.

1. Introduction

Wind power generation and photovoltaic power generation are prone to irregular output fluctuations because they depend on the weather conditions. With their increased introduction to power systems, there are concerns over the influence on power quality such as frequency. Considering this background, the Ministry of Economy, Trade and Industry has been promoting the "Large-scale Storage Battery System Demonstration Project" in order to suppress output fluctuations of renewable energies in power systems. One of the attempts is the power system stabilization demonstration project using redox flow (RF) batteries pursued jointly by Hokkaido Electric Power Co., Inc. and Sumitomo Electric Industries, Ltd. A demonstration test has been conducted on it since December 2015. This power system stabilization demonstration facility has the rated output of 15,000 kW, rated capacity of 60,000 kWh and consists of 13 banks[*1]. This facility offers the highest power storage capacity in the world.

As part of this demonstration system, Fuji Electric received an order for a large-scale power conditioning system from Sumitomo Electric Industries, Ltd. and installed it in the Minami-Hayakita Substation of Hokkaido Electric Power Co., Inc. in December 2015.

Currently in some areas, it is necessary to install a storage battery system in a wind or photovoltaic power generation plant in order to suppress output fluctua-

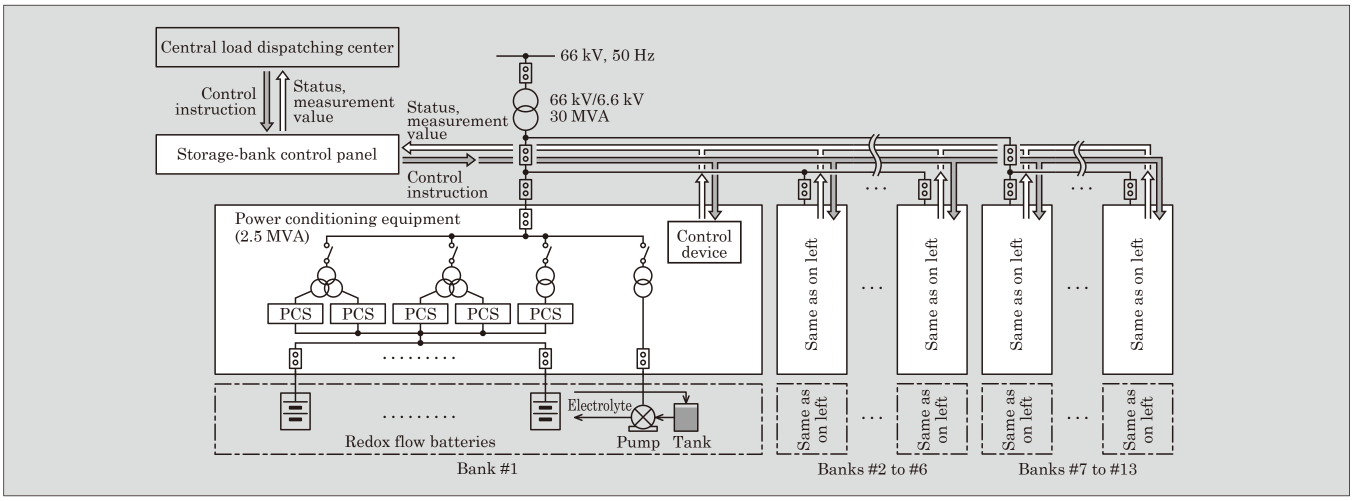

Fig.1 Overview of power conditioning system

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[*1] Bank: In this paper, a "bank" is defined as a unit of the combination of power conditioning equipment and the storage batteries connected to it.

tions. As an alternative, we installed the power conditioning system in a substation to suppress the fluctuations in a large-scale power system.

This paper describes a large-scale power conditioning system for a grid storage battery system using redox flow batteries having the world's highest capacity class of 60 MWh.

2. Overview of Power Conditioning System

Figure 1 shows an overview of the power conditioning system. Although most conventional power conditioning equipment used for a storage battery system was small scale, up to 1 MVA capacity, this system offers high capacity with a maximum output of 30 MW. It consists of 13 banks, each of which contains power conditioning equipment with 2.5 MW capacity, and a storage-bank control panel that manages these banks. This configuration has achieved space saving as well as large-scale and high-speed parallel operation.

(1) Power conditioning equipment

The power conditioning equipment, which connects the RF batteries to an AC system, charges and discharges the batteries based on the governor-free equivalent control or the instructions from the central load dispatching center. The installation status is shown in Fig. 2.

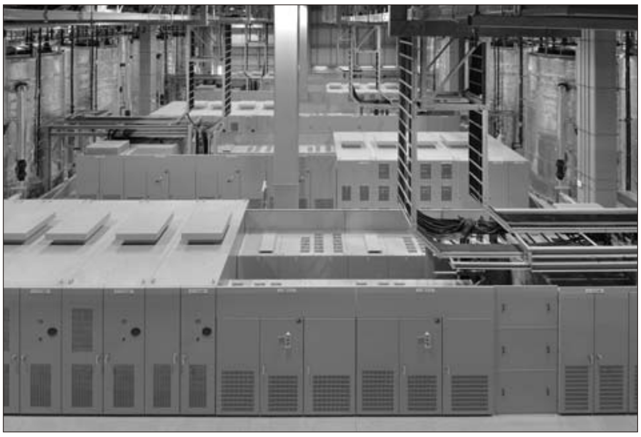


Fig.2 Installation status of power conditioning equipment

(2) Storage-bank control panel

The storage-bank control panel distributes control instructions from the central load dispatching center properly to the power conditioning equipment of each bank and controls the power conditioning equipment.

3. Configuration of Power Conditioning Equipment

Figure 3 shows the configuration of the power conditioning equipment in one bank, and Table 1 shows

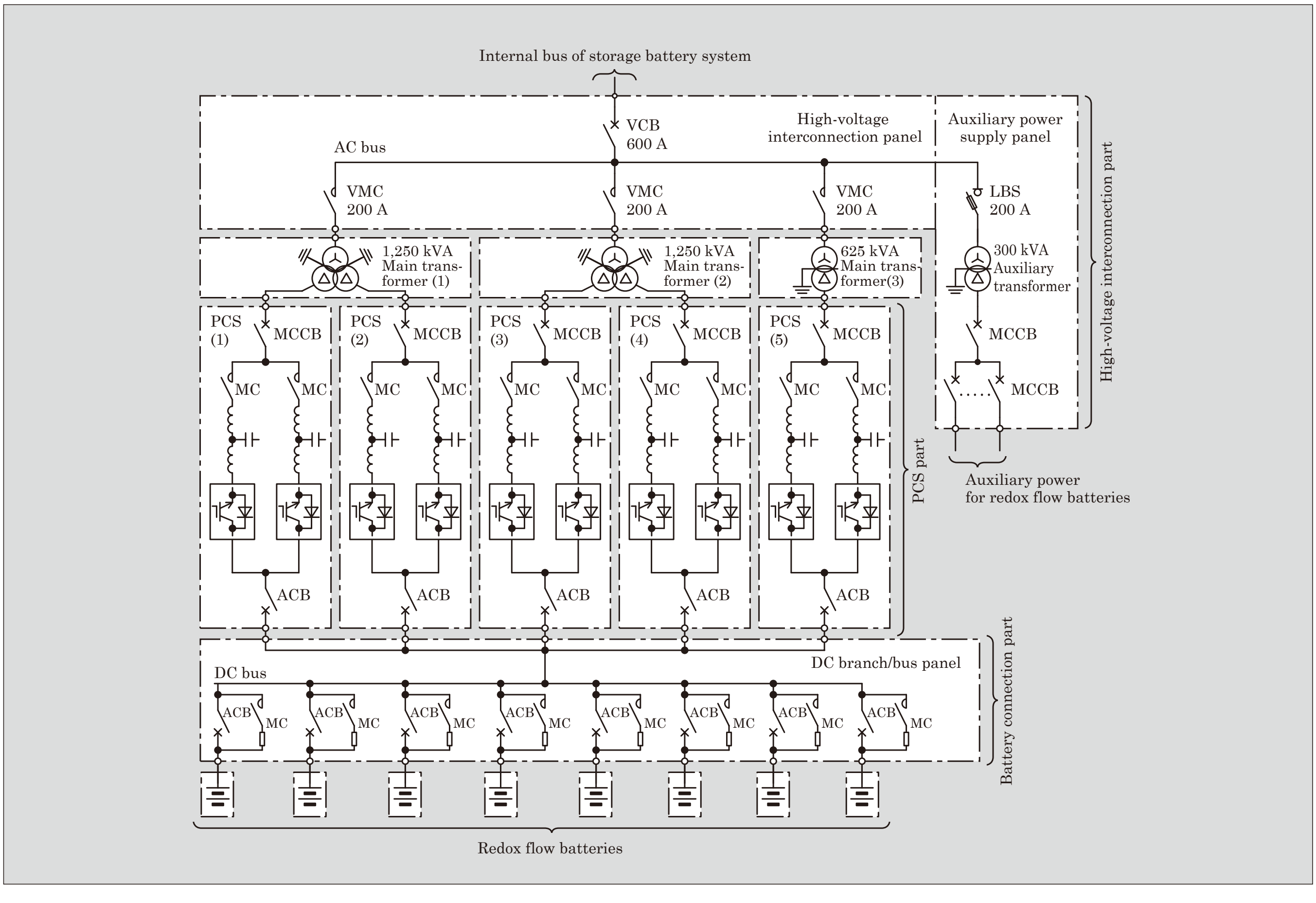


Fig.3 Configuration of power conditioning equipment (one bank)

Table 1 Major specifications of power conditioning equipment (per bank)

Item		Specification
Method	Main circuit/conversion method	Self-commutated voltage sine wave PWM
	Control system	Voltage type current control
	Operation method	System-linked
	Cooling system	Forced air cooling
DC input/output	No. of DC branches	8 branches
	DC voltage range	480 to 750 V DC
	Maximum DC current	Continuous 6,400 A (800 A × 8 in parallel)
AC input/output	Number of phases	3-phase 3-wire
	Rated voltage and fluctuation range	6,600 V±10%
	Rated frequency and fluctuation range	50 Hz±1 Hz
	Rated capacity at AC power receiving end	2,500 kVA
	Harmonic current content	Total: 5% or less, individual: 3% or less
	Power-factor	0.95 or more
Control response time		100 ms or less between −100% and +100%
Acoustic noise		70 dB or less
Dimensions		W15,233 × D2,920 × H2,870 (mm)

the major specifications. The power conditioning equipment consists of a power conditioning sub-system (PCS) part, a high-voltage interconnection part and a battery connection part.

3.1 PCS part

The PCS part has a structure of 5 units of the "PVI800-3/600" connected in parallel and is characterized by high efficiency, space saving and low noise. The PVI800-3/600 was developed for storage battery applications based on the "PVI750-3/500(1)," which is a mega solar PCS equipped with advanced T-type neutral-point-clamped (AT-NPC) 3-level insulated gate bipolar transistor (IGBT) modules. This part offers a system interconnection protective function, a fault ride through (FRT) function, a communication interface with upper systems through the "MICREX-SX" programmable controller (PLC) within the PCS, a high-speed response function to the control instructions from upper systems and an output suppression function for stable charging and discharging.

3.2 High-voltage interconnection part

The high-voltage interconnection part of the power conditioning equipment consists of (1) a high-voltage interconnection panel that integrates the AC output from 5 PCSs into an AC bus and connects it to the internal bus (6.6 kV) of the storage battery system, (2) a main transformer panel for boosting up the AC output from the PCS, and (3) an auxiliary power supply panel that supplies the auxiliary power for the RF batteries from the internal bus.

The high-voltage interconnection panel uses a high-voltage vacuum circuit breaker (VCB) for the connection between the internal bus of the storage battery system and the AC bus. It also uses a vacuum magnetic contactor (VMC), which is smaller than the VCB, for the circuit that integrates the AC outputs from the PCSs into the AC bus. These devices contribute to space saving.

For the main transformer panels, two 3-winding mold transformers are mounted to cover 4 PCSs. This has saved on the mounting space greatly compared with the case where 2-winding mold transformers are used. For the remaining PCS, an ultra-high-efficiency mold transformer is mounted. This combination enables high efficiency of the high-voltage interconnection part.

In addition to the high-voltage interconnection panel and main transformer panel, this part contains protection relays required for protecting the equipment for system interconnection and other functions in the high-voltage interconnection part and a programmable controller (PLC) that operates as the main controller of the power conditioning equipment. The PLC in the high-voltage interconnection part conducts governor-free equivalent control and works as the communication interface with the PLCs inside the storage-bank control panel and PCSs. All of these communication activities use Fuji Electric's "PE-link" high-speed data communication network to save on wiring and space and achieve high-speed control responses.

3.3 Battery connection part

The battery connection part of the power conditioning equipment consists of a DC branch panel that receive the outputs of the RF batteries in 8 branches and a DC bus panel that consolidates 5 branches into the DC bus and distributes common DC power to 5 PCSs. This part detects the current and voltage of the battery connection part with signal converters and inputs these measurement signals to the PLC of the high-voltage interconnection part.

The DC branch panel consists of low-voltage air circuit breakers (ACBs), circuits for RF battery initial charging [resistors and magnetic contactors (MCs)] and signal converters for DC current detection. The signal converter for DC current detection is mounted on each shunt as a measure for improving the control accuracy.

The DC bus panel has a main circuit configured with a bus bar passing 6,400 A DC, and the main circuit has DC ground fault detection equipment and signal converters for DC voltage detection on it.

This configuration of power unit and the layout of measuring and protective functions achieves a DC circuit suitable for the connection of high-capacity RF batteries.

4. Control Functions of Power Conditioning Equipment

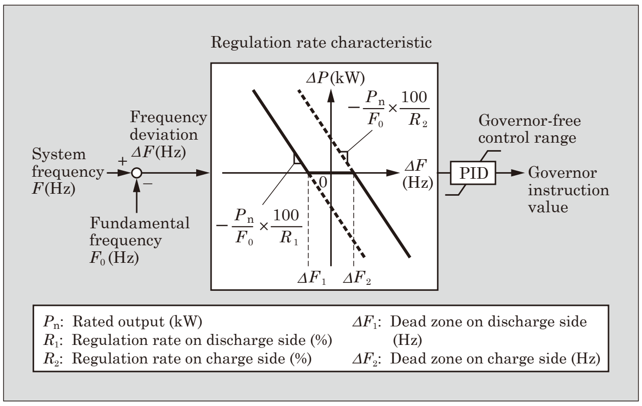
The power conditioning equipment provides innovative control functions that allow the large-scale storage battery system to perform governor-free control conventionally used in thermal power plants or hydraulic power plants and the load frequency control based on the instruction from the central load dispatching center. It also conducts a long-period fluctuation suppression control that takes advantage of the characteristics of storage batteries.

4.1 Governor-free equivalent control

The governor-free equivalent control is a short-period fluctuation suppression control that detects the frequency of the power system (system frequency) in the power conditioning system and adjusts the output of the power conditioning equipment to restore the fundamental frequency. The controller calculates the amount of power change from the change in the system frequency and from the regulation rate, and generates governor instruction values every 10 ms from a PID controller to determine the output of the power conditioning equipment (see Fig. 4).

When the system frequency is lower than the fundamental frequency, supply is below demand in the power system. In this case, the controller generates governor instruction value to increase the system frequency. On the contrary, when the system frequency is higher than the fundamental frequency, supply is above demand in the power system. In this case, the controller generates the governor instruction value to decrease the system frequency. The output of the power conditioning equipment responds within 100 ms after the system frequency is detected.

In this way, the governor-free equivalent control by the power conditioning equipment adjusts the system frequency with high-speed in both charging and discharging directions.



P_n: Rated output (kW)
R_1: Regulation rate on discharge side (%)
R_2: Regulation rate on charge side (%)
ΔF_1: Dead zone on discharge side (Hz)
ΔF_2: Dead zone on charge side (Hz)

Fig.4 Block diagram for control logic of governor-free equivalent control

4.2 Remote control

The power conditioning equipment receives instruction signals from the central load dispatching center via the storage-bank control panel and remotely controls the charging and discharging of the RF batteries by the following control functions:

(1) Short-period fluctuation suppression control

This includes fluctuation compensation control to mitigate short-period fluctuations (cycle of 20 minutes or shorter) in the compound output of multiple wind and photovoltaic power systems and load frequency control to distribute imbalanced supply and demand in the entire system to hydraulic power plants or RF batteries.

(2) Long-period fluctuation suppression control

This is a control to mitigate long-period fluctuations (cycle of 20 minutes or longer) based on the output forecasts of wind and photovoltaic power systems.

(3) Operation control against insufficient lower control margin

This is a control to avoid generation of surplus power based on output forecasts and supply-and-demand planning.

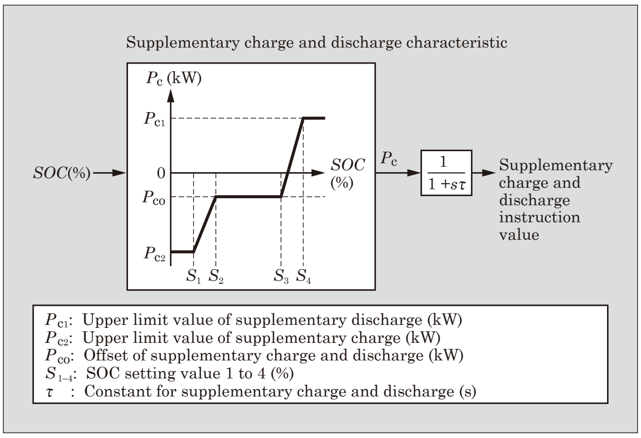
(4) Short- and long-period hybrid control

This is a combination of the short-period and long-period fluctuation suppression controls to ensure optimum operation in the entire electric power storage system.

4.3 Supplementary charge and discharge control

The supplementary charge and discharge control detects the state of charge (*SOC*) of the RF battery and adjusts the *SOC* to a value within the target range based on the supplementary charge and discharge instruction value based on the supplementary charge and discharge characteristics (see Fig. 5).

If the *SOC* is lower than the setting value S_2, the supplementary charge and discharge instruction value for charging is issued. If the *SOC* is higher than the setting value S_3, the supplementary charge



P_{c1}: Upper limit value of supplementary discharge (kW)
P_{c2}: Upper limit value of supplementary charge (kW)
P_{co}: Offset of supplementary charge and discharge (kW)
S_{1-4}: SOC setting value 1 to 4 (%)
τ : Constant for supplementary charge and discharge (s)

Fig.5 Block diagram for control logic of supplementary charge and discharge control and discharge instruction value for discharging is issued. When the supplementary charge and discharge instruction value is combined with a power instruction value, such as of the governor-free equivalent control, and given to the PCS, allowing the *SOC* to be adjusted within the target range.

The temporal change of the supplementary charge and discharge instruction value can be adjusted not to affect the power system with the appropriate setting value τ.

4.4 Initial charging and maintenance control

Initial charging refers to the act of charging the RF battery from the power conditioning equipment when the battery's electromotive force is 0 V such as at delivery or during maintenance.

At the beginning of the initial charging, one PCS operates in the rectification mode of the DC voltage constant control and the remaining 4 PCSs operate in the system-linked mode. The outputs of the PCSs in the system-linked mode are connected to the RF batteries one by one via the initial charging circuits with resistance while being adjusted to reduce the charging power generated in the PCS in the rectification mode. This can reduce the inrush currents of the RF batteries and the PCS in the rectification mode to their allowable current values or lower.

Next, when the inrush current disappears, all of the electrical paths are switched from the initial charging circuits to the ACB circuits one by one, and then the PCS in the rectification mode is switched to the system-linked mode. Finally, all the PCSs are operated with constant power charging until the electromotive forces of the RF batteries increase to the specified amount to complete the charge.

Although applying low DC voltage to the RF battery with an electromotive force of 0 V can reduce the inrush current, a chopperless PCS cannot technically control low DC voltages. In contrast, power conditioning equipment can perform the initial charging by using a combination of several PCSs as described above and opening or closing the MCs and ACBs in the initial charging circuit designed with the optimum resistance.

The maintenance control is control of charging and discharging based on the setting values or operation signals input from the control panel of the RF battery in order to confirm the performance of the RF battery. It allows operations with the following operating characteristics:

(1) DC charge operation

This is charge operation with the characteristics of DC constant current, DC constant power and DC constant voltage.

(2) DC discharge operation

This is discharge operation with the characteristics of DC constant current, AC constant power and DC constant voltage.

(3) AC charge operation

This is charge operation with the characteristics of AC constant power and DC constant voltage.

(4) AC discharge operation

This is discharge operation with the characteristics of AC constant power and DC constant voltage.

5. Functions of Storage-Bank Control Panel

The storage-bank control panel manages the statuses of as many as 65 PCSs connected in parallel and still achieves high-speed optimum control. Based on the control information received from the central load dispatching center, the panel selects banks to operate, determines output values, then distributes the control instructions to the power conditioning equipment of 13 banks. The panel also collects and manages the operation information of the banks and sends it to the central load dispatching center.

In order to obtain a desirable response in the short-period fluctuation suppression control, such control information should be processed and exchanged quickly. Accordingly, for the storage-bank control panel, we selected the optimal methods for operations, in terms of the high speed performance, such as bank operating algorithm, the detection of control measurement signals, and the communication with the central load dispatching center and power conditioning equipment.

5.1 Bi-directional communication with central load dispatching center

The storage-bank control panel has a bi-directional communication function that uses a PLC to receive downstream control instructions from the central load dispatching center and send upstream information such as the measurement values and status signals of the power conditioning systems to the central load dispatching center. A special protocol is used for the communication between the central load dispatching center and the storage-bank control panel to enable the exchange of control information necessary for the power system operation using a high-capacity storage battery system.

5.2 Bi-directional communication with power conditioning equipment

The storage-bank control panel has a communication function that a PLC receives the measurement values and status signals of power conditioning equipment and sends control instructions such as power instruction values and operation instructions to the power conditioning equipment. PE-link is used for the communication between the power conditioning equipment and storage-bank controller, allowing the power conditioning system to achieve high-speed control responses as a power conditioning system.

5.3 Frequency measurement with high-speed frequency measuring device

A high-speed frequency measuring device in the storage-bank control panel determines the system frequency, which is the main factor of the governor-free equivalent control. This high-speed frequency measuring device is the customized “PowerSATELITE II” high-performance and versatile composite measurement terminal specifically to use for high-speed frequency detection. This device has also been adopted in the micro grid system intended for remote islands(2) and can detect a system frequency within approximately 30 ms in the 50-Hz system. Fuji Electric has improved the response performance of frequency adjustment by using the system frequency signals detected at high speed for the governor-free equivalent control conducted by the power conditioning equipment of each bank or for the governor-free equivalent control intended for the batch instruction operation described later.

5.4 Individual instruction operation

The individual instruction operation operates and controls the banks individually from the central load dispatching center.

The storage-bank control panel receives the load frequency control and other control instructions from the central load dispatching center and sends them to the power conditioning equipment of the bank specified by the central load dispatching center. This configuration allows the central load dispatching center to perform the remote control, governor-free equivalent control and supplementary charge and discharge control of the specified bank.

5.5 Batch instruction operation

The batch instruction operation handles the batteries of multiple banks as one high-capacity storage battery under the control by the storage-bank control panel to carry out the control instruction for the batch of banks from the central load dispatching center.

When the central load dispatching center specifies target banks for the batch instruction operation and a power instruction value for the batch of banks, the PLC determines the number of banks to operate according to the size of the power instruction value and select banks to start or stop based on a specific priority. The priority can be determined by selecting either of the following 2 modes:

(1) Schedule reference mode

The priority of banks is registered in a daily schedule in advance and the priority of the banks to be operated on the day is determined according to the schedule.

(2) Battery status reference mode

The priority of banks to operate is continually updated based on the battery condition of the RF batteries such as *SOC* of each bank.

Governor-free equivalent control with the power conditioning equipment supports individual instruction operation. On the other hand, the storage-bank control panel includes governor-free equivalent control for a batch instruction operation and can generate a batch governor instruction value.

The batch governor instruction value generated by the storage-bank control panel is combined with the power instruction value for the batch of banks from the central load dispatching center to make a composite instruction value for the batch of banks. The composite instruction value for the batch of banks is divided up according to the size of the *SOC* and other conditions of the RF batteries and distributed to the operating banks. If this power instruction value exceeds the output limit value of individual banks, it is redistributed to other banks. This is called interbank output distribution control. This instruction value is distributed with the PLC every 20 ms. Since the output of the power conditioning equipment follows the distributed power instruction value, the composite output of the power conditioning equipment always matches the composite instruction value for the batch of banks.

5.6 Measuring server

The measuring server uses the “MICREX-VieW PARTNER(3)” equipment monitoring system. This server performs unitary management to recognize the operating condition of the entire power conditioning system. It does this by collecting the upstream and downstream information exchanged with the central load dispatching center and the status and alarm signals, measurement values and control variables of the RF batteries and power conditioning equipment from the storage-bank control panel via Ethernet*2. The measuring server is capable of displaying a history of

Fig.6 Example of trend display of “MICREX-VieW PARTNER”

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*2: Ethernet: Trademark or registered trademark of Fuji Xerox Co., Ltd.

status and alarm signals, 1-second trend display of measurement values and control variables and automatic saving in CSV data. Figure 6 shows an example of the trend display.

6. Postscript

This paper described a large-scale power conditioning system for a grid storage battery system using redox flow batteries having the world's highest capacity class of 60 MWh. The demonstration test confirmed several effects including frequency fluctuation suppression. The system is expected to work as a new adjustment measure against the output fluctuations of renewable energies.

To expand the introduction of renewable energies further, high-capacity power storage equipment is particularly indispensable for power systems and is expected to be introduced to many applications in the future. Fuji Electric will help to promote the introduction of renewable energies by aggressively acquiring capable technologies and providing optimally configured and controlled electric power storage systems.

In closing, we would like to express our deep gratitude to Hokkaido Electric Power Co., Inc. for the cooperation for the development, design and manufacturing of the large-scale power conditioning system.

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Power Stabilization System with Lead-Acid Batteries and Lithium-Ion Batteries for Galapagos Islands

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ABSTRACT

Fuji Electric has developed a power stabilization system using lead-acid batteries and lithium-ion batteries and delivered it to the Galapagos Islands, a World Natural Heritage site, in March 2016. By combining the outputs from wind turbine generators and two types of batteries with different characteristics, this power stabilization system smooths periodic fluctuations over several tens of seconds to several hours and transmits stable combined output to the electric power system. This achieved a great increase of the maximum output and facility utilization ratio of the existing wind turbine generators and markedly contributed to taking the first step toward zero consumption of fossil fuels.

1. Introduction

The electric power of the Galapagos Islands, a World Natural Heritage site located in the Republic of Ecuador, is mostly supplied by small-scale thermal power plants such as those that use diesel, and there are fears that the exhaust gas will pollute the environment. In order to respond to the growing population and increase in tourists due to the expansion of tourist spots in recent years, the preparation and adoption of an environmental friendly power supply system has become an urgent issue. The government of Ecuador adopted a measure in April 2007 aiming to achieve zero consumption of fossil fuels on Galapagos Islands by 2020, and since then, it has been working to achieve this goal.

As part of “The Project for Introduction of Clean Energy by Solar Electricity Generation System” by the Japanese government to provide grant assistance for environmental programs, Fuji Electric received the go ahead on a full turnkey project to provide equipment consisting of a photovoltaic power generation system and power supply stabilization system. Both systems were delivered in March 2016.

This paper describes the power stabilization system, which is the core component of this project.

2. Project Overview

Figure 1 shows a panoramic view of the project. Figure 2 shows the image of the overall system for the project, and Table 1 shows the specifications of the system and main equipment.

Fig.1 Panoramic view of plant

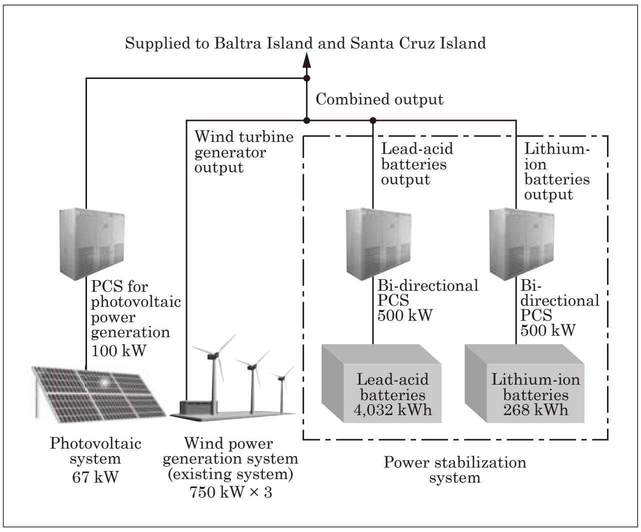

Fig.2 Overall image of system used in this project

Among the various kinds of renewable energies, the power generation output of photovoltaic power generation and wind power generation systems vary

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Table 1 Specifications for system and major equipment used in this project

System and major equipment		Specifications
Photovoltaic power generation system		Output: 67 kW
Power stabilization system	Bi-directional PCS	Model: PVI650-3/500
		Conversion system: 3-level sine-wave PWM
		DC input Operating voltage range: 345 to 600 V Maximum input current: 1,507 A
		AC output Rated capacity: 500 kVA Rated voltage: 210 V Maximum output current: 1,527 A
		Maximum conversion efficiency: 97.3%
	Lead-acid batteries	Capacity: 4,032 kWh
	Lithium-ion batteries	Capacity: 268 kWh
Wind power generation system (existing system)		Output: 750 kW × 3

greatly depending on weather conditions. Therefore, the integration of these types of power sources into small-scale power systems will impact the power quality (voltage and frequency). The government of Ecuador installed a wind power plant consisting of three 750-kW wind turbine generators ahead of the project. However, power quality issue due to the output fluctuations prevented the plant from operating at its rated output, causing its low utilization despite sufficient amount of wind.

By employing the power stabilization system, the power plant has been able to suppress output fluctuations for the wind turbine generators to increase the equipment utilization and succeeded in raising the amount of renewable energy based power supply. The system controls the high-speed charging and discharging of storage batteries by means of a bi-directional power conditioning sub-system (PCS). It combining lead-acid batteries with lithium-ion batteries to supply high-quality power by taking advantage of the characteristics of those storage batteries.

3. Power Stabilization System

3.1 Overview

The power stabilization system combines the outputs of the wind turbine generators, lead-acid batteries and lithium-ion batteries to smooth periodic fluctuations over several tens of seconds to several hours and transmits a stable combined output to the power system. The lead-acid batteries are suitable for peak shifting control that needs a large battery capacity because of their low cost-to-capacity ratio. On the other hand, lithium-ion batteries are suitable for controlling output fluctuations over short periods of time because they have a high energy density and can highly frequently charge and discharge with high-speed.

Table 2 Main functionality of power stabilization system

Function	Lead-acid batteries	Lithium-ion batteries
Wind turbine generator output fluctuation suppression function	Required (Restricts output during peak shifting)	Required
Peak shifting function	Required (Stops use during backup)	—
Output fluctuation suppression backup function	Required	—

Table 2 shows the main functionality of the system is described, and Fig. 3 shows the configuration.

The purpose of the output fluctuation suppression function for wind turbine generators is to compensate periodic fluctuations that occur in the output of the wind turbine generators over several tens of seconds to several hours by using the output of the batteries. With this function, the system calculates output fluctuation suppression command values and allocating them to the lead-acid batteries and lithium-ion batteries.

The peak shifting function aims to smooth loads by charging the batteries during times of low power demand such as night when there is an excess of power and discharging the batteries during times of peak power demand. Target values for peak shifting output and time periods for starting and stopping the function are set in the monitoring control PC, which calculates the peak shifting command values for smoothing the power.

The backup function of the output fluctuation suppression function stops the peak shifting with the lead-acid batteries and performs backup of the output fluctuation suppression when the lithium-ion batteries are stopped due to maintenance or accidents. It aims to increase the output of the lead-acid batteries that can be used for output fluctuation suppression in order to ensure continuous wind power generation.

Each battery supplies high-quality power by providing an output according to each command value.

3.2 Output fluctuation suppression function for wind turbine generators

(1) Design

In order to minimize the impact of wind power generation on an interconnected system, measures to suppress frequency fluctuation are sometimes taken, such as keeping the difference between the maximum and minimum output values within a specified value at any time period.

The output fluctuation suppression function for wind turbine generators of this system adopts variable time constant control that continuously controls the time constant of a fluctuation component removal filter based on the output fluctuations of the wind turbine generators. the filter is equipped with the output

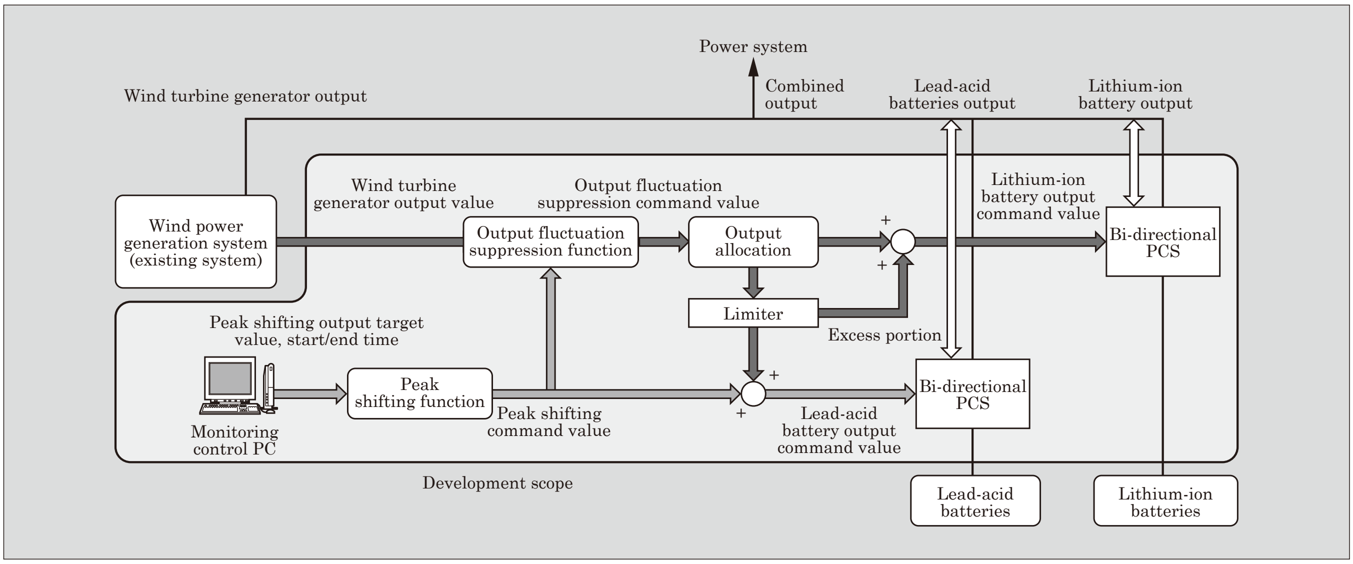

Fig.3 Configuration of power stabilization system

fluctuation suppression function shown in Fig. 3. This control increases the time constant when the output fluctuation is large, and decreases the time constant when the output fluctuation is small, thus ensuring the fluctuation of the combined output to be within a specified rate of change*[1]. Before starting the design, we utilized the measured wind speed data of the Nishime Wind Power Station possessed by Fuji Green Power, a group company of Fuji Electric, to run the simulation of an output fluctuation suppression for the system. From the results, we learned that we could maintain a change rate of 45 kW/min or less for 95% of an entire period. This value is equivalent to 2% of the rated output of the wind turbine generators, meaning that the rate of change is small enough for output fluctuation suppression. Since the site of this project has even less wind speed fluctuation than the Nishime Wind Power Station, we can expect an even better effect.

The output allocation of the output fluctuation suppression command values ensures that the output fluctuation rate is maintained within a specified value by allocating to the lead-acid batteries and lithium-ion batteries so as to maintain the target charging rates for each battery.

Lithium-ion batteries have a smaller capacity than lead-acid batteries; thus, intensive allocation to lithium-ion batteries may cause the shortages of empty-charge capacity needed for charging or charge capacity needed for discharging. If the output of the lithium-ion batteries is restricted because of insufficient empty-charge capacity or charge capacity, it will become difficult to maintain output fluctuation suppression. The lead-acid batteries have a large ratio of charging capacity used for peak shifting to charging capacity used in output fluctuation suppression. For peak shifting operation, charging capacity is, therefore, adjusted to a low target value when in charging, and a high target value when in discharging in advance. For lithium-ion batteries, when the wind turbine generator output is low, the target charging capacity is set low in preparation for a surge in output, but when the wind turbine generator output is high, the target charging capacity is set high in preparation for a sudden drop in output.

After the output fluctuation suppression command value is allocated to the lead-acid batteries, two limiters are established not to inhibit peak shifting. The first is restricting the allocation to the lead-acid batteries during peak shifting from ±500 kW*[2] to ±200 kW in order to ensure that the peak shifting command value, which is another function of lead-acid batteries, is not canceled out. The second is restricting the allocation to the lead-acid batteries when the current charging capacity deviate more than a certain amount from the target charging capacity, thus ensuring the charging capacity needed for peak shifting. Furthermore, the lithium-ion batteries output the portion that exceeds the restriction.

With regard to the wind turbine generator output fluctuation suppression function, we confirmed the operation through a simulation and field test.

(2) Simulation

The simulation generated the simulated wind turbine generator output in a stepwise manner and confirmed the operation of the wind turbine generator output fluctuation suppression function. Figure 4(a) shows the results of the simulation.

At approximately 10:06, we stepped down the simulated wind turbine generator output by 0.5 MW from

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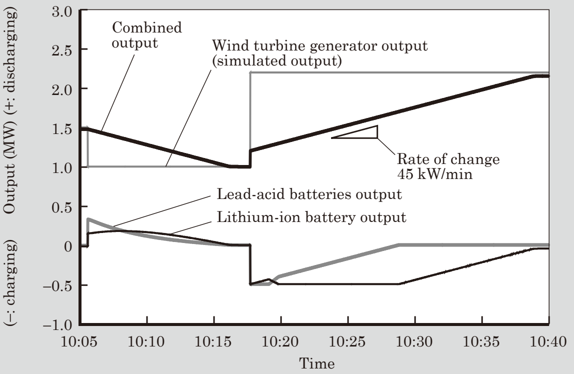
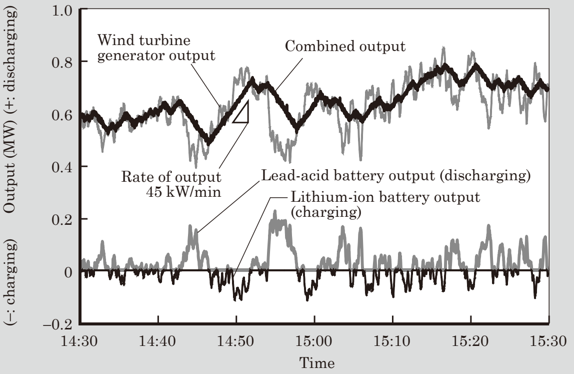
*1: Specified rate of change: refers to dividing the output fluctuation (maximum value − minimum value) in the time width specified by the customer by the time width.

*2: ±500 kW: + refers to discharging and − refers to charging.



(a) Simulation



(b) Field test

Fig.4 Confirmation of operation of wind turbine generator output fluctuation suppression function

1.5 MW to 1.0 MW. The total output capacity of the lead-acid batteries and lithium-ion batteries was 1.0 MW, which is larger than fluctuation of 0.5 MW, the step fluctuation was canceled out by the variable time constant control so that the rate of change for the combined output would be 45 kW/min.

At approximately 10:18, we stepped up the simulated wind turbine generator output by 1.2 MW from 1 MW to 2.2 MW. The fluctuation was larger than the total output capacity of the lead-acid batteries and lithium-ion batteries. Therefore, by maximizing the output of both batteries, we suppressed fluctuation to 0.2 MW, and thus minimized the impact on the system.

Furthermore, during the time period between approximately 10:06 and 10:15, since the charging capacity of both batteries required in approaching the target charging capacity was about the same, both batteries discharged approximately the same amount of power. During the time period between approximately 10:18 and 10:40, when the wind turbine generator output rose, charging for the lithium-ion batteries, which set the target charging capacity high, was given priority in order to prepare for the subsequent sudden drop in output.

(3) Field tests

Figure 4(b) shows the results of the field tests. We confirmed that we were able to suppress the fluctuation of the wind turbine generator output using the output of the lead-acid batteries and lithium-ion batteries similar to the simulation. Combined output maintained a constant rate of change. At this time, the lead-acid batteries were almost fully charged through a equalizing charge test, which was implemented before the field test. In order to ensure room for charging, the discharge of the lead-acid batteries was prioritized, and thus discharging was implemented in lead-acid batteries and charging in the lithium-ion batteries.

3.3 Peak shifting function

(1) Design

The peak shifting function smooths loads by charging the batteries during times such as night when power demand is low and lower than generation capacity, while discharging the batteries during peak power demand. This operation has made it possible to suppress the sharp fluctuations in output of the conventional diesel generators in the Galapagos Islands, reduce the number of start-up and stop operation, and eliminate low output operation that adversely impacted power generation efficiency.

Furthermore, the operation of discharging the lead-acid batteries according to the evening demand peak reduced the number of diesel power generators in operation, thus making it possible to suppress fuel consumption and the accompanying CO_2 emissions. Specifically, since the fluctuation in demand differed on weekdays and holidays, peak shifting time periods can be set accordingly.

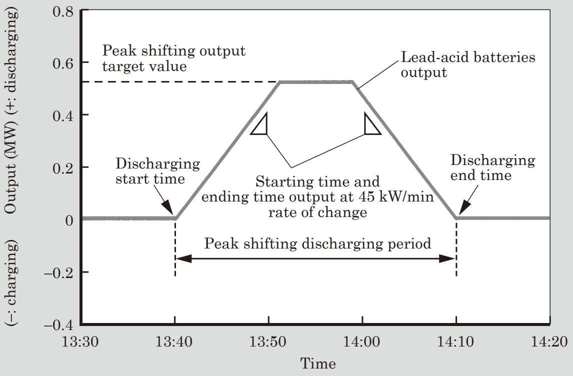
We confirmed the peak shifting function through a factory test and field test.

(2) Factory test

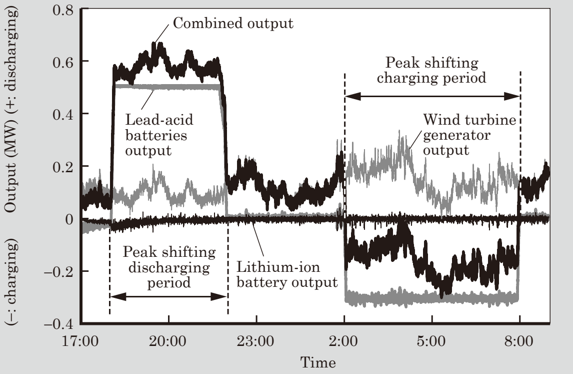
Figure 5(a) shows the results of the factory test. Discharging begins at the peak shifting discharging start time, which was set at 13:40, and discharging ends at the peak shifting end time, which was set at 14:10. In order to reduce the impact on the system, output is implemented at a change rate of 45 kW/min at the peak shifting start and end times. By doing this, we confirmed that peak shifting was implemented according to a target output and start and end times, which were set with the monitoring control PC.

(3) Field test

Figure 5(b) shows the results of the field tests. We confirmed that the lead-acid batteries operated in peak shifting and output fluctuation suppression at the same time. Between approximately 18:00 and 22:00, the lead-acid batteries discharged at 500 kW to shift the demand peak. Between 2:00 and 8:00, they charged at 300 kW for peak shifting due to the low power demand. Since the lead-acid batteries operate in peak shifting and output fluctuation suppression at the same time, their output fluctuates, instead of holding constant at a peak shifting output target value.

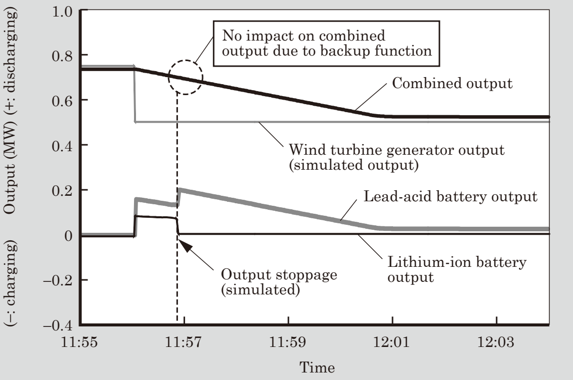


(a) Factory test

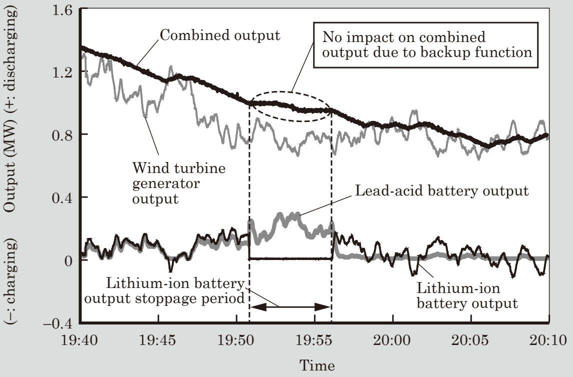


(b) Field test

Fig.5 Confirmation of operation of the peak shifting function



(a) Simulation



(b) Field test

Fig.6 Confirmation of operation of the output fluctuation suppression backup function

3.4 Backup function for output fluctuation suppression

(1) Design

When the lithium-ion batteries are stopped due to maintenance or accidents, the lead-acid batteries stop peak shifting and back up output fluctuation suppression. By doing this, the output of the lead-acid batteries that can be used for output fluctuation suppression is increased, and the wind power generation can continue to operate.

During the lithium-ion batteries are stopped, the lead-acid batteries alone hardly perform both output fluctuation suppression and peak shifting at the same time. When the output fluctuation suppression function cannot be kept, the fluctuation of the wind turbine generator output may adversely impacts the power quality of the interconnected power system. In this case, the output of the wind turbine generator has to be suppressed, or in the worst case, be stopped. However, since this may lead to a loss in power generating opportunities for the wind turbine generators, the lead-acid batteries only implement output fluctuation suppression without implementing peak shifting when the lithium-ion batteries are stopped. This backup function enables continuous operation of the wind turbine generators.

We confirmed the operation of the backup function for suppressing output fluctuation through simulation and field tests.

(2) Simulation

Figure 6(a) shows the results of the simulations. When the lithium-ion batteries are stopped during the operation of output fluctuation suppression, their output drops to zero. We confirmed that, in this case, the lead-acid batteries take over the operation and keep it without any impact on the combined output.

(3) Field test

Figure 6(b) shows the results of the field tests. As one of the test conditions, we stopped the operation of the lithium-ion batteries from approximately 19:51 to 19:56. When the output of the lithium-ion batteries decreased, the output of the lead-acid batteries simultaneously rose to back up the output of the lithium-ion batteries. We confirmed that the operation of output fluctuation suppression continues without any impact on combined output. Furthermore, when the lithium-ion batteries restarted, the operation of output fluctuation suppression by the lithium-ion batteries simultaneously started. We confirmed that the operation continues without any impact on combined output.

4. Postscript

We described the power stabilization system that uses lead-acid batteries and lithium-ion batteries for the Galapagos Islands. The use of this system has achieved a significant increase in the maximum output and facility utilization ratio of the existing wind turbine generators and greatly contributed to taking the first step toward zero consumption of fossil fuels.

Based on our technology cultivated through building this system, we intend to develop a power stabilization system that can suppress both short-cycle and long-cycle output fluctuations to contribute to the expanded use of renewable energies.

New Wastewater Treatment Solution Using *Bacillus*

TAGUCHI, Kazuyuki* **SATO, Masanori*** **HANAI, Yosuke***

ABSTRACT

Fuji Electric has developed a new wastewater treatment solution using *Bacillus*. This solution uses special *Bacillus* that we found suitable for wastewater treatment among a number of such species existing in nature. This allows existing wastewater treatment facilities to reduce the electric power cost for aeration and sludge disposal cost without the need for large-scale modification or extension of the facilities. The sludge-less wastewater treatment system has a magnetic separator that separates sludge by magnetic force, achieving significant space-saving and better treatment performance. In an application example for factory wastewater treatment, the new wastewater treatment solution reduced the running cost by 20%, and the sludge-less wastewater treatment, by 25%.

1. Introduction

It is mandatory to treat wastewater from factories and workplaces properly according to stringent wastewater standards based on the “Water Pollution Prevention Act” and “more stringent standards” specified in ordinances of local governments. Although the conventional activated sludge process is widely used for wastewater treatment, it has a high running cost such as the costs of electricity and sludge disposal.

In order to reduce such running cost in food, beverage and chemical plants, Fuji Electric has developed a new wastewater treatment solution using *Bacillus*.

2. Wastewater Treatment and Running Cost

Biological treatments, the conventional activated sludge process in particular, have been used widely for the treatment of organic wastewater in various plants because they are easy to maintain and manage. Figure 1 shows the basic flow of wastewater treatment and an example of the facility. The conventional activated sludge process is a method to use microorganisms suspended in wastewater to take in the pollutants and purify the wastewater, and then have the microorganisms settle and remove them. Since the microorganisms require oxygen to decompose the pollutants they take in, air injection with a blower (aeration) is necessary for the waste water to increase concentration of the dissolved oxygen in the wastewater to the level required by the microorganisms. Moreover, the microorganisms decompose the pollutants to grow and propagate, and they need to discharge the agglomeration of

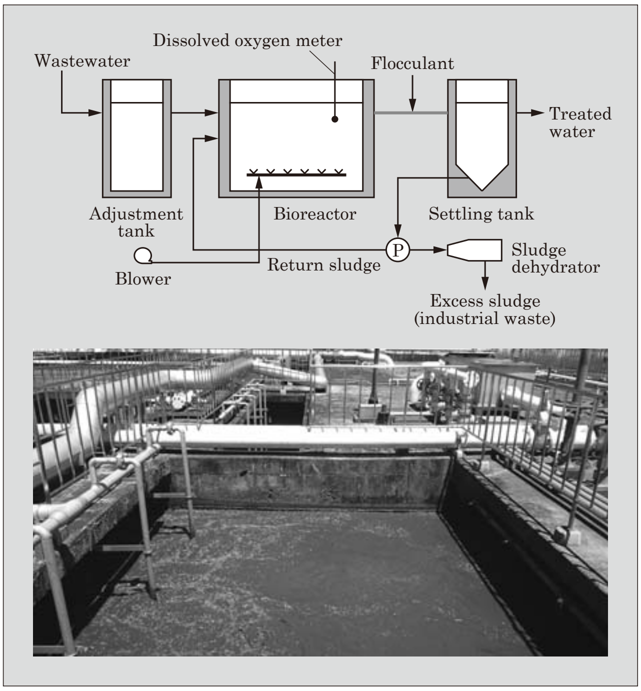


Fig.1 Basic flow of wastewater treatment and example of facility

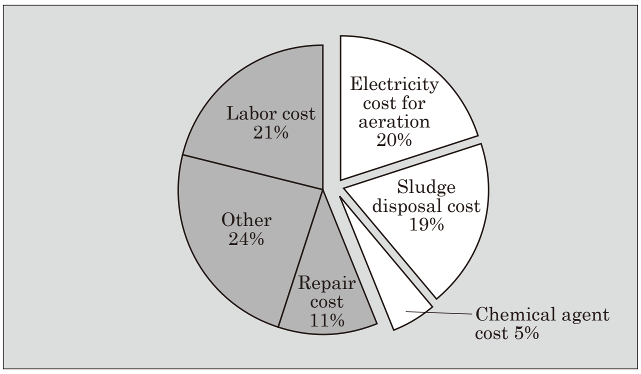


Fig.2 Example of running cost for wastewater treatment

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excessively propagated microorganisms (excess sludge) out of the system. The discharged excess sludge is treated as industrial waste.

Figure 2 shows an example of the running cost for wastewater treatment in a plant. The electricity cost for aeration and sludge disposal cost (industrial waste disposal cost) account for a large portion of the running cost for wastewater treatment, around 40%.

3. Wastewater Treatment Using *Bacillus*

There are many *Bacillus*[*1] species existing in nature and some of them have a high wastewater purification ability to decompose highly concentrated organic substances in a short time and also secrete a large quantity of enzymes that can decompose excess sludge. By finding such a species and using it as *Bacillus* for wastewater treatment, Fuji Electric has managed to both reduce running cost and improve the performance of wastewater treatment.

3.1 Features

(1) Reduced running cost
  - (a) Electricity cost for aeration can be reduced by 10% to 40% compared with conventional methods.
  - (b) Sludge disposal cost can be reduced by 20% to 40% compared with conventional methods.
  - (c) Chemical agent cost can be reduced by 10% to 20% compared with conventional methods.

(2) Improved treatment performance
  - (a) The capacity for addressing fluctuations in the quality of the wastewater that flows into the facility can be expanded. This provides a better treatment performance compared with conventional methods and improves water quality.
  - (b) Foul odors can be suppressed to improve the surrounding environment and work environment.

(3) Easy introduction, maintenance and management
  - (a) Large-scale capital investment is unnecessary because the wastewater treatment using *Bacillus* can reduce sludge production and aeration volume without the need for alteration or extension to existing wastewater treatment facilities and equipment.
  - (b) The operation starts by pouring *Bacillus* into an existing bioreactor. This is required for the first time only. After that, the operator needs only to add a small amount of chemical agent (activator) daily in order to retain the dominance and performance of the *Bacillus*.
  - (c) Retaining the number of *Bacillus* that exceeds about 100 times the initial number (*Bacillus* dominant state) can maintain the effects of reducing excess sludge and aeration volume while preserving the water quality.

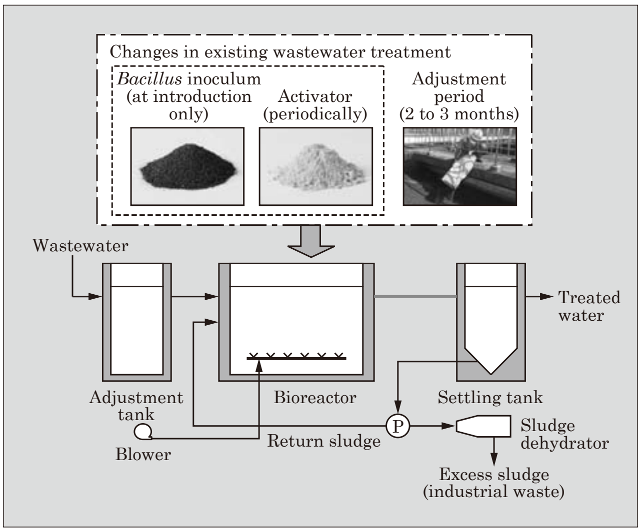

Fig.3 General process of wastewater treatment using *Bacillus*

  - (d) The adjustment period is 2 to 3 months, during which the aeration volume and sludge concentration should be adjusted to ensure *Bacillus* are dominant.

Figure 3 shows a typical process of the wastewater treatment using *Bacillus*. The major items to be adjusted are aeration volume and the amount of return sludge.

3.2 Effects of *Bacillus* in wastewater treatment

(1) *Bacillus* for wastewater treatment

Bacillus is one of facultative anaerobic bacteria[*2] that can live with a low amount of dissolved oxygen[*3]. The conventional activated sludge process uses *Bacillus* existing extensively in activated sludge. The *Bacillus* for wastewater treatment can purify pollution components with less amount of oxygen. This allows the blower to operate with lower air volume, resulting in a reduction in the electricity cost for aeration.

(2) Activator

Adding an activator consisting mainly of minerals such as silicon, iron and magnesium to the *Bacillus* for wastewater treatment promotes the propagation of the bacteria, so that it retains its dominance, resulting in stable purification performance. The activator for wastewater treatment enhances the ability of the *Bacillus* for wastewater treatment to secrete enzymes which decompose proteins, carbohydrates and other sludge components. This promotes the decomposition

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[*1] *Bacillus*: Refer to “Supplemental Explanation” on page 60.

[*2] Facultative anaerobic bacteria: Generic term referring to bacteria that can live with or without oxygen, or more specifically that can live with oxygen in a low concentration.

[*3] Dissolved oxygen: Oxygen that is dissolved in water

of excess sludge and decreases the amount of sludge production.

Moreover, the *Bacillus* for wastewater treatment has a property of increasing the activity of a proteolytic enzyme (secretion) by about 30 times in response to the addition of the activator. This activity is about 10 times higher than those of other *Bacillus* species (see Fig. 4). The *Bacillus* for wastewater treatment has another property of increasing the activity of a carbohydrate-degrading enzyme by about 25 times in response to the addition of the activator. This activity is about 3 times higher than those of other *Bacillus* species (see Fig. 5). These properties contribute to the improvement of the abilities of decomposing the pollution components and purifying sludge components in wastewater compared with conventional methods.

(3) Sludge reduction

Fuji Electric has found out that the ability of the *Bacillus* for wastewater treatment to reduce excess sludge relies on the working of the enzymes secreted by the bacteria.

Figure 6 is a graph showing the comparison of the remaining sludge before and after the enzymes of the *Bacillus* for wastewater treatment (sterilized culture liquid) were added to the excess sludge of a wastewater treatment facility using the conventional activated sludge process. Adding the enzymes promoted the decomposition and removal of about 40% of the sludge. This explains how the enzymes could reduce the amount of sludge.

(4) Improved sludge settlement and odor removal

The *Bacillus* for wastewater treatment has high flocculation and cohesion, so that it can improve sludge settlement.

Figure 7 shows a comparison of sludge volumes (SV, rate of activated sludge settlement) in 30 minutes between the sludge treated with *Bacillus* for wastewater treatment and the sludge treated with conventional activated sludge process. The sludge treated with *Bacillus* for wastewater treatment settles faster than the sludge treated with the conventional activated sludge process. This makes solid-liquid separation easier and reduces discharge of the sludge.

Moreover, the *Bacillus* for wastewater treatment can remove odors by decomposing foul odor components such as hydrogen sulfide and ammonium.

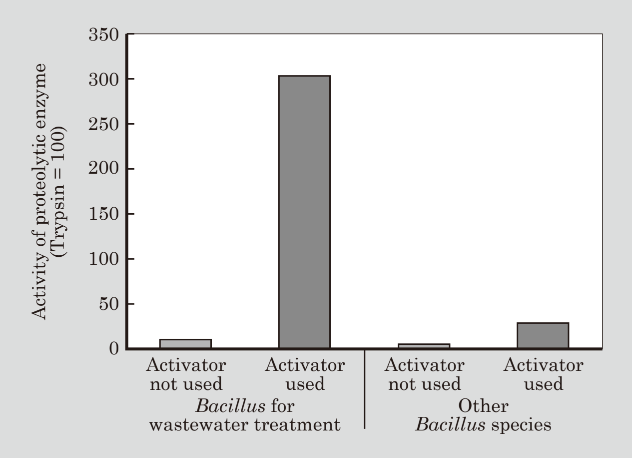


Fig.4 Activity of proteolytic enzyme

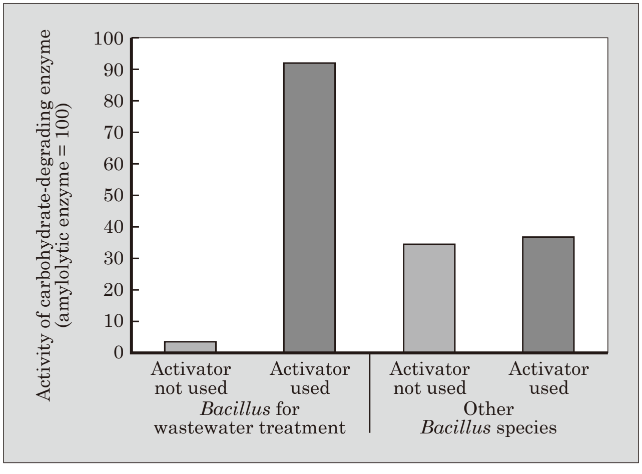


Fig.5 Activity of carbohydrate-degrading enzyme

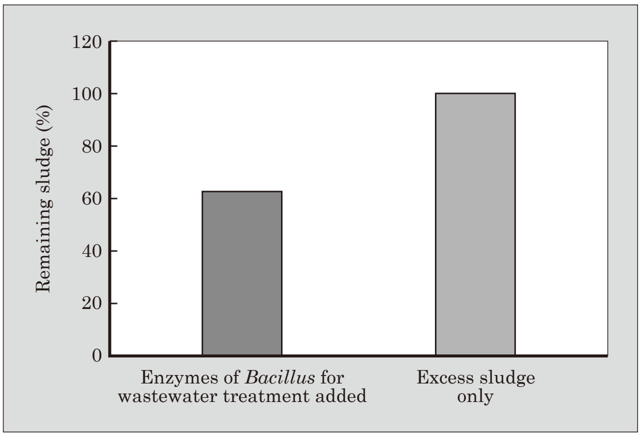


Fig.6 Sludge decomposition with enzymes of *Bacillus* for wastewater treatment

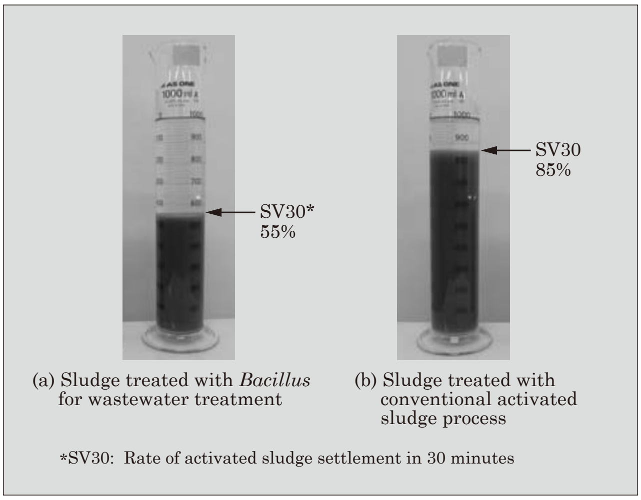


Fig.7 Improvement of sludge settlement due to use of *Bacillus* for wastewater treatment

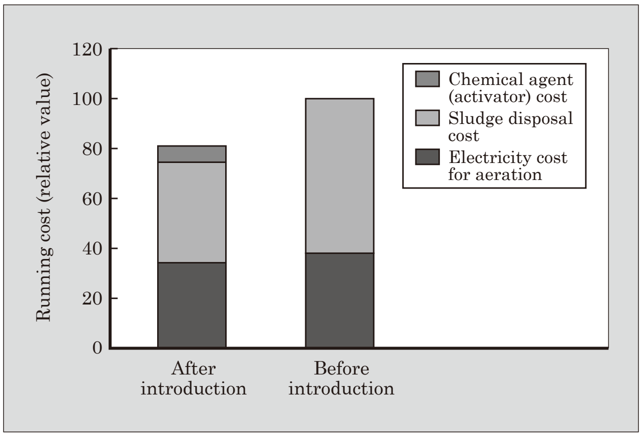


Fig.8 Example of introducing *Bacillus* for wastewater treatment

3.3 Application example

Fuji Electric has applied the wastewater treatment using the *Bacillus* for wastewater treatment to a factory of company A. This factory has introduced the conventional activated sludge process and the amount of wastewater is 1,500 m^3/day. The purpose is to reduce the sludge disposal cost in the running cost for wastewater treatment.

(1) Introduction method

For the introduction, we did not make any alteration or extension to the existing wastewater equipment but only poured an inoculum of the *Bacillus* for wastewater treatment. A specified amount of activator was added to the bioreactor every day. The aeration volume and the amounts of return sludge and waste sludge were adjusted during the 3-month adjustment period. In this adjustment period, we confirmed that the number of *Bacillus* for wastewater treatment increased to about 100 times the initial number, and it reached its dominant state.

(2) Introduction effects

Using the *Bacillus* for wastewater treatment reduced the electricity cost for aeration and sludge disposal cost by 10% and 35% respectively compared with the costs before the introduction. After subtracting the increased cost of the activator added every day, the running cost for the entire wastewater treatment was reduced by about 20% (see Fig. 8).

4. Sludge-Less Wastewater Treatment System

Using the *Bacillus* for wastewater treatment together with a magnetic separator makes it possible to construct a sludge-less wastewater treatment system that produces almost no excess sludge. Figure 9 shows the process of this system. When a magnetic separator is added to the wastewater treatment using *Bacillus* shown in Fig. 3, the settling tank and return sludge can be eliminated and the sludge dehydrator is also unnecessary.

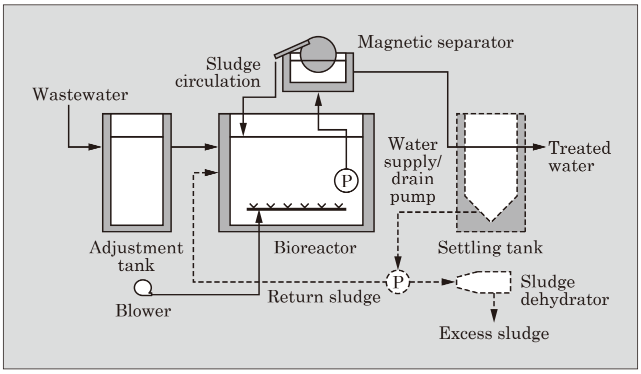


Fig.9 Process of sludge-less wastewater treatment system

4.1 Features

This system is targeted mainly at workplaces that have to upgrade, newly construct or extend their wastewater treatment facilities due to increased wastewater and pollutants caused by increased production or plant integration. It can satisfy the need for building a facility in an extremely tight space or for suppressing the increase in running cost for wastewater treatment. The system is characterized by the following features compared with conventional systems using the conventional activated sludge process.

(1) Effects on running costs

- (a) Sludge disposal cost can be reduced by 90% or more. No organic sludge is produced, and the system only requires inorganic sediments to be disposed of several times a year.
- (b) There is no electricity cost for aeration for sludge treatment.
- (c) There is no chemical agent cost for sludge treatment.

(2) Improved ability of purifying pollution components

The system can handle a pollutant concentration 3 times higher than that of the conventional system.

(3) Reduced initial investment

- (a) A settling tank is unnecessary.
- (b) The capacity of the bioreactor can be reduced one half to one third.
- (c) A sludge dehydrator is unnecessary.

Since the magnetic separator separates the sludge into solid and liquid, a settling tank used in conventional methods becomes no longer necessary. Since no organic sludge is produced, a sludge dehydrator is unnecessary. Inorganic sludge, however, should be removed several times a year.

(4) Space saving

The space occupied by wastewater treatment equipment can be reduced to half compared with conventional systems.

(5) Improved treatment performance

- (a) The nitrogen removal rate is 90% or more.
- (b) Foul odors can be suppressed to improve the surrounding environment and work environ-

ment.

4.2 System construction

(1) Calculating sludge production

As shown in equation (1), the sludge production during wastewater treatment is calculated by multiplying the biochemical oxygen demand (*BOD*) and suspended solid (*SS*) by the amount of wastewater and their sludge conversion rates respectively, adding the products to obtain the amount of increased sludge (propagated microorganisms), and then subtracting the amount of decreased sludge due to sludge self-digestion and the decomposition by enzymes from the sum.

As described above, the *Bacillus* used in this system secretes a large quantity of enzymes that decompose sludge. The amount of these enzymes increases with the concentration of the *Bacillus*. Consequently, when the sludge concentration (mixed liquor suspended solids [MLSS]) in the bioreactor is increased to enhance the concentration of the *Bacillus* of this system, the amount of sludge decomposing enzymes secreted by the *Bacillus* increases to effectively treat the sludge that has increased due to the biological treatment of pollutants. This promotes the decomposition of the sludge, allowing the operation to produces no sludge.

$$W = A \times BOD \times Q + B \times SS \times Q - C \times MLSS \times V \cdots\cdots(1)$$

W: Sludge production (kg/d)
BOD: Biochemical oxygen demand (kg/m^3)
SS: Suspended solid (kg/m^3)
$MLSS$: Mixed liquor suspended solids (kg/m^3)
Q: Amount of wastewater (m^3/d)
V: Capacity of bioreactor (m^3)
A: BOD sludge conversion rate (%)
B: SS sludge conversion rate (%)
C: Self-digestion rate (%)

(2) Solid-liquid separation of sludge

The surfaces of the bacterial bodies in the activated sludge are negatively charged and magnetic powder (magnetite, Fe_3O_4) is positively charged. Consequently, when mixed, they adhere to each other and the activated sludge is magnetized.

As shown in Fig. 10, when magnetic powder is added to the activated sludge and the sludge is stirred, the solids in the sludge and the powder quickly adhere to each other. This makes the activated sludge become magnetic activated sludge that allows for quick and efficient solid-liquid separation with a magnetic force.

(3) Magnetic separator

Fuji Electric has developed a magnetic separator capable of continuously separating solids and liquids in the magnetic activated sludge with a magnetic force and established a wastewater treatment process without a need for final settlement. Unlike conventional solid-liquid separation based on gravity settlement, sludge is forced to concentrate, so that the system can retain a high concentration of the sludge in the bioreactor. This strikes a balance between the increase in and self-digestion of the sludge to operate without producing sludge.

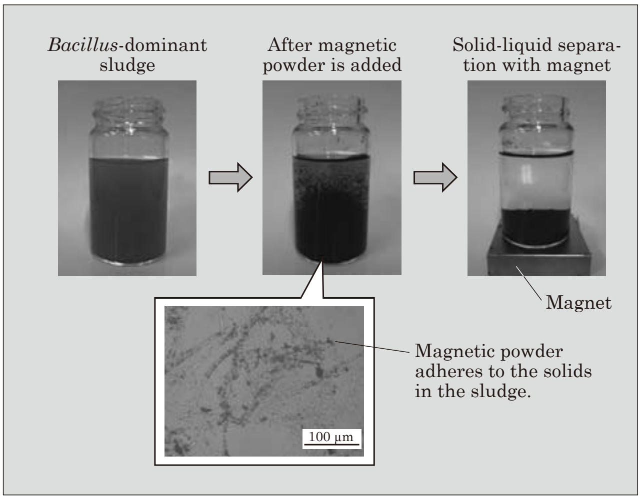


Fig.10 Magnetic activated sludge

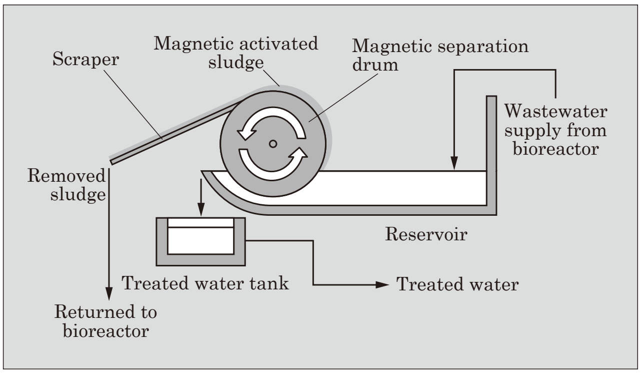


Fig.11 Schematic diagram of magnetic separator

Figure 11 shows a schematic diagram of the magnetic separator used in the system. The magnetic activated sludge in the bioreactor is pumped up and sent to the reservoir of the magnetic separator. A magnetic drum for magnetic separation is turning inside the reservoir. When the magnetic activated sludge passes by the drum, it adheres to it. The sludge is later removed with a scraper and returned to the bioreactor.

(4) Improved purification ability

Since the system can ensure a high concentration of the activated sludge is retained in the bioreactor, the pollutant purification ability of the bioreactor per unit volume can be increased to about 3 times.

4.3 Application example

Fuji Electric has applied this system to the factory of food manufacturing company B. This factory has introduced the conventional activated sludge process and the amount of wastewater is 2,000 m^3/day. The purpose is to reduce the sludge disposal cost and to address the increased wastewater load due to increased production.

(1) Introduction procedure

For the introduction, we installed a magnetic separator and a pump that feeds magnetic activated sludge to the separator. We poured an inoculum of the *Bacillus* and magnetic powder into the bioreactor of the system. A specified amount of activator was added to the bioreactor every day.

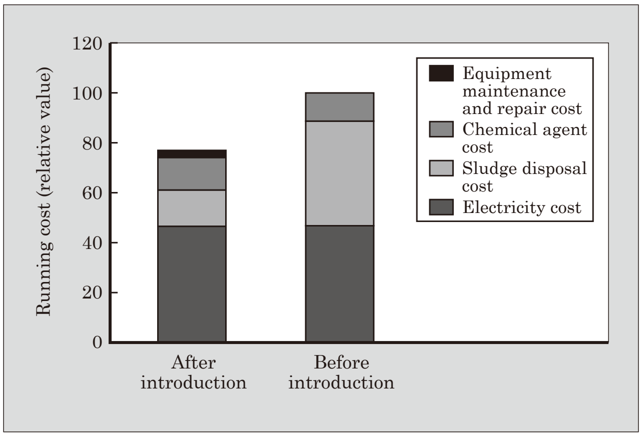


Fig.12 Introduction effects of sludge-less wastewater treatment system

(2) Introduction effects

This system reduced the sludge produced through biological treatment by 90% compared with conventional methods, and the amount of total sludge production including the sludge produced in pretreatment by about 66%. The system can treat 3 times more pollutants in wastewater than the conventional amount. After subtracting the increased costs of the chemical agent (activator) added every day, supplementary magnetic powder, and maintenance and repair of the magnetic separator, the running cost for the entire wastewater treatment was reduced by about 25% (see Fig. 12).

5. Postscript

This paper described a new wastewater treatment solution using *Bacillus* that targets wastewater treatment equipment in food, beverage and chemical plants. By expanding the applications of this solution, Fuji Electric intends to help reduce the operation and maintenance costs for wastewater treatment and lessen environmental loads.

Supplemental Explanation

Supplemental explanation 1 *Bacillus*

p.55

Bacillus is a genus of gram-positive bacteria existing ubiquitously in nature such as in soil or under water. It is a heterotrophic bacterium that produces endospores, has rod-shaped cells, and can be either aerobic or facultative anaerobic. *Bacillus* species includes *Bacillus subtilis* used for the production of various industrial enzymes (for food or detergent) and *Bacillus thuringiensis* used as biological pesticide. *Bacillus natto* is a strain of *Bacillus subtilis*. There are many other species that adapt to various extreme environments including high and low temperatures, high and low pH, high salt concentration and high pressure. About 300 species of *Bacillus* are known to live with different properties. Fuji Electric has found a *Bacillus* species suitable for wastewater treatment among these and used it for wastewater treatment systems.

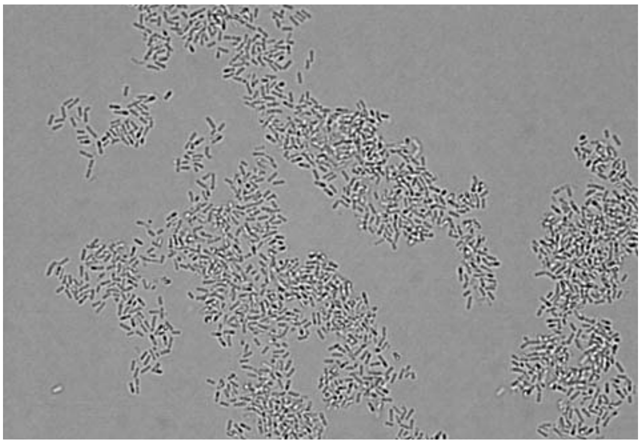


Fig.1 *Bacillus* for wastewater treatment

3rd-Generation Direct Liquid Cooling Power Module for Automotive Applications

ENOMOTO, Kazuo* KOYAMA, Takahiro* SATO, Kenichiro*

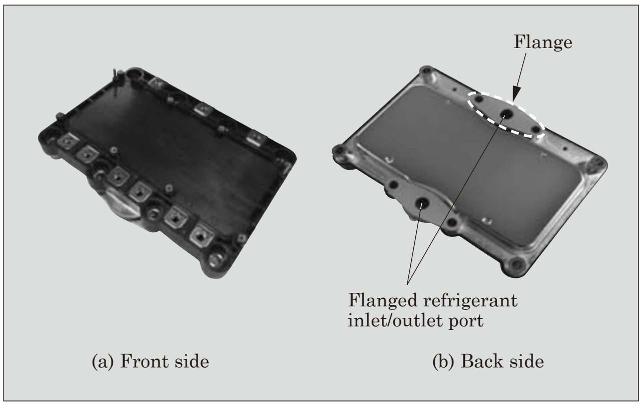
As the control of CO_2 emissions becomes tighter in order to prevent global warming, the development of hybrid electric vehicles (HEVs) using both an engine and motor and electric vehicles (EVs) propelled only by a motor, has been advancing at a rapid pace and their further proliferation is anticipated. In HEVs and EVs, the space for installing an inverter used for power control is limited. High power density and further miniaturization have been required to accommodate the high output batteries and motors.

To satisfy such requirements, Fuji Electric has developed the 3rd-generation direct liquid cooling power module for automotive applications (see Fig. 1). This product provides higher heat dissipation performance than conventional products by using an optimal refrigerant passage. Moreover, by employing a cover-integrated aluminum water jacket and refrigerant inlet and outlet ports with a flange structure, users only need to ensure the flow of a specified amount of refrigerant through the inlet and outlet flanges.

Fuji Electric has applied the 7th-generation chip technology to insulated gate bipolar transistors (IGBTs) to reduce power loss and used reverse-conducting IGBTs (RC-IGBTs) with built-in free wheeling diodes (FWDs) to increase the power density of the module and reduce the size .

1. Features

The major specifications of this newly commercialized 3rd-generation direct liquid cooling power module for automotive applications are shown in Table 1. The main features are as follows:



(a) Front side (b) Back side

Fig.1 3-generation direct liquid cooling power module for automotive applications

Table 1 Major specifications of 3-generation direct liquid cooling power module for automotive applications

Item	Specification
Collector - emitter voltage	750 V
Rated current	800 A
Maximum operating temperature	175 °C
Dimensions	W162 × D116 × H24 (mm)
Mass	560 g

(1) Smaller power module

The use of RC-IGBTs integrating an IGBT with FWD has enabled a 15% miniaturization compared with conventional products.

This power module has a cooling structure integrating high heat-dissipating liquid cooling fins with a cover to improve heat dissipation performance and allow a low-profile design. These have helped to achieved about 1.6 times higher power density than that of the 2nd-generation direct liquid cooling power module.

(2) Lower inductance of main terminal wiring

Separating the input terminal of each phase having the shortest wires lower the inductance. This reduces the switching loss caused by quick switching operation and the surge voltage during current cutoff.

2. Background Technologies

2.1 RC-IGBT applied technology

RC-IGBT employs a field stop IGBT (FS-IGBT) and has a structure that allocates the IGBT and FWD regions alternately in stripes on one chip (see Fig. 2). This one-chip structure can reduce an area called a guard ring, which is provided to ensure the

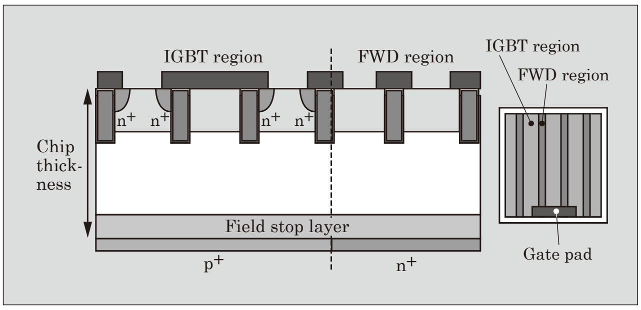


Fig.2 Schematic structure of RC-IGBT

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* Electronic Devices Business Group, Fuji Electric Co., Ltd.

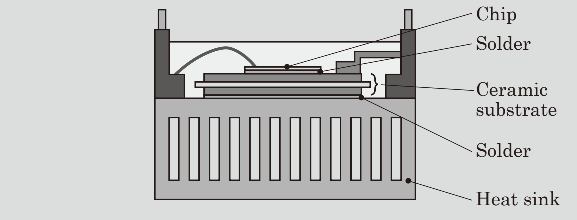
withstand voltage on the periphery of the chip, so that the chip area becomes smaller compared with conventional products consisting of 2 chips. Since the FWD region releases heat while the IGBT is operating and vice versa, it is effective in reducing thermal resistance during respective operations of IGBT and FWD. Furthermore, application of the latest thin wafer processing technology and optimization of a trench structure and channel density have led to low power dissipation, which allows the chip to be miniaturized.

2.2 Heat dissipation and cooling technologies

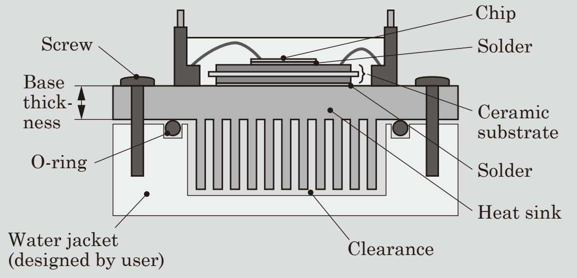
Figure 3 shows the cross-section views of the conventional structure of a direct liquid cooling power module and the new structure adopted in the new product. In the conventional structure, users design and prepare their own water jackets, so the heat sink and water jacket were provided as separate parts. Consequently, users had to not only design the flow passage but also consider water-tightness and the clearance between the fin end and jacket bottom in the design. The new structure that integrates the heat sink with water jacket eliminates the need of considering the clearance. The fin shape has also been designed to improve heat dissipation to 30% higher than that of the conventional structure.

2.3 Inductance reducing technology

Lowering the inductance inside the package decreases the surge voltage during turn-off and reverse recovery. The use of RC-IGBT and the optimized internal layout allows the new product to have an internal inductance that is almost half compared with conventional products. When a power module is used, smoothing capacitors are connected to it. Consequently, it is also important to suppress the surge voltage generated across P- and N-terminals during turn-off. Figure 4 shows the surge voltage across the P- and N-terminals during turn-off.

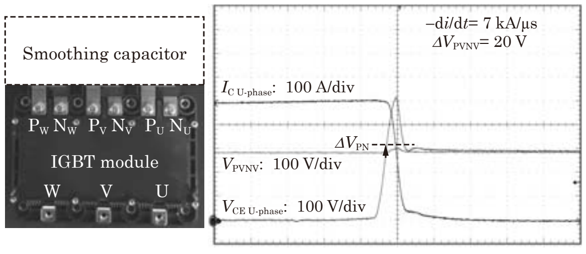


(a) New structure

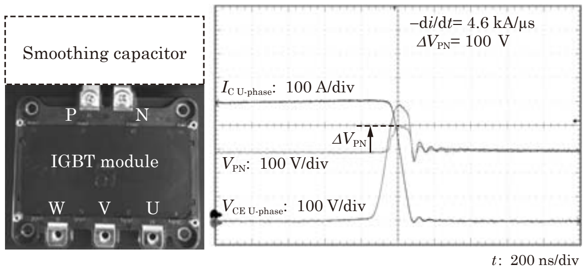


(b) Conventional structure

Fig.3 Cross-section structure of power module



(a) New product



(b) Conventional product

Fig.4 Surge voltage across P- and N-terminals during turn-off

In conventional products, both the P- and N-terminals are wired together across the 3 phases within the module, and 100-V surge voltage is generated between the P- and N-terminals. As for the new product, both the P- and N-terminals are wired independently in the 3 phases. We designed the length of wiring to be as short as possible including internal wiring to reduce the wiring inductance. As a result, the surge voltage across P- and N-terminals has been reduced greatly to 20 V although the current cutoff speed is about 1.5 times higher.

Launch time

November 2016

Product inquiries

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“UPS7300WX-T3U,” Large-Capacity UPS Using SiC Hybrid Modules for North America

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The stable operation of information and communication systems, which comprise communications equipment and networks, has become a requirement in our IT based society, and as such, events such as system failures could massively impact social activities. An uninterruptible power system (UPS) is an essential piece of electric equipment in supplying a stable source of power 24 hours a day, 365 days a year in data centers, which plays a major role in our IT based society.

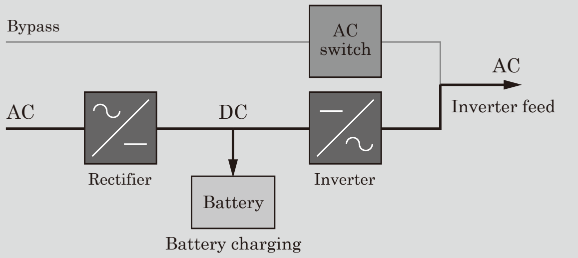
The market for data center UPS systems has been growing on a worldwide scale. Fuji Electric commenced sales of a 500-kVA UPS that is compliant with North American standards in FY2015. In order to meet the various needs of customers, it became necessary to expand the product capacity line-up, and as a result, we developed the “UPS7300WX-T3U,” a new high-efficiency online UPS for 480 V (see Fig. 1).

Fig.1 “UPS7300WX-T3U” (480-V series 333-kVA unit)

1. Features

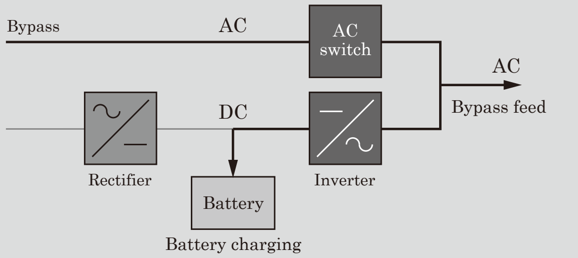
1.1 High efficiency

The UPS can switch between 2 modes: double conversion mode, that is, voltage and frequency independent (VFI) mode and eco-mode, that is, voltage and frequency dependent (VFD) mode (see Fig. 2).



○ Rectifier and inverter both in start-up state (Supplying power to customer equipment by converting AC to DC to AC)
○ Charging battery from rectifier side
○ The use of RB-IGBTs and SiC diodes reduces conversion loss for the rectifier and inverter

(a) Double conversion mode (VFI)



○ Rectifier stops
○ Inverter in start-up state (the active filter works to implement power factor correction and harmonics suppression)
○ Charging battery from inverter side
○ By directly supplying the bypass (commercial power supply) without a rectifier or inverter, highly efficient power feed is possible (However, it will be impacted by the voltage fluctuation and frequency fluctuation of the commercial power supply)

(b) Eco-mode (VFD)

Fig.2 Double conversion mode and eco-mode

In VFI mode, the unit can achieve high system efficiency with a maximum efficiency of 97.5%. This makes it possible to decrease the power loss of the UPS while also reducing the power consumption of the air conditioner for the UPS system.

Duplication and redundancy of equipment ensures the reliability of systems in data centers, and in general, this type of configuration is characterized by a low operational load factor. Accordingly, the UPS also reduces power loss in the low load range (20% to 50%). This reduction is achieved by using the SiC diodes, which enable the reduction of conduction loss in the light load range, and using the 3-level converters, which enable the reduction of fixed loss in reactors.

Figure 3 shows the results of the certification test for the International Energy Star Program*1. In VFI mode, efficiency is 96.3% or higher when the load factor is between 25% and 100%. Highly efficient operation is possible even when the actual operation load is low, which saves much energy. When applying the calculation method of the International Energy Star Program, which uses weighted values based on the

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* Power Electronics Business Group, Fuji Electric Co., Ltd.

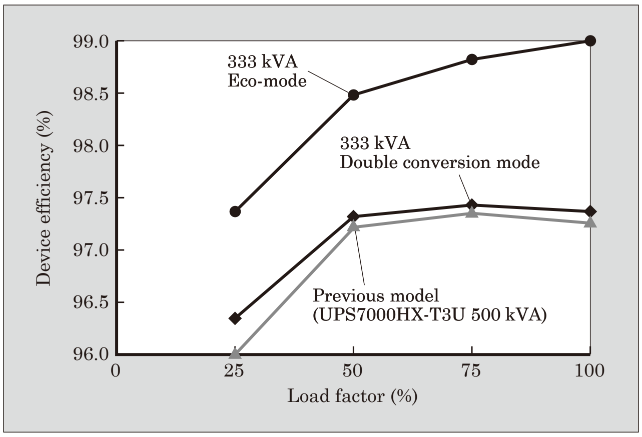


Fig.3 Results of certification test for International Energy Star Program

load factor, the certification efficiency is 97.1%. In VFD mode, the UPS has a maximum efficiency of 99.0%, achieving a significantly higher efficiency than previous products.

1.2 High reliability

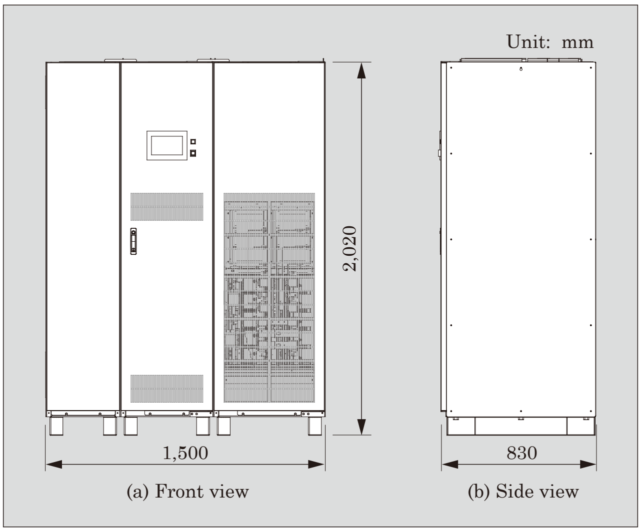
In data centers, UPS systems need to continuously supply stable power 24 hours a day, 365 days a year. The UPS7300WX-T3U can be used for high-reliability power systems such as parallel redundant systems and stand-by redundancy systems, and it is capable of providing a continuous supply of power during times of maintenance or in case of equipment failure.

1.3 Handling high power factor loads and leading power factor loads

In recent years, the demand for a high power factor has increased the number of electronic equipment equipped with power factor correction (PFC). Accordingly, we have developed the capability to supply power to loads with a load power factor of 1.0 (333 kW), so that the UPS can supply power to high power factor loads that utilize PFC without the equipment capacity reduction. On the other hand, when the load utilizing a PFC stops, the load power factor becomes leading. In order to deal with various loads including those just described, the UPS was designed with an applicable load power factor range between 0.7 (lagging) to 0.7 (leading).

1.4 Specifications

Figure 4 shows the dimensions of the



(a) Front view

(b) Side view

Fig.4 "UPS7300 WX-T3U" dimensions

Table 1 "UPS7300WX-T3U" specifications

Item		Specification
Feeding method		Double conversion mode (VFI) Eco-mode (VFD)
Rated capacity		333 kVA/333 kW
Maximum efficiency		97.5% (during VFI)
Switchover time		Uninterruptible (during VFI) 2 ms (during VFD)
Mass		1,100 kg
Input	Number of phases	3-phase 3-wire
	Voltage	480 V +10%, −30%
	Frequency	60 Hz ±10%
	Input power factor	0.99 or higher
	Input harmonic current	3% or less
Bypass input	Number of phases	3-phase 3-wire
	Voltage	480 V ±10%
DC	Rated voltage	480 V (240-cell, lead-acid batteries)
Output	Number of phases	3-phase 3-wire
	Voltage	480 V
	Frequency	60 Hz
	Rated output power factor	1.0 [0.7 (lagging) to 0.7 (leading)]
	Voltage accuracy	±1% or less
	Transient voltage fluctuation	±3% or less (Abrupt load change 0% ↔ 100%)
	Transient fluctuation setting time	50 ms
	Voltage waveform distortion	2% or less (100% linear load) 5% or less (100% rectifier load)
	Frequency accuracy	±0.01% (asynchronous time)
	Frequency bypass synchronization range	±5%
	Overload capability	125%: 10 minutes 150%: 1 minute

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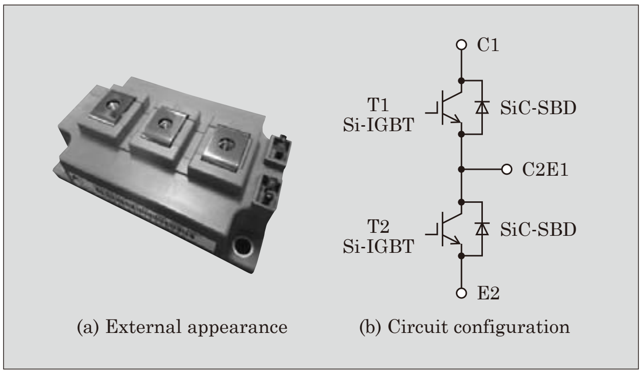
*1: International Energy Star Program (Energy Star): An international environmental labeling system for achieving energy savings in electric equipment The program is operated under the mutual recognition of the Ministry of Economy, Trade and Industry and United States Environmental Protection Agency. It includes a wide range of products such as home appliances, industrial machines and computers.

UPS7300WX-T3U, and Table 1, specifications.

2. Background Technologies

The UPS employs Fuji Electric's SiC hybrid modules that use SiC diodes (see Fig. 5).

Figure 6 shows a comparison of characteristics between a SiC diode and Si diode. In the actual usage range for the electric current, the SiC diode exhibits less loss because it has a lower on-voltage.



(a) External appearance (b) Circuit configuration

Fig.5 SiC hybrid module

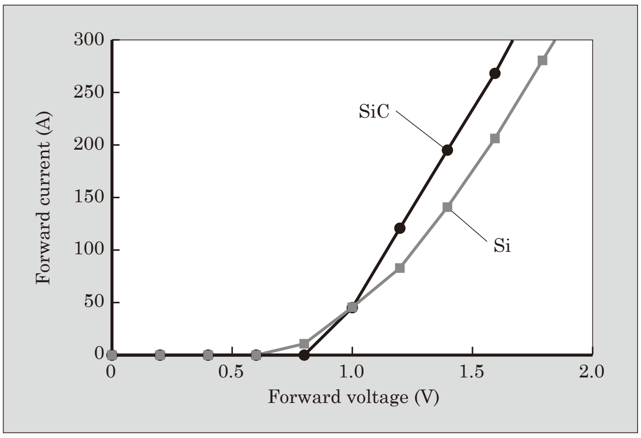


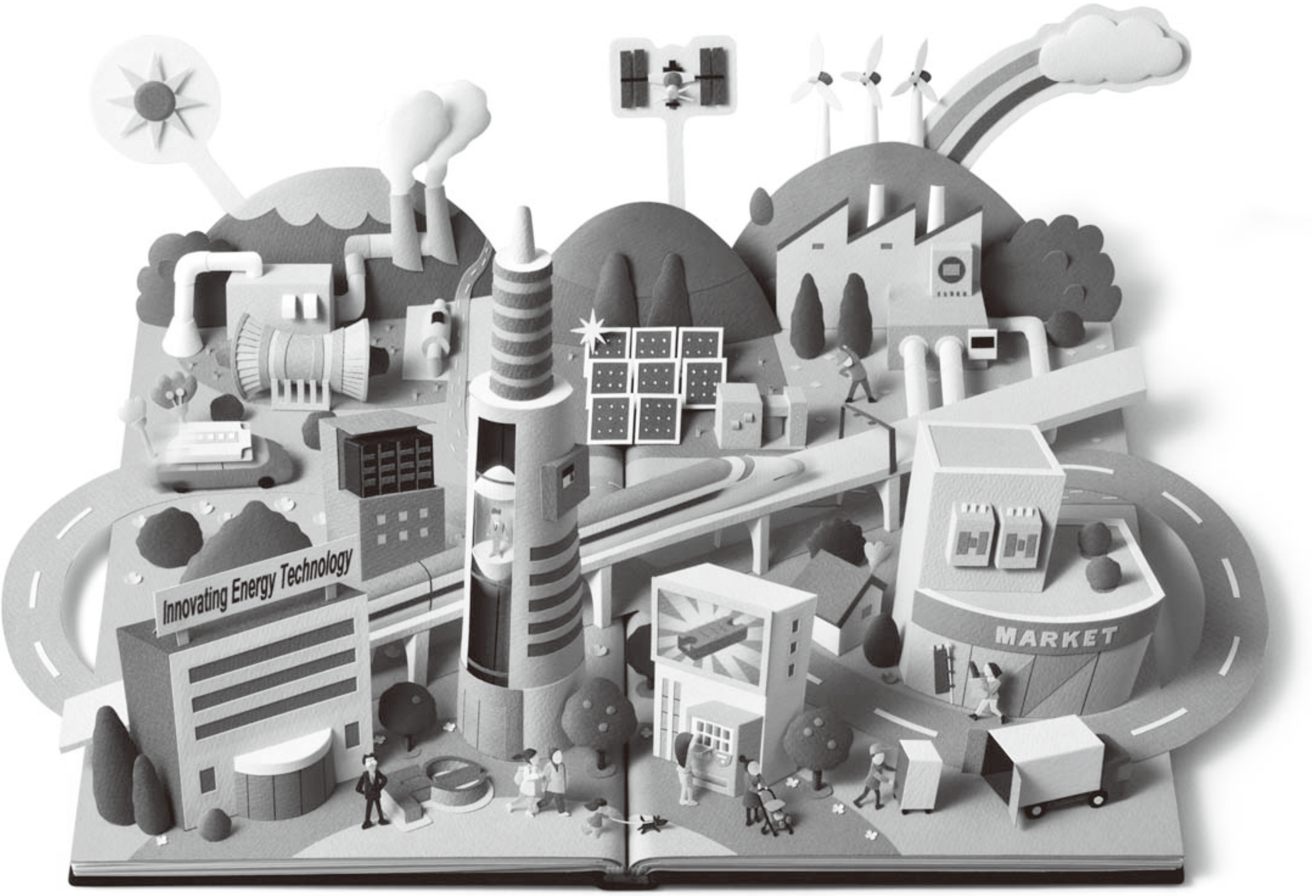
Fig.6 Comparison of diode characteristics

PWM converters have high conduction ratios for the diodes in the current pathway during DC link capacitor charging, it is thus most effective to use low on-voltage SiC diodes to a rectifier.

Launch time

October 2016

Innovating Energy Technology



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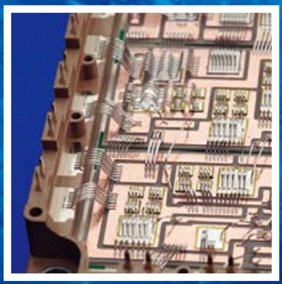

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