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Energy Creation Technologies－Power Plants and New Energy

Fuji Electric

Innovating Energy Technology

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Energy Creation Technologies−Power Plants and New Energy

Through the difficulty of meeting the demand for electricity caused by the long-term shutdown of nuclear power plants in the wake of the Great East Japan Earthquake in addition to the problem of global warming due to carbon emissions, power plants are demanded of lower environmental impact and higher reliability. Fuji Electric is advancing the development of power plants and new energy technologies as "energy creation" technologies for clean energy creation that is gentle on the environment. At its power plants, Fuji Electric is contributing to preservation of global environments and provision of electrical power through high performance and high reliability in each of the areas of "thermal power," "rotating machines" and "nuclear power." In terms of new energy (renewable energy), Fuji Electric is advancing development in areas such as geothermal power (binary system, flash system) wind power and photovoltaic power (mega solar) to promote widespread use of these forms of power generation.

In this feature we present the various energy creation technologies that contribute to the preservation of global environments and the stable provision of electrical power.

Cover Photo:

The Abu Mega Solar Power Plant of the Okinawa Electric Power Company, Incorporated (photo courtesy of the Okinawa Electric Power Company, Incorporated), "PVI1000 Series" of power conditioners for mega solar applications, 139 MW steam turbine rotor for the Nga Awa Purua Geothermal Power Station in New Zealand, the Yoshinoura Thermal Power Station of the Okinawa Electric Power Company, Incorporated (photo courtesy of the Okinawa Electric Power Company, Incorporated) and prototype 3,000 kW permanent magnet synchronous generator for wind-power generation

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Energy Creation Technologies—Power Plants and New Energy

Energy Creation Technologies: Current Status and Future Outlook

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1. Introduction

In the "energy creation" sector, Fuji Electric has worked to increase the efficiency and performance of thermal power generating facilities, has made deliveries of such to many countries throughout the world in addition to Japan, and has contributed to the stable supply of energy in the world. Moreover, in the renewable energy sector that includes geothermal power generation and the like, Fuji Electric has also worked to develop power generating facilities that are capable of supplying stable energy. Further, with an eye toward renewable energy, Fuji Electric is also advancing the technical development and commercialization of photovoltaic power generation, wind power generation, biomass power generation, and the like. This paper describes the present status and future outlook for energy creation technology that will contribute to a more stable supply of energy and a reduced impact on the environment.

2. Global Energy Situation

2.1 Global energy trends

The global demand for energy is expected to grow significantly due to the economic growth of emerging countries and an increase in population. "World Energy Outlook 2012,"[1] a 2012 report by the International Energy Agency (IEA), predicts that demand for electric energy will increase greatly, growing at an annual rate of 2.2%, and that by 2035, the global demand for electric energy will be 36,637 TWh (see Fig. 1). The report predicts an annual growth rate of 0.9% for developed countries, and an annual growth rate of 3.3% for emerging countries.

Thermal power generation mainly from coal-fired power generation and natural gas accounts for a large proportion of energy production, while the percentage of thermal power from oil-fired power generation is decreasing. Meanwhile, reducing the environmental impact is also a major issue, and energy-friendly renewable energy that does not emit CO_2 has increased significantly, with particularly large increases in biomass power generation, wind power generation and photovoltaic power generation. The percentage of power generation from renewable energy, including hydroelectric power generation, will increase approximately 30%. In light of the anticipated increase in energy demand, the pursuit of economic efficiency of the power generating cost, including fuel costs, as well as the reduction of the environmental impact are important issues. With regard to coal-fired power generation, combined-cycle power generation that uses natural gas and shale gas as fuel is being introduced, and the efficiency of coal-fired power generation is being increased.

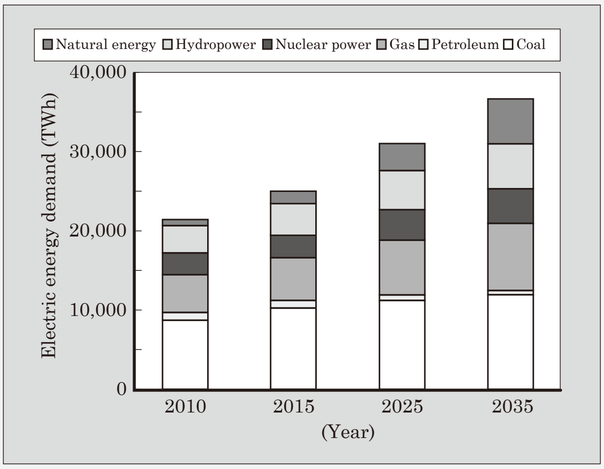


Fig.1 Global demand for electric energy

To meet the growing demand for electric energy, the capacity of power generating facilities must be increased. Figure 2 shows the global capacity of power generating facilities. The global power generating capacity in 2012 was 5,400 GW, but it is estimated that 9,300 GW of power generating capacity will be needed by 2035. However, due to such factors as aging, the need to reduce CO_2 emissions, rising fuel prices and so on, the power generating facilities currently in operation will need to be replaced with state-of-the-art power generating

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

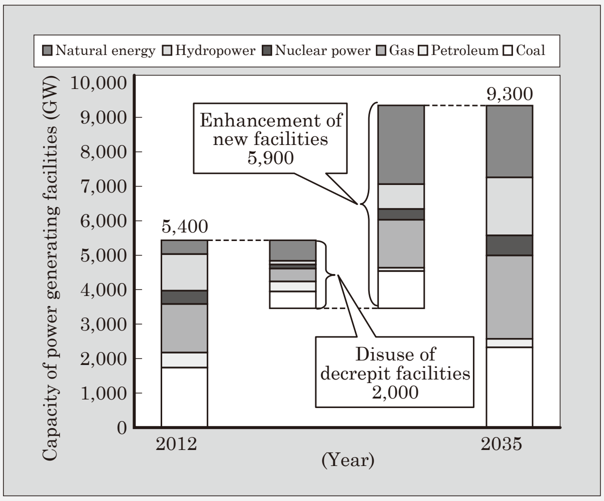
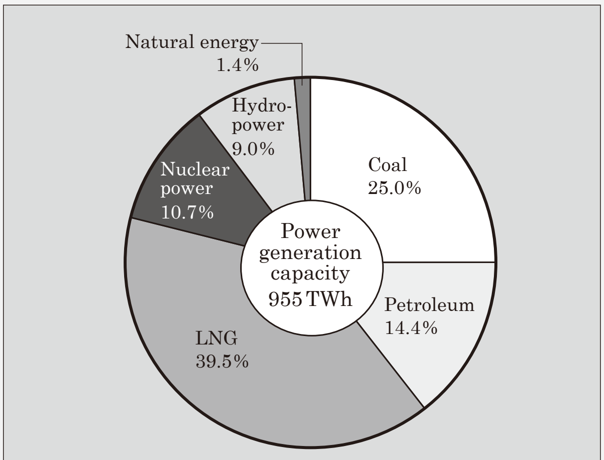


Fig.2 Global capacity of power generating facilities

facilities. The IEA report predicts that by 2035, 2,000 GW, corresponding to approximately one-third of the existing power generating facility capacity, will have been renewed, and that 5,900 GW of new power generating facilities will be built.

2.2 Energy trends in Japan

Figure 3 shows the composition of power generation capacity in Japan. As a repercussion of the tsunami-related disaster at the Fukushima Daiichi Nuclear Power Plant as a result of the Great East Japan Earthquake of March 2011, the shutting down of nuclear power plants in Japan has continued, and measures for the stable supply of electric power are being reviewed. The issue of restarting the nuclear power plants continues to be debated at a national level. The September 2012 "Innovative Energy and Environmental Strategy" indicated a policy of promoting the advanced use of thermal power generation, advanced use of heat such as through cogeneration, and the development and use of next-generation energy related technologies in order to ensure a stable supply of energy. In particular, the main features of this strategy are to enhance and augment thermal power plants and to promote the introduction of renewable energy. In the enhancement and augmentation of thermal power plants, the introduction of high-efficiency combined cycle power generation that uses natural gas as fuel and ultra super critical (USC) power generation*[1] that uses coal as fuel, and the like, have attracted attention. In terms of renewable energy, with the goal of introducing of 300 TWh (more than 3 times the current amount) by 2030, the introduction of renewable energy coupled with the "Feed-in Tariff Scheme for renewable energy" that began in July 2012 has gained momentum.



(Reference: the Federation of Electric Power Companies of Japan)

Fig.3 Composition of power generation capacity in Japan

3. Thermal Power Generation

As shown in Fig. 1, thermal power generation presently accounts for approximately 67% of the power generated to meet the global demand for electric energy, but as a result of initiatives to promote the introduction of renewable energy and so on, this percentage will decrease to 57% by 2035. Meanwhile, the demand for power can be seen to be increasing to approximately 1.5 times the present level. Under these circumstances, from the perspective of reducing CO_2 emissions and of increasing economic efficiency, including consideration of the fuel cost, oil-fired power generation will be cut in half, combined cycle power generation that uses natural gas as fuel will be increased to 1.8 times its present level, and coal-fired power generation will also be increased to nearly 1.4 times its present level mainly in emerging countries.

In the thermal power sector, high-efficiency combined cycle power generation based on a combination of gas turbines and steam turbines and that uses natural gas as fuel and ultra super critical (USC) power generation that uses coal as fuel will become the mainstream types of power generation in the future.

3.1 Combined cycle power generation

Combined cycle power generation has the characteristics of being highly efficient, contributing to the prevention of global warming with low CO_2

***1: Ultra super critical (USC) power generation**

USC power generation is thermal power generation technology in which the steam is used under the conditions of ultra super critical pressure (steam temperature of at least 593°C and steam pressure of at least 24.1 MPa). USC power generation enables the thermal energy required to vaporize water to be reduced so that power can be generated more efficiently.

Fig.4 Yoshinoura Thermal Power Station of the Okinawa Electric Power Company, Incorporated (Photo: provided by the Okinawa Electric Power Company, Incorporated)

emissions, short startup time, good tracking performance according to load fluctuations, etc., and will play an important role in future thermal power generation. Furthermore, combined cycle power generation has until now used natural gas as fuel, but recently, shale gas development has been advancing rapidly mainly in the US and expectations for the future use of shale gas with gas turbines is increasing.

Fuji Electric has also been working with combined cycle power generation, and has moved forward with the construction of combined cycle power generation equipment (two 251 MW units) at the Yoshinoura Thermal Power Station of the Okinawa Electric Power Company, Incorporated (see Fig. 4). In November 2012, Unit No. 1 completed its comprehensive testing and began commercial operation. In addition, Unit No. 2 began commercial operation in May 2013. This power generating facility was developed jointly with Siemens AG and is a single-shaft type combined cycle power generating plant that combines a Siemens-made gas turbine (STG6-4000F, F-class), a single-cylinder reheat steam turbines with axial-flow exhaust developed by Fuji Electric, and a generator. In plant performance testing, efficiency of at least 51% (HHV*2 basis) was achieved, and good results that surpassed the expectations of the original design were confirmed for the short-term load response capability and frequency adjustment capability.

In the future, combined cycle power generation will progress toward larger sizes and improved thermal efficiency as a result of higher combustion temperatures of the gas turbine. Siemens AG has also developed a larger capacity H-class gas turbine that employs a higher combustion temperature, and in an actual combined cycle power plant, that achieves the world's highest efficiency, significantly above 60% (LHV*2 basis, sending end). Fuji Electric continues to improve the performance of steam turbines and generators and to make equipment more compact, and is working on combined cycle power generation both in Japan and overseas. (see “Global VPI Insulated Indirectly Hydrogen-Cooled Turbine Generator for Single-Shaft Type Combined Cycle Power Generation Facilities” on page 113.)

3.2 Coal-fired power generation

Coal-fired power generation is being developed mainly by emerging countries in order to increase its economic efficiency. In developed countries, efforts to reduce CO_2 emissions are seen to restrict new development, but with new technical developments such as higher efficiencies resulting from the development of the ultra supercritical pressure turbine and the gasification of coal, the merit of coal-fired power generation has been reconsidered.

In the medium capacity sector, Fuji Electric has delivered many high-performance, highly reliable coal-fired power generation facilities to countries throughout the world. Recently, Fuji Electric has been working on steam turbines and generators (4 units, 300 MW) for the Haiphong Thermal Power Plant in Vietnam, and steam turbines and generators (2 units, 300 MW) for the Nghi Son Thermal Power Plant.

For ultra supercritical power generation, Fuji Electric, in collaboration with Siemens AG, has delivered the turbine and generator (1 unit, 600 MW) for Unit 1 of J-Power's Isogo Thermal Power Plant. Utilizing a main steam temperature of 600 °C and a reheat steam temperature of 610 °C, an advanced blade stage design achieves high plant efficiency and contributes to reduced CO_2 emissions and improved economic efficiency. Higher efficiency by increasing the temperature and pressure of the main steam in steam turbines will continue to be sought in the future. On the other hand, improving the reliability of turbines is also an important factor. Thus, in addition to improving the performance of the steam turbine stage, Fuji Electric continues to develop rotor material, casing material and turbine blade material, improve the corrosion resistance of turbine blades, and develop corrosion monitoring technology.

The development of 700 °C class steam temperature, advanced ultra-supercritical (A-USC) power generation technology that aims to further

***2: HHV, LHV**

After a unit quantity of fuel placed in a constant state is completely combusted adiabatically, the amount of heat that must be dissipated in order for the combustion gas to be returned to its original temperature is called the “calorific value.” The calorific value is specified as either the higher heating value (HHV), which includes the latent heat of the water vapor, or as the lower heating value (LHV), which does not include that latent heat.

improve efficiency is being advanced for next-generation steam turbines. Fuji Electric is also is advancing the technical development of A-USC technology through its participation in the "METI-sponsored development of advanced ultra-supercritical power generation." (see "Latest Steam Turbine Technologies for Thermal Power Plants" on page 107.)

4. Geothermal Power Generation

Among renewable energy sources, geothermal power has the characteristics of (a) being usable as a base load supply with an output that does not fluctuate due to weather or the like, (b) having a high capacity utilization rate, and (c) being highly economic efficiency, and is being developed in geothermal resource-rich countries throughout the world.

Geothermal resources exist in abundance in the Pacific Rim (Japan, United States, Indonesia, Philippines, New Zealand and Chile) and in Africa (Kenya and Ethiopia), and geothermal power generation is being developed in various countries. Japan is said to be ranked third in geothermal resources (having geothermal resources of approximately 23.5 GW) behind the United States and Indonesia. Fuji Electric has focused on geothermal power generation, and having been involved in the research and development of geothermal power generation equipment since the 1960s, has a successful record of delivering many highly reliable geothermal power generation systems and has a large share of the global market in terms of deliveries.

Described below are two methods of geothermal power generation, large-scale flash power generation used directly with a geothermal turbine whereby hot water and steam ejected from the ground are boiled at low pressure and only the steam is removed, and small-capacity binary power generation in which a secondary medium having a low boiling point is vaporized by relatively low-temperature geothermal water and that vapor is harnessed to rotate the turbine and generate power.

In regard to flash power generation, in October 2010, Fuji Electric delivered a 140 MW geothermal power system, the world's largest capacity for triple-flash power generation*3, to the Nga Awa Purua Geothermal Power Station in New Zealand (see Fig. 5). More recently, in December 2012, Fuji Electric delivered a geothermal power system (2 units, 55 MW) to the Ulubelu Geothermal Power Station in Indonesia. (see "Power Plant Technologies for Thermal and Geothermal Power Plants" on page 91.)

Fig.5 Nga Awa Purua Geothermal Power Station in New Zealand

In geothermal power generation, large quantities of corrosive gas and impurities are contained in the geothermal fluid and may cause such problems as corrosion, erosion-corrosion*4, scaling, and the like. Based on onsite verification test data and on inspection and maintenance data obtained from a track record of many deliveries, Fuji Electric is researching and developing optimal materials and coating technology for the turbine blades and casing in order to improve the reliability of the turbine, generator and ancillary equipment. It is important to improve both reliability and performance, and turbine blades and the like that are highly resistant to corrosion and that are highly efficient are under development. (see "Recent Technology for Improving Corrosion-Resistance and Performance of Geothermal Turbines" on page 96.)

The method of binary power generation was developed in order to effectively utilize geothermal hot water that is at a relatively low temperature, and this method is expected be introduced in small-size geothermal power systems. On the other hand, the binary power generation method can also be used with reinjection hot water that, through use of the flash power generation method, has been returned to a reinjection well because that reinjection hot water still contains thermal energy. Fuji Electric calls this power generation method "hybrid

***3: Triple-flash power generation**

In the flash method of power generation, geothermal resources extracted as hot water are separated into steam and hot water, and the separated steam is sent to a turbine, where power is generated. The separating of the steam and hot water in 3 stages is called triple-flash power generation, and enables the extracted geothermal resources to be utilized maximally.

***4: Erosion-corrosion**

Erosion-corrosion is the phenomenon whereby the thinning of metal is accelerated as a result of the synergistic action of erosion (mechanical wear due to flow and solid particles) and corrosion (electrochemical wear within a corrosive solution).

geothermal power generation" and seeks to apply it to improve the energy recovery efficiency of entire power plants. Silica scaling occurs easily in low temperature reinjection hot water, and constriction in the reinjection well must be prevented. Fuji Electric is also researching the occurrence of silica scaling in reinjection hot water, and is utilizing the results of that research to promote hybrid geothermal power generation. (see "Technology to Counter Silica Scaling in Binary Power-Generating System Using Geothermal Hot Water" on page 101.)

5. Renewable Energy

The prevention of global warming is important as a corporate social mission, and the introduction of renewable energy that does not emit CO_2 is being promoted in various countries throughout the world. According to the IEA report, the introduction of renewable energy is expected to grow at an annual rate of 6 to 8%. In Japan, the best mix of energy, distributed energy systems, the construction of smart communities, and the like are being debated as part of the national energy policy, and renewable energy is positioned as a significant portion of that policy. The Feed-in Tariff Scheme for renewable energy applies to photovoltaic energy, wind power, geothermal energy, medium and small hydropower, and biomass power generation, and stipulates that generated power is to be purchased for a predetermined term at a fixed price. For this reason, renewable energy power producers are easily able to establish business plans, and the introduction of renewable energy generation is gaining momentum. Presently, the introduction of photovoltaic power generation, for which construction is relatively simple, is advancing, but the introduction of wind power and thermal power is expected to advance subsequently. Fuji Electric is also advancing the research and development of renewable energy power generating devices and equipment, and has been working on the commercialization of high efficiency, high performance devices and plant construction with EPC*5.

5.1 Photovoltaic power generation

Photovoltaic power generation can be broadly classified as small photovoltaic power generation systems installed on house roofs and large-scale photovoltaic power generation (mega-solar) systems installed mainly on the ground. Fuji Electric is working primarily on mega-solar. The key to photovoltaic power generating systems lies in the extent to which its economic efficiency can be increased. Important factors include minimizing loss of the power generating system, increasing the amount of power generated per unit area, improving device reliability to increase the utilization rate and thereby boost the amount of power generated annually, reducing the construction costs for photovoltaic panel installation and wiring, and so on.

Fuji Electric is applying its power electronics technology and system design technology acquired thus far to build photovoltaic power generation systems that have high economic efficiency. In the power electronics technology sector, Fuji Electric has developed a 1,000 V DC, 1 MW power conditioner (PCS) (see Fig. 6) that incorporates industry-leading advanced T-type neutral-point-clamped (AT-NPC) 3-level conversion circuit*6 for use in mega-photovoltaic systems. The application of an AT-NPC 3-level conversion circuit dramatically reduced the switching loss and filtering loss and resulted in achieving the world's highest efficiency of 98.5%. With the DC input set to 1,000 V, DC-side loss is reduced, and lower construction costs are anticipated as a result of an outdoor type model that eliminates the need for a structure to house

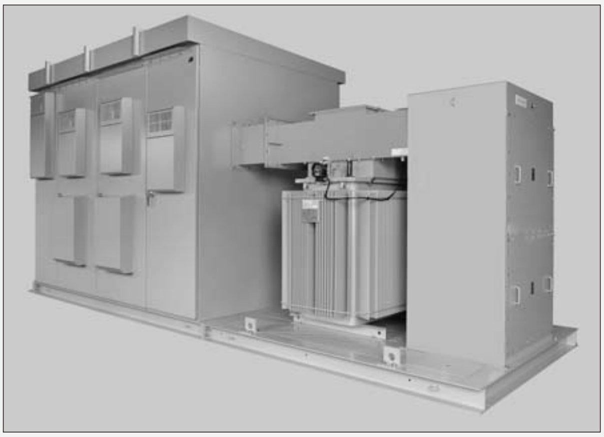


Fig.6 Outdoor PCS (1,000 V DC, 1 MW)

***5: EPC**

EPC is an acronym for engineering, procurement and construction, and indicates the engineering design, procurement of materials, and construction work as the scope of services at the time of plant construction. The contracting of this work collectively is called the EPC method or EPC business of contracting.

***6: AT-NPC 3-level conversion circuit**

Compared to a typical 2-level conversion circuit that has two output voltage stages, a 3-level conversion circuit has one additional stage. As a result, the waveform of the output line-to-line voltage more closely resembles a sine wave, and this has the advantages of allowing the LC filter of the device to be made smaller, increasing the power conversion efficiency, and so on. A conventional 3-level circuit is connected to the neutral point of a DC power supply and is therefore referred to as a neutral-point-clamped (NPC) scheme. With the advanced T-type NPC (AT-NPC) scheme, elements having different rated voltages are combined and a reverse blocking IGBT (RB-IGBT) is used as an intermediate element to simplify the circuit compared to the conventional scheme and to realize higher power conversion efficiency.

the PCS. In the system design sector, Fuji Electric is improving design techniques for a comprehensive system design that considers the installation environment and economic efficiency through optimizing the photovoltaic module and array according to the environment, reducing wiring loss, planning of interconnection equipment that conforms to the grid interconnection requirements, and designing monitoring controls that incorporate smart technology and/or are cloud based, etc. (see "Technology for Large-Scale Photovoltaic Power Generation Systems" on page 118.)

In addition, Fuji Electric plans to build a 2 MW photovoltaic power facility on vacant land in Yamanashi Prefecture in Japan. This facility will be used to carry out verification testing of the developed PCS and grid interconnection equipment, to collect data for reliability confirmation and product improvement, and to improve construction techniques. This facility is expected to be completed in March 2013, and the verification data and effective construction techniques obtained here will be applied to advance the construction of high performance and highly economic efficient photovoltaic power systems.

5.2 Wind power generation

Wind power generation occupies an important position among types of renewable energy. In Japan, onshore installations of wind power generation have been mostly small-scale until now. From the perspective of economic efficiency and due to limited installation sites, offshore wind power generation is being eyed for large-scale wind power generation (wind farms) in the future. The large-scale wind power generating equipment at such sites will have power generating capacities of 3 to 5 MW per unit. Fuji Electric is focusing its efforts on large-scale generators for wind power facilities, PCSs, power stabilization devices, and the like.

For wind power generation, it had been common to use a double-fed system that employs a speed-increasing gear to increase the rotational speed of the wind turbine and cause the generator to rotate at high speed. However, as the power generating capacity increases, such as in the case of offshore wind power, a large-size speed increasing gear becomes necessary, and trouble and maintenance associated with that speed-increasing gear becomes a large issue. As a recent trend, a direct-drive system that omits the speed-increasing gear is being used in large-scale wind power generation.

Fuji Electric has developed and commercialized a 3,000 kW permanent magnet synchronous generator for use in a direct-drive system. With the direct-drive system, the rotational speed is slow, at approximately 15 min^{-1}, and the generator is large in size, but by using a method of excitation with a permanent magnet and optimizing the ventilation and cooling system, the winding method and the structure, smaller size, lighter weight and higher performance are achieved. Additionally, with this method, a large-size PCS at full capacity is required for the generator, but high efficiency is realized by applying an AT-NPC 3-level conversion circuit that incorporates Fuji Electric's power electronics technology in the PCS. (see "Permanent Magnet Synchronous Generator for Wind-Power Generation" on page 130.)

In consideration of applications to offshore wind power generation, the cooling system is characterized by the use of water cooling, rather than cooling with the outside air. FRT capability*7 is also provided as a standard feature.

Moreover, wind power output fluctuates from moment to moment, and the effect of such fluctuations on the power quality is an issue. To advance the introduction of wind power generation, Fuji Electric combines a storage cell and power stabilizer so that fluctuations in the output from wind power generation can be suppressed through control of the charging and discharging of the storage cell, and also applies a power stabilizer to increase the quality of the voltage and frequency of the power grid. (see "The Circuit and Control Technology in the Power Conditioner and Converter for Wind Turbine Systems" on page 124.)

6. Postscript

The global demand for electric power energy will increase greatly in the future, and accordingly, "energy creation" to produce electric power energy will play an important role. In order to realize a stable supply of electric power and a low carbon society, Fuji Electric remains committed to the pursuit of energy creation. Fuji Electric will continue to advance the research and development of large-scale thermal power generation and geothermal power generation, and to provide highly efficient, high performance and highly reliable power generation equipment. Renewable energy is environmentally friendly, does not emit CO_2, and is positioned as an important energy for achieving the best mix of energy. In the renewable energy sector, in addition to power generation capability, grid intercon-

***7: FRT capability**

Fault ride through (FRT) capability is, at the time of a three-phase short circuit or two-phase short circuit with the power grid, the ability to continue operation so as to output three-phase current within a specified range and to suppress power supply fluctuations of the grid, without the inverter quickly halting its output. The specified range indicates the duration of momentary line drop and the voltage drop range and is determined by each country.

nection technology and stabilizing technology are also important factors. Fuji Electric seeks to combine the power electronics technology and control technology at which it excels in order to build optimal systems.

Fuji Electric is also working to build smart communities for which further growth is anticipated. To build a smart community society, it is important to aggregate technologies for energy creation, energy savings, power electronics and energy optimizing control, information communication and the like, and Fuji Electric intends to use its collective strengths to contribute to society.

Reference

(1) International Energy Agency. World Energy Outlook 2012, Organization for Economic, 2012.

Power Plant Technologies for Thermal and Geothermal Power Plants

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ABSTRACT

In construction of thermal and geothermal power plants, many kinds of elemental technologies are concerned. This paper describes about main technologies in plants completed in recent years. The Yoshinoura Thermal Power Station is Okinawa Electric Power Company's first LNG-fueled single-shaft type combined-cycle thermal power plant, and has the largest capacity generator in Okinawa Island. Governor-free control system is adopted both for gas turbine and steam turbine to enhance response to variation of frequency. The Ulubelu Geothermal Power Station is the first geothermal power plant developed under the Second phase of Indonesian government's electricity crash program, and has received attention as a model case. Hybrid gas-extractor facilities and overall optimization in arrangement of major equipment have been achieved.

1. Introduction

The Yoshinoura Thermal Power Station (Unit No. 1) of the Okinawa Electric Power Company, Incorporated and the Ulubelu Geothermal Power Station both started operation in 2012. In both cases, since the power generating facilities supplied by Fuji Electric would become the main facility in each regional power system, each project was carried out under the watchful eye of the stakeholders and customers.

The Unit No. 1 of the Yoshinoura Thermal Power Station is the largest capacity gas turbine combined cycle (GTCC) generator built by Fuji Electric as a turnkey (EPC) project, and is also the largest capacity generator on the main island of Okinawa. The Ulubelu Geothermal Power Station has been built at a highland on the Indonesian island of Sumatra, where the power grid infrastructure is fragile, and is also the largest capacity geothermal power plant on that island.

The plant technology used in large-scale thermal and geothermal projects is described below using these power plants as examples.

2. Yoshinoura Thermal Power Station of the Okinawa Electric Power Company, Incorporated

2.1 Plant overview

Fuji Electric and Siemens AG delivered a single-shaft type combined-cycle power plant to the Yoshinoura Thermal Power Station of the Okinawa Electric Power Company, Incorporated. Figure 1 shows a panoramic view of the Yoshinoura Thermal Power Station. As a measure to curb global warming, this

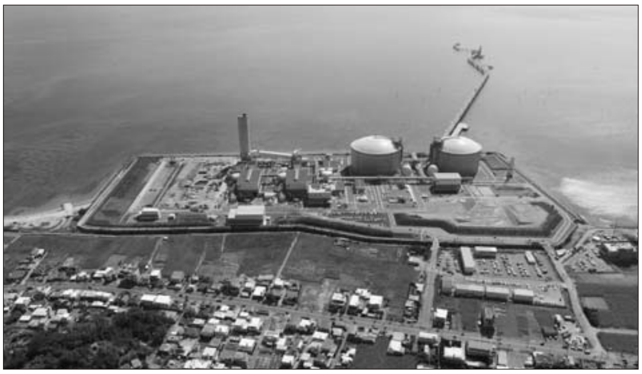

Fig.1 Panoramic view of the Yoshinoura Thermal Power Station

power plant is a liquefied natural gas (LNG) combined cycle thermal power plant that is more efficient than and has approximately one-half the CO_2 emissions as a coal-fired power plant. The Unit No. 1 and the Unit No. 2 both have output power of 251 MW, which is the largest capacity on the Okinawa Main Island, and they provide approximately 20% of the power for the local prefecture.

Using a 1,400 °C class SGT6-4000F type (F class) gas turbine, made by Siemens AG a single-shaft type combined cycle generation system configured from a gas turbine, generator, clutch and steam turbine was used. The generator employs a static frequency converter in the startup electric motor, and at startup, the clutch is operated to disengage the steam turbine and realize lower startup loss. The Unit No. 1 started commercial operation in November 2012, and the Unit No. 2 in May 2013.

2.2 Plant technology relating to layout design and construction

For the Unit No. 1, the installation of an exhaust

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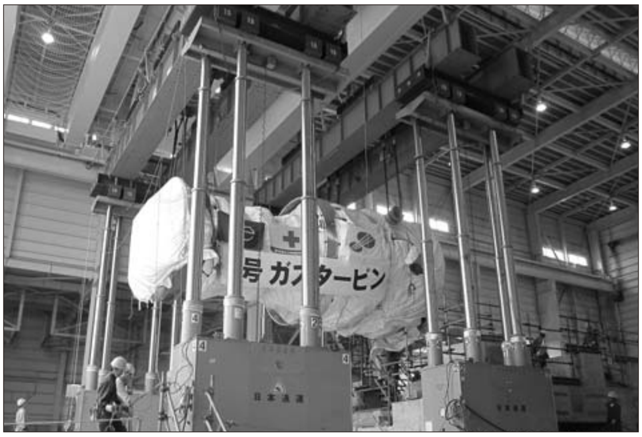


Fig.2 Installation of a gas turbine on a foundation.

heat recovery boiler began in March 2011, and the installation of a gas turbine, generator and steam turbine began in May 2011. These large pieces of equipment were loaded into the power plant from a newly constructed loading wharf, carried onto the site via a low-floor trailer, and then were installed on the foundation inside the turbine building with a power jack.

In the past, a main turbine consisting of a No. 1 gas turbine, generator and steam turbine would be located on the 3rd floor of the turbine building, and therefore the building was required to have a height of at least 25 m. At the Yoshinoura power plant, however, the building was planned in consideration of its economic efficiency and the shaft center of the main generator is positioned at +5.5 m above FL (1st floor height) so that the turbine building can have a height of approximately 20 m, which is lower than in the past. Inside the building, machinery, piping and electrical equipment are compactly arranged both vertically and horizontally, and although it was expected that the installation work would become crowded, the processes and work tasks were coordinated, and installation of the Unit No. 1 was completed without accident. Figure 2 shows the installation of the gas turbine on the foundation.

In transporting the equipment, it was assumed that typhoons, which are an Okinawa region-specific weather condition, would occur frequently. In consideration that shipping vessel delivery schedules would be cancelled, so that processes would not be delayed due to the suspension of outdoors work or while waiting for the repair of damages due to strong winds, we anticipated the expected path of typhoons on a daily basis, and substituted work processes and processed remaining loads. As a result, the effect on the installation process was minimized, and testing could begin in May 2012.

2.3 Control technology and plant technology

In May 2012, as the initial event in the trial operation of the Unit No. 1, the first firing of the gas turbine was carried out. Subsequently, the gas turbine was operated under no-load conditions and combustion tuning was carried out, the exhaust heat recovery boiler was cleaned with hot water and blow-out of the steam piping was carried out. In June 2012, the Unit No. 1, was put into parallel operation*[1] (i.e., connected to the power grid) for the first time at 6 MV, and comprehensive trial operation of the plant was initiated. In the comprehensive trial operation that spanned a six-month period, confirmation of the static characteristics of each device prior to the load rejection test, and confirmation of the dynamic characteristics of each device after the load rejection test were advanced steadily with the cooperation of the Okinawa Electric Power Company, Incorporated.

The power grid on the Okinawa Main Island is independent of the power grids of the other power companies. When this power generating facility, which has capacity equivalent to 20% of the power grid, is connected to the power grid, there was concern over the possibility of a significant adverse effect on power availability on the Okinawa Main Island should a problem occur during testing. For this reason, the 100% load rejection testing was carried out under particularly tense circumstances (see Fig. 3).

In order to limit the effect of fluctuations in the amount of power supplied during trial operation, i.e., to maintain the balance between supply and demand in the power grid, the Okinawa Electric Power Company, Incorporated has made elaborate plans for a supply system that is coordinated with other power plants that are connected to the power grid. At the power plant, after the load rejection, the steam turbine was disengaged via the clutch (a disengageable connecting device positioned between the turbine and the generator) and stopped, and testing proceeded to the gas turbine no-load independent operation.

Because this power generating facility has a capacity equivalent to 20% of the power grid, it also plays

Fig.3 Central control room during load rejection tests

*1: Parallel operation: The connection of a generator to a power transmission system and the start of transmitting power.

an important role in maintaining the frequency of the power grid. It is important to provide the power generating facility with a load change function capable of responding rapidly to short-duration changes in the electric power demand to stabilize grid frequency. This power generating facility is also provided with an operating function that can incorporate economic dispatching control (EDC), automatic frequency control (AFC) and governor free (GF)*2 control over the normal range of operation, from minimum load to maximum load. As characteristic functions, in addition to governor free control provided for the gas turbine, governor free control is also provided for the steam turbine to utilize effectively the heat stored in a high-pressure steam drum. As a result, the slight delay of the gas turbine output control due to the fuel control system is supported by the function of the steam turbine, and by adjusting the response performance and the load response width in the responsivity test, the requirements were satisfied.

In plant performance tests conducted in October, it was confirmed that the efficiency of at least 51% (HHV basis), which is the highest level for a 1,400 °C gas turbine (F class) installed in Japan, is possible. As a result of the combination of a two-stage combustor and a denitration apparatus that are used to realize low NO_X emissions in the normal operating load range, NO_X emissions well below 5 ppm (corresponding to 16% oxygen) were confirmed.

A heat run test, which is the last voluntary test before use, was performed from November 26th to 27th in 2012, and successful commercial was started on November 27th.

2.4 Future developments

In this project, for the first time in Japan, a large, industrial-use gas turbine made by Siemens AG was used for the combined-cycle power generation facility. Siemens AG has a track record of delivering gas turbines throughout the world, and Siemens AG's gas turbines have maintained a share of 40% or more of this market. In addition to their F-class gas turbines which have a successful track record of many deliveries, orders for their H-class gas turbines (SGT-8000H) are also brisk.

Fuji Electric intends to build upon its successful record of delivering the Yoshinoura Thermal Power Station and will continue to focus on delivering combined-cycle thermal power plants in Japan.

3. Ulubelu Geothermal Power Station

3.1 Overview of Ulubelu Geothermal Power Station project

For this project, Sumitomo Corporation (hereinafter, Sumitomo) was the main contractor, and in February 2010, orders for 2×55 MW geothermal power block (Portion A), a substation block (Portion B) and a transmission line (Portion C) were received in an EPC contract from PT.PLN (hereinafter, PLN), a state-owned power company in Indonesia. Fuji Electric and a local engineering company, PT. Rekayasa Industri (hereinafter Rekayasa), received sub-contracts from Sumitomo. The main services provided by Fuji Electric, as a technical leader, were in the design, production, procurement and commissioning of main equipment that includes the steam turbine. Rekayasa was responsible for the design, procurement of balance of plant (BOP), construction and installation.

The Indonesian government is promoting a second-phase electricity crush program to solve their domestic power shortage. From 2010 through 2014, approximately 9,500 MW of power will be developed, and of that amount, approximately 4,000 MW will be geothermal power. The Ulubelu Geothermal Power Station is the first geothermal power plant developed under this program and therefore attracted attention as a model plant.

The plant site is located approximately 100 km west of the provincial city of Bandar Lampung in South Sumatra at an elevation of 780 m above sea level, and requires about 3 hours to be reached by car (see Fig. 4).

The time to completion of the project after the contract until delivery was 28 months for the Unit No. 1 and 32 months for the Unit No. 2.

The Ulubelu Geothermal Power Station applies single-flash power generation. The water dominant geothermal resource is separated into steam and brine (hot water) by a separator installed at the production well pad. Steam is sent to the power plant and the brine (hot water) is returned to a reinjection well. The steam is controlled to a constant pressure by a venting system provided in the vicinity of the tie-in point to the power plant, and a demister installed at the power plant performs the final moisture removal, and then the steam is fed to the steam turbine to generate power. Figure 5 shows the main power system of the power plant.

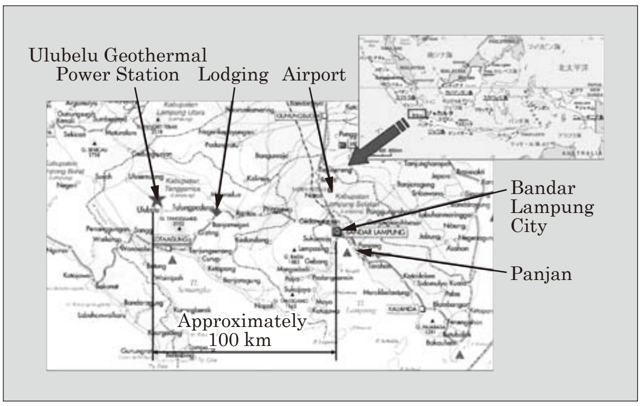


Fig.4 Construction site of the Ulubelu Geothermal Power Station

*2: GF (governor free) control: Function for varying the load according to system frequency fluctuations

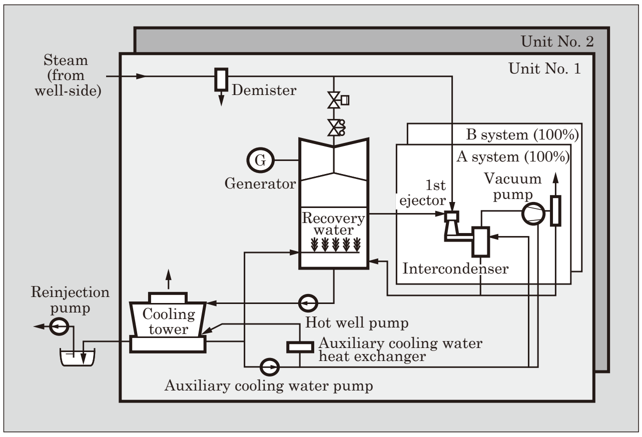


Fig.5 Ulubelu Geothermal Power Station main power system

The main equipment of the power plant – the steam turbine, the generator and the steam condenser – are made by Fuji Electric. The cooling tower, non-condensable gas extraction system, hot well pump, piping, valves and the like were procured from Japan as well as third countries, while the electrical equipment, FRP pipes, cables and the like were procured from Indonesia.

The geothermal resource supply and reinjection systems were managed separately by PT. Pertamina Geothermal Energy (hereinafter PGE); a steam purchase agreement was entered into with PLN, and tie-ins to the steam and reinjected water are in the vicinity of the power plant site.

3.2 Plant technology employed at the time of design and construction

For the steam turbine, Fuji Electric's "GK Series" steam turbine for geothermal applications was used (see Fig. 6). This is a single cylinder, double flow, reaction type condensing turbine. A 21.8-inch blade size, which has a proven record of success in geothermal power generation applications, was selected as the size of the final stage low-pressure blades. At the turbine inlet steam conditions of 0.76 MPa and 168 °C, the rated output is 55 MW (max. output is 57.75 MW)

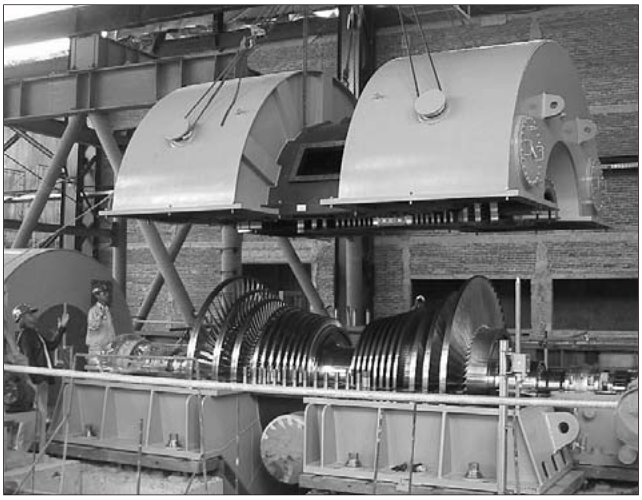


Fig.6 Steam turbine in installation process

The generator has a rated capacity of 68.75 MVA, and because it is used in a geothermal (corrosive) environment, is provided with a 2-pole fully enclosed air-cooling system that implements proven geothermal countermeasures such as a hydrogen sulfide gas removal filter system and the like.

The condenser and cooling system consists of a condenser, hot well pump, cooling tower and circulation water piping. In consideration of the optimum operating point for the equipment capacity of the system as a whole, we set a design vacuum rating of 0.01 MPa as the optimum point and designed the various systems. The condenser used has a proven record for geothermal power generation and is a highly-efficient direct contact condenser.

The gas extraction system that extracts large quantities of noncondensable gas, which is a major feature of geothermal power generation, is a hybrid system that uses a steam ejector and a vacuum pump. An optimum combination of ejector and vacuum pump capacities was designed to realize a highly efficient system configuration.

Focusing on the main devices described above, we comprehensively optimized the layout. At the same time, we optimized the size and routing of large diameter pipes such as the main steam pipe and the circulating water pipe. As a result, plant efficiency was improved due to the decrease in pipe pressure loss, and the quantity of piping could be reduced.

Additionally, since the construction of Unit No. 1 and No. 2 would be carried out simultaneously for a while, we coordinated with Rekayasa in advance concerning the construction procedures for common parts and for mutually interfering parts, and set deadlines for material delivery that also considered partial deliveries so that necessary equipment and materials could be delivered to the site in a timely manner. For particularly important items, delivery date management that included checking the delivery progress was carried out thoroughly.

During the construction period, there was a relatively large amount of rainfall even during the dry season (April to September), and heavy construction machinery will be inoperable due to heavy muddy land condition when it rains. Thus the construction progress was affected considerably by the weather.

Moreover, because the construction work was performed in the mountains on the island of Sumatra, it was difficult to secure workers or to add additional workers, and so the construction proceeded with limited manpower. Fuji Electric also dispatched advisors to the site, and these advisors proposed efficient work processes and endeavored to implement process control.

In the future, it is expected that geothermal power plants will increasingly be constructed at locations having even poorer access. Careful consideration of not only the accessibility, but also the ability to secure manpower will be necessary.

3.3 Plant technology during testing

In Southern Sumatra, the largest power plant is the Taharan Thermal Power Plant (2×100 MW) to which Fuji Electric has delivered steam turbine generator equipment, and because the power grid infrastructure is fragile, even after receiving power, the commissioning was often affected by power grid trouble from outside the power plant.

After the Unit No. 1 was put into parallel operation for the first time, whenever power grid system trouble occurred, the power plant would be disconnected from the power grid so that it could continue to operate stably as island operation. At such a time, together with the geothermal supply system being operated by PGE, communication is established by exchanging necessary signals such as the signal to transition to independent operation within the plant, and the ability to implement a coordinated following operation, even in the case of abrupt load changes, was confirmed. In October 2012, the plant was handed over one week before the contractual taking over date. The commercial operation of the Ulubelu Geothermal Power Station has made a significant contribution to the stable power supply of Southern Sumatra (see Fig. 7).

Fig.7 Panoramic view of Ulubelu Geothermal Power Station

4. Postscript

This paper has discussed plant technology for thermal and geothermal power plants. Gas turbine combined cycle power generation and thermal power generation are environmentally-friendly power generation methods that have low CO_2 emissions, and technological improvements and improvement activities will be carried out worldwide in the future.

In the field of gas turbine combined cycle power generation, Fuji Electric will play the role of introducing the latest technology in the world to the domestic Japanese market, and in the field of geothermal power generation, we intend to share the latest optimization technology world-wide.

Recent Technology for Improving Corrosion-Resistance and Performance of Geothermal Turbines

MORITA Kohei † SATO Masahiro †

ABSTRACT

Geothermal energy is a clean form of energy that produces almost no CO_2 emissions. Fuji Electric has supplied approximately 60 geothermal turbines to power plants in Japan and other countries. We have developed several technologies for improving corrosion-resistance of geothermal turbines, including shot-peening of turbine blade root and grooves, rotors made from 2% chromium steel and spray-coating technology. In the area of performance-enhancing technology, together with new-generation, low-pressure turbine blades for geothermal energy production and high-load, high-efficiency reaction turbines development, we have also achieved the creation of a high-performance, compact exhaust casing through optimized design. Furthermore, through use of triple-flash power generation, we have achieved the creation of a geothermal turbine with the greatest output for single-unit capacity in the world.

1. Introduction

In geothermal power generation, a fluid mixture (geothermal fluid) of steam and hot water heated by subterranean heat is extracted through a well (geothermal well) dug deep into the earth. The thermal energy of the mixture is then used to generate electricity. The amount of thermal energy in the earth is so vast that it could be said to be an inexhaustible supply for humankind. However, the energy that can be utilized is limited to the very small fraction of it that is in the earth's crust close to the surface of the earth. This is what is particularly referred to as geothermal energy. Geothermal energy differs from the generation of electricity by burning fossil fuels in that it is a clean energy that produces almost no CO_2 emissions, which are a cause of global warming. The energy density is high compared with other renewable energy sources such as wind and sunlight, and it also has the characteristic that the generation of electricity is stable and unaffected by factors such as the weather.

In 1960, Fuji Electric delivered to Hakone Hotel Kowakien, Fujita Kanko Inc. the first geothermal power generation equipment for practical use in Japan. Since then, Fuji Electric has supplied approximately 60 geothermal turbines to power plants in Japan and other countries and is noted as one of the top manufacturers in the field globally. This article introduces the anti-corrosion and performance enhancing technologies used in the latest geothermal turbines from Fuji Electric.

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

2. Technologies to Improve Corrosion-Resistance [1][2]

2.1 Corrosion-resistance evaluation technologies

Large volumes of corrosive impurities are contained in the geothermal fluid. It is therefore essential for designing the geothermal turbines to evaluate the resistance of the materials to corrosion and the stress level at which use is possible. For this reason, in addition to implementing materials testing in a simulated geothermal environment in a laboratory, Fuji Electric installed test equipment at geothermal sites around the world and performed materials tests in the geothermal steam and condensates and accumulated data related to corrosion-resistance.

2.2 Measures against stress corrosion cracking and corrosion fatigue

In the designing of geothermal turbines, particular

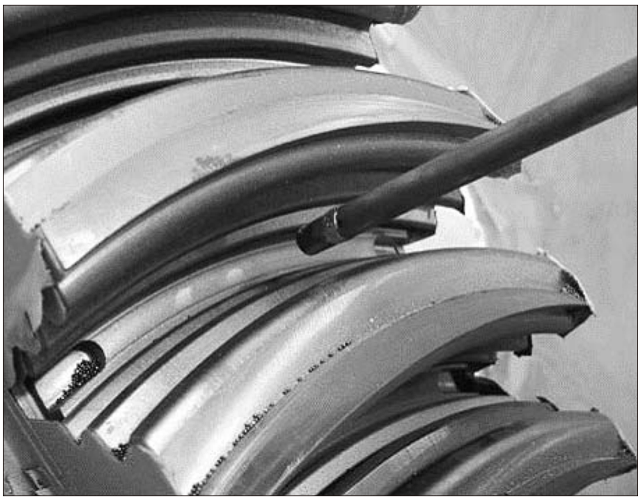


Fig.1 Shot-peening of rotor moving grooves

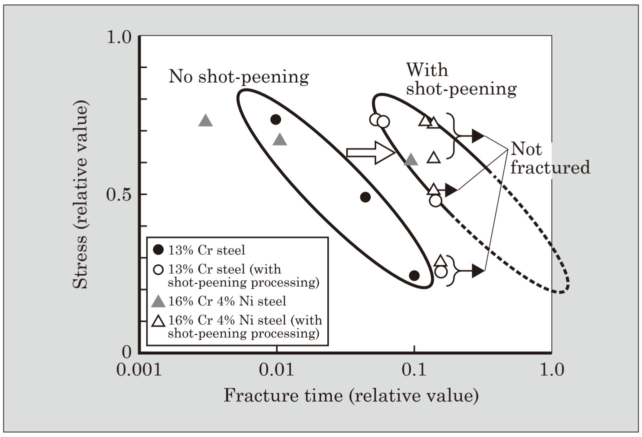


Fig.2 Improved proof stress through shot-peening (Results of stress corrosion cracking tests)

problems arise with the turbine blades root and rotor grooves, which are exposed to high centrifugal force and steam pressure during operation. A technology was developed to improve the corrosion-resistance by performing shot-peening on the parts of the blade root and grooves where the stress is concentrated, and this technology was applied to actual equipment (see Fig. 1). In the results of comparative testing performed in a simulated geothermal environment, it was verified that the shot-peening greatly improved the strength of the components against stress corrosion cracking (SCC) and corrosion fatigue (CF). Figure 2 shows the results of SCC testing.

2.3 Measures against erosion-corrosion

In recent years, progress in exploration techniques and drilling technology for geothermal wells has resulted in the development of geothermal resources at comparatively deeper depths. Accordingly, the steam pressure at the inlet of the geothermal turbine has tended to be higher, rising from the conventional value of approximately 1 MPa to a value of approximately 2 MPa. With wet steam turbines*1, increased steam pressure at the inlet results in a greater tendency for erosion corrosion to occur. Erosion corrosion is a degradation of material surface due to the combined effects of chemical and mechanical action of the steam flow. The stationary blade holders and rotor are made using carbon steel and low alloy steel, and their surfaces are prone to erosion corrosion. As a measure to erosion corrosion, Fuji Electric developed a rotor with 2% chromium steel, which has greater resistance to erosion corrosion than the 1% chromium steel conventionally used as a rotor material.

Technologies were also developed to coat the surface of the rotors with a WC-CoCr material using high velocity oxy-fuel (HVOF) spraying (see Fig. 3).

*1: Wet steam turbine: This refers to turbines where the main steam is saturated or nearly-saturated. They are also called saturated steam turbines.

Fig.3 Coating with high velocity oxy-fuel spraying

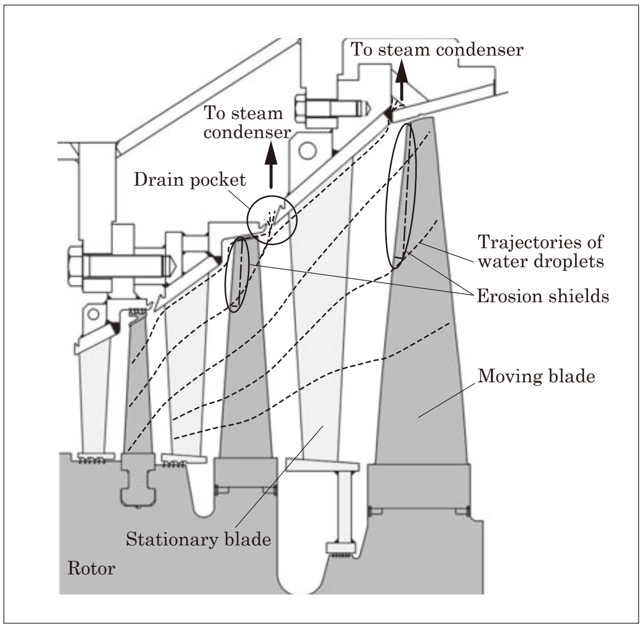


Fig.4 Drain removal structure

2.4 Countermeasures to erosion

Erosion caused by the impact of water droplets (drain attack) is the same phenomenon as in thermal power turbines. In geothermal power generation plants, where there is more hot water than steam, all stages are operated in wet steam, so it is necessary to consider drain attack and erosion in the design process. In addition to adding drain pockets to remove the water droplets that cause the erosion, protective measures are taken with the brazing of an erosion shield onto the leading edge of the moving blades (see Fig. 4).

2.5 Scale countermeasures

Silica, calcium carbonate and other substances contained in geothermal steam are deposited on the surface of components such as the blades, casing and rotor. Those impurities accumulate and become scale.

The scale that builds up on the surface of the blades narrows the passage for the steam and causes a fall in output. Furthermore, the scale that builds up in the gaps between the rotating parts and the static parts becomes a cause of abrasion on the components. Fuji Electric has developed blade washing technology with water droplets sprayed at the inlet of the turbine as a countermeasure to scale.

3. Technologies to Enhance the Performance of Geothermal Turbines(1)

3.1 New-generation, low-pressure turbine blades for geothermal use

Low-pressure blades (for the last 2 to 3 stages) have long blade lengths and are also used in wet steam, so they need to be resistant to excessive stress and erosion. A great deal of time and effort is therefore required in their development. For this reason, a range of products have been prepared as a low pressure blade series and makes it possible to select the optimal low-pressure blade design for a particular plant.

The new-generation, low-pressure turbine blades for geothermal use are based on a wealth of experience in geothermal turbine operation and are highly reliable. As geothermal turbines are used in a corrosive atmosphere, it is essential that special consideration is given in their design to matters such as stress corrosion cracking and corrosion fatigue. For this reason, in the development of the new series, by advancing the development based on established conventional development methods and adding three-dimensional viscous flow analysis and FEM analysis for the high-level optimization of the profile, we have achieved great improvements in efficiency compared with conventional models while securing reliability.

Figure 5 shows an example of flow analysis (Mach number distribution) on a low-pressure blade stage part for geothermal use. There has been minimization of the development of a boundary layer in the interference range slipstream caused by interference between an oblique shock wave from the trailing edge and an adjacent blade back edge boundary layer.

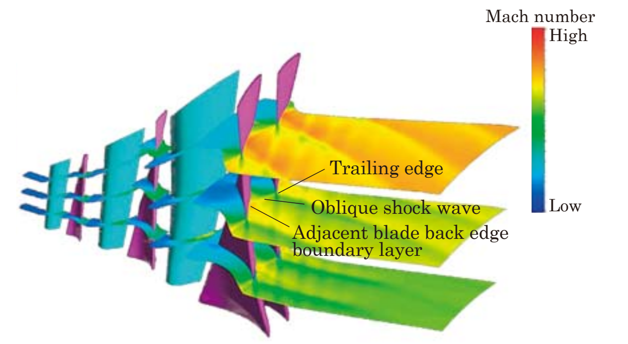


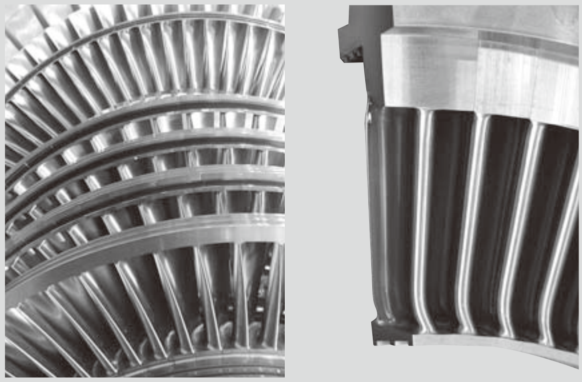
Fig.5 Example of flow analysis on a low-pressure blade stage part for geothermal use (Mach number distribution)

3.2 High-load, high-efficiency reaction blades

In stages other than low pressure blade stages, by using the latest design techniques for twisted blade stages, the stage efficiency was increased by 1 to 2% by adopting high-load, high-efficiency reaction blades that maintain high efficiency while increasing the load per stage. The high-load, high-efficiency reaction blades are integral shroud blades, with the blade and shroud machined together from one piece of bar material. This achieves high reliability against the highly corrosive geothermal steam (see Fig. 6).

3.3 High-performance, compact exhaust casing

The exhaust casing decelerates the steam discharged from the last stage blades and forms the flow passage leading to the condenser. The last stage discharged steam cannot be converted into rotational energy on the rotor and no longer contributes to the generation of electricity. Furthermore, the total pressure loss in the exhaust casing reduces the effective



(a) Moving blade (b) Stationary blade

Fig.6 High-load, high-efficiency reaction blades

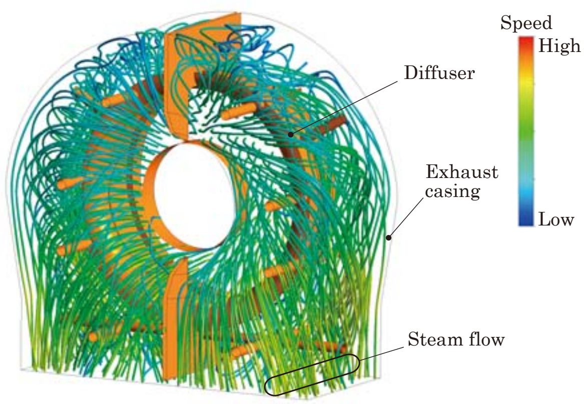


Fig.7 Results of three-dimensional viscous flow analysis on exhaust casing for geothermal use

heat drop on the turbine stage, so the result is that the performance of the turbine is reduced.

In general, if the exhaust casing is made more compact, then the reduction in the passage cross section increases the speed of the steam flow, which is disadvantageous for the performance. Fuji Electric has therefore optimized the profiles of the exhaust casing and the diffuser using three-dimensional viscous flow analysis. This results in a diffuser profile that has a deceleration effect greater than conventional models. By increasing the effective heat drop on the stage and reducing the total pressure loss after the diffuser outflow, a more efficient and compact exhaust casing was achieved (see Fig. 7).

4. Characteristics of the Latest Geothermal Turbines

The geothermal turbine for the Nga Awa Purua (NAP) Geothermal Power Station in New Zealand, which began operations in 2008 (see Fig. 8), uses a 798 mm blade at the final stage, the biggest in the world for geothermal power generation use. Figure 9 shows a cross section diagram of the geothermal turbine for the

Fig.8 Overview of the Nga Awa Purua Geothermal Power Station

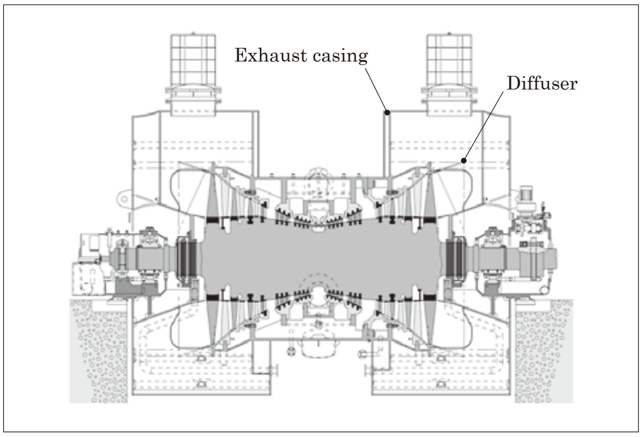


Fig.9 Cross section diagram of the geothermal turbine for the NAP geothermal power station

Fig.10 Geothermal turbine rotor installed

Fig.11 External appearance of the geothermal turbine for the NAP geothermal power station

NAP geothermal power station. Figure 10 shows the geothermal turbine rotor installed and Fig. 11 shows the external appearance of the geothermal turbine for the NAP geothermal power station.

While most geothermal power generation plants use either single-flash power generation or double-flash power generation, the NAP geothermal power station uses triple-flash power generation. After some hot water vaporizes in the first flash tank, the remaining heated fluid is flashed further in 2 additional tanks and the resulting steam is introduced into the intermediate pressure and low pressure sections of the turbine. This makes it possible to maximize the use of the geothermal energy and the maximum output of 140 MW is achieved, which is the greatest output for single-unit capacity geothermal power generation equipment in the world. Fuji Electric received many prizes for the development of this equipment, including the 59th Electrical Science and Engineering Promotion Award and the Low CO_2 Kawasaki Brand 2012 grand prize.

5. Postscript

Geothermal power generation does not consume fossil fuels and is a clean form of power generation that generates almost no CO_2. It is expected that geothermal power generation will develop even further, and Fuji Electric will work as a top manufacturer of geothermal power generation equipment to improve the reliability and performance of geothermal turbines.

We will steadily promote our products development so that we can continue to supply high performance geothermal turbines that are easy to use.

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Technology to Counter Silica Scaling in Binary Power-Generating System Using Geothermal Hot Water

KAWAHARA Yoshitaka † SHIBATA Hiroaki † KUBOTA Kokan ‡

ABSTRACT

A geothermal hot water binary power-generating system that uses reinjection hot water from a flash geothermal power-generating system as the heat source is able to draw heat from geothermal fluid efficiently, achieving high economic efficiency. However, there are concerns that cooling of thermal water causes silica scaling to adhere to power-plant equipment and wells. Field tests at the steam production well pad in the Kakkonda Geothermal Power Plant of Tohoku Hydropower & Geothermal Energy Co., Inc. have proven that in thermal water with low silica concentration the speed of silica scaling is not affected by water temperature, because the silica polymerization reaction is halted; thus, practical use of the system is just in sight. Field tests have also proved that intermittent alkaline injection can help to prevent and/or dissolve silica deposits.

1. Introduction

In geothermal power generation, a geothermal fluid containing steam and hot water is extracted from underground and used to generate electricity. This fluid is at a high temperature and high pressure under the ground, many components are, therefore, dissolved in the geothermal fluid, and these components can cause corrosion and scaling on the power generation facilities. In particular, there is a tendency for silica precipitation and scaling to occur when the heat is recovered from the geothermal fluid and the temperature of the fluid falls. The expense of measures to this scaling has a great effect on the economic efficiency of geothermal power generation.

Fuji Electric has worked with the objective of the efficient extraction and utilization of heat from the geothermal fluid to develop measures technologies for the silica scaling that becomes an issue for it. This article particularly introduces the technologies to evaluate the rate of silica scaling and technologies to inhibit and dissolve the silica scale in geothermal hot water binary power-generating systems.

2. Geothermal Hot Water Binary Power-Generating Systems

The methods of geothermal power generation can be broadly categorized into the flash type and the binary type. The flash method uses a separator to separate off just the steam from the mixed fluid of geothermal steam and hot water, which is taken from underground from a well (production well). This steam is then sent to the steam turbine to generate electricity. The binary method uses the geothermal fluid as a heat source. Heat is exchanged with a medium that has a lower boiling point than water, and then the vaporized medium is sent to the turbines to generate the electricity.

High temperature and high pressure geothermal steam are required for the flash method of geothermal power generation, in which Fuji Electric has accumulated great experience so far, and one issue has been the securing of the geothermal resources sufficient for power generation.

Figure 1 shows the concept of the scope of the geothermal power generation systems for different geothermal fluid temperatures and outputs. The flash method is used when the geothermal fluid temperature is high and the output is large, and the binary method is used when the temperature is low and the output is small.

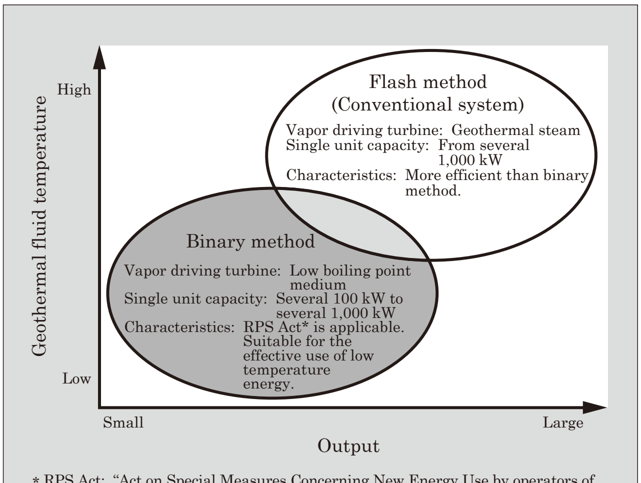

Fig.1 Scope of geothermal power generation systems

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In order to expand its range of geothermal power generation systems, Fuji Electric has performed development work for the commercialization of binary power-generating systems.[1] Verification testing of a binary power-generating system using geothermal steam with a rated output of 150 kW and a maximum output of 220 kW was carried out between August 2006 and October 2009 with the cooperation of the Daiwabo Kanko Co., Ltd. Kirishima Kokusai Hotel in Kirishima City, Kagoshima Prefecture. The continuous operation was achieved according to the plan. The results of the verification testing were then incorporated and the commercialization was completed.

One of the issues for geothermal power generation is the securing of geothermal heat sources. To extract the geothermal fluid that becomes the heat source for geothermal power generation from underground, it is necessary to target a location that has high temperature and high-pressure water in what is called a reservoir, and to drill a production well. If the geothermal fluid that can be taken from the production well is insufficient, or if the amount of heat or flow of the geothermal fluid declines, then it becomes necessary to add another production well. The heat of the earth is generally thought to be an inexhaustible source of heat, but from the point of view of economic efficiency, it is necessary to regard the geothermal fluid as a limited resource.

Fuji Electric is promoting geothermal hot water binary power-generating systems for the efficient generation of electricity using geothermal fluid. This is the additional installation to existing flash type geothermal power generation systems of a binary power-generating system that uses reinjection hot water as a heat source. It is therefore called hybrid geothermal power generation. Up until now, the reinjection hot water that remained after the separation of the steam from the geothermal fluid was returned to the well (reinjection well) while still at a high temperature but unused. This system uses that water as a heat source. Figure 2 shows a conceptual diagram of geothermal hot water binary power-generating systems.

Geothermal hot water binary power-generating systems are highly economical because they utilize the infrastructure of the existing flash type geothermal power generation system, for example, the site, personnel and power transmission lines. Furthermore, as it is not necessary to drill a new production well, there is low business-related risk that the drilling will fail. However, recovering heat from the reinjection hot water and lowering the temperature of the reinjection hot water often results in silica scaling and measures to this silica scaling are an issue for consideration. Silica sometimes attaches to the pipes and valves above the ground, but it causes the greatest problems when it attaches inside the reinjection well and in the geological strata around it, and in some cases the reinjection well can become blocked. If this occurs, then it becomes necessary to dredge the well or to drill a new one, which harms the business.

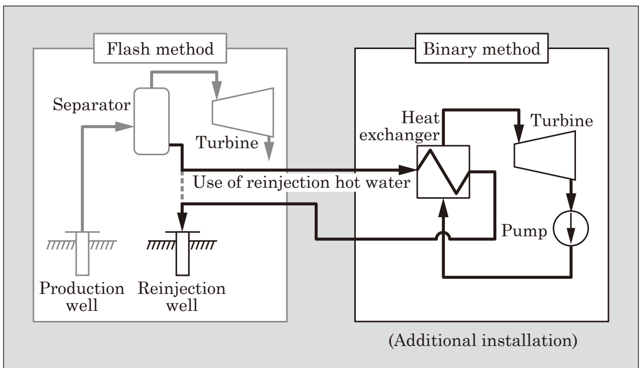

Fig.2 Conceptual diagram of geothermal hot water binary power-generating systems

Fuji Electric considers the problem of silica scaling to be a large risk when using geothermal hot water binary power-generating systems, and has worked to develop technologies for silica scaling measures, in particular technologies to evaluate the speed of scale build up and technologies to inhibit and dissolve the scale.

This development work was carried out with the cooperation of the Tohoku Hydropower & Geothermal Energy Co., Inc. as one part of the feasibility study (FS) carried out for a geothermal hot water binary power-generating system at the steam production well pad in the Kakkonda Geothermal Power Plant. It was joint research with the Tohoku Hydropower & Geothermal Energy Co., Inc., JMC Geothermal Engineering Co., Ltd. and Kyushu University.

3. Technologies to Evaluate the Rate of Silica Scaling

Since the geothermal fluid exists underground in a high temperature and high-pressure state, it dissolves many components. The concentration of the fluid and a drop in temperature occurs when it is taken out of the ground, when it is depressurized and flashed (evaporated) above the ground and when the heat is recovered from the hot water. At this time, silica components in particular reach a concentration above the solubility for amorphous silica, meaning that they reach a supersaturated state, and the more the concentration progresses, and the lower the temperature falls, the more the risk of silica precipitation increases. It is necessary to perform quantitative evaluations before the additional installation of a geothermal hot water binary power-generating system to evaluate whether the installation will aggravate the rate at which the reinjection well becomes blocked and whether that rate is at an acceptable level.

3.1 Mechanism of silica scaling

(1) Characteristics of amorphous silica

When silica precipitates from geothermal hot water, it precipitates in an amorphous state. Amorphous silica grows and precipitates in a polymerization reaction in the silica supersaturation. Therefore, the silica polymerization reaction rate V is the major factor determining the rate of silica precipitation.

The silica polymerization reaction rate V can be simplified and expressed as in Formula (1). The rate increases when the reaction rate constant K increases and when the amorphous silica solubility C_e decreases.

$$V=K\,(C-C_e)^n \quad \cdots\cdots (1)$$

V : Silica polymerization reaction rate
K : Reaction rate constant
C : Silica concentration
C_e: Amorphous silica solubility
n : Constant (n>0)

K and C_e increase with higher temperatures and with higher pH values. Therefore, the relationship is such that V will have a maximum value for some value of temperature and pH. In typical geothermal hot water, the V increases the lower the temperature falls and the higher the pH becomes.

For this reason, the measures generally taken to prevent silica scaling include to prevent the falling of the reinjection temperature and to add sulfuric acid to lower the pH.

(2) Mechanism of silica scaling at geothermal power plants

It is common for the formation of silica scale to be discussed only in terms of the rate of the polymerization reaction. However, when considering the formation of silica scale within a geothermal power plant, it is necessary to consider the form of the silica at each position in the power plant.

It is often the case that the reinjection well is drilled at a location away from the production well so that the reinjection hot water does not affect the reservoir. It is therefore not unusual for it to take several hours for the hot water to flow from the production well to the reinjection well. It is necessary to evaluate the rate of silica scaling in the reinjection well through comprehensive consideration of issues such as how far the polymerization reaction is progressing, how much precipitation as particles there is and whether or not the silica polymerization reaction is progressing in the hot water.

3.2 Method for evaluating the rate of silica scaling

Silica scaling becomes a problem in the reinjection well and particularly in the geological reservoir around the reinjection well. For this reason, reservoir simulation for silica scaling testing equipment was developed to evaluate the rate of blocking at these points beforehand.

Figure 3 shows the conceptual diagram of the testing equipment and Fig. 4 shows the external appearance of the testing equipment.

The reservoir simulation testing equipment is installed inside a geothermal plant and evaluates the changes in the rate of reinjection well blocking that result from a fall in the hot water temperature. Table 1 shows the correspondence between binary power generation facilities and reservoir simulation testing equipment.

The evaluation of the rate of blocking is performed by monitoring the pressure difference between the entrance to the porous material column and the various points inside the porous material. In addition, the concentration of silica at various positions inside the retention piping is measured to evaluate the rate of silica concentration decline and therefore the rate of the silica polymerization reaction.

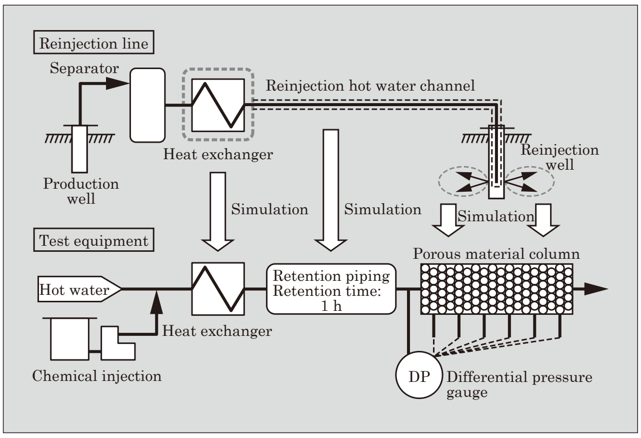

Fig.3 Conceptual diagram of reservoir simulation testing equipment

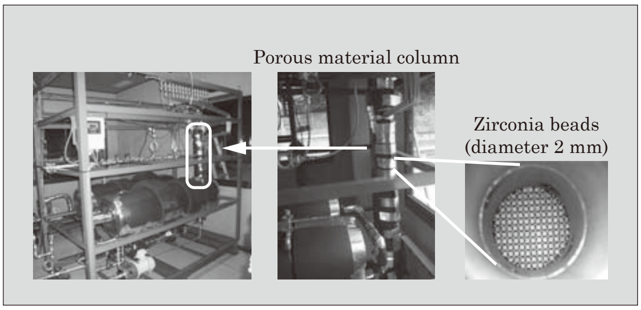

Fig.4 External appearance of the reservoir simulation testing equipment

Table 1 Correspondence between binary power generation facilities and reservoir simulation testing equipment

Binary power generation facilities	Reservoir simulation testing equipment
Heat exchanger	Heat exchanger
Reinjection hot water channel from location of binary power generation facilities to reservoir near to the reinjection well	Retention piping
Reservoir near to reinjection well	Porous material column filled with ceramic beads

3.3 Feasibility study at the steam production well pad in the Kakkonda Geothermal Power Plant

Between July and September, 2011, a FS was implemented for the assessment in advance of the rate of silica scaling that would result if geothermal hot water binary power-generating system facilities were installed at the steam production well pad in the Kakkonda Geothermal Power Plant of Tohoku Hydropower & Geothermal Energy Co., Inc.[2]

The water planned to be used in the geothermal hot water binary power-generating system was used to evaluate the rate of silica scaling using reservoir simulation testing equipment. The hot water temperatures used were 120 °C and 95 °C, and the total silica concentration was 435 ppm. It was confirmed that the silica polymerization did not progress when the water was maintained at 120 °C and 95 °C for 1 hour. In other words, it can be said that during this 1 hour, there is no formation of silica particles and no growth of the silica particles that have already formed. This 1 hour simulates the time required for the hot water to flow from the location of the reservoir simulation testing, which is the planned location of the binary power generation facilities, to the geological reservoir around the reinjection well.

The following knowledge about the rate of silica scaling was obtained over the three weeks of reservoir simulation testing.

(a) It is scale in the form of particle aggregation that contributes to the blocking of the reservoir, and the rate of scaling is not dependent on temperature.
(b) It is thought that the reason why the rate of silica scaling is not dependent on temperature is that the main mechanism of the scaling is particle deposition.
(c) The injection of sulfuric acid is generally done to slow the rate of silica polymerization, but it is also thought that it is effective in preventing the attachment of particles.

The test results and the basis for these findings were as shown below.

(1) Temperature dependence of the rate of scaling

Figure 5 shows the amount of silica attachment to the porous material column after the completion of the three-week long testing. It can be seen that there was

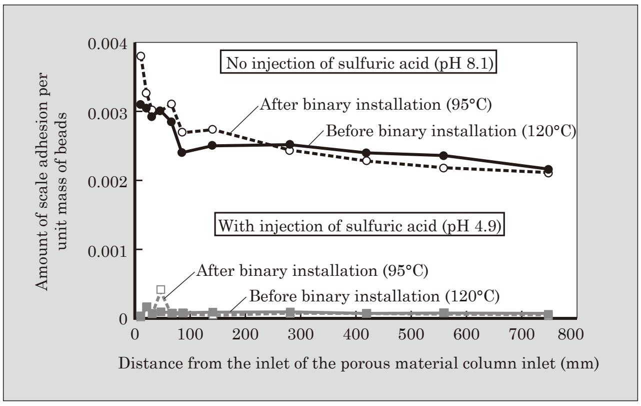

Fig.5 Results of reservoir simulation testing

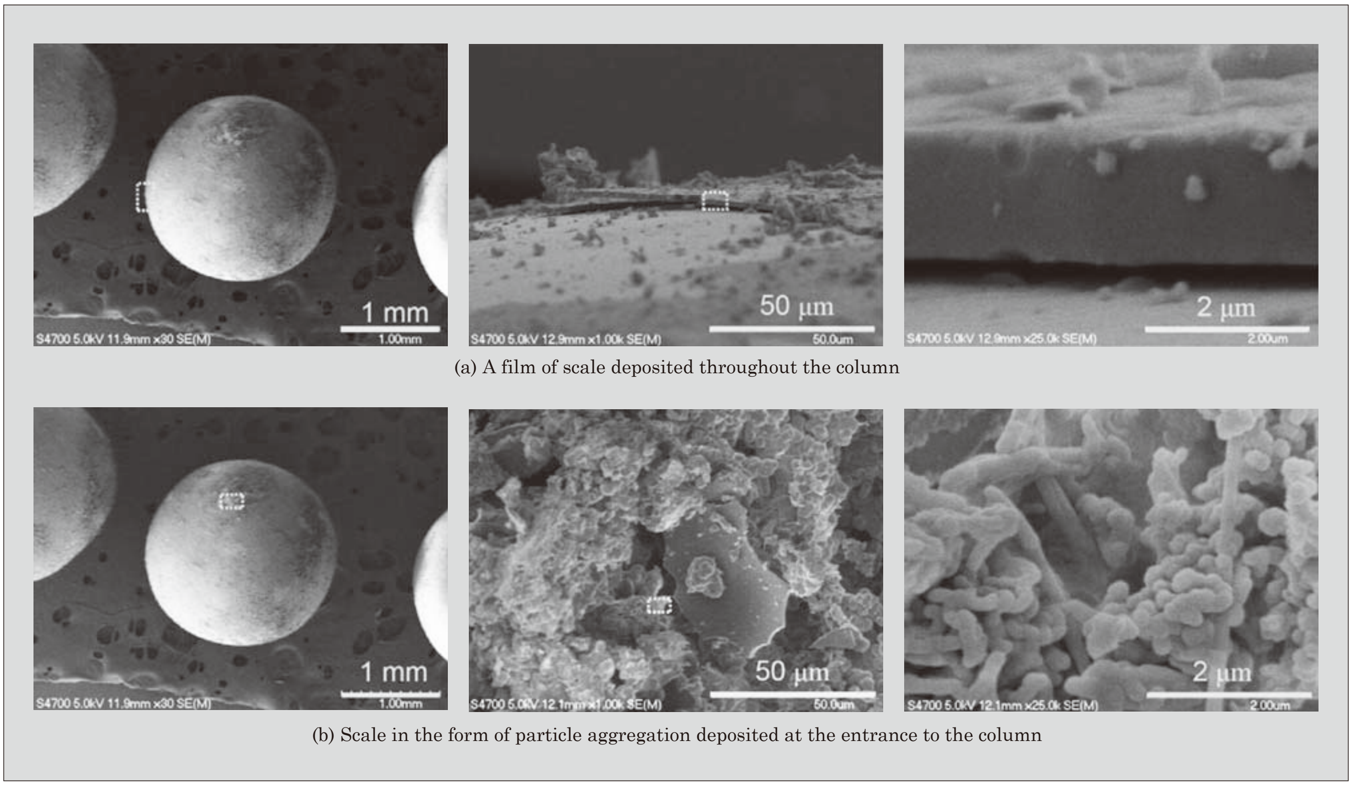

Fig.6 Electron microscope images of the scaling on the beads

no difference in the amount of scale adhesion before and after the hot water temperature reduction (120 °C and 95 °C) in either of the conditions, namely without the injection of sulfuric acid or with it.

Meanwhile, in the conditions of no injection of sulfuric acid, there was increased scaling near the entrance to the column. Figure 6 shows electron microscope images of the scaling in the porous material column. A film of scale was observed on the surface of the beads throughout the entire porous material column. At the inlet to the column, particle aggregation was observed on the surface of the beads. It is thought that the amount of scale deposition is greater at the entrance to the column because the particles in the hot water aggregate together at the entrance to the column and attach to the beads. Furthermore, in the results of the measurement of the water permeability of the porous material column, it was found that the water permeability is mostly reduced around the inlet of the column. It can be said that it is scale in the form of particle aggregation that contributes to the blocking of the reservoir and that the rate of scaling is not dependent on temperature.

(2) Mechanism of scaling

As there is no progression of silica polymerization in the hot water, it is thought that the particles that attached at the entrance to the column were particles that had been formed due to causes other than silica polymerization, for example, particles that were formed in localized concentration of the hot water during the flashing, or particles that came from the production well. It is believed that the rate of scaling was not dependent on the temperature of the hot water because the main factor in the scaling was that these particles attached near the entrance to the column.

(3) Effect of sulfuric acid injection

As shown in Fig. 5, the injection of sulfuric acid greatly reduced the rate of scaling. The injection of sulfuric acid is generally done to slow the rate of silica polymerization, but it is also thought that it is effective in preventing the attachment of particles.

3.4 Possibility of reinjection hot water

The results of the FS at the steam production well pad in the Kakkonda Geothermal Power Plant showed that the rate of the blocking of the geological reservoir is not dependent on temperature. In other words, they show that silica scaling would not become a major problem if a geothermal hot water binary power-generating system is installed. The reinjection hot water for which a geothermal hot water binary power-generating system is used is often hot water that has a low concentration of silica originally, and thus it is often the same conditions as at the steam production well pad in the Kakkonda Geothermal Power Plant. In other words, it is often the case that the silica polymerization stops. Therefore, these results are thought to be relevant generally when geothermal hot water binary power-generating systems are to be used.

Up until now, it has been thought that reducing the temperature of the reinjection hot water would increase the speed of the blocking of the reinjection well. However, it was clarified that within the range of temperatures where the silica polymerization is stopped, if the main mechanism of scaling is the attachment of particles, then there is no change in the rate of the blocking.

4. Technologies to Inhibit and Dissolve Silica Scale

Depending on the nature of the reinjection hot water, it is also conceivable that there may be cases when the rate of blocking of the reinjection well will be aggravated by the use of a geothermal hot water binary power-generating system. Technologies to inhibit and dissolve the silica scale were therefore developed using new methods [3] and verified using reservoir simulation testing equipment.

As described in Chapter 3, it is often the case that sulfuric acid is added to the hot water to inhibit the silica scaling. However, there is concern about the corrosion of piping due to this sulfuric acid injection, the amount that can be injected is, therefore, restricted and the effectiveness in inhibiting scaling is limited.

There have also been other attempts to inhibit the silica scaling through methods such as the retention tank method, where the hot water is retained for a certain amount of time to encourage silica particle growth and lower the adhesiveness of the silica particles. Other methods tried include the injection of a scale inhibitor and the removal of the silica from the hot water. However, these methods cannot be described as generally established technologies due to reasons such as that they are uneconomical or have limited effects depending on the hot water properties.

Fuji Electric therefore focused on the method of alkali injection to inhibit and dissolve the silica scale, which uses the fact that the solubility of silica rises with higher pH levels. This alkali injection has already been considered at some institutions, but has not been put into practical use for mostly the following reasons.

(a) Metal components such as calcium combine with the silica and form scale other than amorphous silica.
(b) The cost of the alkali agent is higher than that of sulfuric acid.

Solutions to these issues were attempted with the following measures and development work was performed to make practical use possible.

(a) Use together with an agent to mask the metal components such as calcium.
(b) Intermittent injection of the agent to reduce the amount used.

Figure 7 shows the scale inhibition results when

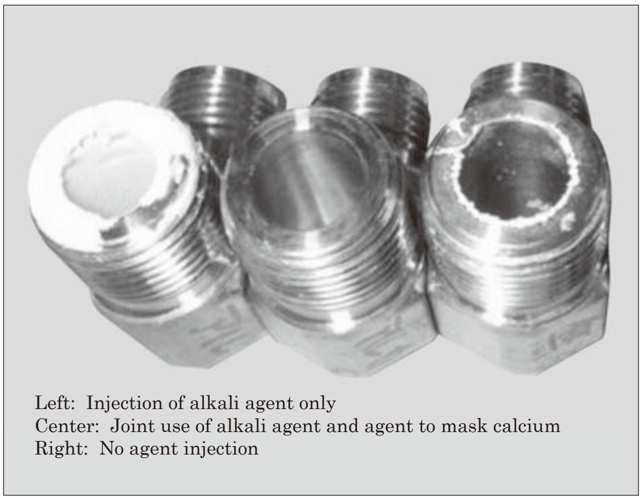

Fig.7 Results in silica scaling inhibition with the alkali injection method

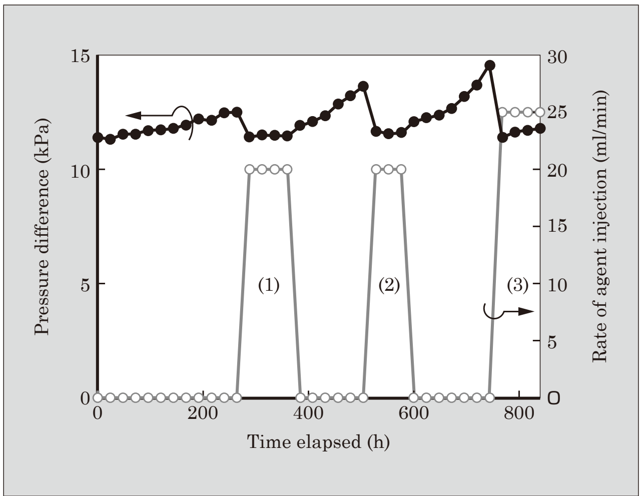

Fig.8 Changes in pressure differences inside the porous material column due to intermittent injection

the alkali injection method is used. If just an alkali agent is injected, then the amount of scaling is greater than when nothing is injected. However, the scaling is suppressed by using an agent to mask the metal components.

Figure 8 shows the changes over time in the pressure differences inside the porous material column when an agent (alkali agent and metal component masking agent) is injected intermittently on reservoir simulation testing equipment. By performing the intermittent injection of the alkali agent (the periods (1), (2) and (3) on the diagram), the pressure differences return to those before the scaling, meaning that the scaling that has attached is dissolved and the water permeability recovers.

5. Postscript

This article discussed measures to silica scaling, which was a major issue for the use of geothermal hot water binary power-generating systems.

Technologies were established to evaluate the rate of silica scaling and to inhibit and dissolve the silica scale and it is believed that the practical use of geothermal hot water binary power-generating systems is now in sight. Fuji Electric will continue development centered on these technologies for the establishment of measures to silica scaling in geothermal hot water binary power-generating systems and further geothermal power generation in general and will contribute to the effective use of geothermal resources.

This development was made possible by the cooperation of the Tohoku Hydropower & Geothermal Energy Co., Inc., for example, in the provision of the field. In addition, this research was performed jointly with Tohoku Hydropower & Geothermal Energy Co., Inc., GMC Geothermal Engineering Co., Ltd., Professor Itoi of the Graduate School of Engineering, Kyushu University and Professor Yokoyama of the Graduate School of Sciences, Kyushu University. We received much valuable advice from them. We would like to express our gratitude here.

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Latest Steam Turbine Technologies for Thermal Power Plants

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ABSTRACT

With features such as high power-generating efficiency and low CO_2 emission, combined-cycle power generation, combined with gas turbine and steam turbine, is gaining wider use. For the Yoshinoura Thermal Power Station of the Okinawa Electric Power Company, Incorporated, which is a combined-cycle power generating facility, we supplied single-cylinder reheat steam turbines with axial-flow exhaust that feature a clutch between the generator and the steam turbine. Also, for SUR power plant in Oman, we supplied two-cylinder reheat steam turbines with dual-sided exhaust that feature exhaust directions are left and right.

As the latest technologies in steam turbines for thermal power plants, we are developing welding technology, USC turbine technologies and technologies to improve reliability of low-pressure blades.

1. Introduction

Combined cycle power plants (CCPP) that use a gas and steam turbine in combination have been used increasingly in recent years in order to increase economic efficiency at power plants and in response to societal needs for reducing the emissions of greenhouse gases. Compared to conventional thermal power plants that combust fossil fuels in a boiler, CCPPs are more efficient, and because they use natural gas as fuel, have lower CO_2 emissions, and the combination of a gas turbine with a small steam turbine enables rapid start up and provides a high level of operability.

The Yoshinoura Thermal Power Station of the Okinawa Electric Power Company, Incorporated, which began operation in November 2012, is a 1-on-1 type CCPP in which the gas turbine, generator and steam turbine are arranged on a single shaft, and uses a single-cylinder reheat steam turbines with axial-flow exhaust (91 MW).

The Oman-SUR CCPP, shipped by Daewoo E&C in January 2013, is a 2-on-1 type CCPP configured from 2 sets of gas turbines and generators, and 1 set of a steam turbine and a generator, and uses a two-cylinder reheat steam turbines with dual-sided exhaust (330 MW).

This paper outlines the characteristics of the steam turbines for these two CCPPs, and also describes Fuji Electric's latest technology for steam turbines.

2. Steam Turbine for the Yoshinoura Thermal Power Station

This facility is a single-shaft type combined cycle power generating facility, and is the first facility in which the Okinawa Electric Power Company, Incorporated used LNG as fuel. Installation of the Unit No. 1 exhaust heat recovery boiler began in April 2011, and installation of the gas turbine unit began in July of the same year. The Unit No. 1 began trial operation in May 2012, and then started commercial operation in November 2012. In addition, the Unit No. 2 began commercial operation in May 2013. Features of the steam turbine used are listed below.

(a) To support a single-shaft type combined cycle system, a clutch for engaging and disengaging with the gas turbine and generator is provided at the end of the steam turbine rotor.

(b) The steam turbine is a compact-size, high, intermediate and low-pressure integrated-type turbine in which high, intermediate and low-pressure turbines are consolidated into a single casing. Figure 1 shows the external view of the

Fig.1 Steam turbine for Yoshinoura Thermal Power Station

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

stream turbine for the Yoshinoura Thermal Power Station.

2.1 Use of a clutch

In the single-shaft type combined cycle system used at the Yoshinoura Thermal Power Station, the gas turbine, generator and steam turbine rotor are aligned in tandem. Compared to a multi-shaft system in which the gas turbine and the steam turbine each have their own generator, a single-shaft type combined cycle system enables the power plant building to be made much smaller in size. Figure 2 shows the single-shaft and multi-shaft configurations. With a single-shaft system, the gas turbine and steam turbine are aligned in tandem, with a generator positioned between them.

With combined cycle power generation, the exhaust heat from the gas turbine is used to supply steam to the steam turbine, and therefore the start timings of the gas turbine and steam turbine are different. For this reason, a clutch is used that can temporarily engage and disengage the steam turbine.

First, with the clutch in the disengaged state, the gas turbine and generator are started, and at the stage when the steam is ready to be supplied to the steam turbine, the steam turbine valve opens and the steam turbine begins to speed up. Then, after the rotational speed of the steam turbine rotor reaches its rated speed and at the stage when it exceeds the rotational speed of the gas turbine rotor, i.e., when the torque from the steam turbine toward the generator becomes positive, the clutch engages mechanically and the torque from the steam turbine is transmitted to the generator.

Figure 3 shows the clutch structure. The clutch lubricating oil is supplied from the bearings located at both sides of the clutch. The clutch is kept constantly lubricated so that it may be engaged at any time. The lubricating oil also functions as a damper that absorbs mechanical shocks at the time when the clutch engages. As a result of the viscosity of the oil in the interior of the clutch, even before opening the valve prior to starting the steam turbine, the rotation of the gas turbine will cause the steam turbine to speed up to about 400 rpm.

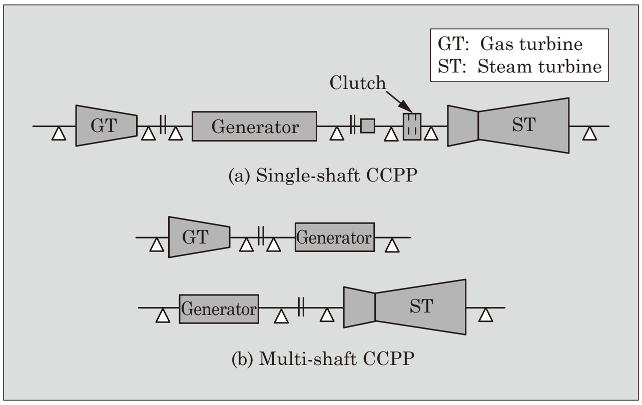


Fig.2 Single-shaft and multi-shaft CCPP configurations

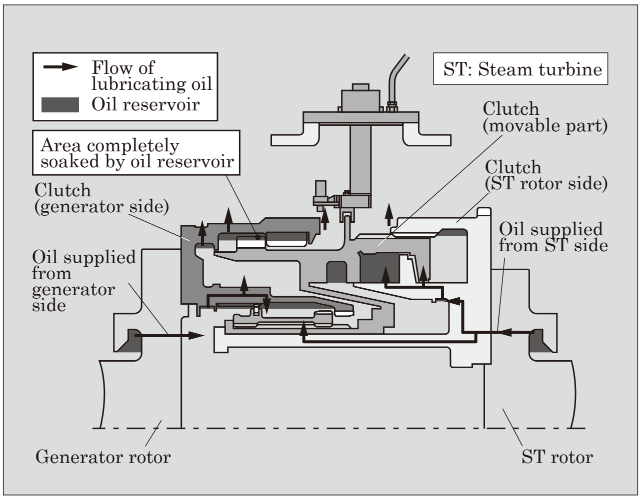


Fig.3 Clutch structure

2.2 High and intermediate pressure integrated-type turbine

Figure 4 is a cross-sectional view and Fig. 5 is a bird's-eye view of the steam turbine used at the Yoshinoura Thermal Power Station.

The turbine is composed of a high-pressure section, an intermediate-pressure section and a low-pressure section. The main steam, at high temperature and pressure, flows into the high-pressure section of the casing via a main steam valve located on the top of the casing, and the steam, after expanding and completing its work, is discharged through a cold reheat steam pipe. The reheated steam is directed back to the turbine via a reheat steam valve located in the middle of the casing. Then, after the steam completes its work at the intermediate-pressure section, it is additionally mixed with the low-temperature steam that has been

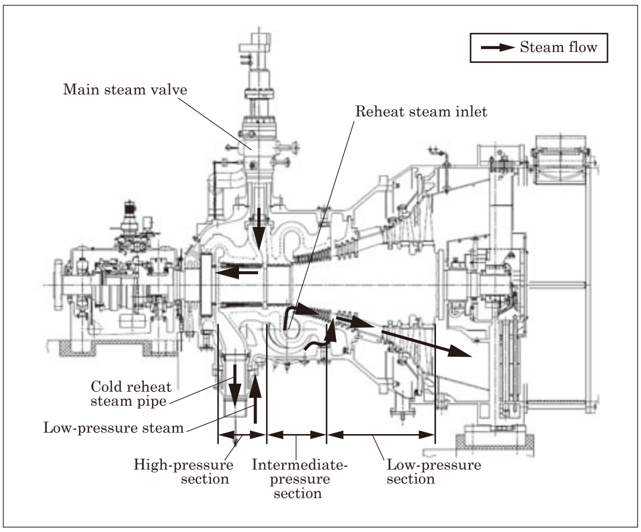


Fig.4 Cross-section of steam turbine for Yoshinoura Thermal Power Station

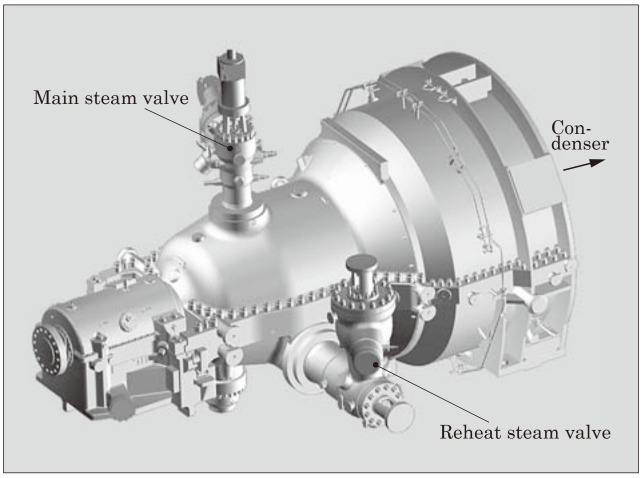


Fig.5 Bird's-eye view of steam turbine for the Yoshinoura Thermal Power Station

supplied to the casing, directed to the low-temperature section and discharged in the turbine axial direction to reach the condenser.

So that a turbine conventionally configured with two casings can be configured with a single casing, the following structure was used.

(a) One set of main steam valves are positioned on the upper side of the turbine casing and one set of reheat steam valves are positioned on the side of the turbine casing.

(b) Because the high-temperature sections are concentrated in the center, the high-pressure section and the intermediate-pressure section utilize counterflow.

(c) By locating the low-pressure steam inlet at the front of the casing and creating a flow of steam between inner and outer casings, the structure makes it less likely for a top/bottom temperature difference of the casing.

In the trial operation of the Units No. 1 and No. 2, a good operating state, with minimal vibration and top/bottom temperature difference of the casing, was confirmed for both continuous operation and start-up/shut-down process.

3. Steam Turbine for the SUR Plant CCPP from Daewoo E&C

This system, a steam turbine that generates power by utilizing the exhaust heat from two gas turbines to generate steam with an exhaust heat recovery boiler, is composed of two components, a high and intermediate-pressure turbine for the high-pressure and intermediate-pressure sections and a low-pressure turbine for the low-pressure section.

Figure 6 shows a bird's-eye view, Fig. 7 shows an external view and Fig. 8 shows a cross-sectional view of the steam turbine.

The high-temperature high-pressure main steam flows through a main steam valve, located at the lower

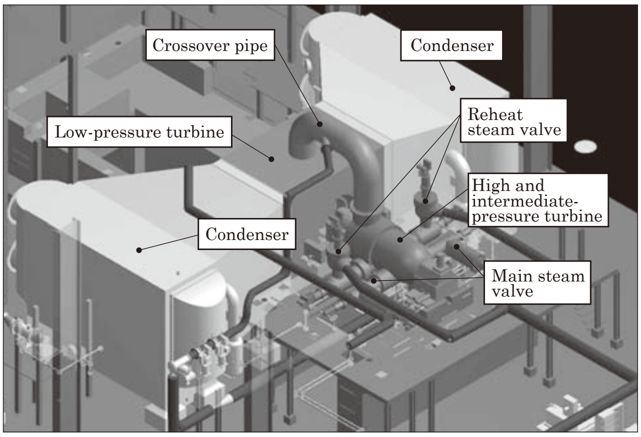


Fig.6 Bird's-eye view of steam turbine for SUR plant CCPP

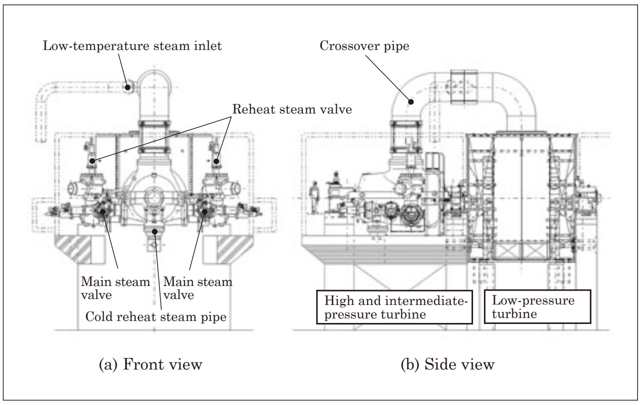


Fig.7 Outline view of steam turbine for SUR plant CCPP

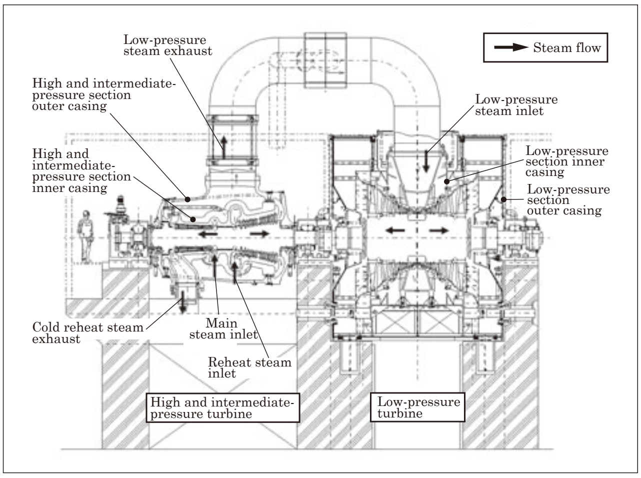


Fig.8 Cross-sectional view of steam turbine for SUR plant CCPP

part of the casing, and into the high-pressure section. Main steam then expands toward the front of the turbine, and after completing its work, is discharged through a cold reheat steam pipe. Reheat steam flows through the reheat steam valve, located at the lower central part of the casing, into the intermediate-pressure section. Reheat steam then expands toward the rear of the turbine, and after completing its work, is discharged through cross-over pipe, and then is supplied to the low-pressure turbine. Low pressure steam is mixed at the midpoint on the crossover pipe. After completing work at the low-pressure turbine, the steam reaches condensers located on either side of the low-pressure turbine.

Features of this turbine are as follows.

(a) The largest capacity high and intermediate-pressure turbine for Fuji Electric
(b) Low-pressure turbine with dual-side exhaust system allows for lower building height

3.1 330 MW high and intermediate-pressure turbine

Previously, this class of equipment (330 MW) has used a three-casing reheat steam turbine, consisting of a high-pressure turbine, an intermediate-pressure turbine and a low-pressure turbine. With the Sur CCPP, a more compact size has been realized by combining the high-pressure turbine and intermediate-pressure turbine components together as a two-casing reheat steam turbine. Fuji Electric's previous maximum capacity of a two-casing reheat turbine was 210 MW, but a larger size has been achieved by adopting the measures described below.

In order to cool the compact inner casing, in a double casing structure consisting of an inner casing and an outer casing as shown in Fig. 8, the pressure and temperature acting inside the turbine are apportioned so that a more compact volume can be achieved and intermediate-pressure section exhaust steam is flowed between both casings so that the inner casing can be cooled. Additionally, because the high-pressure exhaust steam is exhausted with an L-ring structure that does not contact the high-pressure outer casing, lower grade cast steel or cast iron is used as the material of the outer casing. Furthermore, to enhance the compactness of the outer casing and facilitate maintenance at the time of regular inspections, main steam valves and reheat steam valves are located at the lower left and right of the high and intermediate-pressure turbine as shown in Fig. 7(a).

3.2 Dual-side exhaust type low-pressure turbine

The low-pressure turbine casing consists of a low-pressure inner casing and a low-pressure outer casing. Steam discharged from the intermediate-pressure turbine is introduced via a crossover pipe to the low-pressure inner casing. Then, the steam expands to a vacuum pressure and passes between the low-pressure inner casing and the low-pressure outer casing and is discharged to the condenser. With a conventional structure, the exhaust steam is output to a condenser located directly beneath the turbine. Such a structure, however, has the disadvantage that the large volume condensers located under the turbine floor result in a turbine building that has a high height and is more expensive to build. In this system, as shown in Fig. 6, condensers are located on either side of the low-pressure turbine so that the turbine building does not have to be as tall, and can therefore be constructed less expensively. In developing the low-pressure outer casing for the dual-side exhaust type turbine, we studied how to ensure the same steam flow area as with a downward exhaust type and how to reinforce the inner structure so as to be able to withstand vacuum pressures, and also reviewed the turbine anchor points and considered a divided approach to improve the ease of maintenance. By applying a proven structure for the low-pressure inner casing, the same level of quality as in a conventional structure is ensured.

4. State-of-the-art Steam Turbine Technologies

4.1 Welding technologies

(1) Welding technology for rotor made of dissimilar materials

The material used in the rotor of a single-casing steam turbine is required to have the opposing characteristics of good creep strength at locations exposed to high temperature steam and good toughness at locations exposed to low temperature steam. Previously, 2% Cr steel, which is expensive but high toughness, or 1% Cr steel, which has poor toughness but is inexpensive, was used according to the magnitude of the centrifugal force acting on the center of the shaft, i.e., the length of low pressure blade or rotational speed. Recently, some plants require the use of longer low-pressure blades for which even 2% Cr steel provides insufficient toughness. For this reason, Fuji Electric has developed welding technology for a 1% Cr steel rotor having high creep strength at high temperatures and a 3.5% Ni steel rotor having higher toughness than 2% Cr at low temperatures. This technology can also be applied as an alternative to 2% Cr steel rotors for which material manufacturers are limited. Figure 9 shows a steam turbine that uses a rotor made from welded dissimilar materials.

(2) Rotor repair welding technology

In aged plants, cracks due to thermal fatigue may,

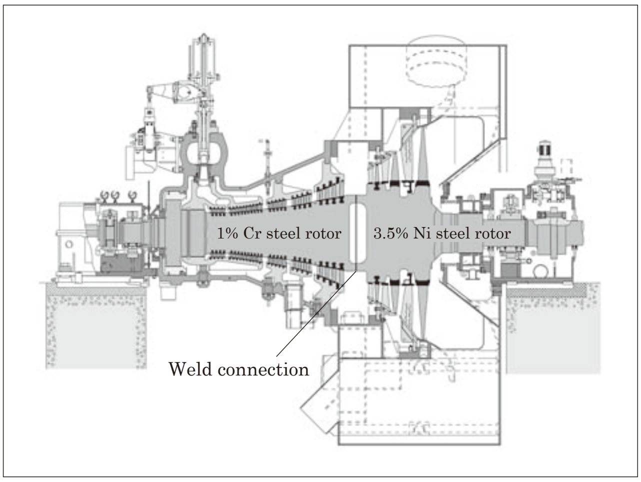


Fig.9 Steam turbine using rotor made from welded dissimilar materials

in some cases, be observed on the surface of rotors used at high temperatures. The operation of a turbine in which cracks exist in this state would be extremely dangerous. The manufacture of a new rotor requires that a plant be stopped for an extended period of time and thus results in a tremendous loss of profit to the customer. In order to minimize the duration of plant stoppage, Fuji Electric has developed weld repair technology for locations in which cracks have occurred.

(3) Weld repair technology for cast iron products

Because cast iron does not require complex heat treatment processing and has few material defects, for use at intermediate and low-temperatures where high thermal strength is not required, it is advantageous compared to cast steel in terms of a shorter manufacturing period and lower cost. With cast iron, however, defect areas are difficult to repair by welding and if a defect exceeds the allowable size in an area where strength is required, disposal and remanufacture will be necessary.

Welding tests were conducted on a test sample cut out from the excess material of an actual iron casting, and based upon the results of non-destructive testing, optimal welding conditions were established. The welding tests were performed using two welding methods, gas shielded tungsten arc welding (GTAW) for welding in a narrow range and shielded metal arc welding (SMAW) for welding in a broad range, two welding orientations, downward and horizontal, and three types of filler materials, Ni alloys, Fe-Ni alloys and Inconel alloys.

4.2 USC turbine technologies

(1) Domestic production of materials for use in USC turbines

In contrast to oil and natural gas that are concentrated in regions of political instability, coal is widely distributed over the earth, and thus from an energy-security perspective, coal-fired power generation is positioned as an important source of power.

On the other hand, coal-fired power generation has the largest amount of CO_2 emissions among the various types of thermal power generation that use fossil fuels (oil, gas or coal). Therefore in recent years, in the construction of large capacity coal-fired power generation facilities, ultra super critical (USC) plants that utilize high temperature and higher pressure to achieve higher thermal efficiency in power generation plants have become mainstream.

In 2002, Fuji Electric worked on a USC plant that used a steam turbine manufactured by Siemens AG and in which the main steam temperature was 600 °C and the reheat steam temperature was 610 °C. At that time, the main material of improved 12% Cr steel that was used in high temperature components was made all in Europe.

Because there are a limited number of suppliers of the main material used in USC plants, the domestic manufacture of USC turbines is considered to be an important factor in facilitating procurement of the main material. In collaboration with domestic materials manufacturers, Fuji Electric carried out prototype testing of rotor material and casing material of improved 12% Cr steel, established manufacturing technology and methods of evaluating material deterioration and embrittlement, and set domestic production of the main material as a goal. Figure 10 shows a prototype of a rotor made from improved 12% Cr steel.

Fig.10 Improved 12% Cr steel prototype rotor

(2) Remaining life assessment technology

Because of the significant cost and preparation time required for the renewal of a steam turbine in an aged plant, assessment of the remaining life and plans for renewal must be made at appropriate times.

For the 1% Cr steel used in subcritical pressure plants and supercritical pressure plants that have lower steam conditions than in a USC plant, master curves relating to the deterioration characteristics and embrittlement characteristics of the material have already been obtained. On the other hand, for the improved 12% Cr steel used in USC plants, however, master curves relating to deterioration characteristics and embrittlement characteristics have not yet been obtained. For this reason, in collaboration with Kagoshima University, Fuji Electric is advancing research to obtain master curves, with the goal of establishing basic technology for performing remaining life assessments.

4.3 Technologies for improving the reliability of low-pressure blades

(1) Corrosion monitoring technology

It is known that the likelihood for stress corrosion cracking at the low-pressure blades increases as

*1: Cation conductivity: The electric conductivity of a solution after having passed through a cation exchanger resin whereby the cations were exchanged for hydrogen ions. Cation conductivity is used to detect harmful anion concentrations such as trace quantities of chloride ions, sulfate ions, and the like.

the cation conductivity[*1] of the main steam increases. Since the main steam properties are controlled at the boiler side, and because stress corrosion cracking occurs at the low-pressure blades which are located far away from the boiler outlet, real-time monitoring of the steam properties inside the turbine and accurate assessment of the risk of stress corrosion cracking are necessary.

For this reason, in collaboration with Tohoku University, Fuji Electric has developed a corrosion monitoring sensor and is conducting field tests. Figure 11 shows a drawing of the installation of a corrosion monitoring sensor. The corrosion monitoring sensor consists of sensors able to measure pH, chloride ion concentration and the corrosion potential, and enables the online monitoring of the corrosive environment at clearance gaps where corrosive components are likely to concentrate. Furthermore, a micro sampling device enables the steam inside a turbine to be sampled and analyzed.

(2) Vibration monitoring technology

The vibration characteristics of long low-pressure blades are complex and therefore if unproven low-pressure blades are to be used in an actual device, an acceleration sensor is attached at the time of shop balance testing, and rotation vibration tests are performed to verify the actual characteristics.

However, in contrast to shop balance tests that are conducted in a vacuum chamber at room temperature, the actual conditions in a turbine are a steam environment of changing temperature, pressure and flow rate. Thus, in order to ascertain the actual characteristics, low-pressure blade vibration must be measured under various operating conditions in a power plant. Therefore, we measured the vibration of low-pressure blades in operation. Figure 12 shows a drawing of the installation of a vibration monitoring sensor. By attaching multiple non-contact type eddy current sensors along the circumference of the stationary blade ring opposite the tip of the low-pressure moving blade, we successfully recorded continuous online measurements of the vibration of individual blades in operation. The sensors are housed in a titanium case so that long-term blade vibration monitoring will be possible.

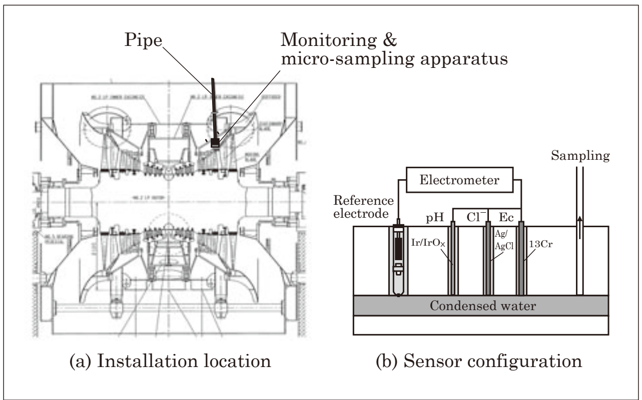


Fig.11 Installation of corrosion monitoring sensor

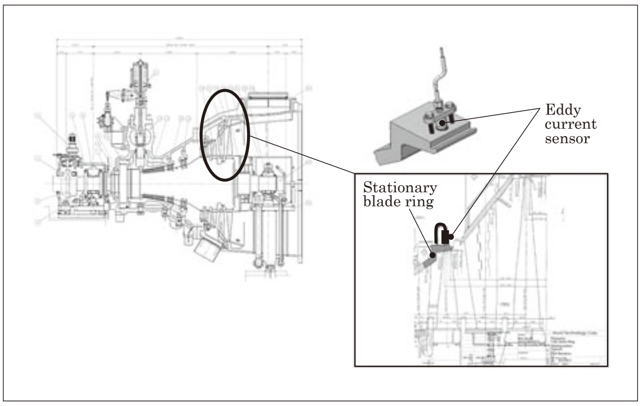


Fig.12 Installation of vibration monitoring sensor

5. Postscript

After the Great East Japan Earthquake that occurred on March 11, 2011, nuclear power plants in Japan have successively shutdown, and there are as yet no prospects for restarting them. During this period of prolonged shutdown of nuclear power plants, renewable energy and combined cycle power generation are seen as the future leaders for power generation.

In the field of coal-fired power generation, research and development of advanced ultra super critical (A-USC) power generation and integrated gasification combined cycle (IGCC) power generation, which are capable of further reducing CO_2 emissions below the levels of USC power generation, are being advanced. Fuji Electric intends to continue to pursue technical development in order to supply steam turbines that have high levels of performance and operability.

Global VPI Insulated Indirectly Hydrogen-Cooled Turbine Generator for Single-Shaft Type Combined Cycle Power Generation Facilities

YAMAZAKI Masaru † NIIKURA Hitoshi † TANIFUJI Satoshi †

ABSTRACT

Fuji Electric has a great deal of experience in air-cooled turbine generators for global VPI insulation systems. We designed and built global VPI indirectly hydrogen-cooled turbine generators for the Yoshinoura Thermal Power Station Unit No. 1 and No. 2 of the Okinawa Electric Power Company, Incorporated. These are double-end drive generators for a single-shaft type, combined cycle power generation facilities that use many of the same basic construction and manufacturing methods as air-cooled turbine generators. Using data obtained through experience and results from ventilation analysis and strength analysis, we are achieving optimization and increased reliability.

Through each type of test, we are obtaining results that satisfy performance expectations and we are seeing favorable operating conditions at the power plants.

1. Introduction

The method of combined cycle power generation using a gas turbine and a small steam turbine has the advantages of good power generation efficiency and operability and a low environmental burden. It has therefore been adopted widely in recent years. Furthermore, a rapid start-up is possible with this power generation method. Thus, it is easy to carry out daily start and stop (DSS) operations and it is possible to deal with situations where there is a large difference in demand for power between the daytime and the nighttime hours. It is therefore expected that demand for the method will continue to increase.

The electricity generator that Fuji Electric has designed and built for the Yoshinoura Thermal Power Station Unit No. 1 and Unit No. 2 of the Okinawa Electric Power Company, Incorporated, is an indirectly hydrogen-cooled turbine generator using a global vacuum pressure impregnation (VPI) insulation system for single-shaft type combined cycle power generation facilities. This article introduces the characteristics of it and the technologies that were applied.

2. Characteristics of Single-Shaft Type Combined Cycle Power Generation Facilities

Combined cycle power generation facilities include the single-shaft type, where a gas turbine, generator and steam turbine are lined up along one axis, and the multi-shaft type, where the gas turbine power generation facilities and the steam turbine power generation facilities are installed separately. In general, with single-shaft type power generation facilities, multiple systems are installed and each can be operated independently. Individual systems can be stopped when the amount of power generation necessary falls and the other systems can be operated at the rated load. This makes it possible to maintain high partial load efficiency for the plant as a whole. Figure 1 shows an example of configuration of the single-shaft type combined cycle power generation facilities developed jointly by Fuji Electric and Siemens AG.

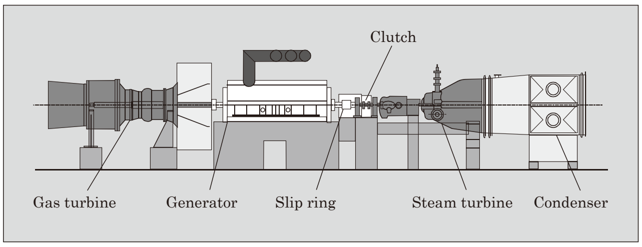


Fig.1 Example of configuration of single-shaft type combined cycle power generation facilities

3. Characteristics of the Power Generator

Table 1 shows the main specifications of the generator and Fig. 2 shows a cross section view. The structures and manufacturing methods used on the stator windings, stator core and rotor windings for this indirectly hydrogen-cooled turbine generator are roughly the same as those used for air-cooled turbine generators. This made it possible to achieve high reliability based on the great deal of experience gained in air-cooled turbine generators and by sharing the common technologies and equipment.

3.1 Cooling methods

This generator uses the indirect hydrogen cooling method for the cooling of the stator. The ventilation

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

Table1 Main specifications of 300 MVA indirectly hydrogen-cooled turbine generator

Item	Specification
Output	300 MVA
Voltage	16,000 V
Power factor	0.85
Frequency	60 Hz
Coolant	Stator: Hydrogen indirect Rotor: Hydrogen direct
Hydrogen gas pressure	0.4 MPaG
Coolant gas temperature	43 °C
Speed	3,600 min^{-1}
Excitation	Static
Total length	13.1 m
Total mass	325 t

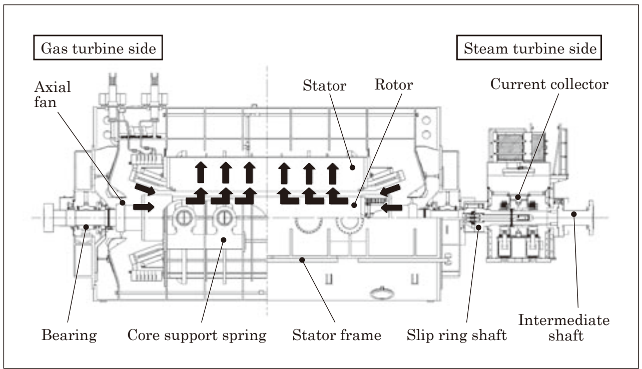


Fig.2 Cross section diagram of 300 MVA indirectly hydrogen-cooled turbine generator

path is as shown with the arrows in Fig. 2. Cooling gas is fed to the stator and rotor parts from an axial fan at both ends of the rotor. All the flow of the stator cooling gas is from the inner diameter side to the outer diameter side.

These cooling and ventilation methods are the same as on air-cooled turbine generators, in which Fuji Electric has a great deal of experience. The design was based on the data obtained from prototype experimental models and actual results. The optimal positioning of cooling ducts and distribution of cooling airflow is used to achieve a uniform distribution of temperature on the windings.

In addition, for the rotors, in order to achieve a uniform cooling flow in each part of the coil, inlet guide vanes were added to the internal diameter of the retaining ring support, as shown in Fig. 3. This improves the cooling performance.

3.2 Rotor structure

As shown in Fig. 1, in single-shaft type combined cycle power generation facilities, the gas turbine and steam turbine are positioned at both ends of the generator. The following consideration is therefore made.

(1) Bending and torsional vibration response calculations for the entire shafting

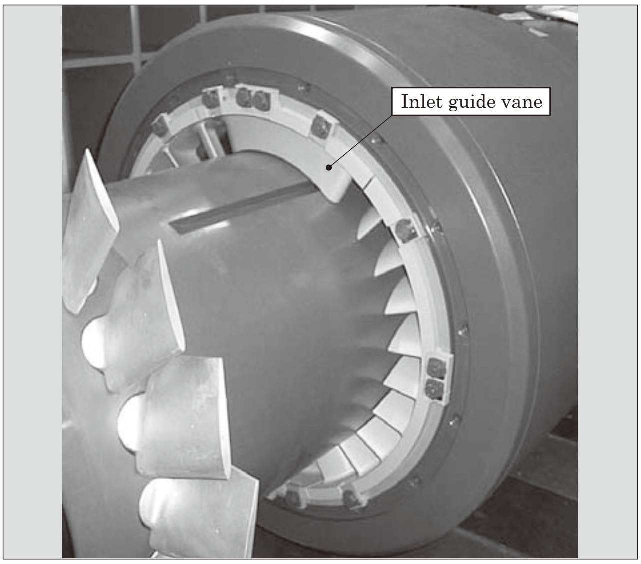


Fig.3 Inlet guide vane

Both gas turbine simple cycle*1 and combined cycle operations are possible on this power generation equipment. For both of these methods of operation, consideration is made so that a rated rotation speed and critical speed of the generator are not approached and there is sufficient consideration made for the vibration response.

(2) Slip ring shaft material

The generator rotors are double-end driven and the driving torque is transmitted. In addition, it is necessary to prepare sufficient strength to endure short-circuit accidents, and thus the same NiCrMoV steel material as on the generator shaft was adopted as the slip ring shaft material.

(3) Insulating coupling

There is a risk on the rotor axis that the electromotive force generated during operations may result in a return current between the main axis, the bearings and the structures connecting the two bearings, and this may interfere with the operation of the generator. Insulation is therefore installed on the bearings to cut off the electrical circuit and prevent a circulation of current flow. This time, in order to prevent the circulation of current flow through the intermediate shaft bearings, an insulating coupling is used in the connection between the slip ring shaft and the intermediate shaft.

3.3 Stator structure

The stator core is supported through the core support plate shown in Fig. 4 on the cylindrical stator frame, which is a pressure vessel. The structure has an appropriate spring effect to suppress the transmis-

*1: Simple cycle: An energy system where just power generation is performed with a motor using fuel.

Fig.4 Core support spring

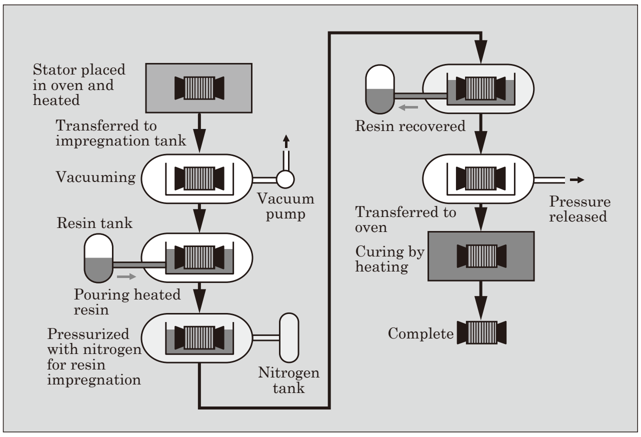


Fig.6 Global VPI insulation processes

sion of electromagnetic vibration from the core to the stator frame.

4. Global VPI Insulation Technology

The stator insulation is performed using the global VPI insulation technology that Fuji Electric has accumulated in many years of experience and a global VPI insulation system with global VPI manufacturing facilities that are the biggest in Japan and one of the greatest in the world.

Figure 5 shows the global VPI insulated stator. The stator windings and core are impregnated with insulating resin as one whole, the core, windings and wedges are therefore strongly attached and less likely to become loose. This improves the reliability and makes it possible to reduce maintenance work. Furthermore, as the spaces between the windings and core are filled with resin so that there are no gaps, there is the advantage that the heat dissipation from the windings to the core is improved, and the cooling performance is better than with impregnation of the

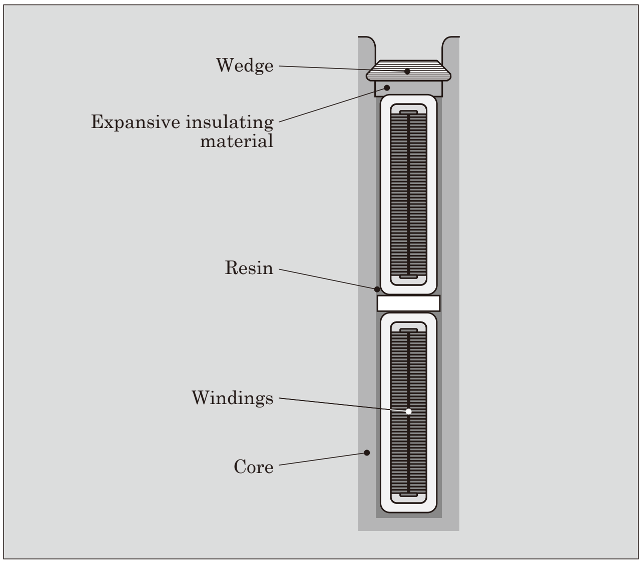


Fig.5 Global VPI insulated stator

windings alone.

Figure 6 shows the impregnation processing stages in global VPI insulation. After winding the mica glass tape or other on the conductors as the main insulating material, the windings are inserted into the stator core slot and the specified winding connections are made. Next, the stator core and windings are placed as one into an epoxy resin tank for vacuum pressure impregnation. With this process, all the windings are impregnated with resin at one time, and consequently it is extremely important for large-scale generators. For this reason, factors such as the viscosity of the resin and the compounding ratio of curing agent are strictly controlled, and a monitoring system takes measurements during the impregnation processing of a temperature, degree of vacuum, pressure during pressurization and capacitance of the windings for the constant monitoring and control of the status of the resin impregnation.

5. Analysis Technology

5.1 Ventilation analysis

In ventilation analysis, the improvements in hardware and software performance in recent years have made it possible to increase the number of elements in the analysis model and it has become possible to calculate complex flows such as the cooling ventilation in a generator with comparatively high accuracy. Furthermore, it is extremely difficult to actually measure the flow inside the rotor during operations, but it is now possible to understand the distribution of flow and other matters to a high level of accuracy by using thermo-fluid analysis. Fluid analysis is also used to realize optimal ventilation cooling in the design of global VPI insulated indirectly hydrogen-cooled turbine generators.

The following is an example of flow analysis on the rotor coil end part. Figure 7 shows a ventilation analysis model for the rotor. The outlet part of the axial fan at the shaft end, the space on the inner side of the coil end, the rotor coil cooling duct and air gaps have been modeled. Flow distribution was calculated for the con-

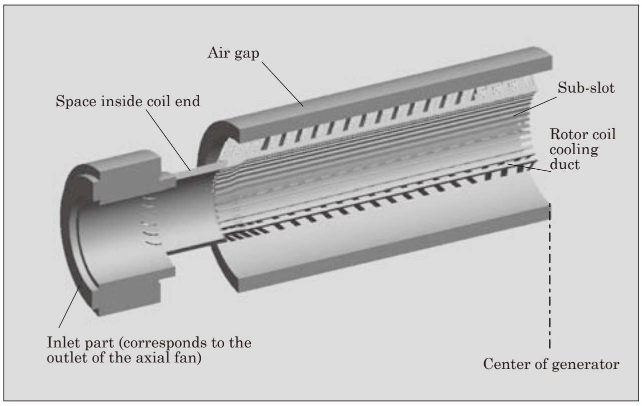


Fig.7 Ventilation analysis model for the rotor

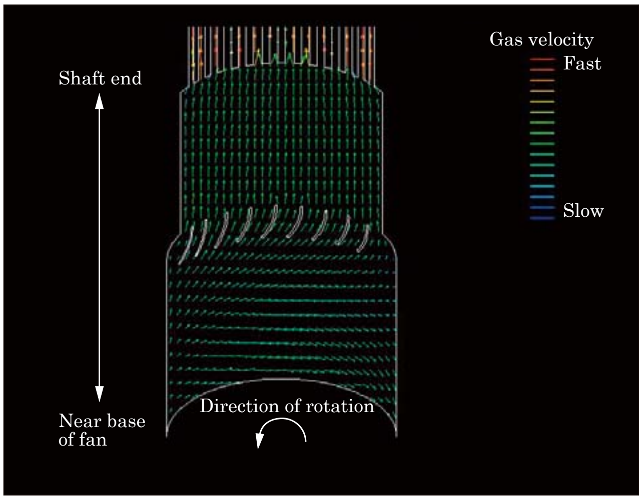


Fig.8 Example of results of ventilation analysis on the rotor coil end part

dition that the rotor rotates at its rated speed. For the boundary conditions for the axial fan part, which is the inlet to the analysis area, and the air gap, which is the outlet, flow distribution values calculated separately were used for the analysis. Figure 8 shows an example of the results of ventilation analysis on the rotor coil end part.

5.2 Strength analysis

Strength analysis was performed on the rotor retaining ring shrink fit area in order to secure reliability in frequent start-up/stop operations, which are a characteristic of combined cycle power generation. In order to retain the rotor coil end under the centrifugal force during rotation, the rotor-retaining ring is shrink-fitted to the rotor shaft end with a certain shrink-fit allowance. When stationary, compressive stress occurs on the shrink fit part on the rotor shaft end. When rotating, the centrifugal force means that the retaining ring diameter expands and the compressive stress is released. Consequently, start-up/stop operations mean that the stresses occur repeatedly. For this reason, in addition to avoiding the concentration of stress, consideration was also given to the reliability

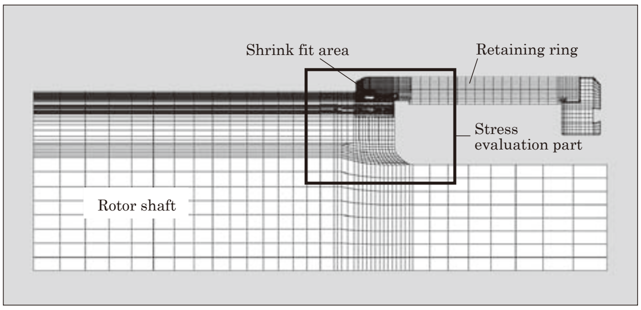


Fig.9 Strength analysis model of retaining ring

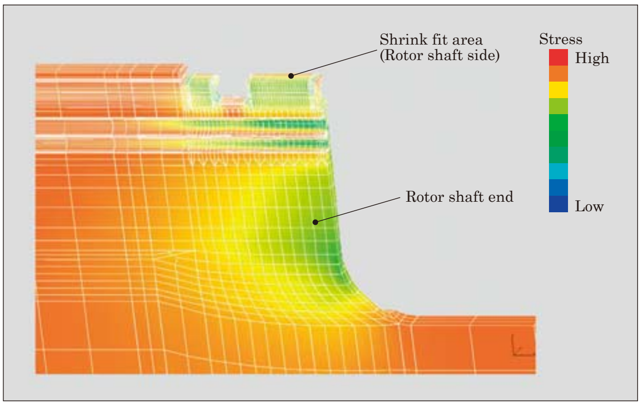


Fig.10 Results of stress distribution analysis on the rotor shaft end (Stress evaluation part)

against repeated stress.

Figure 9 shows the retaining ring strength analysis model. The structure of the retaining ring shrink fit area is very complicated, the strength analysis is therefore performed using a three-dimensional model. In addition, in order to correctly model the state of the stress, consideration was given to the non-linearity of the strain and stress, and the shrink fit surfaces of the rotor and the retaining ring were taken to be contact elements. Figure 10 shows the results of stress distribution analysis as an example of strength analysis at the rotor shaft end.

6. Related Equipment

6.1 Adoption of clutch

In between the generator and steam turbine, there is a clutch installed that can absorb the differential expansion and be automatically attached and removed. This means that the gas turbine and steam turbine can be designed independently for the thrust loading and the difference in thermal expansion that occurs due to changes in temperature during start-up/stop operations. Furthermore, the starting and stopping of the gas turbine is possible with no effect on the steam turbine. Thus the loss at the starting and stopping can be reduced.

6.2 Adoption of static frequency converter (SFC)

The method used for starting up the gas turbine is to use an SFC to drive the generator as a synchronous motor. This SFC is made up of a converter and an inverter, and it supplies the generator stator with the voltage and frequency necessary for the starting up and speeding up of the gas turbine. In addition, the generator excitation power supply during the speeding up is supplied from an excitation system. The use of this method means that a starting motor is not necessary and the shafting and overall arrangement is simplified. Furthermore, maintenance work is also simplified as the configuration includes only electrical equipment.

7. Factory Test Results

Fig.11 Global VPI insulated indirectly hydrogen-cooled turbine generator during factory testing

In June 2010, the various aspects of performance were verified in a no-load saturation test, three-phase short-circuit test, loss characteristic test, temperature rise test, sudden three-phase short-circuit test and overspeed test. Figure 11 shows a global VPI insulated indirectly hydrogen-cooled turbine generator during factory testing. The factory testing results were good, which satisfied the specifications and had good agreement with the design values.

8. Postscript

This article was centered around the characteristics and technologies of the global VPI insulated indirectly hydrogen-cooled turbine generators for single-shaft type combined cycle power generation facilities at the Yoshinoura Thermal Power Station Unit No. 1 and Unit No. 2 of the Okinawa Electric Power Company, Incorporated. Unit No. 1 started trial operations in May 2012 and commercial operations in November, and the status of operations is good. Moreover, commercial operations at Unit No. 2 started in May 2013. Fuji Electric will continue to respond to the needs of the market and to carry out technology development to produce high quality and highly reliable turbine generators.

Technology for Large-Scale Photovoltaic Power Generation Systems

NAKAGAWA Masayuki † XIANG Donghui †

ABSTRACT

The market for photovoltaic power generation systems in Japan is expanding to large-scale photovoltaic power generation (mega solar), and the need for high efficiency, high reliability, and compact equipment increases. Fuji Electric supplied a package of mechanical and electronic equipment for Abu mega-solar plant of the Okinawa Electric Power Company, Incorporated including devices for a solar power generation system and a remote surveillance control system, which commenced operation in the end of March 2012. We have applied a highly-efficient, high-capacity power conditioner utilizing the power electronics technology and a large-scale surveillance control system.

We are also developing system-interconnection technologies to resolve issues that would arise in the power grid with large-scale implementation of renewable-energy power production through microgrid verification equipment using stable systems etc. for remote islands.

1. Introduction

The "Kyoto Protocol" was adopted at the 3rd Session of the Conference of the Parties to the U.N. Framework Convention on Climate Change (COP3) in December 1997. It clarified the reduction of greenhouse gases and a low carbon society became the goal. In order to promote the introduction of photovoltaic power generation, the Japanese government provided support for the installation of large-scale photovoltaic power generation facilities with outputs of 1 MW or greater, which are generally described as mega solar facilities. After the Great East Japan Earthquake in March 2011, the government announced a policy of accelerating the development of renewable energy to secure an alternative energy source to nuclear power generation. Furthermore, after the start of the "Feed-in Tariff Scheme for renewable energy" in July 2012, there have been increasing examples of photovoltaic power generation facilities being constructed by parties other than the electric power companies, for example, ordinary companies or local governments, both for the purpose of selling the power and for their own use.

Fuji Electric has been supplying photovoltaic power generation systems both in Japan and overseas since 1980. This article introduces the company's technologies for large-scale photovoltaic power generation systems, which are based on that track record.

2. Fuji Electric's Solutions for Photovoltaic Power Generation System

Fuji Electric has utilized the plant technologies developed in power generation facilities, transforming facilities and factory facilities, and has supplied many photovoltaic power generation systems and verification facilities both within Japan and overseas. The company is also a world leader in the development and delivery of film-type amorphous solar cells, which are "thin, light and flexible."

Figure 1 shows an overview of measures for photovoltaic power generation systems. Fuji Electric performs all processes from the selection of solar cells to the design, installation and maintenance of extra-high voltage and high voltage facilities, power grid inter-

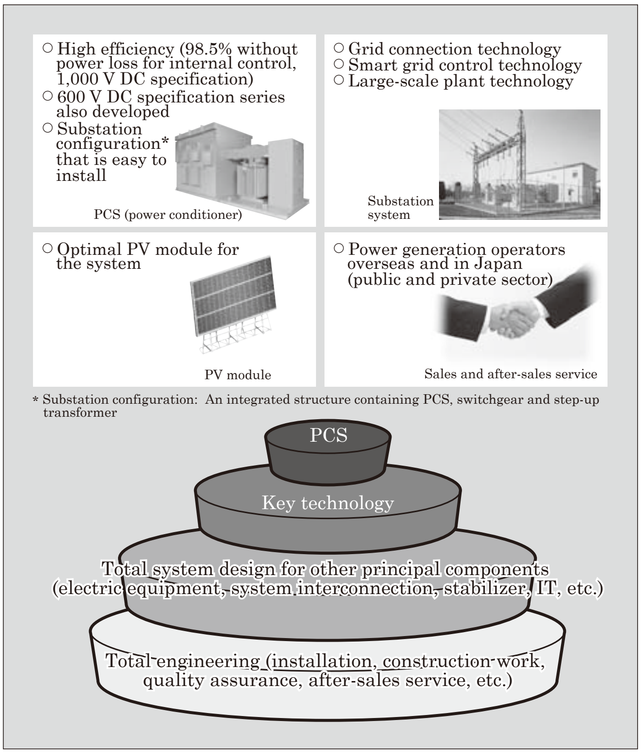


Fig.1 Measures for photovoltaic power generation systems

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

connection facilities, and supply and demand control systems. In the installation of mega solar facilities, an elaborate plan is necessary as a great deal of time is required for the various procedures and technical considerations. This includes the acquisition of land, an investigation of the environmental conditions where the facilities will be installed, the investigation of investment and return with consideration of the feed-in tariff system and subsidies, and also conformity with the various laws and regulations related to the security of the facilities.

As shown in Fig. 2, photovoltaic power generation systems such as mega solar are made up of photovoltaic module (PV module), arrays, junction boxes, connection boxes, power conditioner (PCS), interconnection facilities, environmental measurement equipment and monitoring control systems. Figure 3 shows the procedure for their installation. The main points of the system plan are as follows.

(a) There are many different types of solar cell, including single crystal and polycrystalline types, amorphous and multi-junction thin-film types and types that do not use silicon, such as those with CI(G)S compounds and other, organic types. Each of these has their own characteristics and different costs and power generation efficiencies. The optimal solar cell is selected from solar cell manufacturers both in Japan and overseas after considering the requests of the customer and the conditions such as the installation environment and the price.

(b) The angle of inclination, direction for PV module attachment and number of rows and columns on the arrays are planned after consideration of the environment, the setting area and the costs.

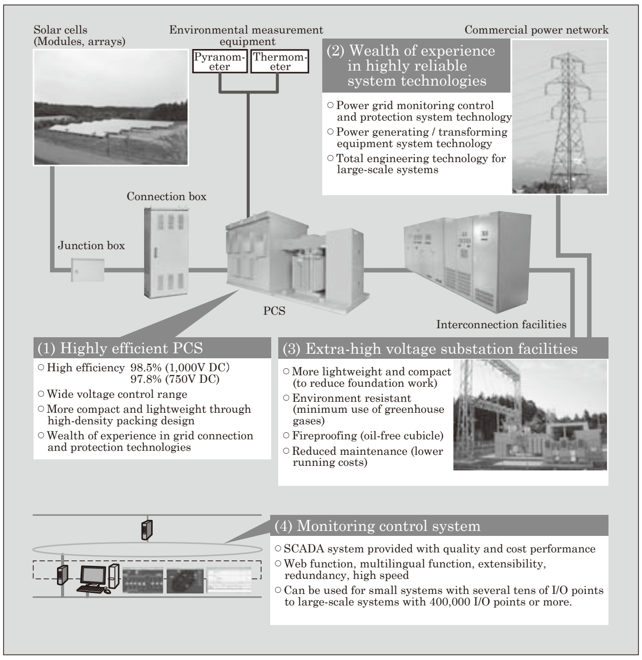


Fig.2 Configuration of photovoltaic power generation systems

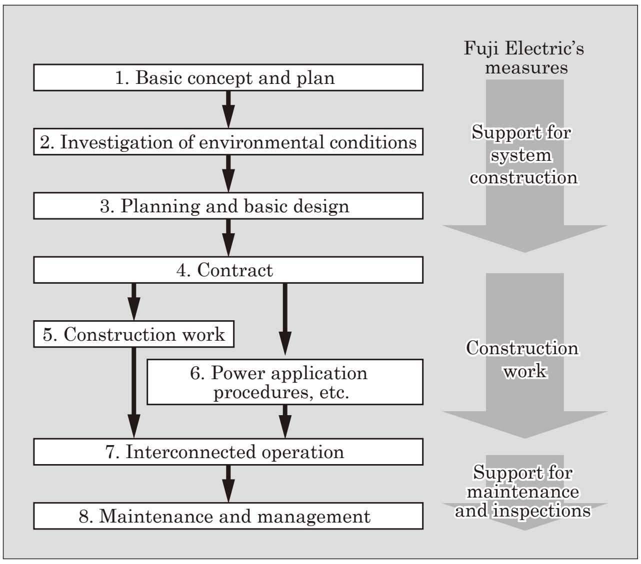


Fig.3 Procedure for the installation of photovoltaic power generation systems

(c) The junction boxes and connection boxes are planned with consideration of the installation environment and by investigating the arrangement with consideration of the optimal number of solar cells in series and the transmission losses, and then designing the number of branches.

(d) Highly efficient large-capacity and transformer-less PCS are used.

(e) For the switchgear for the interconnection facilities, at the 22 to 77 kV class, cubicle type gas-insulated switchgear using SF_6 gas or environmentally friendly dry air is selected. For larger classes, SF_6 gas-insulated switchgear is used.

(f) For the transformer for the interconnection facilities, an oil-immersed transformer using a highly efficient mineral oil or environmentally friendly palm oil is selected.

(g) For the purpose of energy management and environmental enlightenment, the environmental measurement equipment includes pyranometers are installed at the same inclination as the arrays, and external thermometers to measure air temperature are installed at a location not exposed to direct sunlight.

(h) For the monitoring control systems, CitectSCADA[*1] systems suitable for processing large numbers of I/O points are used in order to enable to perform monitoring control remotely and measure the current and voltage per individual junction box unit.

(i) For the design of the direct current side, the "Regulations on photovoltaic power generation facilities" were revised based on the "Partial revision of the interpretation of the technical stan-

*1: CitectSCADA: Trademark or registered trademark of Schneider Automation, Inc., France.

dards for electrical equipment" (Nuclear and Industrial Safety Agency, Ministry of Economy, Trade and Industry, June 29, 2012) and PV cables can now be used in the high voltage range (limited to 1,500 V DC and below) (see Fig. 4).

Table 1 shows a comparison of 600 V and 1,000 V DC distribution systems. Compared with the 600 V DC distribution that is currently the most common, with the 1,000 V DC distribution it is theoretically possible to increase the number of PV module in series to 10/6 and reduce the number in parallel to 6/10. This makes it possible to reduce the number of PV cables and junction/connection boxes, and it is possible to reduce the cost of the power generation and to reduce the transmission losses. Fuji Electric is actively including the 1,000 V DC distribution method in system plan.

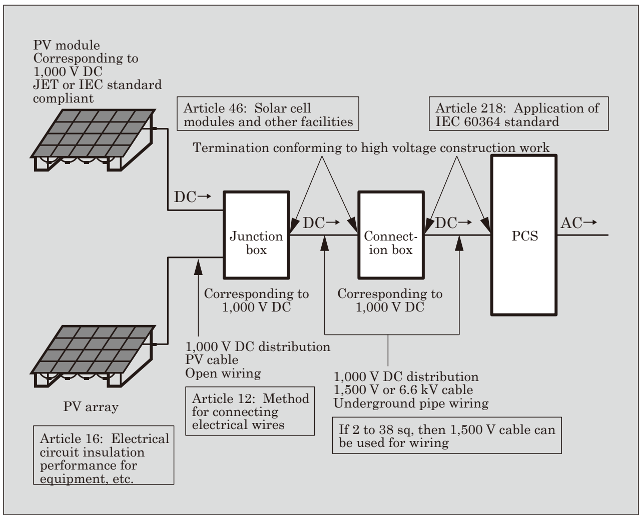


Fig.4 Examples of photovoltaic power generation facilities and related technical standards

Table 1 Comparison of 600 V and 1,000 V DC distribution systems

	1,000 V DC distribution	600 V DC distribution
Circuit division	1,000 V DC ◄ ► AC; PV module → Junction box → Connection box → PCS → Transformer → Distribution board → Electric power company distribution system	600 V DC ◄ ► AC; PV module → Junction box → Connection box → PCS → Transformer → Distribution board → Electric power company distribution system
Circuit image	Less parallel and more series circuits compared with 600 V DC circuit; Number of parallel circuits (60%); Number of series circuits (160%); Circuit voltage 1,000 V DC; Junction box	Number of parallel circuits (100%); Number of series circuits (160%); Circuit voltage 1,000 V DC; Junction box
Number of pieces of DC side equipment and construction costs	○ Junction box: 60% ○ Cables between junction box and PV module: 60% ○ Cables between junction box and connection box: 60% ○ PCS: Number reduced by use of 1,000 V DC large-capacity equipment ○ Construction costs: Reduced because there are fewer wires and units to install	○ Junction box: 100% ○ Cables between junction box and PV module: 100% ○ Cables between junction box and connection box: 60% ○ PCS: 600 V DC unit ○ Construction costs: Proportional to number of wires and units to install
Transmission loss on DC side*	60%	100%

* Transmission losses = Current^2 × cable resistance
Because the solar cell current is the same for both systems, the transmission losses are proportional to the cable resistance (the length of the cables if they have the same diameter).

3. Photovoltaic Power Generation System for the Abu Mega-solar Plant in the Okinawa Electric Power Company, Incorporated

Figure 5 shows an overview of the Abu mega-solar plant. The Okinawa Electric Power Company, Incorporated installed the 1 MW power output Abu mega-solar plant in Nago City, Okinawa prefecture. The objective of this plant was to gain knowledge about the effects on the power grid if photovoltaic power generation is introduced to contribute to reductions in CO_2 emissions and to improve the ratio of zero-emission power supplies. Fuji Electric supplied a package of mechanical and electronic equipment, including devices and a remote monitoring control system. Operations began at the end of March 2012.

For the solar cells, 2 types of thin film solar cell were selected (CIGS type and amorphous silicon + polycrystalline silicon multi-junction type), for an evaluation of the solar cells suitable for the meteorological conditions in Okinawa prefecture.

Figure 6 shows an outline of the Abu mega-solar plant system. The characteristics of this facility are as follows:

(a) There is monitoring control at the 2 locations of

Fig.5 Overview of Abu mega-solar plant (Photograph supplied by the Okinawa Electric Power Company, Incorporated)

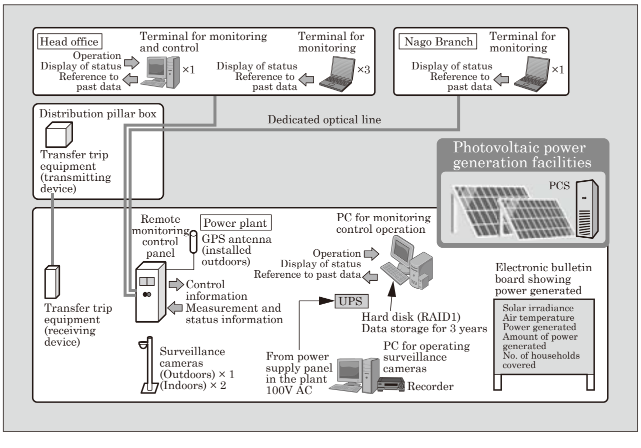


Fig.6 Outline of the Abu mega-solar plant system

the power plant and the head office, and monitoring at a branch.
(b) Generated power output control and reactive power control have been realized.
(c) It is possible to compare the amount of power generated, etc., for different angles of array installation.
(d) Large-capacity 500kW PCS×2 systems are used.

4. Large-Capacity Power Conditioners

The demands placed on mega solar are for a reduction of the unit cost per watt for the solar cells, as well as for high reliability and a reduction of the power generation unit price of the PCS, which is a major component. For this reason, it is necessary for the PCS to realize high efficiency, reduced total costs and the high reliability necessary for connection to the power system.

For these reasons, Fuji Electric commercialized the "PVI1000 Series" and "PVI750 Series," which realize these aims. Figure 7 shows the external appearance of the PVI1000 Series and Fig. 8 shows the external appearance of the PVI750 Series.

Table 2 shows the PCS specifications. The main characteristics are as follows.

(a) An advanced T-type neutral-point-clamped (AT-NPC) 3-level insulated gate bipolar transistor module is used to achieve the global top level efficiency of 98.5%.[1]
(b) Both the 1,000 kW and 750 kW PCS are substation types that integrate the step-up transformer and PCS on a common base and they can be installed outdoors. A standard specification and a salt-tolerant specification have been prepared to suit the installation location. Cooling by air conditioner was made unnecessary to reduce installation costs. Cooling is possible with just the built-in fan, and the power supply capacity for cooling is around 2 kW.
(c) To achieve high reliability, a fault ride through (FRT) function was included as standard.[1]
(d) The AC circuits and DC circuits of the 250 kW unit have been placed in a parallel configuration, and even if one of the units fails, the Fuji

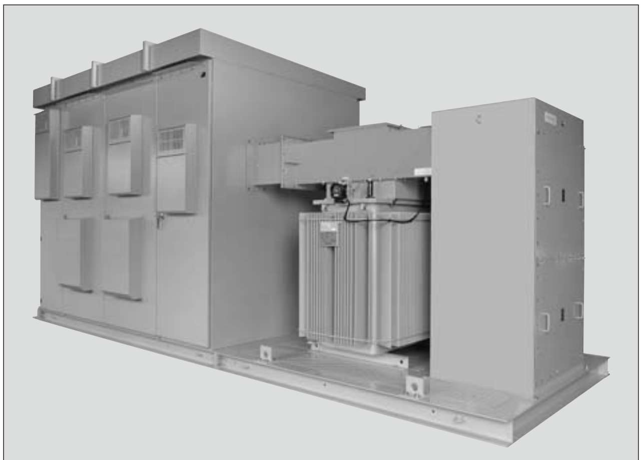


Fig.7 "PVI1000 Series"

Fig.8 "PVI750 Series"

Table 2 PCS specifications

Item	Product		
	PVI1000-3/1000	PVI750-3/750	PVI750-3/500
Rated output	1,000 kW	750 kW	500 kW
Max. DC input voltage	1,000 V	750 V	750 V
DC input voltage (MPPT control range)	460 to 850 V	320 to 700 V	320 to 700 V
No. of DC input branch circuits	4 (Optional: 24)	4 (Optional: 24)	5
PCS output voltage	270 V AC (–12 to +10%)	200 V AC (±10%)	200 V AC (±10%)
Equipment's max. efficiency (without power loss for internal control)	98.5%	97.8%	97.7%
Installation location / method	Outdoor package (built-in PCS + TR + LBS)	Outdoor package (built-in PCS + TR + LBS)	Indoors (PCS and DC input panel) (Separate housing necessary if installed outdoors)
Cooling method	Forced air cooling	Forced air cooling	Forced air cooling (Separate air conditioning equipment is necessary)
Dimensions	W 6,150× D 2,400× H 2,830 (mm)	W 6,150× D 2,400× H 2,830 (mm)	W 2,400× D 900× H 1,950 (mm)
Mass	About 13,000 kg (including step-up TR + LBS panel)	About 12,200 kg (including step-up TR + LBS panel)	About 2,000 kg (PCS and DC input panel)
Acoustic noise	85 dB or below	85 dB or below	75 dB or below

Electric service personnel can remove the failed unit and operations can continue using the sound units remained.

(e) The 1,000 kW PCS has a maximum DC input voltage of 1,000 V, which is the global standard. Furthermore, as a safety standard for the equipment, third-party certification was obtained for IEC 62109 (Safety of power converters for use in photovoltaic power systems).

5. Monitoring Control System for Mega Solar

Monitoring control systems for mega solar play an important role in the power generation status of the power plant, the early detection of failures on equipment such as PV module, connection box and PCS, the understanding of the operating status of the equipment and the long term maintenance and operation.

Specifically, these include the early discovery of equipment failure through the collection of data and the communications network etc., the improvement of the operating ratio of the power plant through preventative maintenance based on equipment trend analysis and also the reduction of maintenance and operation expenses through the reduction of maintenance and inspection work hours at the site. These make a contribution to the maximization of profit for the power generation company.

Fuji Electric's monitoring control system for photovoltaic power generation plants was developed based on CitectSCADA, a general-purpose SCADA package. For this reason, in addition to being able to support power generation facilities from various manufacturers, it also has high reliability and high scalability.

5.1 Monitoring control system configuration

Figure 9 shows the configuration of the monitoring control system. The remote station (RS) panels

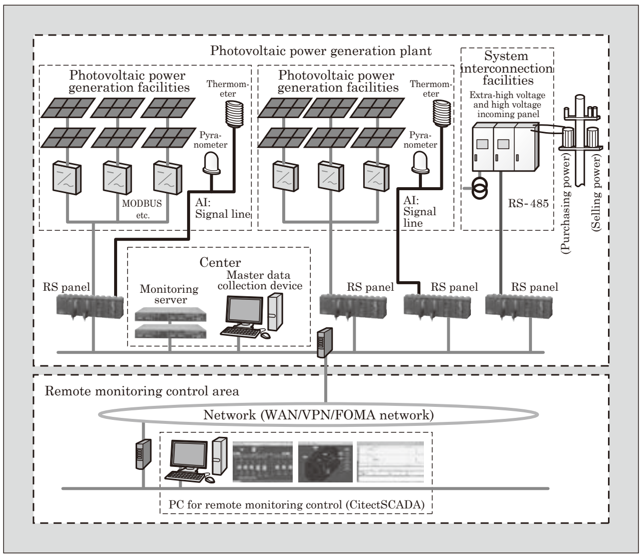


Fig.9 Monitoring control system configuration

that perform data collection and the communications network equipment are placed in the area of the mega solar installation. A master data collection device and monitoring server are placed in the "Center." When PCS of Fuji Electric is used, it is possible to integrate the RS panel functions into the PCS.

In addition, the data communications are compliant with hardware configurations such as Ethernet and RS-485 and open protocols such as TCP/IP and MODBUS. Furthermore, if a wide area network environment is used, it is also possible to perform monitoring control from a remote location.

5.2 Characteristics of monitoring control system

The monitoring control system is built based on the highly functional monitoring control SCADA package (CitectSCADA), and it has the following characteristics.

(a) CitectSCADA has been accepted widely in various fields such as social infrastructure and industry. It already has a track record of over 50,000 licenses supplied around the world and it is highly reliable.

(b) It is designed for web servers and for display servers, and has high speed, extensibility and redundancy.

(1) High speed

Data communications are continually optimized and unnecessary communications are reduced so that, even on large-scale systems, it achieves high-speed data collection and display.

(2) Extensibility

The measurement signals can be increased from 75 points to 400,000 points and various systems from small-scale to large-scale configurations can be supported.

(3) Redundancy

In the construction of communications and servers, completely redundant configurations are possible with just simple settings. This realizes a safe system on which operations will not be damaged even if a problem occurs with the network or a server.

(c) The five functions of I/O, alarms, trends, displays and reports can be split into multiple servers to fit the scale of the system, and various systems up to extremely large-scale system can be realized.

(d) The web function and multilingual function make it possible to obtain information on the photovoltaic power generation system at any time and from any location around the world.

5.3 Functional Structure of Monitoring Control System

The main targets monitored by the monitoring control system are as follows:

(a) System interconnection facilities

(b) PCS

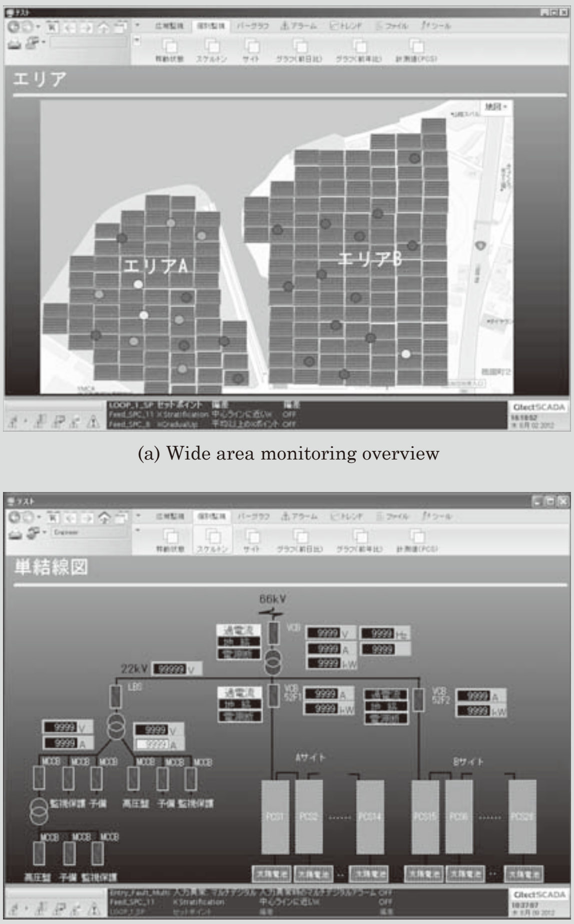
(c) Photovoltaic power generation facilities (Junction boxes and connection boxes)
(d) Meteorological and other environmental data

Table 3 shows the standard monitoring screens and the main functions. Figure 10 shows examples of monitoring screens.

Fuji Electric's monitoring control system has the standard monitoring control functions and optional functions to meet the individual requirements of customers. Examples of this include linking with other systems through the automatic generation of CSV files and control of the number of PCS units, which is performed to respond to requests from the electric power companies for a restriction of the generated output. It is possible to flexibly configure these various extension functions.

Table 3 Standard monitoring screens and main functions

Standard monitoring screens	Main functions
Wide area monitoring overview Individual area overview Skeleton monitoring screen Power generation status monitoring screen Meteorological data screen Trend monitoring screen Alarm monitoring screen	Web function Multilingual function Process analyst function Security function Mail sending function Reporting function (Annual, monthly and daily reports) Function for linking to other systems



(a) Wide area monitoring overview

(b) Skeleton monitoring screen

Fig.10 Example of monitoring screens

6. Measures for Microgrids

The output of photovoltaic power generation and other renewable energies is unstable because it is affected by environmental conditions such as the solar radiation and temperature at the place of installation. In the future, when there is large-scale connection of these to the power grid, there is concern that there may be adverse effects on the power grid, for example, from the generation of surplus power, voltage fluctuations and frequency fluctuations. Solutions must be found to these issues.

Fuji Electric has realized the balanced operation of diesel power generation together with renewable energies such as photovoltaic power generation and wind power generation with systems using a stabilizer with storage batteries and capacitors for remote islands power systems in the Kyushu Electric Power Company, Incorporated and The Okinawa Electric Power Company, Incorporated. These systems are verification facilities for microgrids aiming to reduce CO_2 and lower the cost of power generation.(2) The proliferation of the technologies verified is expected as they are systems that absorb the changes in demand and the fluctuations in output from renewable energy sources in the region by having facilities to store the electric power, and as they are also systems that are kind to the network and do not affect the existing electric power. At the same time, these technologies can be utilized as system interconnection technology for mega solar.

7. Postscript

Mega solar is a system of power generation that contributes to the prevention of global warming and the protection of the global environment, and it is expected that its proliferation will continue for the time being through the "Feed-in Tariff Scheme for renewable energy." We will utilize the technologies we have accumulated so far in distribution system control and microgrids, and will work at large-scale photovoltaic power generation that considers the effects on the power network. We will also continue to develop and apply new technologies to offer systems that match the requirements of the market.

Reference

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The Circuit and Control Technology in the Power Conditioner and Converter for Wind Turbine Systems

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ABSTRACT

Because the generating power of wind turbines fluctuates according to changes in wind speed, this affects system voltage. To enable large-scale implementation of wind turbines, power system supply quality is demanded. Power conditioning subsystems are available for stabilizing power as a means to compensate for fluctuations in power supply. Using an AT-NPC 3-level conversion circuit, we have greatly reduced switching loss in IGBT devices and also, by halving harmonic components, we have reached 98.1% efficiency, the highest in the industry. Moreover, we have achieved power supply quality sufficient for grid connection by incorporating a fault ride through function so that the system continues to operate without disconnecting even if there is a drop in system voltage due to lightning strike or other causes.

1. Introduction

The introduction of renewable energy is about to be accelerated by the "Feed-in Tariff Scheme for renewable energy," which was initiated in July 2012. Although conventional wind power generation was mainly done on land, development of offshore wind power generation has accelerated because it has few restrictions in terms of increasing capacity to improve power generation efficiency and selecting from available installation locations, and because the wind conditions offshore are stable. For large-volume introduction of wind power generation in the future, it is becoming essential to improve power quality. Therefore, this paper describes a power conditioner (PCS) that alleviates changes in the amount of wind power generation and contributes to higher power quality, and it also describes circuit technology and control technology on converters for wind power generation.

2. PCS for Power Stabilization

2.1 Structure of wind power generation system with storage battery

The basic structure of a wind power generation system with a storage battery is indicated in Fig. 1. This system is a method of converting the output of a wind power generator to direct current via an AC/DC converter, which is connected to a synchronous generator, and interconnecting to a system by conversion to alternating current via a DC/AC converter. In wind power generation, the amount of power generated is in proportion to the cube of the wind speed; therefore, only a subtle fluctuation in wind speed causes a large fluctuation in the amount of electric power generated.

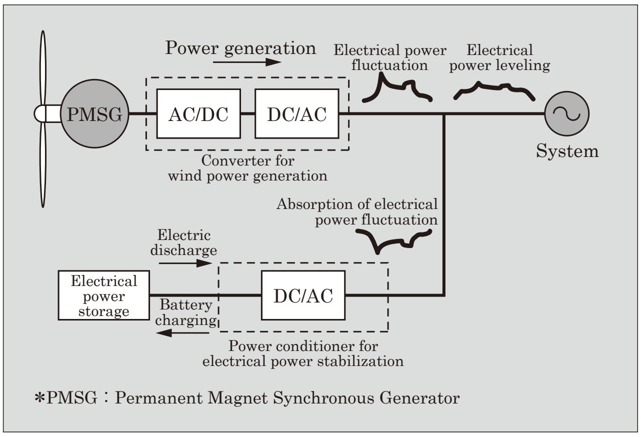

Fig.1 Basic structure of wind power generation system with storage battery

There is a concern about prompting voltage fluctuations or frequency fluctuations in power grids, which would lead to deterioration in electric power quality, when the number of wind power systems increases in the future. A PCS for electrical power stabilization eliminates such concern. For an electrical power storage section, select a lead-acid battery, lithium ion battery, or other type of battery according to the use. Electric power fluctuations in wind power generation are stabilized by means of controlling battery charging and electric discharging of the electrical power storage section by using a DC/AC converter.

2.2 PCS for electrical power stabilization "PVI750-3/500"

Figure 2 indicates the external appearance of PCS for electrical power stabilization, "PVI750-3/500."

(1) System structure

PVI750-3/500 is comprised of two 250 kW inverters (see Fig. 3). In order to replace and maintain storage batteries individually, two secondary-side direct

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Fig.2 “PVI750-3/500”

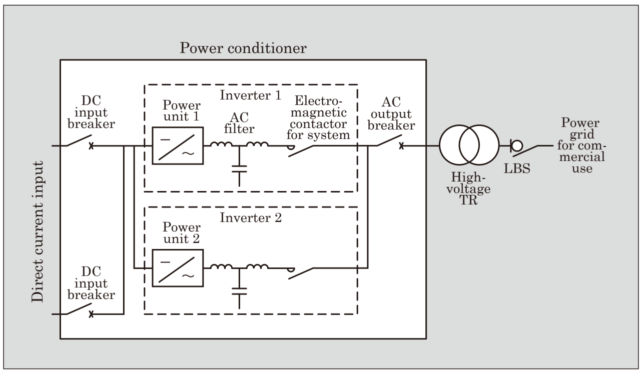

Fig.3 System structure of “PVI750-3/500”

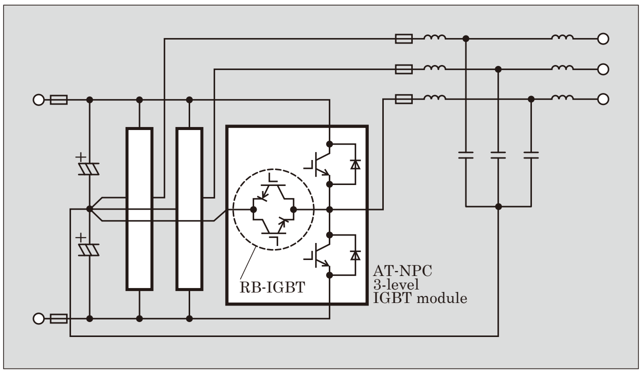

Fig.4 Power unit and filter circuit

current input breakers are connected to one direct current link. During start up, it is possible to complete start-up without generating a rush current in the system by interconnecting to the system by turning the contactor on while each inverter outputs the voltage, which was synchronized with the system.

The power unit of the inverter is comprised of an IGBT module of an advanced T-type neutral-point-clamped (AT-NPC) 3-level, fuse, and LCL filter (see Fig. 4). Although a 3-level converter circuit has already been proposed in the 1980s, it did not become popular because it was not possible to increase the withstand voltage of the insulated gate bipolar transistor (IGBT) element. However, there is a merit that the number of element passages of output current can be reduced and as a result, conductor loss can be reduced in the inverter that does not require elements to be connected in series.

Fuji Electric made practical use of the AT-NPC 3-level IGBT module[1] in which reverse-blocking IGBT (RB-IGBT)[2] is applied to the switch that connects the direct current intermediate and AC output, which requires reverse withstand voltage. As a result, we produced a 3-level inverter comprised of the same number of modules as the existing 2-level inverter and it was possible to achieve a highly efficient inverter without making the circuit complicated.

(2) Specifications

Table 1 shows the specifications of PVI750-3/500. The range of the direct current voltage corresponds to 750 V DC, with which construction at low voltage is possible, and the AC voltage output by the PCS is 200 V. In addition, Fig. 5 indicates the efficiency curve. By using a conversion circuit for which an AT-NPC

Table 1 Specifications of “PVI750-3/500”

Item	Specifications
Capacity	500 kVA
DC voltage range	310 to 750 V
Maximum input current	1,600 A
AC voltage	200 V (–10 to +10%)
Frequency	50/60 Hz
Power-factor	0.99
Harmonic distortion factor	5% or below
Highest efficiency*	98.10%
EU efficiency*	97.80%
Maximum value of internal power capacity	900 W
Stand-by loss	130 W

* Indicate IEC-61683 efficiency tolerance, excluding internal power source

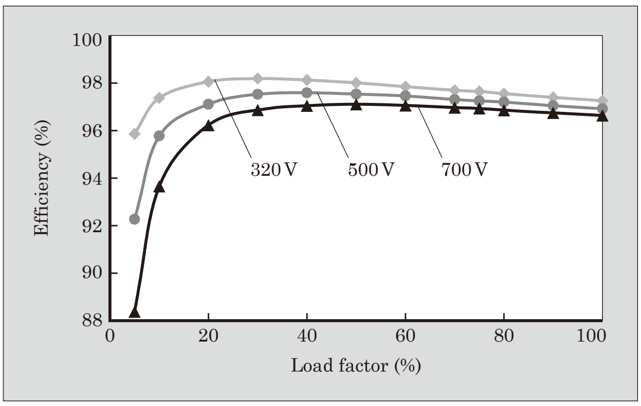

Fig.5 Efficiency curve

3-level IGBT module is applied, the switching loss of the power unit was significantly reduced. Furthermore, by halving the harmonic contained in the pulse width modulation (PWM) waveform that the inverter outputs reduced by one half compared to conventional products, filter loss was reduced and the highest efficiency in the industry of 98.1% (according to IEC-61683 efficiency tolerance, excluding internal power supply) was achieved.

(3) Characteristics (FRT performance and inverter control method)

An fault ride through (FRT) function, which is becoming a prerequisite for new energy sources, is mounted on PVI750-3/500 as standard. The FRT function is used to allow for continuous operation by enabling the inverter to output a three-phase current within the specified range (within the instantaneous voltage drop time and voltage drop required in each country) and suppress electric power fluctuation of the system even if system three-phase short-circuit and two-phase short-circuit occur. This FRT function became mandatory in the EU and USA and it is mandatory for devices that are to be introduced from FY2013 in Japan. In addition, the residual voltage and continuation time required as an FRT function differ depending on the country. As a result, in order to enable continuous operation even with 0% of residual voltage, it became possible for the controlled source to select either external supply or self-supply from the system. Power flickers that last no more than one second are backed up by an internal condenser and there is an option to be able to have continuous time of FRT that exceeds one second. As a result, it has become possible to achieve the requirements from both cost and specification aspects.

The FRT function of operational verification was performed with a control verification machine (10 kW). By putting residual voltage 0% constantly into a gate lock state and by performing 0 A control, operation is continued. As shown in Fig. 6, it was confirmed that at residual voltage 20%, spasmodic gate lock no longer occurs from 6 ms after occurrence of instantaneous voltage drop and it is possible to output a rated current after about 2 cycles. By doing so, it is confirmed that PCS can continue operating when an instantaneous voltage drop occurs.

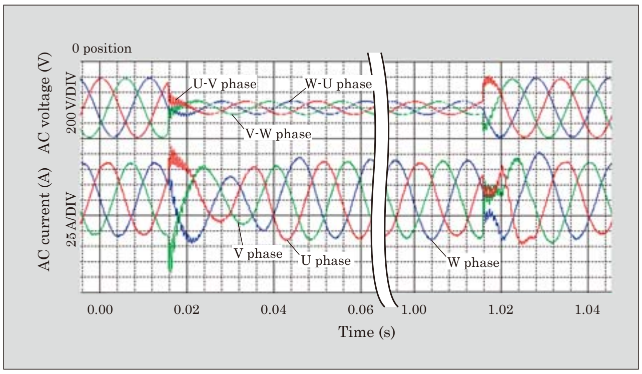

Fig.6 Operation verification wave of FRT function

3. Converter for Wind Power Generation

Figure 7 indicates the structure when a wind power generator is a multi-winding type. Two converter boards of 1,500 kVA are connected in parallel.

A converter board is comprised of 3-parallel DC/AC converters as a water cooling power unit of 500 kVA, chopper, and resistance for energy consumption. This chopper is used to control the DC/AC converter so that the direct current intermediate voltage does not go up at times such as when a system abnormality occurs. A water cooling power unit has a plug-in structure and there are three in parallel, and the converter board consists of two boards in parallel. Therefore, maintainability was improved and when a failure occurs, it is possible to operate with the sound section; as a result, operating ratio was improved. Table 2 indicates the specifications of a converter for wind power generation

3.1 Water cooling power unit

Water cooling power unit that uses IGBT

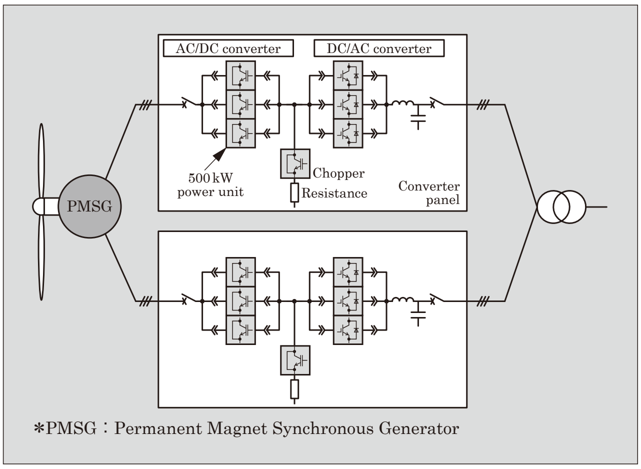

Fig.7 Wind power generation system (synchronous power generator)

Table 2 Specifications of converter for wind power generation

Item	Specifications
Capacity	1,500 kVA×2 (3,000 kVA)
Rated effective power	1,350 kW
Rated reactive power	650 kVar
Rated voltage	690 V
Rated current	1,255 A
Frequency	50/60 Hz
Power-factor	0.99
Harmonic distortion	5% or below
Highest efficiency	97.20%

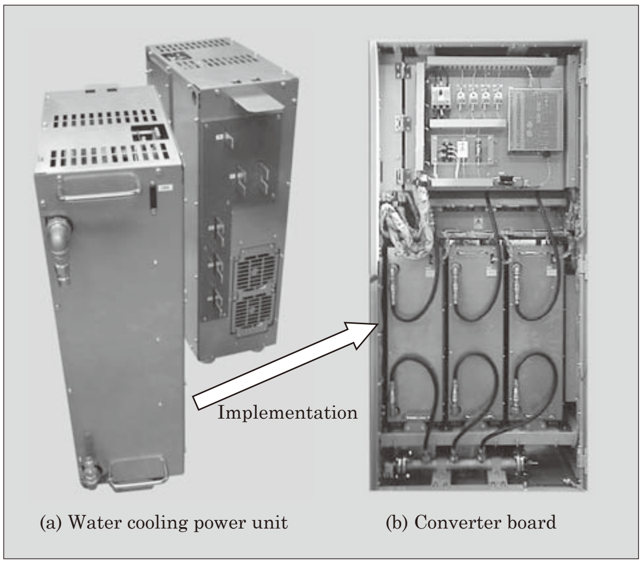

Fig.8 Water cooling power unit (500 kVA)

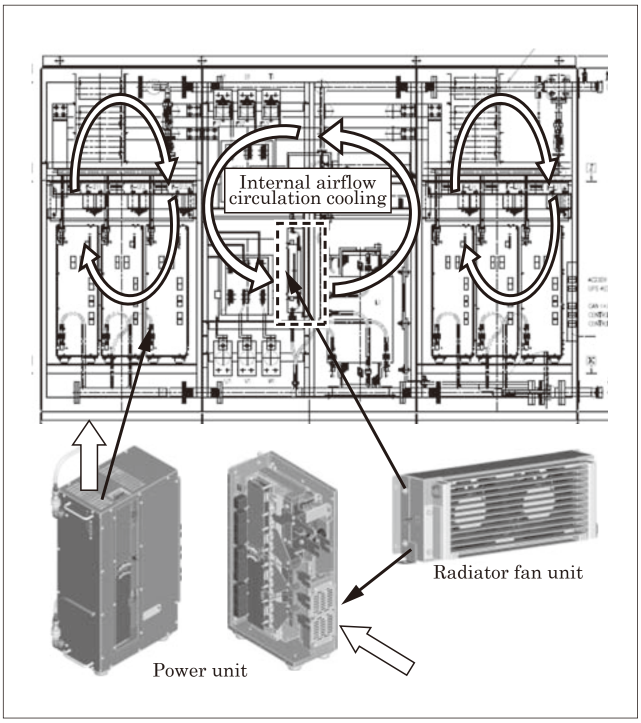

Fig.9 Internal airflow circulation cooling by radiator

"6MBI450V-170-50" of Fuji Electric comprises parts such as a water cooling heat sink, film condenser for direct current intermediate, radiator fan, gate drive, and protection monitoring circuit. This power unit is easier to maintain because it has a plug-in structure, and it enables operation by eliminating the failed power unit. In order to achieve this, a laminated bus bar and common mode core are combined so that impedance becomes constant before and after the power unit is plugged in. As a result, the currents between each power unit are in balance with each other and the cross current becomes 5% or lower. For that reason, it has become possible to continue operation even if the power unit on any position is disconnected according to necessity. Figure 8 shows the outside appearance of the cooling power unit and converter board.

An optical fiber connects the control unit and power unit and transmits a gate signal from the control unit and failure information from the power unit. In addition, as a self-monitoring function, arm-short protection, abnormality in element temperature, abnormality in temperature within the unit, and excessive current protection, and abnormality in gate voltage, abnormality in clock are detected and the information is sent to the control unit at the same time as abnormality judgment protection.

3.2 Air current circulation cooling within panel by radiator

The converter board, which is applied to wind power generation, is fit into IP54*[1] in order to be able to withstand an environment such as floating on the sea and the structure provides air tightness without taking in the outer air. In order to do so, as shown in Fig. 9, a radiator fan is installed in the power unit and a reactor for filtering is prepared in the vicinity to cool inside the board by means of forced airflow circulation with the fan.

*1: IP54: Protection level pertaining to dust-proofing performance and water-resistant performance defined in IEC 60529

3.3 System arrangement

Along with the increase in wind power generation capacity in the future, it will be necessary to restrain any increase in expected power influence and improve the operating ratio. As Fig. 7 shows, by operating two converter boards in parallel with a power generator, a torque reduction request command is sent from the sound converter even if one of the converters fails. As a result, by operating with reduced capacity by means of pitch control of wind power generator blade, it is possible to realize a system that allows continuous operation within the allowance capacity of the healthy converter.

3.4 System voltage safety control

Depending on the fluctuation of power from wind power generation, fluctuation of system voltage occurs. As a countermeasure against this, the following two types of reactive power control functions are equipped to improve the compensation performance.

(a) Reactive power control by power-factor constant command

This is applied in order to restrict any influence on system voltage by supplying reactive power so that the predetermined power factor can be obtained. In particular, a system controller to control the voltage of power grid and power factor is unnecessary.

(b) Control by command from system controller

From a system controller, send a command to each wind power generator. Apply when voltage of grid connection point is surely controlled.

By doing so, it is possible to control system voltage without preparing for facilities such as static var compensator (SVC) within a allowable range.

3.5 FRT function

When the degree of importance increases as a result of an increase in generation capacity of power sources such as photovoltaic power generation and wind power generation in the interconnection system, if parallel off*2 occurs simultaneously due to decrease in system voltage when thunder or a system accident occurs, the risk of causing a power failure due to lack of system power increases. The function to prevent this risk is the FRT function, which is similar to the PCS as described in Section 2.2. It makes it possible to continue operation even during power system disturbance.

There are various phenomena regarding system accidents such as system three-phase short-circuit and two-phase short-circuit. At this time, an imbalance of system three-phase voltage or phase hit occurs. It is important to be able to control a converter without performing overload trip for this phenomenon. There are the following three technologies to continue stable operation by responding at high speed even if any changes in the system occur.

(a) When the system voltage decreases and it becomes impossible to output the generated output to the system, power is consumed by the chopper within the device and resistance.

(b) In order to respond to a rapid change in system voltage, create basic voltage command of converter from sine wave, for which band bus filter and phase were adjusted by a system voltage detection process of converter, and improve the wave form responsiveness.

(c) In order to reduce waveform distortion at start-up from system residual voltage 0% and perform stable control, perform synchronous control of the 3rd harmonic wave form that is generated from system voltage and the 3rd harmonic table data that is synchronized with PWM career within the control device (see Fig. 10).

By doing so, it becomes possible to synchronize PWM carrier and basic wave by about 0.1 second. Figure 11 shows the FRT operation characteristics that are implemented in a test device for control validation (3 kW). Stable operation was achieved for both output current and input current when an abnormality in the system occurred.

*2: Parallel off: Disconnecting power generation equipment and so on from a power grid

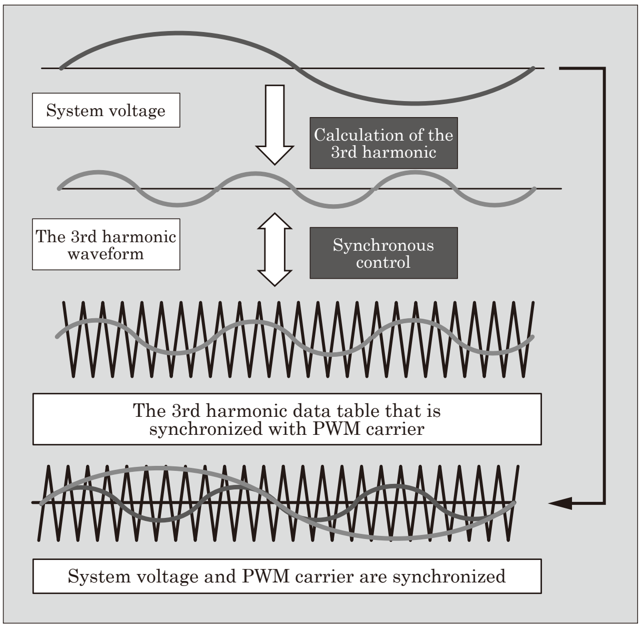

Fig.10 Synchronization of system voltage and PWM carrier

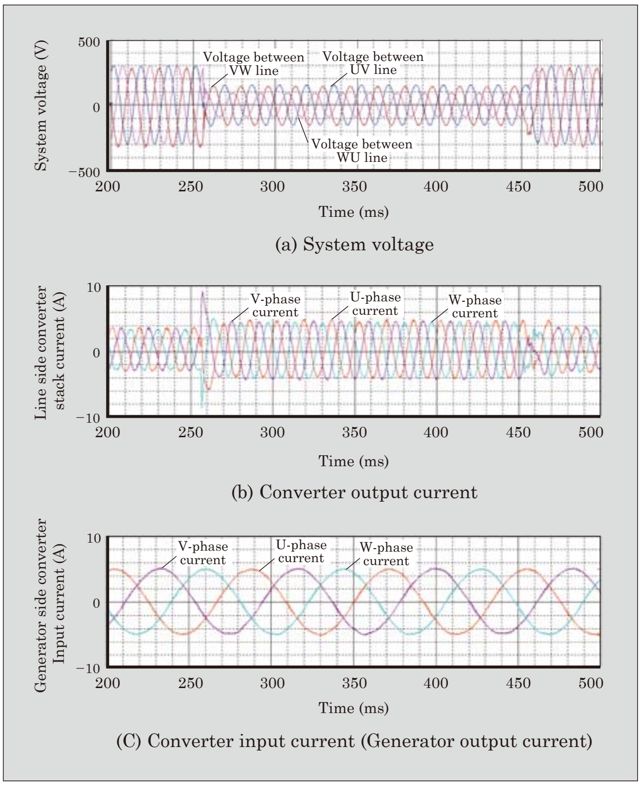

Fig.11 FRT operation characteristics by control verification device

4. Postscript

This paper described circuit and control technology used in a power conditioner and converter for wind power generation. In the future, aiming for mass introduction of wind power systems, we will promote technical development further, and achieve control technology and power conversion circuit technology.

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Permanent Magnet Synchronous Generator for Wind-Power Generation

MASHIMO Akihide † HOSHI Masahiro † UMEDA Mio ‡

ABSTRACT

Amid the attention on renewable energy, the market for wind-power generation is expanding on a global scale. At Fuji Electric, we are pushing forward the commercialization of wind-power generation equipment with the aim of achieving highly efficient operation of wind-power plants. We recently completed production and testing of a prototype 3,000 kW permanent magnet synchronous generator, which is the largest class in Japan. This is a low-speed generator for use in direct drive wind-power generation systems. The device incorporates new technology to achieve a suitable structure for weight-reduction, environmental resistance and multi-unit production. We have obtained favorable prototype test results, and verified that the device sufficiently meets the functional requirements for a wind-power generator.

1. Introduction

Amid the attention on renewable energy, Fuji Electric is pushing forward on the commercial manufacture of highly efficient wind-power generation equipment. We have recently completed the production and testing of a prototype 3,000 kW permanent magnet synchronous generator[1], which is the largest class in Japan. This is a low-speed generator for use in direct drive wind-power generation systems, and the development of the generator has incorporated new technologies to make full use of various analysis techniques. The prototype test results fit our expectations exactly, and we have verified that the device sufficiently meets the performance requirements of wind-power generators. In this paper, we will describe the key technologies of the wind-power permanent magnet synchronous generator that we have developed.

2. Development Policy and Application System

Figure 1 shows a system overview of the double-fed system, based on a wound-rotor induction generator, and the direct drive system, based on a permanent magnet synchronous generator.

The wound-rotor induction generator is the mainstream in power generation systems that utilize a speed-increasing gear, while there is also a method that employs a squirrel-cage induction generator. Systems that use a wound-rotor induction generator are called double-fed systems, and by controlling rotor-side current frequency, while making use of a power converter of a excitation capacitive component, it is possible to create a constant-frequency power generating system that is unaffected by changes in the rotational speed of the wind turbine (see Fig. 1(a)). This type of power generation system benefits from its ability to reduce the size of the generator; however, it has the drawback that its speed-increasing gear is susceptible to frequent trouble and maintenance requirements.

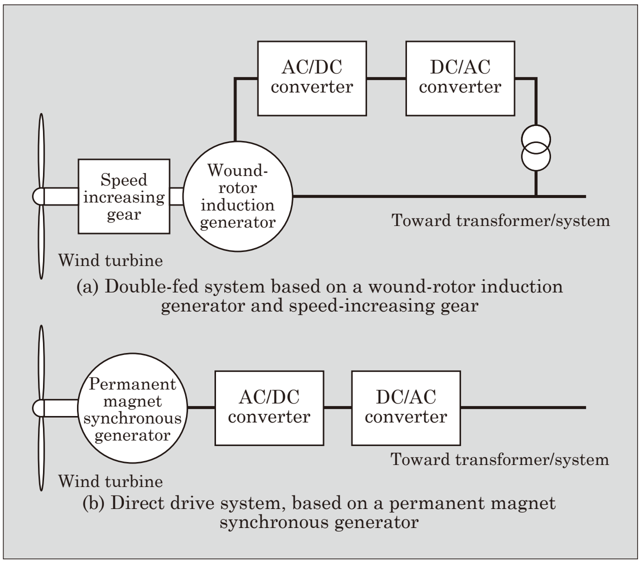

Fig.1 Overview of wind power generation system

Alternatively, the power generation system of the direct drive system requires a large-size generator, but it has the advantage of reducing the amount of system trouble and maintenance since it doesn't require a speed-increasing gear. In addition, it has the added benefit of producing a small amount of noise (see Fig. 1(b)). Most power generators utilize either a permanent magnet synchronous generator or an ordinary synchronous generator. Since the frequency of

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the output power of the generator varies depending on the changes of the rotational speed of the wind turbine, a power converter for the capacitive component is required. On the other hand, since power is supplied through the converter, it becomes possible to respond to a wide range of wind speeds. This produces many operating advantages, such as improvements in the power generation efficiency in low wind speed ranges(2), in particular. Many wind power generators are often installed at a site. Herefore, our development efforts have resulted in the adoption of a structure that is especially suited for highly efficient production of large-size generators. In order to obtain performance suitable for wind power generators, we carried out our development according to the following policy:

(a) Adoption of a structure suitable for multi-unit production
(b) Reduction of weight and external dimensions in consideration of land transport
(c) Insulating structure that is environmentally resistant

3. Specification and Structure of Prototype

3.1 Specification of prototype

The external appearance of the prototype is shown in Fig. 2, and the specifications in Table 1. The output of the generator is in 3,000 kW class, which is the largest class in Japan. The rotational frequency is 15 min-1 assuming a general rotational speed for this class of wind turbines. Furthermore, a rotary shaft structure was adopted so that testing could be undertaken in a factory. The structure enabled direct connection to the drive unit. In addition, the basic design of the peripheral structure was carried out using a structure that assumed a connection with the actual wind turbine, and after this, insertion to the structure of the prototype was performed. Cooling is performed by air-cooling to the frame surface and internals, with fins attached to the frame surface under the assumption of external placement in direct connection to the wind turbine. The entire mass of the prototype has seen a significant reduction, resulting in a weight of 75 t. In general, the size of an electrical rotating machine is proportional to the magnitude of the torque, but with regard to the mass per magnitude of torque, it has a value that is smaller by one order of magnitude when compared with water turbine generators.

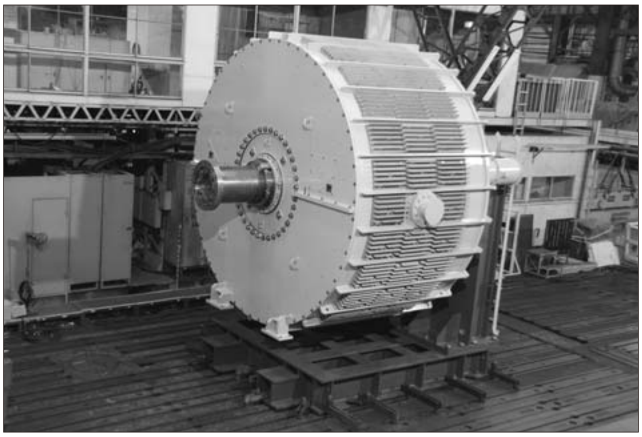

Fig.2 3,000 kW permanent magnet synchronous generator prototype for wind-power generation

Table 1 Specification of 3,000 kW permanent magnet synchronous generator prototype for wind-power generation

Item	Specifications
Output	3,000 kW
Rotational speed	15 min^{-1}
Voltage	690 V
Efficiency	94.7%
Cooling system	Frame surface + internal cooling
Temperature rise	F class

3.2 Structure of the prototype

In accordance with our development policy, we adopted the following characteristic structures in order to achieve weight reduction and improve manufacturing efficiency.

(1) Structure of stator

The outer shape of the stator exceeded a diameter of 4 m, and this gave us some concern as we proceeded to the next phase of the production process. We were worried that production efficiency might suffer from large parts being positioned in a wide space. In order to solve this problem, we used a split iron core for the stator and proceeded to assemble each split core and windings. Finally, we mounted the split core to the inner diameter of the stator frame and utilized a manufacturing technique for assemblage to a cylindrical stator. Split core structures are commonly employed in large-diameter generators such as water turbine generators. Since the width of the winding pitch is large and the windings can span between different split cores, the insertion of some of the windings was performed after the cores were assembled.

By adopting the concentrated winding method described below for the windings of the prototype, we were able to completely deal with each split core, achieving a state wherein all of the windings were incorporated into the cores. Figure 3 shows a comparison between conventional distributed winding coils and the relationship of split cores and coils.

(2) Structure of winding

As mentioned previously, the concentrated winding method that has been adopted for the stator winding is a method that is often employed in compact rotating machines such as servomotors. Usually, round enamel coated wire is often used.

Since the prototype is a large capacity unit, concentrated winding was performed while using rectangular copper wire. As shown in Fig. 4, the winding

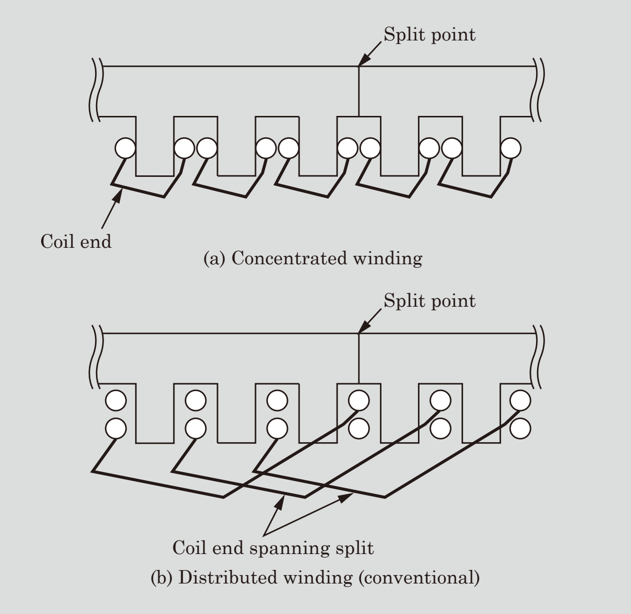

Fig.3 Core split and coil relationship

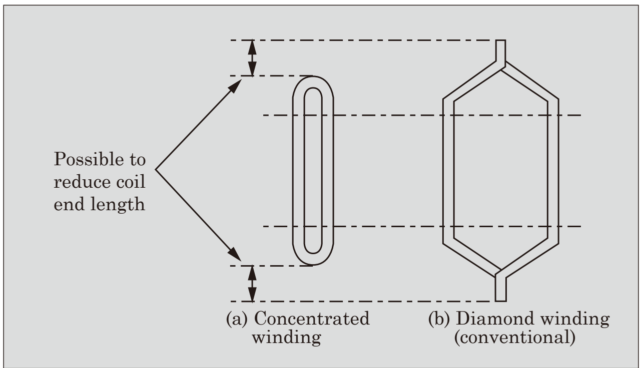

Fig.4 Winding comparison

pitch of traditional distributed windings is wide and results in a diamond winding. This, in turn, creates excess loss (copper loss) at the part of the coil end that protrudes from the stator core. Alternatively, since concentrated winding can shorten the dimensions of the coil end, the overall length of the power generator can be reduced and the amount of copper loss created at the coil end can be decreased. When the stator core has the same length with regards to the distributed winding, the total length can be reduced by about 150 mm, and it is estimated that loss can also be decreased by approximately 6%.

(3) Structure of rotor

The structure of the rotor is the so-called surface permanent magnet (SPM) structure, wherein a permanent magnet is installed to the surface of the rotor. The permanent magnet makes use of a sintered magnet of a high-energy neodymium-iron-boron composition. When installing to the rotor after magnetization, operability will be significantly reduced due to the large suction force. In order to improve this, we employed a method for the structure in which multiple non-magnetized magnets were attached to an iron magnet pole mounting plate, allowing for the assembly of a single magnetic pole, and we, thereafter, made installation to the rotor after magnetization with the single magnetic pole. By using this method, the magnetized flux, which entered the air from the magnetic surface, passed through the circuit that spans the surface on the opposite side via the magnetic pole mounting plate, which consists of a magnetic material. Therefore, rather than directly installing the magnetized magnet to the rotor, we were able to improve operability by reducing the amount of flux surrounding the rotor, which, in turn, lowered the amount of suction force. Figure 5 shows that scattering is prevented even in the case that the magnet chips or breaks down. This is accomplished by covering the outer-shell of the magnetic poles with a stainless steel cover plate. Configuration for a single pole of the generator is made by connecting several of these magnetic poles in the direction of the rotor axis.

Fig.5 Rotor pole (cover attached)

In addition, cogging torque occurs between the magnet and the core, as a characteristic type of torque pulsation that is created by the permanent magnet unit. As a countermeasure to this, cogging torque was reduced by shifting each of the magnet poles of the single pole to a predetermined angle, thus creating a skew-like positioning. Electromagnetic field analysis was used to verify that cogging torque did not present a problem by comparing it with rated torque and ensuring that it was sufficiently low.

(4) Structure testing for reducing weight

In order to reduce the weight of the generator, the shape configuration of each part was determined by carrying out structural design via the finite element method. As one example of the analysis, Fig. 6 shows the analysis results pertaining to the deformation of the rotor relative to the load of the wind turbine.

Shape configurations used for the analysis are structures determined under the assumption of a fixed shaft according to the installation situation of the wind turbine. The prototype has a different struc-

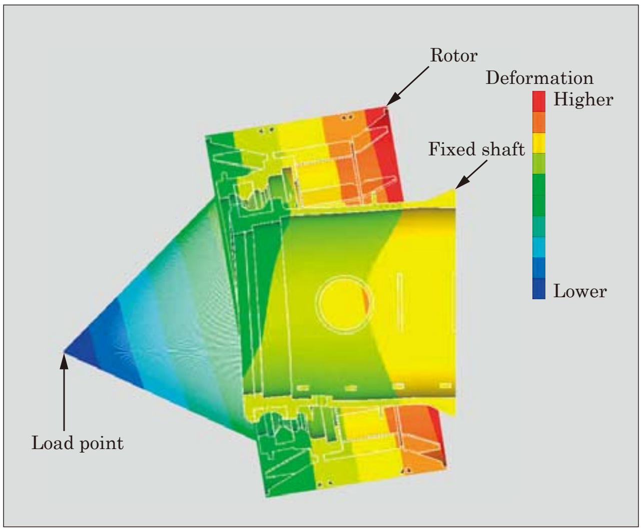

Fig.6 Results of rotor deformation analysis via a fixed shaft model

ture. Since a magnet exists on the surface of the rotor, suction is always exerted between the gaps of the rotors. In addition, since suction may change depending on whether variation exists in the gaps, analysis was undertaken while giving attention to the changes in suction due to deformations. By using the analysis results, we were able to develop an optimized structure contributing to weight reduction.

3.3 Ventilation and cooling structure

Since improvements in cooling performance greatly contribute to miniaturization, the cooling method of the prototype was carefully designed.

There are no gear units between the hubs of direct drive generators, and as a result, they do not need to be installed in the nacelle. Therefore, air that passes through the wind turbine can be used as cooling air to cool down the surface of the generator frame.

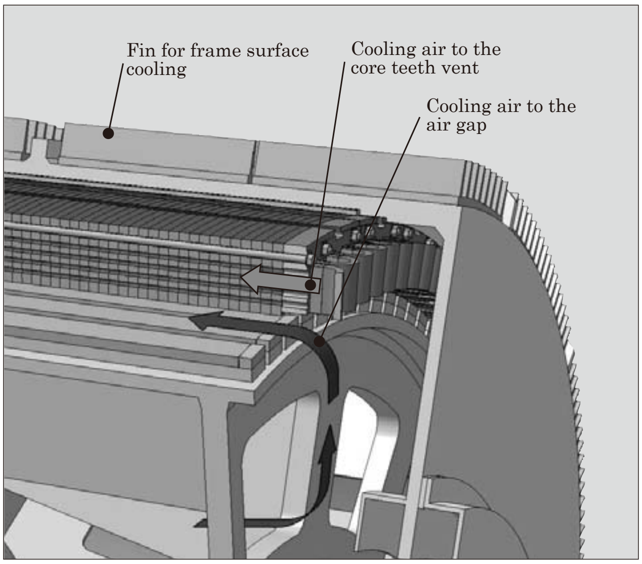

Fig.7 Flow of cooling air

However, in the case of cooling the frame surface, since thermal resistance is high due to the core and structural materials between the windings (i.e., the main heating part) and the frame surface (i.e., the heat radiation part), cooling performance is slightly inferior to interior recirculation air cooling in the vicinity of the coil. As a result of this, we were able to improve the cooling performance for the prototype by implementing a hybrid cooling system that prioritizes outer-shell cooling, while simultaneously ventilating the interior of the power generator. Figure 7 shows the cooling structure.

The outer-shell fins were installed and the air inside the generator was designed to flow through air gaps as well as the vents installed for the core. As confirmed in the design stage by using a thermal fluid analysis, the cooling effect obtained a torque density (torque per unit of capacity) of close to 1.5 to 2 times with regards to rotating machines of the general-type outer-shell cooling system.

3.4 Insulation performance

The rated voltage of the prototype is 690 V, but in order to connect to the system via a pulse width modulation (PWM) control power converter, it is necessary to consider the surge voltage that is generated from the pulse power supply and the DC intermediate voltage of the power converter, while also making preparation of insulation specifications for higher voltage classes. The DC intermediate voltage is 1,150 V, so a maximum of 2 times the voltage is needed when considering the surge voltage. Therefore, insulation with a withstand voltage of 2,300 V is required.

It is not easy to repair wind power generators when problems occur because they are installed at high altitude locations that are a good distance from the ground. Therefore, the insulation system must be highly reliable. Furthermore, wind power generators are often installed near the shore or close to forests, and since these are environments that are susceptible to high levels of condensation, a system with a high

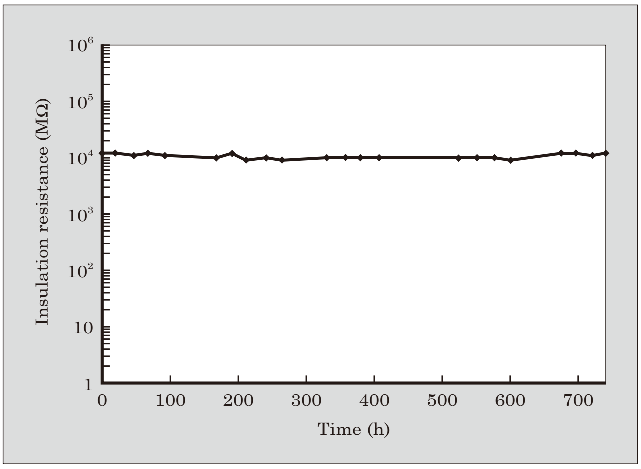

Fig.8 Insulation resistance and time characteristics (submersion test results)

level of moisture resistance is necessary.

We have adopted global vacuum pressure impregnation (VPI) insulation as insulation that has a proven track record and is environmentally resistant. In order to confirm the water resistance of this insulation, we carried out verification by a submersion test. For the submersion test, a structure was developed by using a model that had a core with a split stator, and by connecting multiple coils, phase-to-phase wiring insulation was also able to be simulated. The results of the testing are as shown in Fig. 8. No decrease in insulation resistance occurred even after a month of submersion.

4. Test Results of the Prototype

For the prototype, we performed a power generator single-unit test and a combination test with a power converter. Figure 9 shows the conditions of the combination test.

Favorable test results were obtained for both the single-unit test and combination test, and we were able to verify performance that matched our design plans. In particular, we were able to verify the insulation performance of the stator, which employed a split core structure and concentrated windings (for which it was the first-time ever that such a configuration was implemented for a large-class generator). No problems occurred in the insulation with regards to performance and the insulation easily withstood the 2,380 V of the withstand voltage test (rated voltage 690 V×2+1,000 V).

The results of the temperature rise test showed that the temperature rise of the windings was well within standard values. In addition, the result of noise measurements indicated that the unit met the standard specification of being 80 dB or less, and we were able to verify low noise levels on account of the unit being a low-speed power generator. Figure 10 shows the waveform of the back electromotive force. We were able to obtain a waveform that had very little strain which becomes a factor for vibration.

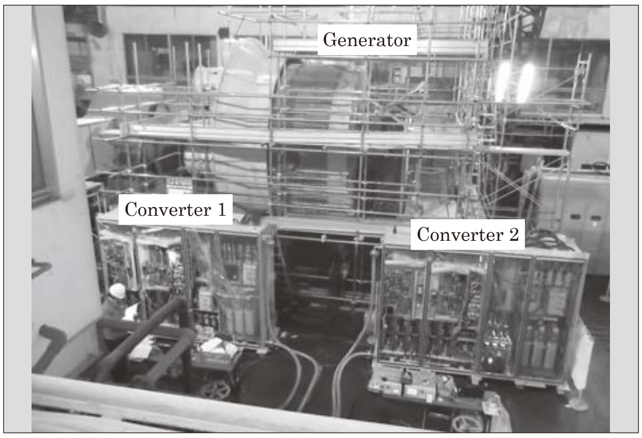

Fig.9 Combination test conditions

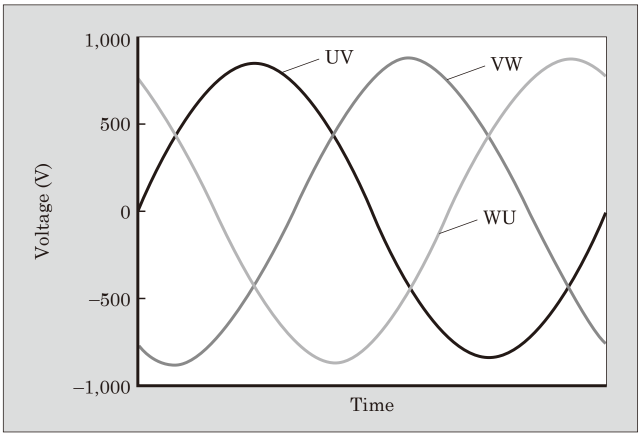

Fig.10 Back electromotive force

5. Postscript

We are planning to start mass-producing and supplying our newly-developed permanent magnet synchronous generator for wind-power generation to the market in FY2013. Currently, we are advancing with several studies that will bring us closer to the stage of mass-production.

We are expecting that the wind-power generation field will continue its market expansion in the future, and we are presently carrying out studies throughout Japan with regards to offshore installation of power generators. Since offshore installations are more costly than on shore installations, a greater power generation capacity is required to reduce per unit cost. From now on, we plan to further our efforts in this field in order to develop higher capacity power generators.

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Development of Fuel Cells Adapted to Meet New Needs

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ABSTRACT

Since the Great East Japan Earthquake, there has been broad investigation into the improvement of the quality of power-source security through introduction of 100 kW fuel cells, which are a highly efficient form of distributable power, and into the use of fuel cells for sewage digester gas power generation, which is a form of renewable energy.

Utilizing technology for switching to independent power during power outages and technology for converting to LP gas, Fuji Electric has developed fuel cells with improved power security and installed them in the Kawasaki Factory. Fuji Electric is also developing fuel cells adapted to meet new needs, such as fuel cells that can operate on both sewage digester gas and utility gas for small-scale sewage treatment plants and fuel cells that meets the CE marking requirements for the EU.

1. Introduction

Since the Great East Japan Earthquake in March 2011, there has been increasing expectation with regards to improved power supply security and distributed power sources. In addition, biomass power generation has come to be widely studied since the start of the "Feed-in Tariff Scheme for renewable energy" in July 2012.

Fuji Electric began selling its 100 kW fuel cells in 1998, and since then, the fuel cells have accumulated a track record of usage at a wide range of sites. The fuel cells have often been used for utility gas, but they have also been used for sewage digester gas (i.e., bio-gas) at two sites, which utilize a total of 6 fuel cells. From 2010, we started offering our latest model, the "FP-100i," to the market. In addition, we have also developed and made delivery to Germany a model that uses the cathode exhaust gas (low-oxygen concentration air) of the fuel cells as a new application.

This paper discusses the development of fuel cells adapted to meet new markets including power-source security use, small-scale sewage treatment plant use as well as EU standard specified with the CE mark.

2. Fuel Cells for Power-Source Security

Figure 1 provides an overview of Fuji Electric's fuel cells that correspond to power-source security needs. Diesel generators, which can be put into operation in a short period of time, have been most often used as emergency power generators at times of system fault or blackout due to natural disasters. Although they are economical to implement, they have the drawback of being noisy, emitting exhaust gas, and providing low-efficiency equipment utilization. Fuji Electric's 100 kW fuel cells allow for normal operation of equipment since they are cogeneration systems that are always clean, highly efficient and environmentally friendly. They utilize a technology for switching to grid-independent mode during time of blackouts, and they provide the power required to operate the most specific loads. Thus, it is possible to increase the reserve of emergency power supply sources by using diesel power generators etc., as emergency power sources for emergency loads, while also utilizing fuel cells to supply power to other specific loads. In addition, in the event that utility gas supply stoppages occur, the fuel cells can be used to switchover to LP gas reserves for continued operation of services.

(1) Switching from grid-connected operation to grid-independent operation

Figure 2 shows an example of switching to grid-independent operation. If a blackout occurs in the grid-connected operation mode, parallel off*[1] is automatically made from the grid, and shift to standby operation mode. At such a time, the fuel cells can be used stand-alone to supply power, and because the generated power is consumed inside in the fuel cells, grid-independent operation mode can start in about 30 seconds from the time of blackout detection. Furthermore, during grid-independent operation mode, rotating machines, in which inrush current occurs, can be activated through overcurrent and overload protection functions as well as limiter functions. A constant state of process connection can be maintained as is even when a load increases or decreases during grid-independent operation. This contributes to creating a

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*1: Parallel off: Disconnecting power generation equipment and so on from a power grid

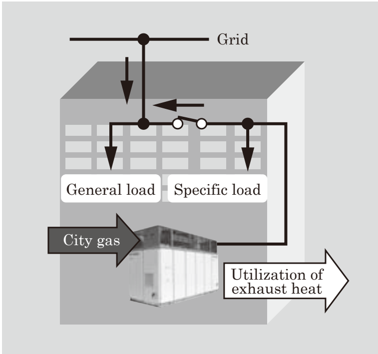
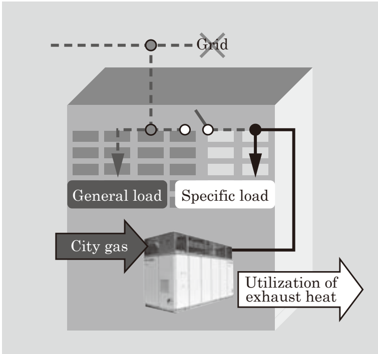
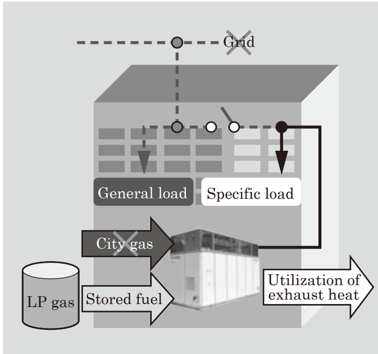
Situation	Normal operation	Blackout	Blackout+Stoppage of fuel gas supply
Overview	Highly efficient and energy-saving clean power source Efficiency of 42% at generation terminal	Shifting to the standby mode and supplying power to electric loads	Shifting to the standby mode and supplying power to electric loads
Power	100 kW	100 kVA	70 kVA
Fuel	City gas	City gas	Stored LP gas (A 50 kg cylinder of LP gas allows for 3 hours of operation)
Operation	Grid-connected operation	Grid-independent operation	Grid-independent operation
Power supply range			

Fig.1 Overview of fuel cell functions that correspond to power-source security needs

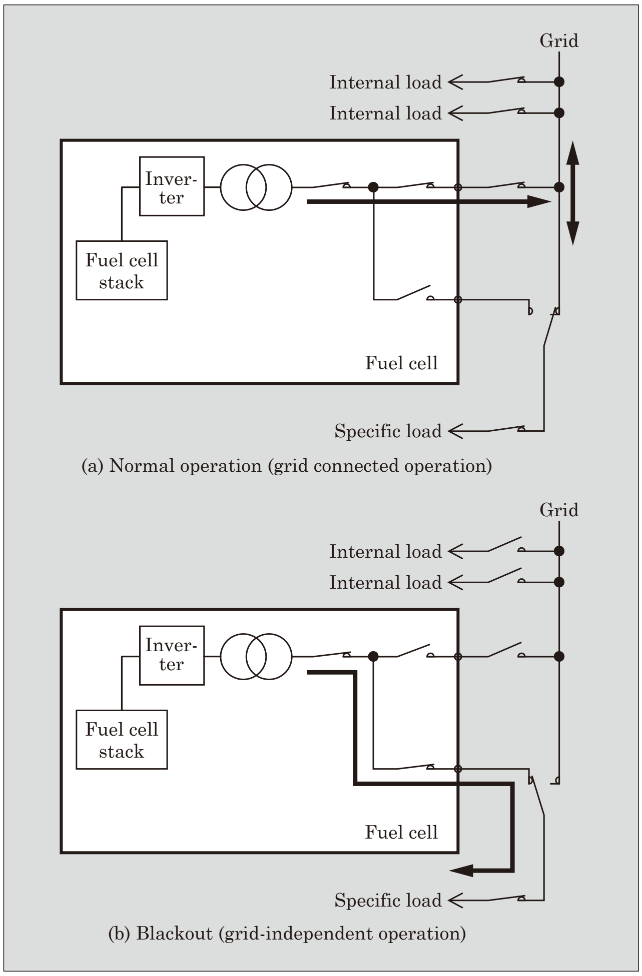


Fig.2 Example of switching during blackout

system that has stable control of the fuel cells by stepwise switching of independent loads and the electric heater in the fuel cells.

(2) Switching from city gas to stored LP gas

Switching from city gas to stored LP gas is carried out by closing the shut-off valve of the city gas and opening the shut-off valve of the stored LP gas when detection is made of a pressure drop signal in the original city gas.

Since the calorific value of LP gas per unit of volume is about 2 times the calorific value of city gas reforming conditions for producing hydrogen are different. In addition, several difficult elements exist in the switching of various types of fuel during operation, such as the need for gas replacement in the process equipment, which is built into the generating system, as well as the occurrence of start-up delays in the LP gas flow meter. Therefore, we utilized simulation results to incorporate a valve operation for maintaining a suitable amount of gas flow, while also making switching to various fuel types possible through specially designed control operation via the standby mode. It should be also noted that since operations that utilize stored LP gas are limited to an output of 70 kVA, approximately 3 hours of power supply is possible per 50 kg cylinder.

(3) Case of an installation at a factory

Power-source security fuel cells have been installed at Fuji Electric's Kawasaki Factory and have been in operation since February 2012 (see Fig. 3). During normal operations, they are used as a city gas cogeneration resource, but they can also be used to supply power to critical factory equipment during a blackout. Exhaust heat is being used to preheat water that is supplied to the air-conditioning, heating and boiler systems.

Fig.3 Fuel cells installed at Fuji Electric's Kawasaki Factory

3. Fuel Cells for Small-Scale Sewage Treatment Plants

Sewage treatment plants exist for the conservation of the water quality of public water resources. They collect the domestic wastewater that is discharged from each household, and then, purify the wastewater so that it can be returned to rivers and oceans. Dirt or grime that is removed during water purification is referred to as sewage sludge. In order to reduce and stabilize the amount of sewage sludge, anaerobic digestion treatment is performed to decompose organic materials in an oxygen absent state, and as a result, sewage digester gas is generated, which acts a principal ingredient for methane gas.

Currently, anaerobic digestion treatment of sewage sludge is being performed at approximately 260 sewage treatment plants throughout Japan. The total amount of sewage digestion gas produced annually is about 260 million cubic meters. Most of this amount is used as auxiliary heating fuel for heating sludge digestion tanks and for performing sludge combustion; however, digester gas power generation systems are still in the small minority. However, in the aftermath of the Great East Japan Earthquake, expectations have been increasing with regards to sewage digester gas power generation as a way to secure power supply sources during a time of disaster, and this has been especially true since the start of the "Feed-in Tariff Scheme for Renewable Energy" in 2012.

Sewage digester gas is composed of 60% methane and 40% CO_2, and approximately 1,200 m^3 of sewage digester gas is required per day in order to ensure the rated operation of a 100 kW fuel cell. About half of the sewage treatment plants that produce sewage digester gas are small-scale facilities that do not meet the per day production requirements mentioned above. Therefore, in order to install 100 kW fuel cells at these sewage treatment plants, we have developed a power generation system that works in combination with utility gas and can be used at plants that do not produce enough sewage digester gas.

The power generation system produces energy based on sewage digester gas, and falls back on city gas only when there is an insufficient amount of sewage digester gas to produce the required amount of power needed. Figure 4 provides an overview of the gas mixing operation.

In February 2012, this power generation system was installed at a sewage treatment plant in the city of Osaka as a power generator for the "Breakthrough by Dynamic Approach in Sewage High Technology Project" (B-DASH Project) of the Ministry of Land, Infrastructure, Transport and Tourism. Demonstration testing has been ongoing since April 2012. Demonstration projects related to energy management systems that utilize the ultrahigh solids-

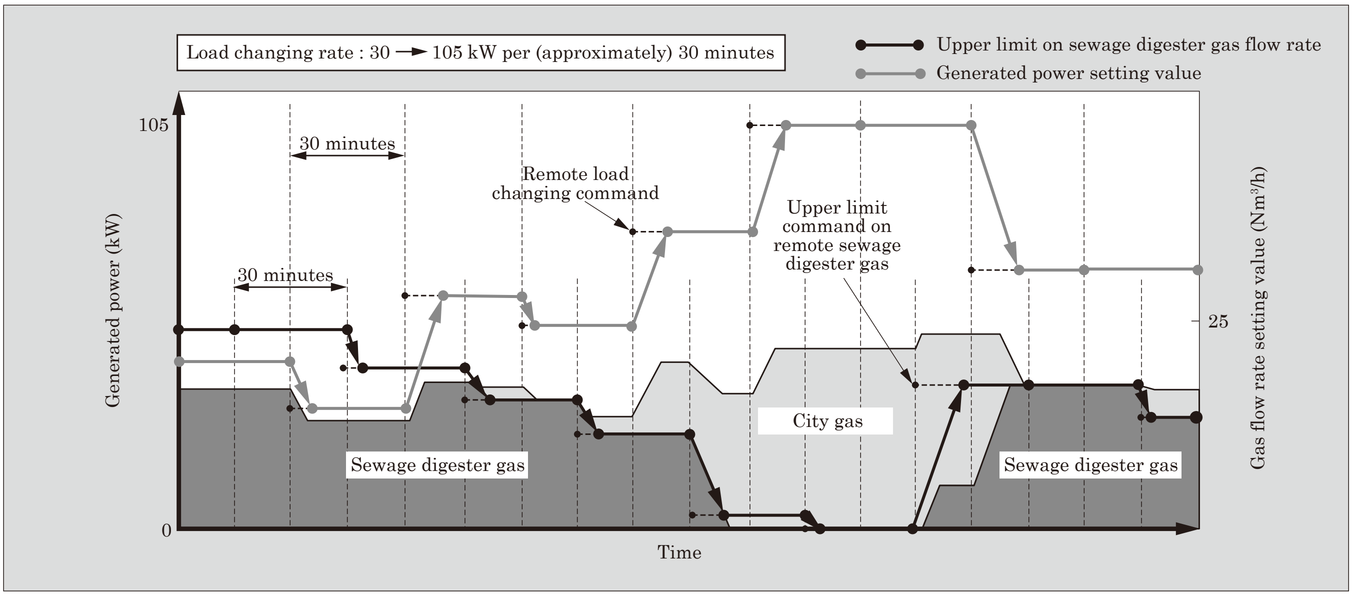


Fig.4 Overview of gas mixing operation

liquid separation technology of the B-DASH project aim at creating sewage treatment plants that can generate a self-sufficient amount of energy. This is accomplished by implementing a system that combines the use of three break-through technologies including "ultrahigh solids-liquid separation," "high efficiency high-temperature digestion" and a "smart power generation system." Among the types of systems for smart power generation, fuel cells are used as power sources in hybrid-type power generators that combine the use of sewage digester gas and city gas.

4. CE Mark Compliant Fuel Cells

4.1 State of cogeneration in the global market

Figure 5 shows the penetration rate of cogeneration in the global market. The EU and the United States are both outpacing Japan with respect to their cogeneration penetration rate. Natural gas is being increasingly used in the EU as a means of securing energy and alleviating climate change problems. In particular, natural gas cogeneration is being set forth as a substantial and popular assistance measure since it is one of the few technologies that is immediately effective toward energy conservation and savings. As a popular assistance measure, it provides initial cost assistance (cogeneration, heat infrastructure subsidies, grants and tax incentives) and running cost assistance (electricity purchasing and tax incentives for fuel costs).

4.2 German market and low-concentration oxygen air supply

Fuji Electric is expanding its business in the German market in partnership with the German company N2telligence GmbH. The German market is characterized by the following two points:

(1) Generous support measures by the German government

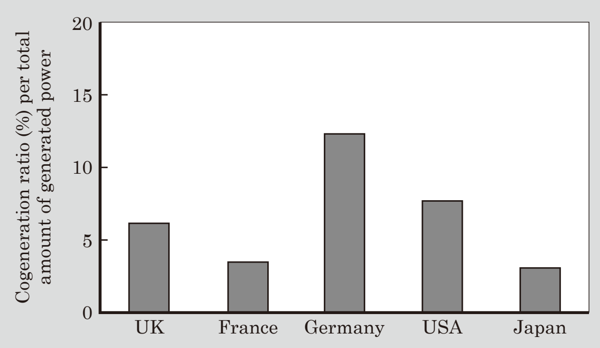
Germany plans to abolish its nuclear power plants. However, conventional coal-fired thermal power station have to be renewed, and thus they are difficult to complement those. Therefore, expectations are high with respect to renewable energies and natural gas cogeneration as a means of backing up power output fluctuations. The German government revised the Combined Heat and Power (CHP) Law in 2009, and has set forth a target to achieve a 25% increase in its cogeneration utilization ratio by 2020. Hydrogen-based infrastructures are also becoming more popular, and there is high anticipation regarding the use of hydrogen fuel cells.

(2) Popularization of fire prevention system based on low-concentration oxygen atmosphere

Fire prevention systems that utilize a low-concentration oxygen atmosphere inside buildings such as data centers and warehouses in order to prevent the outbreak of fires are becoming popular in Germany. Generally, since supply of such an atmosphere to the inside of a room is done by separating nitrogen from the air by a nitrogen generator, capital investment is required; in addition to this cost, other issues also become a factor including compressors, etc., which operate by consuming a large amount of energy.

Unlike gas engines that generate power through combustion of fuel and air, fuel cells generate electricity by an electrochemical reaction of oxygen in the air and fuel which are separated by an electrolyte. With regards to the air that is supplied by the fuel cell, since only the oxygen in the air is selectively consumed, the air that is discharged has a low-concentration oxygen that does not contain harmful flue gas. This low-oxygen concentration air is supplied to the inside of a room, and as a result, a low-concentration oxygen atmosphere is created. Therefore, initial costs and running costs required for nitrogen generators can be reduced. The German company N2telligence GmbH has developed a fire prevention system that utilizes low-concentration oxygen air produced by fuel cells, and they are selling their system under the concept of "Quattro Generation," a system that provides 4 additional values in relation to electricity, hot water, cold water and low-concentration oxygen air.

In order to contribute to the development of



Source: Drawing based on "The International CHP/DHC Collaborative" http://www.iea.org/chp/

Fig.5 Penetration rate of cogeneration (2005)

Fig.6 Fuel cell installed at Wismar

Fig.7 Fuel cell installed at Hamburg

Quattro Generation, Fuji Electric started implementing demonstration operations in 2010 at the Wismar testing site of N2telligence GmbH. In 2011, we developed a model for the EU that is the CE mark compliant, and in July 2012, we made delivery of Unit 1 to Mercedes-Benz building (Hamburg). Figure 6 shows the installation at the Wismar testing site, and Fig. 7 shows the installation at Hamburg.

4.3 CE mark compliance

The CE mark is required for selling products to the EU. The CE mark was established under the framework of a unified law by the EU in order to ensure the free flow of products within the EU. Alternatively, products that do not have the CE mark will be denied customs clearance and will not be able to be exported. In order to receive the CE mark on a product, a compliance assessment is performed on the product in accordance with applicable EC directives. A declaration of conformity is required to be carried out based solely on the responsibility of the product manufacturer. EN regulations are used to determine if compliance is made to the applicable EC directives.

Fuels cells are different than general electrical products and they also have the aspects of a small chemical plant. At the same time, the applicable EC directives and conformity regulations cover a lot of ground with respect to electrical products and machinery. Since there was no precedent, we received the cooperation of a public institution to conduct a study on the applicable EC directives and EN regulations. The result of the study was that our product was applicable to several EC directives including the machinery directive, electromagnetic compatibility directive, pressure equipment directive and safety directive for devices that are used in an atmosphere that has potential for explosion.

Fuel cells for use in Japan are designed based on the “Electricity Business Act,” technical standards for thermal power generation equipment, technical standards for electrical equipment, and Japanese Industrial Standards (JIS). In order to export the fuel cells to the EU, we revised the design based on Japanese regulations, while making enhancements to conform to and accommodate additional international regulations. Risk assessment through hazard analysis is critically important with regards to the CE mark compliance. Inflammable gas leaks were particularly considered as significant events with the greatest possible impact, and thus we changed a part of the design to better meet international regulations. In addition, we also implemented risk assessment with regards to user maintenance work and enhanced measures to prevent shocks and injury from occurring. Based on these measures, we issued a self declaration of the CE mark compliance after receiving confirmation from the public institution in March 2011.

When we delivered the first product for the EU, the fuel cell was accommodated with several additional devices as a result of revising the Japanese market based design for fuel cells. We are currently working on a design that is especially dedicated for the EU and are planning on commencing sales in fiscal 2013.

5. Postscript

Even in the Great East Japan Earthquake, 100 kW fuel cells continued operation. One hundred kilowatt fuel cells are expected to gain increasing popularity in the future as a highly efficient distributed power source, since they are capable of grid-independent operation during times of disaster as well as provide a fuel switching option when working in combination with city gas and LP gas.

Fuji Electric is dedicated in its efforts to apply its cultivated technologies and fuel cell functionalities to continually enhance the range of application of its products and improve user benefits, while also contributing to prevention of global warming and environmental conservation.

Technology for Dry Decontamination and Volume Reduction of Contaminated Dirt

JINZA Keisuke † TOMIZUKA Chiaki †

ABSTRACT

The Fukushima Dai-ichi Nuclear Power Station accident, caused by The Great East Japan Earthquake, has resulted in leakage of radioactive materials and contamination of the environment. Separating highly-contaminated dirt from the total amount of dirt removed for decontamination makes it possible to reduce the volume of dirt that needs to be stored.

In cooperation with Ube Machinery Corporation, Ltd., Fuji Electric developed technology for dry decontamination and volume reduction of contaminated dirt. This technology combines the dry sorting and grinding equipment used in general industry with a radiation measurement device, enabling mass processing. Verification tests using actual contaminated dirt have demonstrated that radiation levels are reduced to less than half after crushing and separation.

1. Introduction

Fukushima Daiichi Nuclear Power Station accident, caused by the Great East Japan Earthquake, has resulted in leakage of radioactive materials and contamination of the environment. The released radioactive materials are mainly cesium, which adheres to soil and woodlands. The government is planning to decontaminate certain areas so that the radiation dose from radioactive materials released by this accident becomes 1 mSv or less annually.*1

In the decontamination plan, the authorities are reviewing how to scrape away and decontaminate the top few centimeters of soil in contaminated fields of rice and other crops. Doing so will generate a large amount of soil as contaminated waste. This soil (original soil) is to be temporarily placed in an appropriate location and is planned to be disposed of permanently after being placed in interim storage. However, the area to decontaminate is very wide and in order to store all this soil, an extensive area is necessary. As a result, there is a difficult issue to overcome in terms of securing such an area and decontamination work is making slow progress.

The scraped off original soil is not all contaminated, and thus separating highly-contaminated parts from the total amount of soil removed for decontamination makes it possible to reduce the volume of soil that needs to be stored. Accordingly, Fuji Electric has developed dry decontamination and volume reduction technology for contaminated soil. This paper describes the characteristics and demonstration of this technology.

*1: "Act on Special Measures pertaining to measures against contamination of environment by released radioactive substances due to the accident of nuclear power station caused by The Great East Japan Earthquake that occurred in March 11, 2011" issued in August 2011

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

2. Characteristics of Technology for Dry Decontamination of Contaminated Soil and Volume Reduction

According to public and private research institutions, it is reported that soil contamination caused by radioactive cesium is concentrated in a few centimeters of the surface layer and among the soil, most of the radioactive cesium is adhered to the grain section such as clay and silt.

In cooperation with Ube Machinery Corporation Ltd., Fuji Electric developed technology for dry decontamination and volume reduction of contaminated soil.

2.1 Dry decontamination and volume reduction process flow

The processing flow based on this technology is described in Fig. 1. The point of this technology is section A and the details are as follows:

(a) Grinding superficial coarse particle by mill

Grind the soil, which has become coarse particles superficially as a result of the grain hardening, by using the mill.

(b) Peel-off of grain

Strip off the grain that is adhered to the surface of the coarse particles by means of grinding using a mill.

(c) Grinding surface layer of coarse particles

Strip off the surface layer of coarse particles to which the radioactive cesium is adhered by means of grinding using a mill.

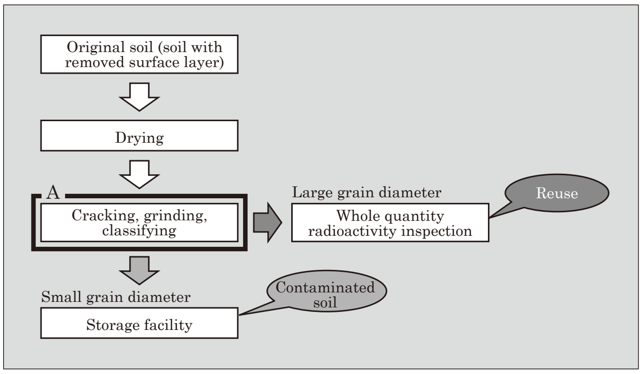


Fig.1 Dry decontamination and volume reduction process flow

(d) Dry classification

Sort the grains by grain diameter by means of dry classification.

With this series of processes, soil is classified into soil which has high contamination and soil which has low contamination.

2.2 Characteristics of dry decontamination and volume reduction process

This technology has been developed by combining proven dry classification and grinding equipment used in general industry with a radiation measurement device, enabling mass processing of soil. The characteristics are as follows:

(1) Method of processing that does not require water and chemicals

Compared to the soil wet processing method, for which prior research has been conducted for volume reduction of contaminated dirt, water and chemicals are not used; therefore, the cost and effort for secondary waste processing is eliminated. In addition, because chemical treatment and high-temperature treatment are not performed, the original characteristics of the original soil are not easily lost.

(2) Classification treatment, volume reduction and space-saving of storage location

Dry classification technology allows the volume reduction process to be performed appropriately for various types of soil because it is possible to set an arbitrary classification threshold for reuse of soil. Applicability for soil in paddy fields, to which it is difficult to apply the wet process, was demonstrated by a basic test.

The volume of the soil which is categorized into soil to be stored as contaminated waste is expected to be reduced further by deairing and compressing it. As a result, it is possible to aim at reducing the amount of space needed for storage.

(3) Ensuring safety and security by whole quantity measurement of radioactive concentration of reusable soil

With the soil monitor for which Fuji Electric applied the principle of the "Food radiation measurement system" that Fuji Electric has already commercialized, the whole quantity of radioactive concentration of reusable low contaminated soil is measured continuously.

Although it takes a few days to obtain the result when outsourcing analysis of radioactive concentration, efficient operation can be performed with this technology because the measurement result can be obtained in real time. This technology is so effective that even when changing settings by condition of classification according to the type of soil and decontamination method, an operator can immediately confirm how much radioactive concentration has changed.

(4) Low cost

A trial calculation of the process cost was made by considering the initial cost and running cost. This technology does not require contamination water treatment and secondary waste disposal cost; therefore, it lowers the costs to between one thirds and one fourth the amount of the wet decontamination method.

3. Dry Decontamination and Volume Reduction Plant

For a dry decontamination and volume reduction plant, two types are planned: movable type and stationary type.

As for the movable-type plant, by mounting the necessary devices on trailers, it will be possible to move the plant to the required location. Since installation and removal of the plant are easy, we expect it will be possible to gain understanding from local people and facilitate the decontamination work. We assume it will be applied in relatively high radiation dose areas because the equipment configuration aims for a decomposition effect. A conceptual image of the movable plant is shown in Fig. 2 and the process flow is shown in Fig. 3.

As for the stationary-type plant, we assume it will be used to decontaminate a large volume of soil in relatively low radiation dose areas because the equipment configuration aims for throughput and volume reduction. Figure 4 shows a conceptual image of a stationary-type plant and Table 1 shows the specifica-

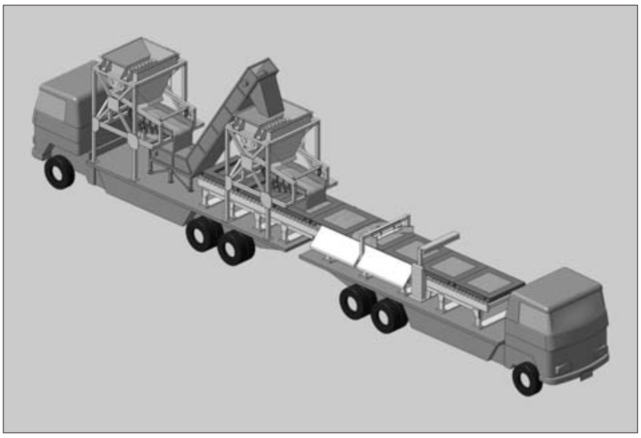


Fig.2 Conceptual image of movable-type plant

merical value in the table is an example of the result of a basic test for soil decontamination and volume reduction. The effective classification of particle diameter (threshold to classify by grain diameter) and decontamination performance differ because the state of contamination differs depending on the type of soil and location. In the future, it is expected that data on each type of soil will be accumulated.

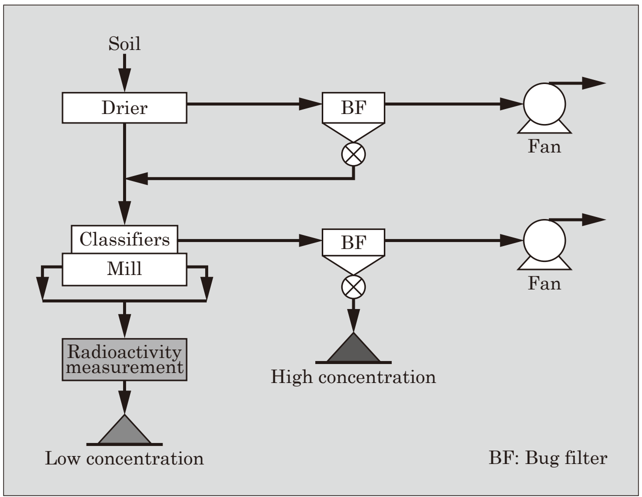


Fig.3 Process flow of movable-type plant

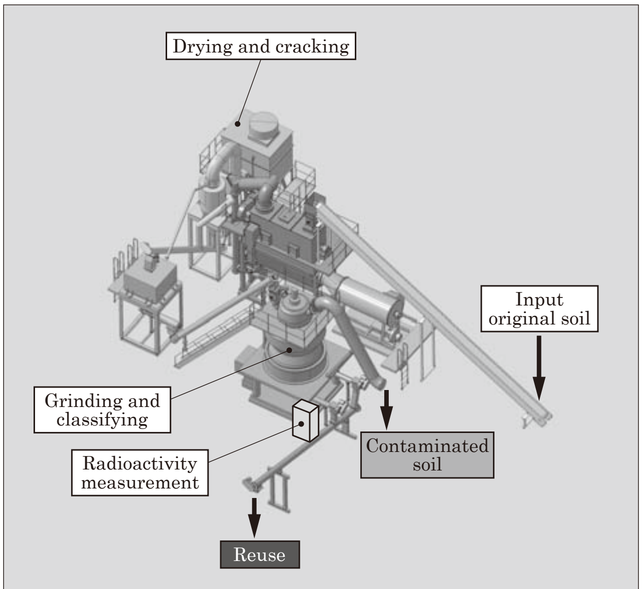


Fig.4 Conceptual image of stationary-type plant

Table1 Specifications of dry decontamination and volume reduction plant

	Movable type	Stationary type
Decontamination rate*1	50 to 86%	20 to 60%
Reduced rate*2	30 to 50%	50 to 70%
Throughput(WB)	3 t/h	20 t/h
Installation space	W18×H7.5×D28 (m)	W20×H10×D35 (m)
installation motive power	350 kW (Generator light oil)	650 kW (Fixed power supply)
Drying room	Kerosene	Kerosene

*1: Decontamination rate: Decreasing rate of radioactive contamination against original soil of reusable soil after treatment
*2: Reduced rate: Rate of mass for original soil of reusable soil after treatment

tions of the dry contamination and volume reduction plant. The ratio of mass against the reusable original soil after treatment is called the reduced rate. The numerical value in the table is an example of the result

4. Demonstration

In order to demonstrate the basic principle of this equipment, a demonstration using actual contaminated soil was carried out in the "Decontamination Technology Demonstration Test Project in FY2011" (Ministry of the Environment).

4.1 Characteristics of soil

In order to grasp the difference in effect of decontamination and volume reduction depending on soil property, three samples — fine grain brown lowland soil (paddy field), rudaceous brown lowland soil (field), and fine grain brown forest soil (forest) — were collected and a decontamination and volume reduction test was conducted. As one test result example, Fig. 5 shows the decontamination effect per type of soil when the particle diameter of classification point is set as 75 µm. Radioactive concentration per particle diameter before grinding and after grinding and classifying is indicated. In all cases, the radioactive concentration of each particle diameter after grinding and classifying was reduced to half or less at the coarse grain side. In this way, it was possible to confirm the basic principle of this equipment including (a) Grinding of superficial coarse grain, (b) Peel-off of grain, (c) Grinding surface layer of coarse grain and (d) Dry classification are feasible.

4.2 Classification point and decontamination effect

Figure 6 shows the result of organizing radioactive concentration of soil before and after grinding using classification points as the parameter.

After grinding the original soil with radioactive concentration of 8,000 Bq/kg, classifying by 45 µm was performed; as a result, radioactive concentration was reduced to 4,000 Bq/kg. In addition, after classifying was performed with 75 µm, radioactive concentration was reduced to 2,000 Bq/kg. However, when the classification particle diameter becomes small, the reduced rate becomes lower.

When soil with low contamination is reused, it is possible to estimate the reusable radioactive concentration of soil and the amount of materials by creating a chart as in Fig. 6 for the soil, which becomes the target. Although we have to wait to see future trends of regulation reference values, it is possible to draw up a detailed decontamination plan while considering the contamination state of original soil.

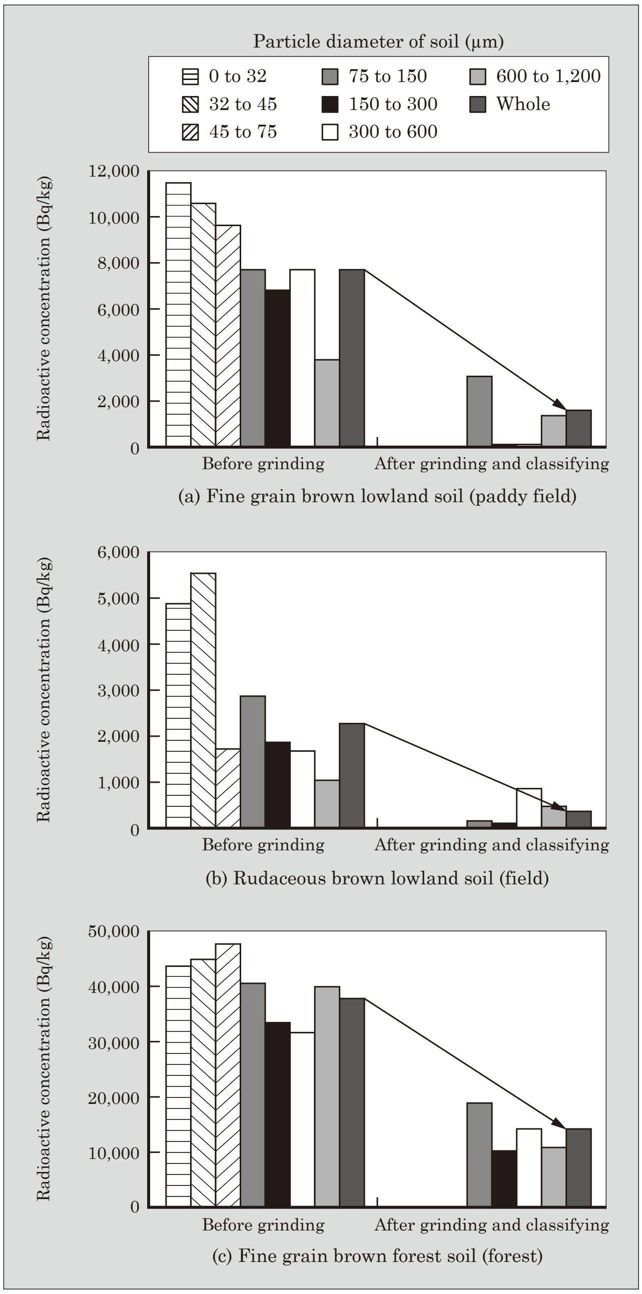


Fig.5 Decontamination effect for each soil (particle diameter of classification point 75 μm)

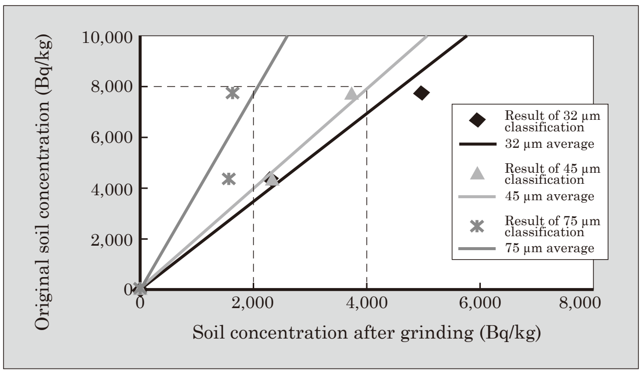


Fig.6 Decontamination effect by classification point (fine grain brown lowland soil: paddy field)

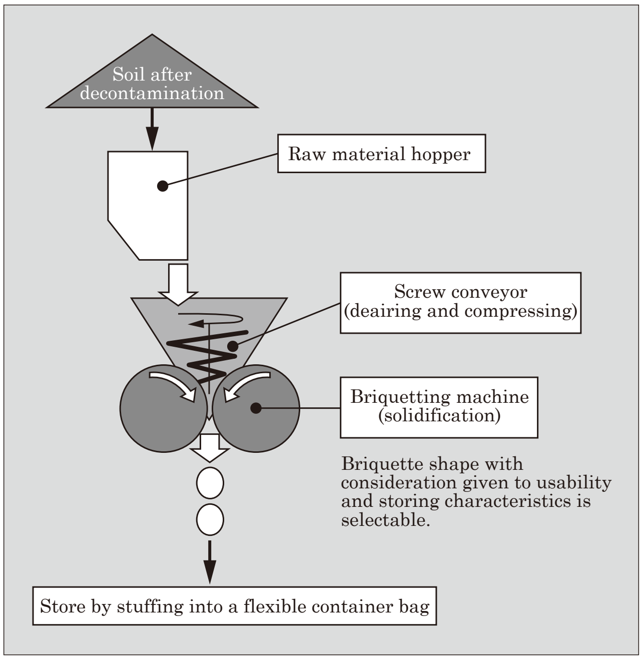


Fig.7 Example of volume reduction flow of high dose soil

5. Future Development

By adding processes for deairing, compressing and solidifying soil with a high radioactive concentration after decomposition treatment (see Fig. 7), further volume reduction can be expected. As a result, a further reduction in the space necessary for temporary storage at the interim storage facility can be expected. In order to evaluate the comprehensive effect of dry decontamination, it is necessary to grasp the volume reduction effect by deairing, compressing, and solidifying.

6. Postscript

This paper described technology for dry decontamination and volume reduction of contaminated soil caused by radioactive substances. In the future, we will develop technologies that can contribute towards recovery and restoration from the Great East Japan Earthquake and Fukushima Daiichi Nuclear Power Station accident.

Fuji Electric has conducted the demonstration as “Decontamination Technology Demonstration Test Project in FY2011” of the Ministry of Environment under Fuji Furukawa Engineering & Construction Co., Ltd. We express our gratitude to the Ministry of Environment and the Japan Atomic Agency, which provided us with guidance.

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