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HITACHI REVIEW

Volume 63 Number 4 September 2014

Electric Power Generation and Transmission Technologies for New Energy Systems

HITACHI REVIEW Carried on the Web

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Next-generation SCADA/EMS Designed for Large Penetration of Renewable Energy

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OVERVIEW: The penetration of renewable energy is on the rise worldwide. When interconnecting renewable energy sources with grids, various problems in rotor angle stability and voltage stability could occur. As penetration of renewable energy becomes increasingly larger in energy sources, the potential for grid instability that leads to major power outages increases, creating a need for heightened awareness among SCADA/EMS operators. Phasor measurement units are gaining attention as a technology that can provide operators with the situation awareness they need. Hitachi is developing grid status monitoring technology using phasor measurement units, and working on initiatives related to this technology in markets throughout the world.*

INTRODUCTION

RENEWABLE energy sources have recently been growing in penetration throughout the world, but the output of renewables such as wind and photovoltaic power may fluctuate due to changing weather conditions. Besides, phenomena such as lightning strike can result in instantaneous voltage drops, causing renewables to trip out. And both renewable and non-renewable energy sources are always subject to the risk of major power outages caused by events such as grid failures. To ensure power grid stability, these problems need to be identified and prepared for in advance.

This article describes the work Hitachi is doing in markets throughout the world to promote grid status monitoring technology using phasor measurement units (PMUs).

PROBLEMS AND SOLUTIONS RELATED TO LARGE PENETRATION OF RENEWABLE ENERGY AND GRID FAILURES

This section discusses problems and solutions related to the large penetration of renewable energy, in areas such as rotor angle stability, voltage stability, and major power outages caused by grid failures.

(1) Problems with rotor angle stability when adopting renewable energy sources

Rotor angle stability is a measure of how well operating synchronous generators can continue to maintain stable operation without stepping out when a disturbance in the power grid occurs such as a transmission line failure. The inertia of conventional thermal power generators makes them highly proficient at restoring their original synchronous state after a grid failure occurs (strong synchronizing power). But wind and photovoltaic power generators are generally interconnected and via inverters therefore lack synchronizing power. Increasing the proportion of wind or photovoltaic power sources and decreasing the proportion of thermal power makes the power grid unstable due to this loss of ability to maintain synchronization.

(2) Problems with voltage stability when adopting renewable energy sources

Conventional thermal power generators operate with stable output and enable appropriate control of reactive power, so they help keep the grid voltage within the appropriate range. But since renewable energy sources can have their output affected by weather conditions, they are less stable than thermal power sources. If energy providers prioritize output of active power to maximize power generation and not provide reactive power, grid voltage maintenance will be adversely affected.

Possible measure for these problems is to maintain grid voltages and inhibit voltage fluctuations during accidents by controlling reactive power with flexible alternating current transmission system (FACTS) devices such as static var compensators (SVCs) and static synchronous compensators (STATCOMs). But the problem of who should be responsible for implementing these methods remains.

* EMS: energy management system

Table 1. Major power outages throughout the world

There have been successions of wide area major power outages in both the developed and emerging economies. There has been recent discussion on whether to incorporate economic losses from power outages into power costs.

Date	Area affected	Accident statistics	Description
August 14, 2003	Northeastern USA	Power lost: 61.8 million kW Affected area: Eight U.S. states and one Canadian province Affected users: About 50 million Total damage: 4 to 10 billion U.S. dollars	Tree contact caused a transmission line shutdown that cascaded into a wide area power outage.
September 28, 2003	Italy	Power lost: 27.7 million kW Affected area: All of Italy except Sardinia	Tree contact caused shutdown of an interconnecting line with Switzerland.
November 4, 2006	Europe	Power lost: 17 million kW Affected area: Eleven countries including Germany, France, Belgium, Italy, Austria and Spain Affected users: About 10 million	A transmission line safety shutdown to enable safe passage of a ship caused an overload shutoff in the German-controlled zone.
February 26, 2008	USA	Power lost: About 3.4 million kW (lost generation capacity) Affected area: Southern Florida Affected users: About 580,000	Fires caused shutdowns of nuclear and thermal power plants.
November 10, 2009	Brazil Paraguay	Affected area: Eighteen Brazilian states and all of Paraguay Affected users: About 67 million	Transmission equipment short-circuit accident
September 8, 2011	USA Mexico	Affected area: California, Arizona and part of Mexico Affected users: About 5 million	Substation work error
September 15, 2011	Korea	Affected area: Seoul and other areas Affected users: About 4 million	Manual overload restriction caused by poor demand forecast
September 24, 2011	Chile	Affected area: Wide area including Santiago Affected users: About 10 million	Transmission equipment failure
July 30 and 31, 2012	India	Affected area: Northern, eastern and northeastern India Affected users: Over 600 million	An accident occurred in a transmission line linking the north and west of the country, and subsequently cascaded into a wide area event.

(3) Problems occurring during major power outages

Many large power outages have occurred recently throughout the world (see Table 1). One of the largest was a failure in the northeastern part of the USA in 2003. High-load operation combined with a line failure led to a power outage from a lengthy accident, lasting between 1 and 2 hours after the initial accident indications. Although it took nearly one hour for power transmission to stop, the problem was the inability to obtain detailed realtime monitoring.

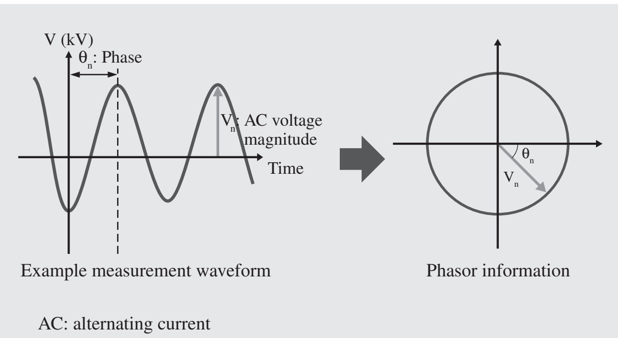

Fig. 1—Measurement waveform example and phasor information

Data is actually acquired as discrete values, but for simplicity is represented here as a waveform graph. The phasor information shown in this example diagram represents AC voltage magnitude and phase as a single vector.

Adopting wide area monitoring across multiple power companies and measurement systems enabling detailed realtime grid monitoring may provide effective solutions in the future to the problems discussed in Sections (1) through (3). There is a need to improve measurement systems, raise operator awareness and implement advance readiness measures to prevent grid instability and accidents. The use of wide area measurement systems (WAMSs) that use PMUs to enable more detailed monitoring has also been gaining global popularity recently.

GRID MONITORING/CONTROL SYSTEM TECHNOLOGIES

PMU-driven grid status monitoring

PMUs are devices that measure time-series measurement information (see Fig. 1) in realtime by appending absolute times obtained from global positioning system (GPS) data to power grid measurement information such as phase, voltage, and current.

Conventional grid status monitoring is done with a supervisory control and data acquisition (SCADA) system. But SCADA systems can only measure the magnitude of parameters such as voltage and current. It can’t measure phase directly, and requires separate data acquired from oscilloscope devices installed in substations to measure information needed to analyze

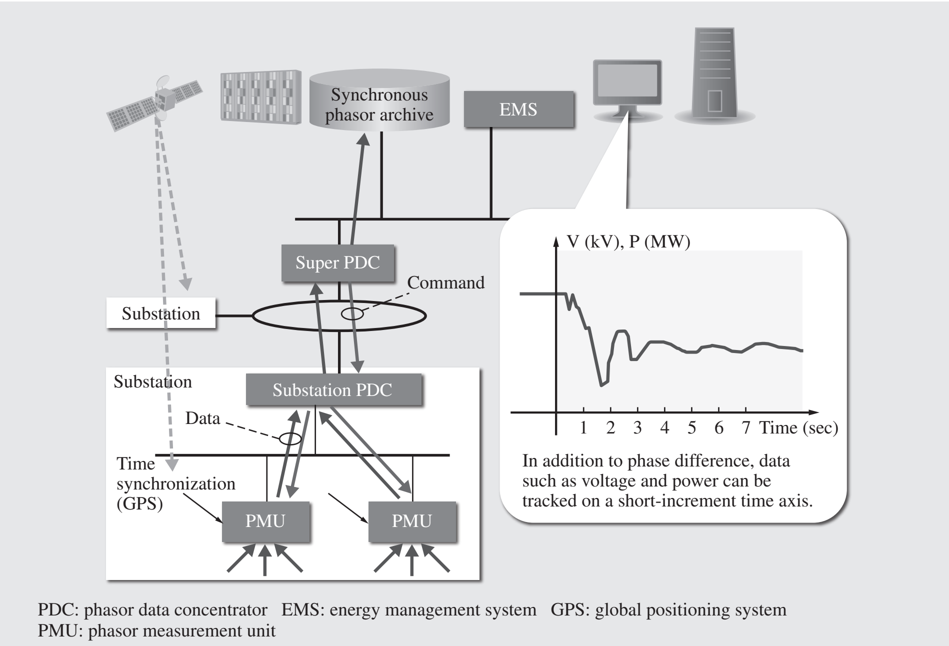

Fig. 2—PMU data transmission route
PMUs have a short measurement cycle, enabling measurements on a short-increment time axis. Measured information is compiled by a PDC.

transient phenomena. Monitoring grid status with a PMU and the transmission route shown in Fig. 2 enables online information measurement from the PMU, with information gathered in realtime as short-cycle, time-series waveform information. It enables instant tracking of power grid transient status, which is not measurable with conventional grid status monitoring systems.

Data gathered by PMUs has a short measurement cycle and is synchronized using absolute time. These advantages mean that even when an accident occurs, waveform information from multiple locations gathered at the time of the accident (caused by generator trip or a transmission line failure) can be used in detailed accident analysis to create prevention measures for future accidents. Table 2 compares grid status monitoring using SCADA systems and PMUs.

TABLE 2. Comparison of SCADA systems and PMUs
PMUs can have a shorter data-gathering cycle than SCADA systems, and can measure phase.

	SCADA systems	PMUs
Sampling cycle	2 to 4 seconds per snapshots	10 to 60 snapshots per second
Measurement items	Magnitudes of parameters such as voltage and power flow	Magnitudes of parameters such as voltage and power flow; phase
Ensuring data synchronization	Not possible	Possible (using absolute time)
Scope of use	Local operating area	Wide area extending beyond local operating area

SCADA: supervisory control and data acquisition

PMUs are becoming increasingly popular worldwide. North America and India have already created PMU measurement infrastructure and installed WAMSs[(1), (2)] (see Fig. 3 and 4).

Use of PMU measurement information

The advantages of PMUs give PMU measurement information a variety of applications. Hitachi initiatives that make use of PMU measurement information are described below.

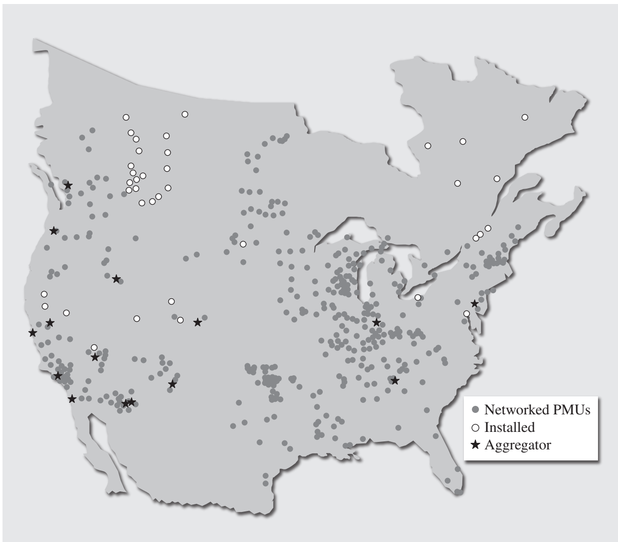

Fig. 3—PMU installation in North America (2012)
Five hundred PMUs had been installed in North America in 2012, and the figure is expected to reach about 1,000 by the end of 2014.

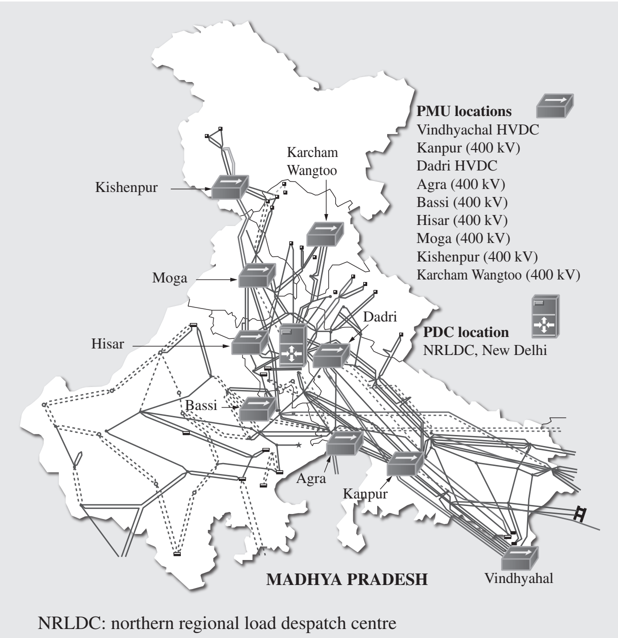

Fig. 4—PMU installation in northern India (2012)
PMUs have been installed in nine substations near large-output generators, scattered over several areas.

(1) Grid status monitoring

Power grid transmission lines must be operated within their total transfer capability (TTC) limits. Using PMU measurement information to monitor phase, voltage stability, frequency and power flow in realtime enables the current grid status to be viewed in detail and can assist transmission line operation.

(2) Wide area grid monitoring

PMUs enable easy measurement of information from wide areas spanning multiple operating areas, enabling tracking of status changes in external grids.

(3) Oscillation monitoring

Since short-cycle waveform information can be visualized in realtime, oscillations difficult to track with conventional systems can be monitored and reported to operators.

(4) Failure analysis

Analysis of waveform information when external disturbances such as grid failures occur enables visual display of accident phenomena and rapid feedback into preventive measures.

(5) State estimation precision improvement

Measurement data can be acquired from multiple measurement points without time lags, and phase data not measurable by SCADA systems can be measured, enabling state estimation with greater precision.

(6) Comparative verification of power grid models

Actual data can be compared and verified against existing power grid models used in analysis tools. This enables parameter adjustments for correction of analysis tool simulation results.

Although hardware for monitoring power flow and voltage is needed when the application is preventing overloading or maintaining grid voltage, PMUs are extremely effective since they enable short-cycle measurement. PMUs also enable actual phase measurement and data measurement ensuring synchronization, so they support high-precision state estimation.

For the future, the use of PMUs for more detailed monitoring will enable power grids to support large penetration of renewable energy sources. But although PMU-driven grid monitoring technology is on the rise worldwide, the only application that PMUs are currently being used for is grid status monitoring. Hitachi is planning to build on this status monitoring application with work on supervisory control applications that make effective use of PMU measurement information.

WORK IN GLOBAL MARKETS

Hitachi is working on multiple projects in markets throughout the world, in locations such as the USA, Europe and Asia.

For example, Hitachi is part of a joint research project titled "Research into Grid Stabilization Systems to promote widespread adoption of renewable energy." The project is part of the FY 2013 Technology Innovation R&D program initiated by the Bonneville Power Administration of the U.S. Department of Energy. The project's aim is to improve power quality by dynamically tracking and controlling the power flow of electricity. The project also aims to create an integrated grid stabilization system designed to popularize and make effective use of renewable energy by using data from PMUs, which are now widespread in the US. Anticipating the widespread use of renewable energy from sources prone to fluctuating output such as wind and photovoltaic generation, Hitachi plans to use the results of this research to create power transmission systems supporting renewable energy.

CONCLUSIONS

This article has presented PMU-driven grid status monitoring technology. It is used as grid monitoring/control system technology enabling solutions to various problems in power grids with large penetration of renewable energy.

The grid status monitoring systems described here enable realtime visual status displays, and make it possible to create advance readiness measures to prevent grid instability and accidents. In the years ahead, effective use of measurement information will result in technology leading to more advanced grid control.

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Development of Medium-voltage Switchgear for Reducing Environmental Impact and Space-saving

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OVERVIEW: To make medium-voltage switchgear (52 kV or less) smaller and more robust, there has been a shift away from AISs and toward GISs that use SF_6 gas[*1]*. However, the high global warming coefficient of SF_6 gas means it was designated as a greenhouse gas by the Kyoto Protocol (Kyoto Protocol to the United Nations Framework Convention on Climate Change) adopted at the Third Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change held in Kyoto in December 1997. Responding to this, Hitachi quickly embarked on the development of medium-voltage switchgear with the aim of eliminating use of SF_6 gas.*

INTRODUCTION

THE demands placed on electric power generation and distribution equipment are changing in response to the growing diversity of power generation and the need to reduce the load on the environment to create a sustainable society, with equipment also being made smaller, easier to maintain, and better able to cope with disasters. The distribution switchgear used to deliver electric power directly to users also needs to adapt to these diverse changes.

In developing medium-voltage switchgear to meet these needs, the key considerations are: (1) The development of alternative insulation techniques to sulfur hexafluoride (SF_6) gas by selecting the best mix of electrical insulators, (2) Making equipment smaller and providing it with multiple functions through greater use of vacuum technology, (3) Protection from internal arcs to prevent three-phase short circuit faults, (4) Save energy, improve maintenance, and enhance reliability by simplifying operating mechanisms and eliminating use of grease, and (5) Creation of added value, including services made possible by advances in protection, measurement, and diagnostic techniques.

This article describes the key technologies for medium-voltage switchgear and the outlook for the future.

KEY TECHNOLOGIES FOR MEDIUM-VOLTAGE SWITCHGEAR

Key technologies for medium-voltage switchgear include greaseless hybrid electromagnetic operating mechanisms that reduce the number of mechanical parts and eliminate the need for lubrication maintenance, multifunction vacuum interrupters that help make the devices smaller, wide-range current transformers (CTs), and diagnostic techniques for assessing the life of insulators. The following sections describe the features of these new technologies.

Greaseless Hybrid Electromagnetic Mechanism

This mechanism uses a hybrid magnet (combining a permanent magnet and electromagnet) and proprietary Hitachi technologies to achieve a number of benefits. These include: (1) Eliminating approximately 85% of mechanical parts[*2], (2) Reducing the energy needed to operate the mechanism by approximately 80%[*2], and (3) Using a greaseless mechanism to eliminate the need for regular lubrication (see Fig. 1).

Multifunction Vacuum Interrupter Technology

To reduce the device size, Hitachi utilized its vacuum technologies built up over many years to develop a vacuum interrupter that: (1) Halves the contact force required by the terminals[*2], and (2) Combines the functions of a circuit breaker and disconnecting switch (see Fig. 2).

Wide-range CT and Multi-relay

The wide-range CT incorporates a multi-relay intelligent control unit (ICU) that has functions

*1 Sulfur hexafluoride (SF_6) gas: A gas with excellent electrical insulation and arc extinction properties but with a global warming coefficient 23,900 times that of carbon dioxide (CO_2). As a result there is a need to manage and reduce release of the gas into the atmosphere.
*2 Compared to the previous Hitachi model.

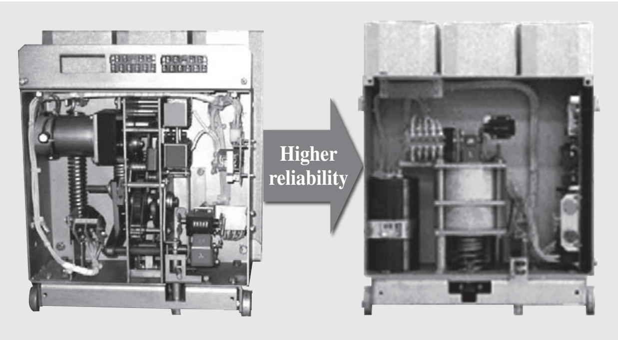


Fig. 1—Advances in VCB Operating Mechanisms.
To improve the reliability of the mechanisms used to operate vacuum circuit breakers (VCBs), the spring mechanisms used in the past, which had many mechanical parts, have been replaced with hybrid electromagnetic mechanisms that have few parts.

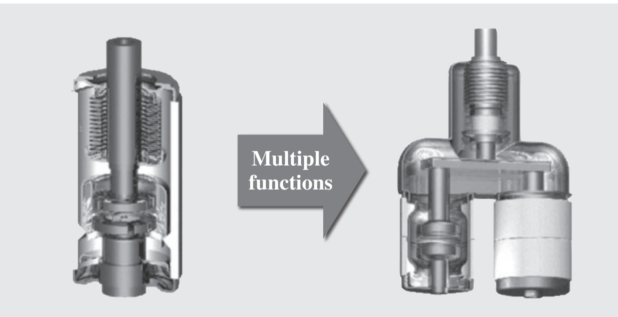


Fig. 2—Combination of Multiple Functions in Vacuum Interrupter.
Switchgear is made smaller and lighter by using vacuum interrupters for both circuit breaker and disconnecting switch functions, rather than as single-function devices as in the past.

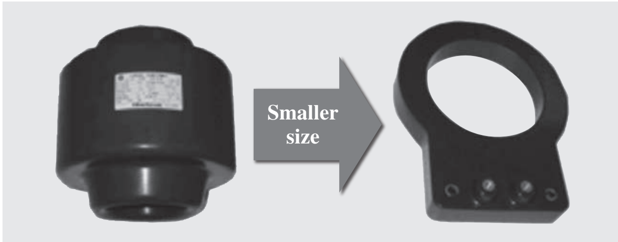


Fig. 3—Wide-range CT.
Wide-range current transformers (CTs) designed for smaller size and lighter weight have become available. These incorporate Hitachi multi-relays to significantly expand the scope of protection compared to previous models.

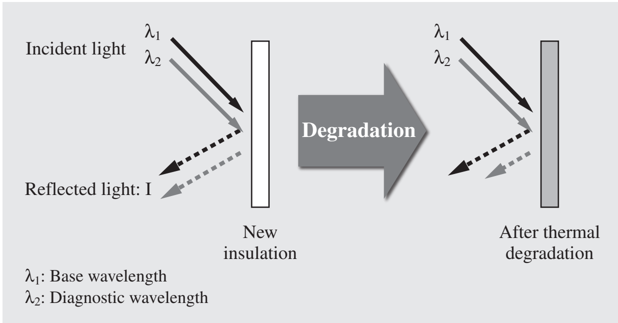


Fig. 4—Principle of Operation of Dual-wavelength Optical Diagnostic Technique.
This proprietary dual-wavelength technique was devised by the Hitachi Laboratory. It provides a non-contact method for assessing insulation degradation.

including protection, control, measurement, and communications, and that provides accurate detection over a wide range. The features of the CT are as follows (see Fig. 3).

(1) Approximately 80% smaller by volume and weight*2 to help make panels smaller.
(2) Does not require replacement or tap changes when load capacity changes.
(3) Equipment can be selected prior to finalizing load capacity.

Dual-wavelength Optical Technique for Assessing Remaining Insulator Life

Hitachi Research Laboratory of Hitachi, Ltd. has demonstrated the ability of this technique to assess deterioration in insulators based on the following principles (see Fig. 4).

(1) Some of the light shined on organic material is absorbed, and the intensity of reflected light differs depending on the material and the wavelength.
(2) While the intensity of reflected light varies depending on variations in the surface condition of the material and the intensity of incident light, the proportion of absorbed light remains constant.
(3) The amount of absorbed light varies depending on thermal degradation and other changes in the chemical structure.

Fig. 5 shows how these principles can be used to assess the condition of a cable. Hitachi is expanding the scope of application of this technique by building up a database of material degradation.

PRODUCTS INCORPORATING KEY TECHNOLOGIES

The following sections describe medium-voltage switchgear products that utilize these key technologies.

Hybrid (Electromagnetic Mechanism) VCB

Hitachi developed the vacuum circuit breaker (VCB) for the Japanese market in 2003 with the aims of minimizing maintenance, reducing the energy required to operate the circuit breaker, and ensuring reliable long-term use. It is now expanding its product

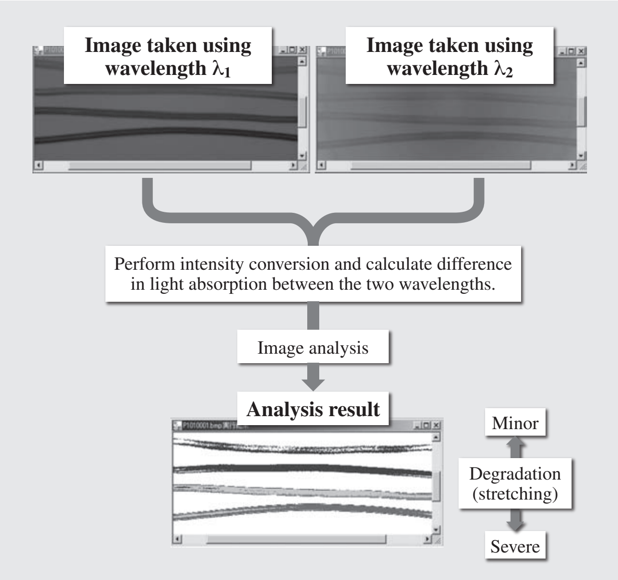


Fig. 5—Use of Dual-wavelength Optical Technique to Assess Cable Degradation.
The technique is used to assess degradation of electric cables.

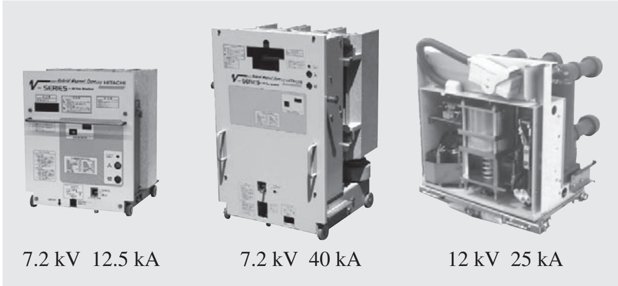


Fig. 6—Hybrid VCBs.
These VCBs with a hybrid electromagnetic operating mechanism have earned a strong reputation in the Japanese market. Hitachi has now started to sell them in overseas markets.

range to include models for overseas markets (see Fig. 6). The features of this VCB include a hybrid electromagnetic operating mechanism, bearings that use solid lubricant, and a stainless steel shaft.

Fig. 7 shows a 12-kV hybrid VCB for the Chinese market undergoing certification testing at a test laboratory in Xi'an, China.

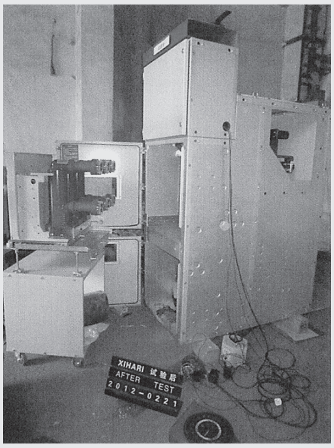


Fig. 7—Certification Testing of 12-kV Hybrid VCB for the Chinese Market.
After testing, the supplied VCB was inspected to ensure it had no problems.

Switchgear with Solid Busbar Insulation

An issue with the air-insulated switchgear (AIS) used in the past has been how to prevent surface degradation of insulators and the breakdown of insulation for exposed live components due to factors such as condensation or other contamination, and infiltration by vermin or rainwater. The following two practices are adopted to resolve this issue (see Fig. 8).
(1) Use of moldings made of a solid insulator for main busbars and cable ducts, and coating the surface with an earthing layer.
(2) Housing the VCB in a sealed chamber protected by a gas-permeable coating.

To make maintenance and inspection easier, the hybrid VCB also incorporates a broader range of protection, including a drawer-mounted zero phase-sequence current transformer (ZCT), wide-range CT, and lightning arrester (see Fig. 9).

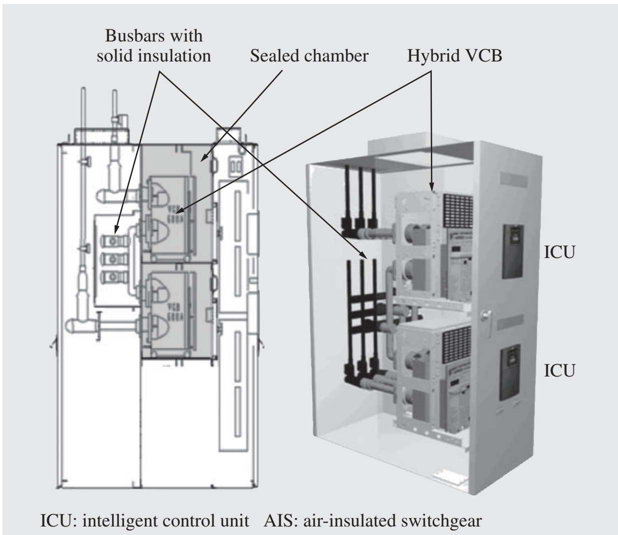
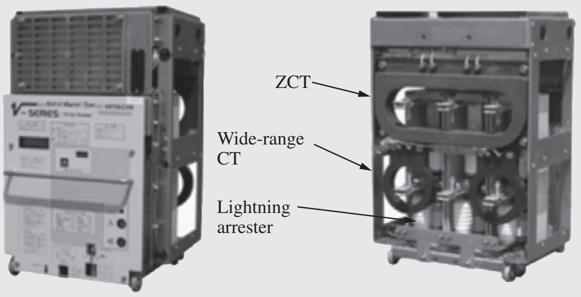


Fig. 8—Layout of 7.2-kV Panel with Solid Busbar Insulation.
The solid busbar insulation and use of a sealed chamber to house the VCB overcome the problems associated with previous AISs.

24-kV C-VIS

In 2006, Hitachi developed a cubicle-type vacuum insulated switchgear (C-VIS) based on a new concept



ZCT: zero phase-sequence current transformer
CT: current transformer

Fig. 9—Overview of All-in-one Hybrid VCB.
Maintenance is facilitated by fitting the CT and lightning arrester in the drawer-mounted hybrid VCB so that they can be pulled out for inspection along with the VCB.

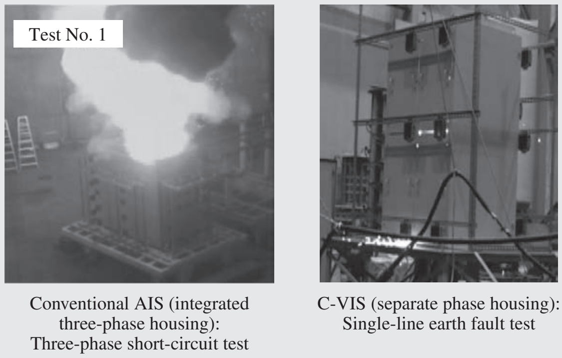
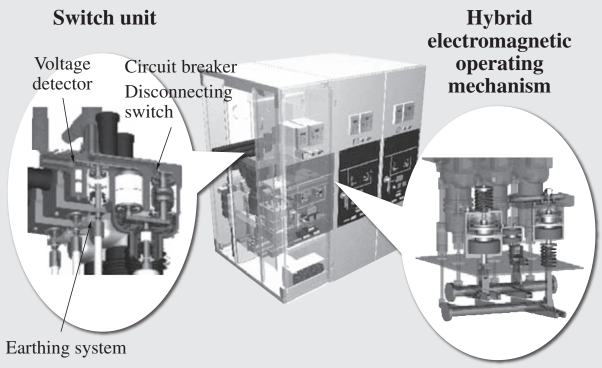


Fig. 11—Internal Arc Testing of Switchgear.
Use of a design in which the phases are kept separate significantly reduced the consequences of internal arc accidents.



C-VIS: cubicle-type vacuum-insulated switchgear

Fig. 10—Overview of 24-kV C-VIS.
Hitachi has developed a switchgear based on a new concept that combines a hybrid electromagnetic operating mechanism with a multifunction vacuum interrupter. In addition to existing markets, Hitachi has also started supplying these for use in harsh environments such as in tropical regions and at sea.

Parameter	Specification
VT rating	110 V
CT rating	Wide-range 1 A
Temperature range	0 – 40°C
Power supply	DC100/110 V
Dimensions	210 × 300 × 100 mm (W × H × D)
Weight	1.5 kg

VT: voltage transformer

Fig. 12—ICU Photograph and Specifications.
Use of the multifunction multi-relay helps make switchgear smaller by integrating the wide-range CT.

that uses neither dry air nor SF_6 gas (a designated greenhouse gas), and has been supplying these in Japan and elsewhere (see Fig. 10). These products have separate moldings for each phase for components such as the multifunction vacuum interrupter and vacuum leak/voltage detector, together with an earthing layer coating for the switch unit and a greaseless hybrid electromagnetic operating mechanism. Combining the ease-of-use of AISs with the small size and reliability of gas-insulated switchgear (GIS), this switchgear also has a potential market for use in harsh environments such as in tropical regions and at sea.

While protection against internal arcing is a major issue for medium-voltage switchgear, these products are designed with safety in mind to prevent short circuits by using a configuration in which the phases are kept separated (see Fig. 11).

Wide-range CT and ICU (Multi-relay)

The ICU is designed for use with Hitachi's own wide-range CT, and has functions that include protection, measurement, control, communications, waveform recording, and operation (see Fig. 12). The ICUs can be used with two types of wide-range CTs: a 600-A model (40 A to 600 A) and a 1,200-A model (100 A to 1,200 A). Fig. 13 shows the performance compensation range of the 600-A model.

OUTLOOK FOR THE FUTURE

Hitachi plans to develop these key technologies further, and is working on research and development that includes: (1) Expanding its range of products that do not use SF_6 gas by making greater use of vacuum technologies and enhancing competitiveness, (2) Upgrading its primary and secondary distribution products for the global market, and (3) Strengthening its service business, including assessment of remaining insulation life.

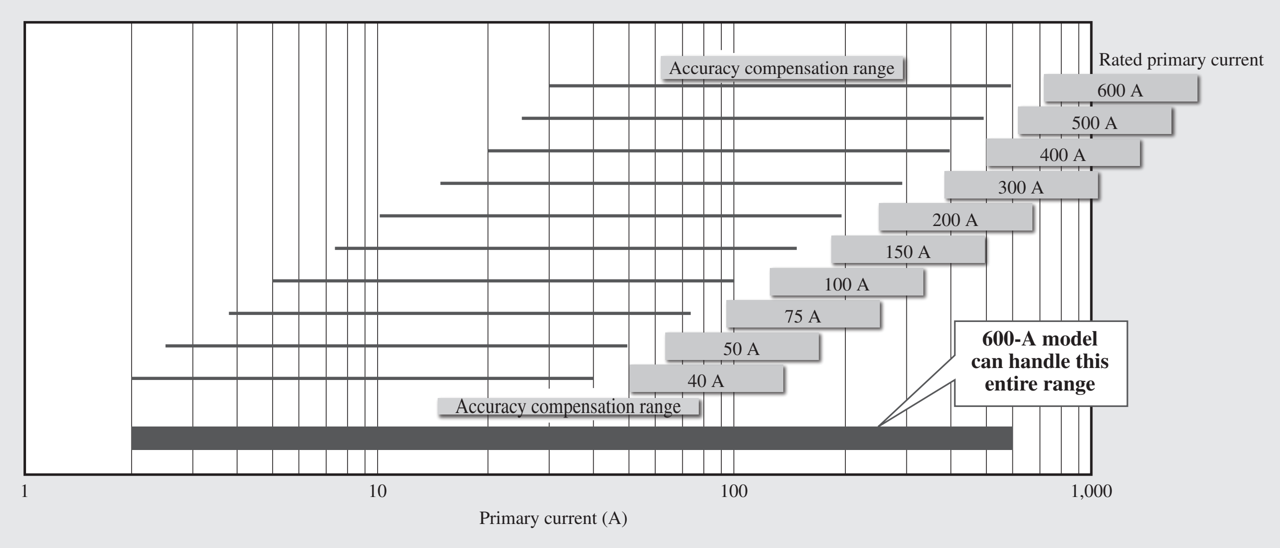


Fig. 13—Comparison of Current Compensation Ranges for Wide-range CT and Previous CT.
The wide-range CT has a wide performance compensation range, reducing the need to replace the CT to handle higher loads.

Construction of New Vacuum Interrupter Factory

The new factory will be adjoined to an assembly line for 72/84-kV switchgear and is scheduled to enter full production in 2014. Hitachi is establishing highly efficient production systems that utilize its research into production technology.

Product Range Expansion

To expand its range of products for the global market, Hitachi is adopting panels with solid busbar insulation for products intended for overseas markets. Fig. 14 shows the design concept for panels with solid busbar insulation (patent pending). Specifically, solid insulation has been utilized for busbars in Hitachi's existing AISs, with VCBs and earthing systems being housed in sealed chambers. Because of growing overseas demand for highly reliable high-end AIS models that provide this level of layout flexibility, Hitachi also sees potential for deploying this technology in the GIS market.

Hitachi is also working on the development of C-VIS+, the next generation of C-VIS. It is also developing a new model that will be compatible at the wiring diagram level with existing cubicle-type GIS. The objective is to reduce device size by adopting a simple design while also keeping to the same concept as the 24-kV C-VIS (see Fig. 15).

Strengthening Service Business

Hitachi is establishing an electronic records system for existing installations in Japan so that it can advise on appropriate upgrade timings based on a database

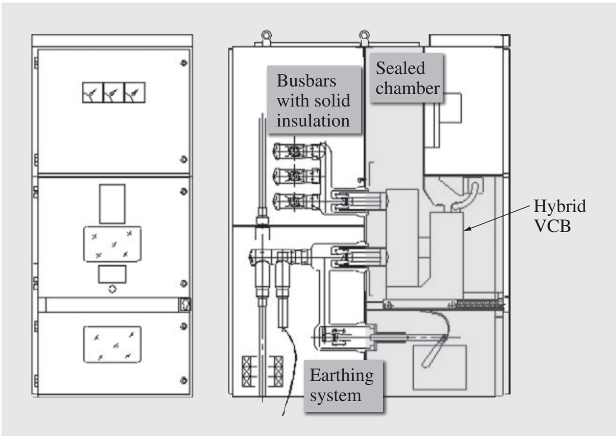


Fig. 14—Panel with Solid Busbar Insulation for Overseas Markets.
Hitachi sells panels with solid busbar insulation in the Japanese market and is now considering expanding into the high-end market overseas.

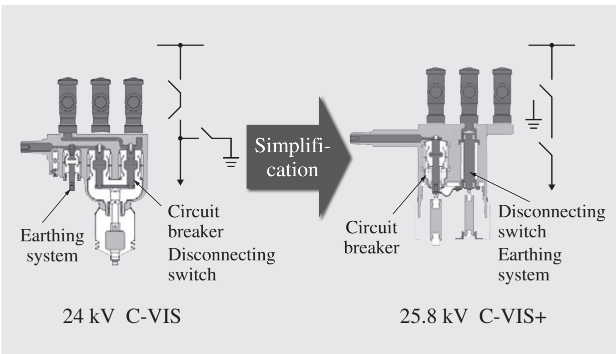


Fig. 15—Advances in Vacuum-insulated Switchgear.
Hitachi is developing the C-VIS+ to have an even simpler design than the C-VIS.

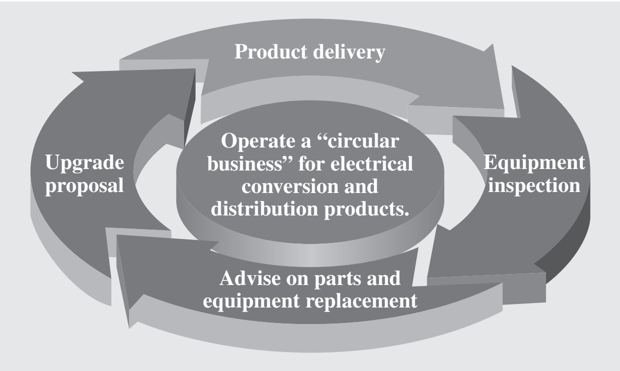


Fig. 16—Circular Business Concept.
To operate its "circular business" globally, Hitachi is establishing facilities around the world.

that includes the results of equipment inspections conducted voluntarily by Hitachi (see Fig. 16). Hitachi is establishing facilities around the world and is also working with partners to create added value for the more than 30,000 units supplied to overseas markets, including using services like this as a base to provide preventive measures against accidents and support for equipment upgrade planning.

CONCLUSIONS

Medium-voltage switchgear is essential for the maintenance of social infrastructure, with an important role in delivering electric power directly to end users. Use of the key technologies described in this article can meet the diverse requirements placed on electrical conversion and distribution equipment, which include reducing the impact on the environment and making the equipment smaller and easier to maintain.

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Numerical Simulation of Electric Power Transmission and Distribution Equipment

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Hiroaki Hashimoto
Tatsuro Kato, Dr. Eng.

OVERVIEW: The market for electric power transmission systems is expected to grow strongly, driven by growing demand for electric power in emerging economies and the adoption of renewable energy. Transformers, circuit breakers, and switchgear are important components of these electric power transmission systems. The emphasis in their development is shifting away from the past focus on technical enhancements like higher voltages and capacities toward economic performance and reduced load on the environment. Limit design plays an important role in achieving good economic performance, and Hitachi is working on enhancing its analysis techniques. Of particular interest are techniques for the analysis of transformer losses and cooling, hot gas flow analysis and mechanical dynamics of high-voltage circuit breakers, and discharge analysis of dry-air-insulated switchgear, which are among the latest analysis techniques.

INTRODUCTION

THE market for electric power transmission systems is expected to grow strongly against a background of expanding electric power supply networks in emerging economies driven by rising demand, and the aging of electric power distribution infrastructure and the strengthening of transmission systems in developed economies as greater use is made of renewable energy. Considerable progress has been made on upgrading the key equipment in electric power transmission systems, namely transformers, circuit beakers, and switchgear, to handle higher voltages and currents. Recent equipment development, meanwhile, has been seeking not only to improve reliability and economic performance, but also to satisfy environmental requirements.

This article describes the latest analysis methods used in the development of electric power distribution equipment.

TRANSFORMER ANALYSIS TECHNIQUES

In the past, transformer development has focused on increasing voltages and capacities as demand for electric power grew. While such development continues, the main focus in recent years has shifted toward improving economic performance and reducing the load on the environment, including energy and resource efficiency. Balancing performance and cost is an important part of development aimed at things like boosting efficiency and reducing size, and this demands precise techniques for analyzing the relevant characteristics.

Important considerations for transformers include insulation, losses, cooling (temperature rise), and short-circuit strength, and techniques such as electric field analysis, system analysis, and strength analysis are used to evaluate the associated characteristics under different operating conditions. Recently, three-dimensional (3D) analyses of stray loss and cooling characteristics have been employed to make precise calculations of losses, temperature rise, and other parameters, even for complex structures.

3D Stray Loss Analysis

Transformer losses include core loss (no-load loss) in the core and load losses. Load losses consist of Joule loss due to winding resistance and eddy current loss (stray loss) due to the presence of leakage flux in electrically conductive components. Electromagnetic field analysis is used to calculate eddy current loss. Fig. 1 shows an example of a detailed 3D calculation of stray loss in an oil-immersed transformer using the finite element method (FEM). It shows how losses occur in the structures around the windings. Based on these results, thermal fluid analysis can be used to conduct detailed assessments, including assessments of where localized temperature rises occur and whether additional measures are needed to reduce losses.

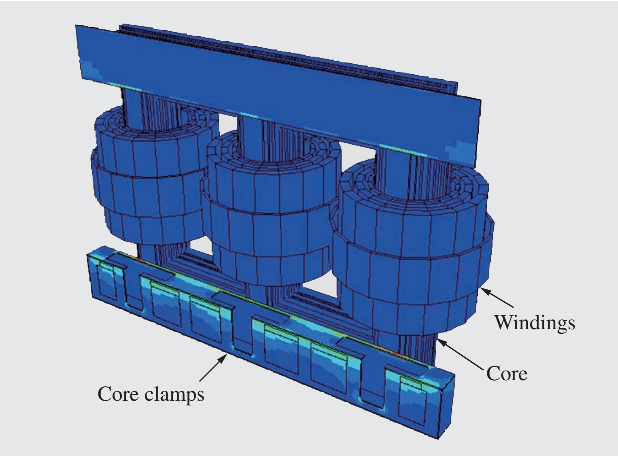

Fig. 1—Results of Stray Loss Analysis of Transformer.
The diagram shows the stray losses that occur in the structural components of a transformer. Localized high stray losses occur in the core clamps located below the windings, which have a complex shape.

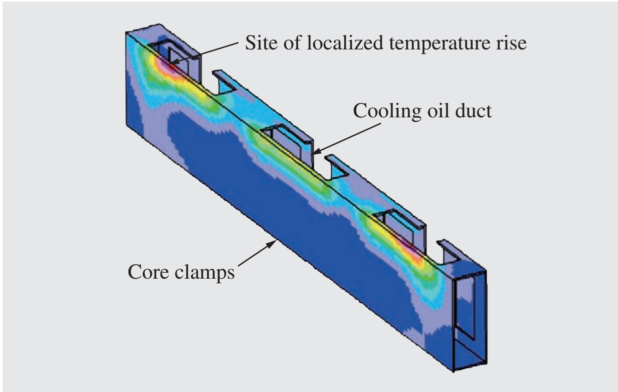

Fig. 2—Results of Thermal Fluid Analysis of Transformer Lower Core Clamps.
The diagram shows the distribution of temperature rises in the core clamps obtained by a thermal fluid analysis that considers the flow of mineral oil. Modifications to the design of the oil ducts and other features can keep the rise in surface temperature within the required limits.

3D Thermal Fluid Analysis

Two-dimensional (2D) and 3D thermal fluid analyses are used to evaluate transformer cooling for the entire transformer or the interior of the windings, for example. Channels through the transformer windings are complex, with localized regions of high temperature occurring due to factors such as flow stagnation. Factors such as temperature rise in the mineral oil or other non-conductive coolant, or localized temperature rises in structural components, are identified based on the distribution of losses (heat generation density) in the structural components or windings calculated by electromagnetic field analysis. Fig. 2 shows the results of a 3D thermal fluid analysis of the lower core clamps of a transformer. Localized temperature rises near cooling oil ducts are influenced by factors such as the design of the ducts and surrounding structural components, and these are optimized to keep the temperature within the required limits. Hitachi introduced a coupled loss and thermal fluid analysis technique for the prototype of a next-generation 500-kV transformer and achieved a high level of precision in the calculation of temperature rise.

ANALYSIS TECHNIQUES FOR HIGH-VOLTAGE CIRCUIT BREAKERS

High-voltage circuit breakers interrupt current by using a mechanical mechanism to operate the contacts at high speed, and an extinguishing gas that is used to blow out the arc plasma generated between the contacts and to provide cooling. High-voltage circuit breaker development work aimed at the use of heavy-duty operating mechanisms to increase voltages wound down after the successful development of ultra-high-voltage (rated voltage: 1,100-kV) circuit breaker technology in the 1990s. In recent years, the main development effort has been directed at improving economic performance through reductions in size, maintenance requirements, and so on. Current work includes producing interrupters that use less operating energy to deliver a high level of interrupting performance, and expanding the use of spring operating mechanisms that feature small size and excellent maintenance compared to heavy-duty hydraulic operating mechanisms.

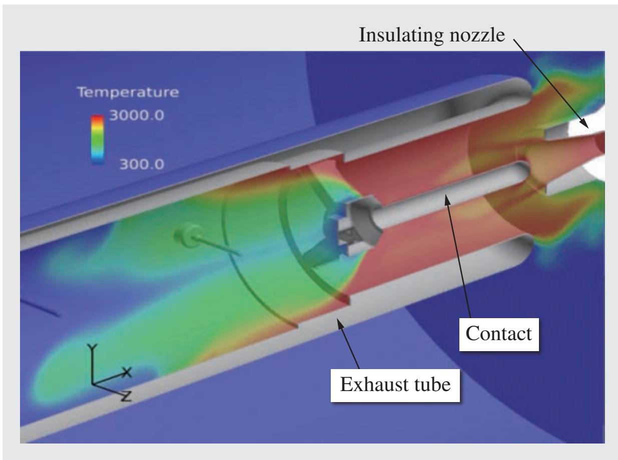

Fig. 3—Results of Thermal Fluid Analysis of Current Interruption by High-voltage Circuit Breakers.
The diagram shows the temperature distribution of the hot gas inside an exhaust tube of an experimental model circuit breaker. This involves a 3D analysis of the entry into the exhaust tube of hot gas heated by the arc gas from the insulating nozzle.

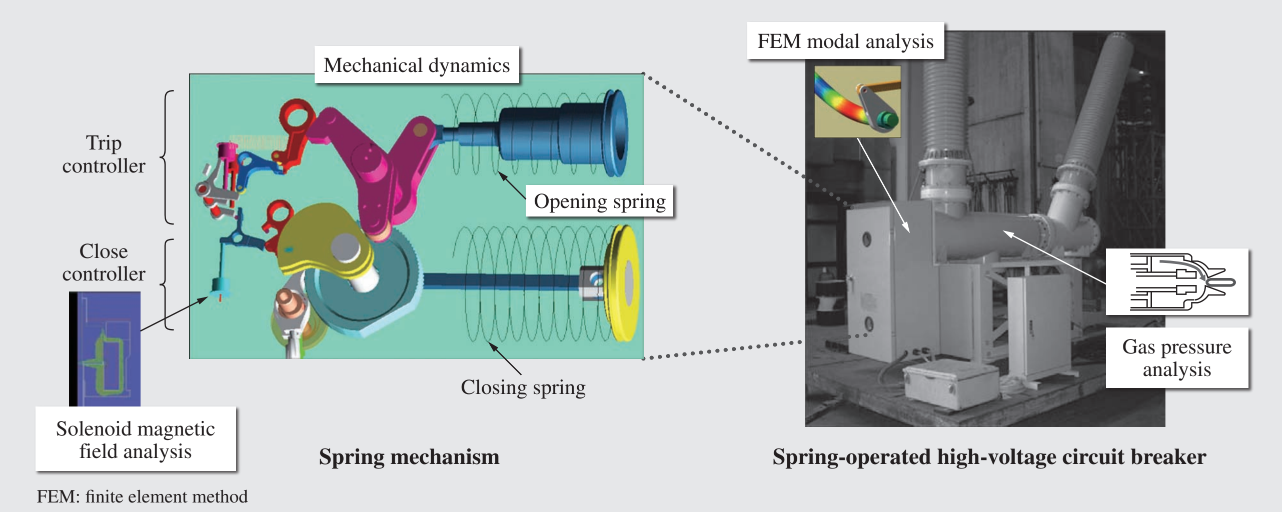

Fig. 4—Overview of Operation Modeling of Spring-operated High-voltage Circuit Breaker.
The coupled model is based on a model of the mechanical dynamics of a complete circuit breaker with a spring operating mechanism and integrates with an analysis of gas pressure and a dynamic magnetic field analysis of the solenoid.

Development of circuit breakers with low operating energy uses hot gas flow analysis to predict the interrupting performance of the interrupter (the core mechanism that breaks the current), and operational analysis of the entire circuit breaker to shorten development times for the spring operating mechanism that drives the interrupter.

Compressible Flow Analysis

Hot gas flow analysis that takes account of arcing is a technique for evaluating the current interruption process. To model arcing more precisely, an arc model is used that also considers the emission and adsorption of light and the ablation of material from the insulating nozzle. Whereas past analyses assumed axial symmetry of the structure, it has recently become possible to analyze 3D structures. Fig. 3 shows the results of a 3D compressible flow analysis of hot gas heated by an arc. It is possible to evaluate how the structural components that support the contacts will be affected by calculating the temperature distribution of the hot gas that flows from the insulating nozzle into the exhaust tube. As the low dielectric strength of the hot gas in the exhaust tube can lead to breakdown immediately after current interruption, 3D thermal fluid analysis is used to study the shape of the exhaust tube.

Mechanical Dynamics of Spring Operating Mechanism

The spring operating mechanism drives the interrupter via an insulating rod. To predict the behavior of a circuit breaker prior to building a prototype, Hitachi has built an operation model that combines magnetic field analysis of the solenoid and FEM modal analyses with gas pressure analysis and the mechanical dynamics of the interrupter to determine the behavior of the entire circuit breaker from the time of inputting the open or close command until the switching operation completes[1] (see Fig. 4).

Because the rigidity of components influences the operating characteristics of the mechanism, the insulating rod, rotating shaft, and lever are treated as elastic bodies that are coupled to the FEM modal analysis (see Fig. 5). The modeling of the spring operating mechanism considers contact, collision, and

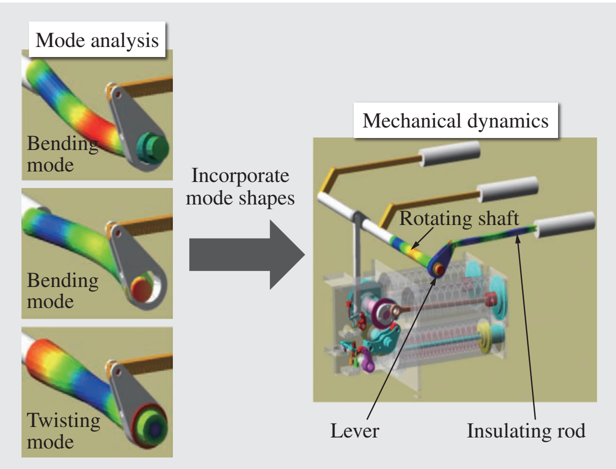

Fig. 5—Elastic Bodies Coupled with FEM Modal Analysis.
The figures show the different mode shapes (curved, twisted) obtained by using an FEM modal analysis of the shaft to calculate the constraint modes.

separation of parts. This modeling makes it possible to predict the opening and closing characteristics and to optimize various aspects. By performing an operation analysis of the entire circuit breaker, it is possible to predict the dynamic loads on the insulating rod and other parts, and to assess the effects of changes in the coefficient of friction between parts in contact. These analyses are utilized in the development of techniques for making circuit breakers operate faster[(2)].

ANALYSIS TECHNIQUES FOR DRY-AIR-INSULATED SWITCHGEAR

Growing environmental awareness is prompting reductions in the use of sulfur hexafluoride (SF_6), a compound with a high global warming coefficient. Hitachi has commercialized 72-kV dry-air-insulated switchgear based on dry air and vacuum insulation technology (see Fig. 6), and plans to expand use of dry air insulation.

Dry air has only one-third the insulation performance of SF_6 gas, and air insulation has a lower electric field dependence than SF_6 insulation. As a consequence, the insulation performance predictions made by the electric field analyses used for SF_6 gas devices are inadequate and discharge phenomena must also be considered. Accordingly, to predict the insulation performance of devices using dry air, Hitachi has developed a new discharge path analysis technique based on discharge phenomenon in air.

Discharge Path Analysis of Air Insulation

To analyze how discharges occur in air, Hitachi used a discharge initiation model based on the streamer theory of spark discharge. After calculating the electric field distribution in the gap, the technique models the electron multiplier effect (an electron avalanche that starts with a single electron) in a way that takes account of electron trajectories. As a result, a self-sustaining discharge (streamer discharge) is defined as commencing when the probability of discharge exceeds 1.0 throughout the mesh. The breakdown voltage is the calculated voltage at which this discharge initiation condition is satisfied.

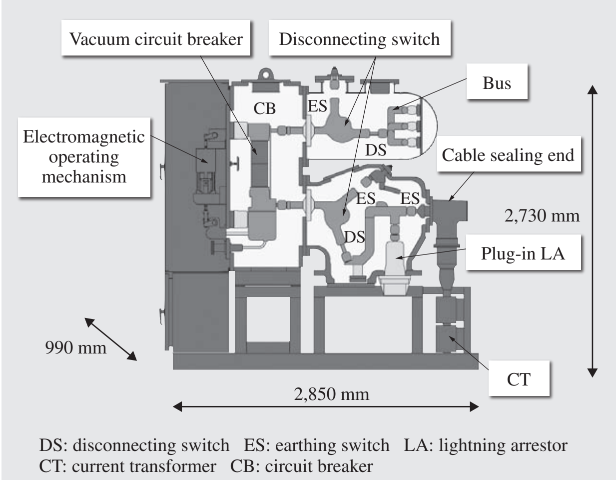

Fig. 6—72-kV Dry-air-insulated Switchgear.
Hitachi has adopted an operating mechanism for the vacuum circuit breaker that works electromagnetically and features excellent maintenance characteristics, and has succeeded in reducing the size of the disconnecting switch/earthing switch by using a three-position linear-drive mechanism.

Fig. 7 shows the results of a discharge path analysis of a disconnecting switch in dry-air-insulated switchgear. Fig. 7 (a) shows the results of an electric field analysis of the electrode shape evaluated in this article, and (b) shows the discharge path obtained by the discharge path analysis. Fig. 7 (c) shows a photograph of arcing in a breakdown test with a discharge path that matches the results of the discharge path analysis. Good agreement was also achieved between the measured and calculated

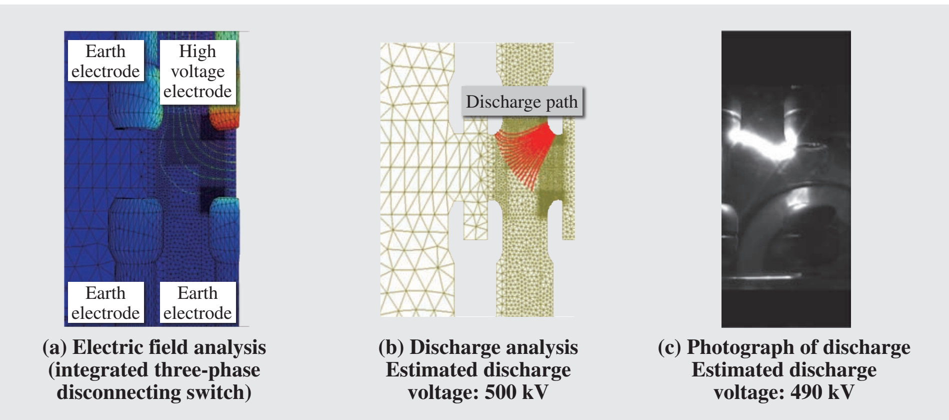

Fig. 7—Example of Discharge Path Analysis.
The discharge analysis described in this article can determine air discharge voltages, something that was not possible with past electric field analysis techniques.

values of breakdown voltage for a variety of different electrode shapes and gas pressure conditions. These results demonstrate that the discharge initiation model is suitable for estimating breakdown voltage. In the future, Hitachi intends to extend these analysis techniques to cover insulator surfaces discharges with more complex phenomena, and to develop them into analysis tools that can be used to evaluate entire air-insulated devices.

CONCLUSIONS

This article has described analysis techniques used in the development of transformers, circuit breakers, and switchgear, which are important components in electric power transmission systems.

By utilizing the analysis techniques described here in the development of this electric power distribution equipment, Hitachi will be able to meet demands that include combining reliability with good economic performance and reducing the load on the environment.

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Power Generation, Distribution and Substation System for Development of Offshore Wind Farms

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Takashi Matsunobu

OVERVIEW: With use of renewable energy growing worldwide, wind power generation in particular is expected to play a major role, having a comparatively low per-kilowatt cost. While most wind power generation in Japan to date has been land-based, an expansion is anticipated in the development of offshore sites, which offer more reliable and stronger wind conditions. Hitachi has developed a large 5-MW downwind wind power generation system for the construction of offshore wind farms, and supplies total solutions that extend from generation to power delivery, including substation and transmission systems.

INTRODUCTION

RECENT years have seen growing interest in renewable energy in Japan because of its potential to help protect the global environment and provide a domestic source of energy. Prompted by the introduction of feed-in tariffs for renewable energy in July 2012, Japan has seen steady progress on developments in this field, including of wind power generation.

While most of the wind power generation systems currently operating in Japan are land-based, offshore sites are seen as having great potential, with advantages that include stronger wind conditions and being less likely to raise concerns such as noise or impact on the scenery. According to the "Report on FY2010 Study of Potential for Introduction of Renewable Energy"(1) published by the Ministry of the Environment, there is the potential in Japan for the installation of as much as 1,570 GW of offshore wind power. This is roughly eight times the 203.97 GW total installed capacity of Japan's ten power companies in FY2009(2).

While the construction of an offshore wind farm typically requires a greater investment than a land-based site, a large part of this is due to the foundations being larger and more complex than on land, and also due to the offshore installation work and transmission system, including undersea cable. Accordingly, to improve the economics of offshore wind farms, it is better to increase the output per turbine so that the total number of installed turbines can be reduced. This requires wind power generation systems that are larger than the 2- to 3-MW-class turbines that are considered large by land-based standards.

This article gives an overview of a large 5-MW downwind wind power generation system designed for use in offshore wind farms, and describes substation and distribution systems for such wind farms.

LARGE 5-MW OFFSHORE WIND POWER GENERATION SYSTEM

Features of Downwind Wind Power Generation System

Fig. 1 shows the overall dimensions of the large HTW5.0-126 wind power generation system with a rated output of 5 MW that is currently under development. Fig. 2 shows the design power curve and Table 1 lists the main specifications.

Like the existing 2-MW HTW2.0-80 wind power generation system, this new model has a downwind configuration. Most large wind turbines have an

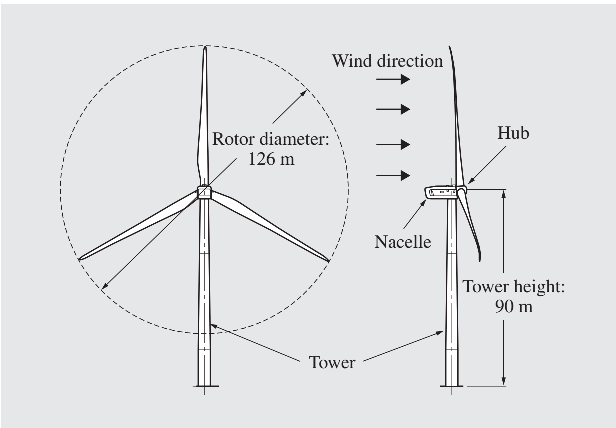

Fig. 1—Overall Dimensions of HTW5.0-126.
The large HTW5.0-126 wind power generation system has a rated capacity of 5 MW.

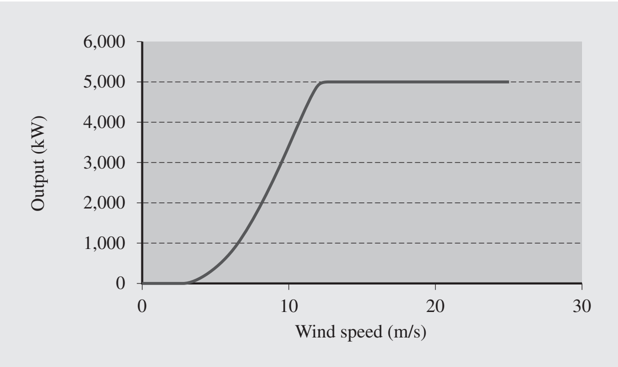

Fig. 2—Design Power Curve.
The design power curve of the HTW5.0-126.

upwind configuration, meaning the rotor is upwind of the tower. However, in situations such as when an outage caused by a grid fault coincides with a sudden change in wind direction, for example, the overturning moment experienced by a downwind turbine is lower because it can immediately switch to free yaw operation in which the nacelle naturally orients itself along the direction of the wind. This should reduce construction costs by simplifying the turbine foundations throughout the wind farm.

Also, wind turbines are fitted with an anemometer for yaw control. Whereas upwind turbines typically mount this anemometer downwind of the rotor, the ability to have the anemometer upwind of the rotor in a downwind turbine minimizes the influence of blade wake turbulence and reduces loss of generation due to yaw error (see Fig. 3).

Another consequence of having the rotor on the downwind side is that, during strong winds, rising wind speeds tend to increase the clearance between the blades and tower. This is a safety advantage because it reduces the risk of the blades coming into contact with the tower, in contrast to an upwind turbine where higher wind speeds reduce the clearance between the blades and tower (see Fig. 4).

Equipment Configuration of Large 5-MW Wind Turbine

Fig. 5 shows the equipment layout in the nacelle of the large 5-MW wind turbine. Large wind turbines typically use variable-speed operation in which the speed of rotation is varied to keep the tip speed ratio (λ) constant with changes in wind speed (see Fig. 6). Because the tip speed ratio for a particular blade shape needs to be kept the same regardless of turbine size, this means that, under the same wind speed conditions, the angular velocity needs to be reduced as the rotor

TABLE 1. Main Specifications
Like the 2-MW HTW2.0-80, the HTW5.0-126 has a downwind configuration.

	HTW5.0-126	**HTW2.0-80 (for reference)**
Rated output	5,000 kW	2,000 kW
Rotor orientation	Downwind	Downwind
Rotor diameter	126 m	80 m
Hub height	90 m	65 m/80 m
Output control	Pitch, variable speed	Pitch, variable speed
Yaw control	Active yaw	Active yaw
Idling in strong winds	Free yaw	Free yaw
Gear ratio	1:40 (approx.)	1:100 (approx.) (50 Hz) 1:120 (approx.) (60 Hz)
Generator	Permanent magnet synchronous generator (36-pole)	Doubly fed induction generator (4-pole)
Cut-in wind speed	4 m/s	4 m/s
Cut-out wind speed	25 m/s	25 m/s
Wind speed class	S (10 m/s mean annual wind speed)	IIA+

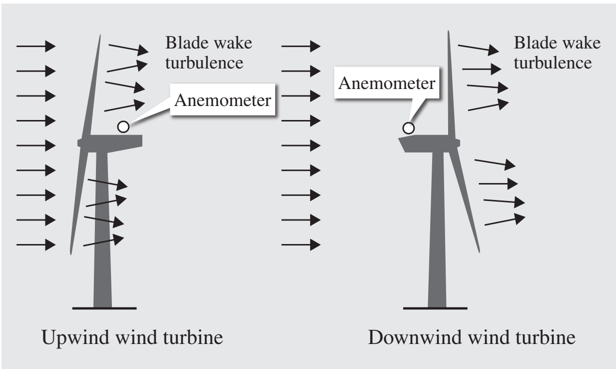

Fig. 3—Location of Anemometer and Relationship with Blade Wake.
Because the anemometer on a downwind wind turbine can be located upwind of the rotor, it suffers less interference due to blade wake turbulence.

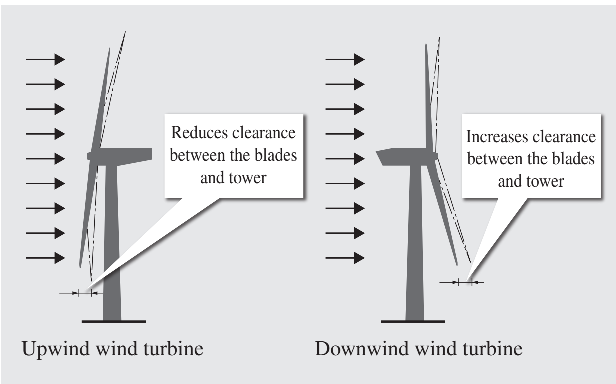

Fig. 4—Clearance between the Blades and Tower during High Winds.
With a downwind configuration, the clearance between the blades and tower increases during high winds, reducing the potential for the blades and tower to come into contact.

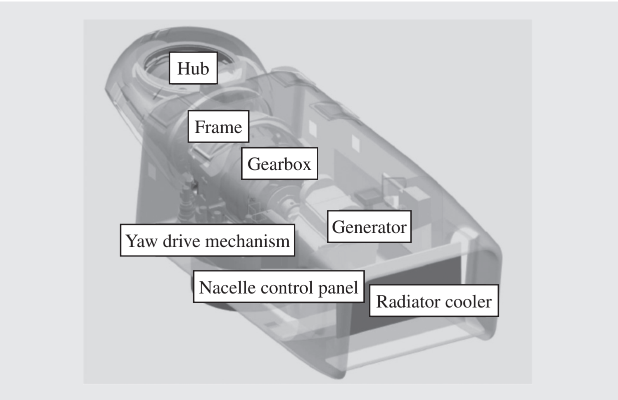

Fig. 5—Equipment Layout in Nacelle.
The equipment inside the large 5-MW wind turbine is laid out as shown.

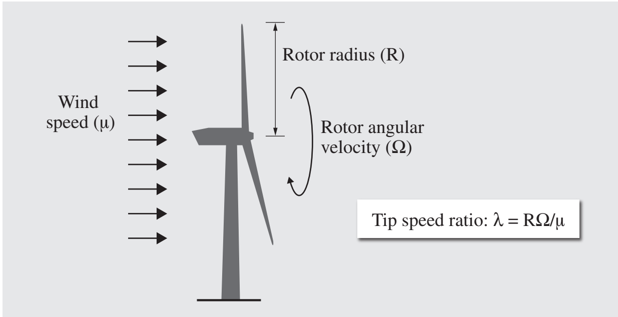

Fig. 6—Wind Turbine Tip Speed Ratio.
Wind turbines typically use variable-speed operation whereby the tip speed ratio (λ) is kept constant as the wind speed varies.

diameter becomes larger[3]. Accordingly, to keep the speed of the input shaft to the generator constant, a higher gear ratio is needed as the rotor diameter becomes larger, increasing the potential for gearbox problems. Hitachi has minimized this potential for gearbox problems by adopting a medium-speed gear drive system that combines a 36-pole permanent magnet synchronous generator with a gearbox that has a gear ratio of no more than about 1:40.

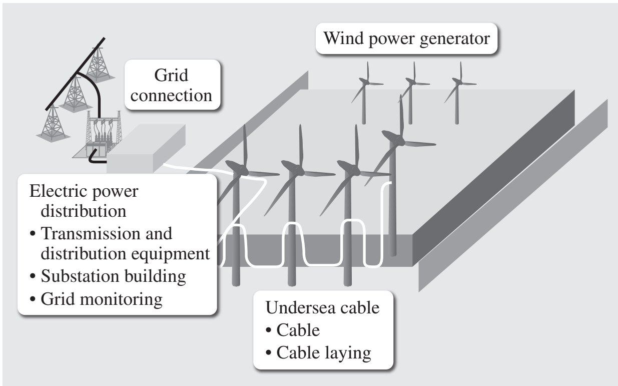

Fig. 7—Overview of Electric Power Distribution Equipment.
The electric power generated by the wind turbines is transmitted to a land-based grid connection substation via array cables and export cables.

ELECTRIC POWER DISTRIBUTION AND SUBSTATION EQUIPMENT

Fig. 7 shows the electric power distribution equipment for linking wind turbines to the existing grid that is intended for use with the 5-MW offshore wind power generation system. The electric power generated by the wind turbine is transmitted to an onshore grid connection substation via a power cable that connects to a number of generators (array cable) and a cable that carries the electric power to land (export cable). At the grid connection substation, a transformer steps up the voltage to the grid voltage and the power is supplied to the grid via a connection point. The following sections describe the substation equipment and undersea cable used by this system.

Substation

Hitachi has many years of multi-faceted experience with ultra-high-voltage switchgear, power system analysis, equipment protection and control, and with static var compensators (SVC), and high-voltage direct current (HVDC) substation equipment. This technology and know-how is available for use in grid connection substations for offshore wind farms. Fig. 8 shows a connection diagram for substation equipment used to connect to the grid. The voltage of the power generated by the wind turbines is stepped up by two transformers and connected to an existing trunk transmission line. As the capacity factor of offshore wind power generators has been estimated at 50% or less[4], a redundant configuration is used so that, if one of the transformers fails, operation can continue using the remaining functional transformer. To improve reliability, an active/backup configuration is also used for the connection to the existing transmission line. In addition to performing grid analyses of voltage fluctuations and other factors for grid connections, detailed protection coordination is also implemented from the grid-side to the wind turbines.

Hitachi is also designing the substation equipment itself to be more compact and place less of a load on the environment. One example is the use of an integrated three-phase bus in 275-kV gas-insulated switchgear (GIS) to reduce both its installation footprint and the amount of sulfur hexafluoride (SF_6) insulating gas used. Also, Hitachi's 33-kV circuit breaker (package GIS) uses a T-shaped cable head. A feature of this

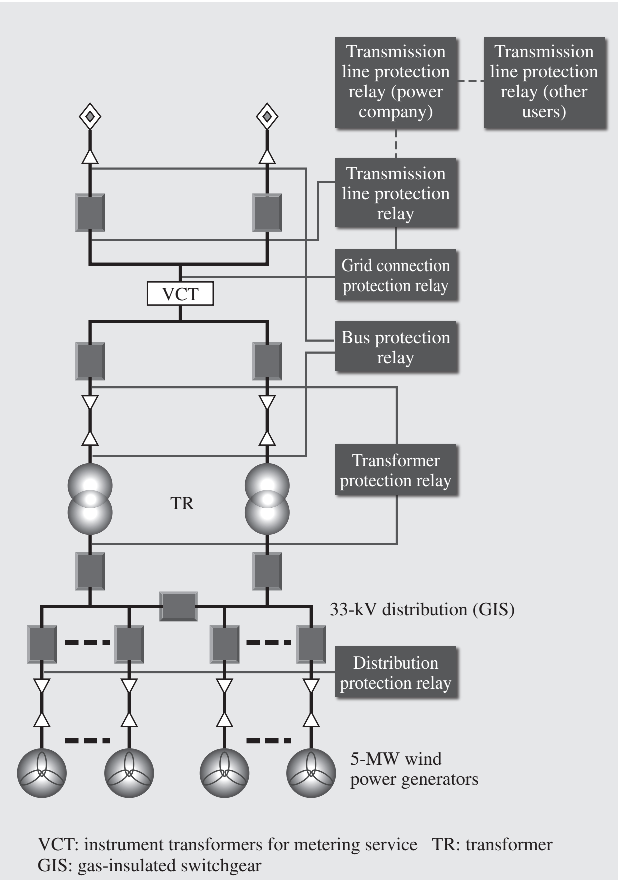

Fig. 8—Connection Diagram for Substation Equipment for Connection to Grid (Overview).
The voltage of the power generated by the wind turbines is stepped up by two transformers and connected to an existing trunk transmission line.

cable head is that it is designed to allow a test voltage to be applied by externally coupling a test lead to the connection terminal provided for this purpose (which is normally sealed off by a plug). That is, it is possible to perform electrical testing of the equipment and the power cable simply by operating an external disconnecting switch, without needing to change any internal wiring. This eliminates the potential for SF_6 gas to escape when making wiring changes.

Undersea Cable

Because of the need to withstand the tension from the cable-laying ship when laying an undersea cable, and to prevent exterior damage due to currents, fishing equipment, or other impediments, it is common to clad cables in a single or double layer of steel armor with a diameter of 6 mm or more. Whether to use one or two layers of steel armor depends on the environment in which the cable will be laid. In most cases, a single layer is used, with a double layer being adopted in only the case of strong currents, deep locations, or rocky or broken seafloor terrain[(5), (6)].

Although cross-linked polyethylene (XLPE), which has low losses, is widely used as cable insulation in Japan, it has problems with long-term exposure to water such as the formation of water trees. Accordingly, a lead sheath or other layer of metal cladding is often used on undersea cables to keep out water.

Despite this use of metal cladding to protect the cable, cases of damage to undersea cables remain common. The International Council on Large Electric Systems (CIGRE) has estimated the annual incidence at 0.7954 incidents per 100 km, the majority of which are due to fouling by fishing equipment, anchors, and so on[(7)]. Because of the potential for repair of a damaged undersea cable, including manufacturing and laying the replacement cable and restoring the link, to take a long time, measures are needed to prevent cable damage from immediately reducing the utilization of offshore wind farms. Hitachi is actively working to offer such measures, which include adopting a cable-laying method that can bury the cable 0.5 m to 1.5 m below the seafloor to prevent fouling by fishing equipment, and designing the system with a loop configuration in which the undersea cable connects together a number of wind power generation systems so that an alternative transmission path will be available in the event of a failure.

Scouring (erosion of seafloor foundations by currents) can occur around the base of wind turbine foundations, with a scouring depth of as much as 2.5 times the diameter of the foundations having been reported[(8)]. This scouring can leave the undersea cable hanging free and, in the worst case, can lead to a cable break. Accordingly, it is desirable that the design of cable-laying near the wind turbine foundations include consideration of how to prevent this scouring.

CONCLUSIONS

This article has given an overview of a large 5-MW offshore wind power generation system with a downwind configuration, and described the substation and distribution systems.

In the future, Hitachi intends to proceed with the full-scale deployment of 5-MW wind turbines through the construction and testing of demonstration systems to verify their performance. Hitachi believes that the technologies described in this article can help expand use of offshore wind power generation and also contribute to the development of a domestic source of energy that takes account of the global environment.

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Core Components for Large-scale PV Generation Systems

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OVERVIEW: Recent years have seen the development and installation of renewable energy systems around the world, with considerable progress having been made on both system performance and cost reduction. Hitachi has been engaged in the development of key technologies for this sector, encompassing inverters for photovoltaic power generation, amorphous transformers, and all aspects of system engineering. The know-how needed to integrate these different elements is an important part of establishing a photovoltaic power generation business. Hitachi's experience includes the development of core components for utilizing renewable energy, and it is drawing on this to operate its business globally.

INTRODUCTION

THROUGHOUT the world, growing use has been made of photovoltaic, wind, and other forms of renewable energy generation in recent years. In Japan, in response to the Act on Special Measures Concerning the Procurement of Renewable Electric Energy Sourced by Electric Utilities passed in August 2011, a rapid expansion has taken place in plans for the installation of large photovoltaic power plants under the feed in tariff (FIT) scheme that started in 2012. Despite a reduction in the price offered by the FIT scheme from 40 yen/kWh (excluding tax) in FY2012 to 36 yen in FY2013, the construction of large power plants is continuing throughout the country.

Meanwhile, construction of photovoltaic power generation systems is also being planned overseas, both in Europe and in sunbelt countries such as those in the Middle East and Asia.

In addition to operating an engineering, procurement, and construction (EPC) business for large photovoltaic power plants in Japan, Hitachi is developing core components that maximize the amount of annual power generation, including highly efficient next-generation power conditioning systems (PCSs) and amorphous transformers with low standby power consumption.

EPC BUSINESS FOR LARGE PHOTOVOLTAIC POWER PLANTS

As a sub contractor to NTT Facilities, Inc. under the Verification of Grid Stabilization with Large-scale PV Power generation systems project of the New Energy and Industrial Technology Development Organization (NEDO), Hitachi has been working on the development of PCSs and of monitoring and measurement systems. The former converts the direct current (DC) from photovoltaic cells into alternating current (AC) and supplies it to the grid, and the latter monitors overall system operation. Hitachi has released heavy-duty PCSs for large photovoltaic power generation systems that it is marketing in Japan and overseas. These PCSs incorporate functions for minimizing voltage fluctuations, maintaining operation through short-duration voltage drops, and the suppression of harmonic currents.

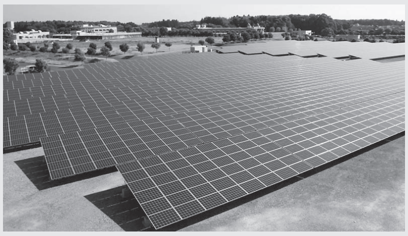
The Ohgishima Solar Power Station, which commenced operation in December 2011, was the largest "megasolar" power plant for commercial power generation in Japan at that time. It has a maximum output of 13 MW and delivers an estimated annual reduction in carbon dioxide (CO_2) emissions of about 5,800 t.

Also, a 1-MW photovoltaic power plant commenced operation in July 2011 for the Ibaraki Prefectural Public Enterprise Bureau. This plant was installed to reduce demand during peak summer hours (peak cutting) in response to the need to save power due to the shortage of power generation capacity in the region covered by Tokyo Electric Power Company, Incorporated (TEPCO) since the Great East Japan Earthquake in March 2011. Hitachi acted as an EPC supplier for this project, providing a complete package that extended from equipment design to manufacturing, site preparation, installation, and commissioning.

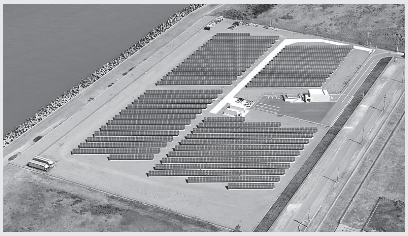
The system incorporates the following features to maximize power generation, and the system configuration is designed for generation efficiency and reliability.

(1) Lightweight mountings achieved through optimal design

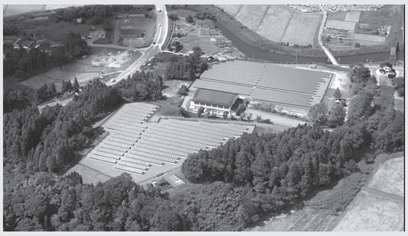
Power plant of SGET Ashikita Mega Solar LLC (output: 8 MW)



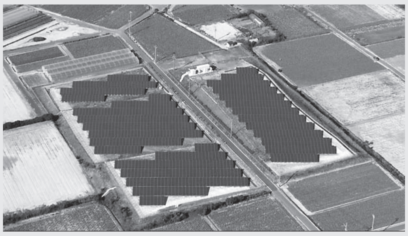
Central District Waterworks Office of the Ibaraki Prefectural Public Enterprise Bureau (output: 1 MW)



Mikuni Photovoltaic Power Station, Hokuriku Electric Power Company (output: 1 MW)



Suzu Photovoltaic Power Station, Hokuriku Electric Power Company (output: 1 MW)



Solar Farm Toyohashi, C-TECH Corporation (output: 1 MW)

Megasolar power plant of Oita Solar Power Co., Ltd. (output: 82 MW)

Fig. 1—Large Photovoltaic Power Generation Systems.
In addition to undertaking large photovoltaic power generation projects under EPC contracts, Hitachi also supplies core components that include highly efficient next-generation PCSs and amorphous transformers with low standby power consumption.

(2) PCSs with high conversion efficiency even at low output levels
(3) Use of modular construction for quick installation
(4) Low standby power consumption due to use of amorphous transformers

Drawing on this development experience, operation has commenced at the Mikuni and Suzu photovoltaic power stations of Hokuriku Electric Power Company, the Solar Farm Toyohashi of Ctec Corporation, and the Ashikita Megasolar plant operated primarily by SGET Ashikita Megasolar LLC, a public-private infrastructure fund run by Tokyo Metropolitan Government. When planned plants are included, plants with a total capacity of several hundred megawatts are in the pipeline (see Fig. 1).

The megasolar power generation system for Oita Solar Power Co., Ltd. will be the largest such system ordered from a supplier in Japan. The plant is to be operated by Oita Solar Power Co., Ltd. and is being constructed in Oita City, Oita Prefecture in readiness for operation to commence in spring 2014. The plant covers 105 ha and has a capacity of 82 MW. Annual power production is estimated at 87,000 MWh, roughly equivalent to the electric power needs of 30,000 homes. If all of the panels were laid out in a line, they would extend for about 500 km, similar to the distance from Tokyo to Osaka.

The system will reduce CO_2 emissions by about 36,000 t annually. The site also features a layout that takes account of the surrounding natural environment.

These generation systems use highly efficient PCSs (capacity: 500 kW, maximum DC input voltage: 660 V, maximum conversion efficiency: 98.0%) to increase generation efficiency significantly across a wide range of load conditions, from sunny to cloudy days. By utilizing amorphous transformers with high efficiency under low load, the system is designed to increase the amount of power generated under weather conditions in Japan.

Since FY2013, Hitachi has been building power plants that use highly efficient PCSs. Described later in this article, these PCSs have a maximum DC input voltage of 1,000 V and a maximum conversion efficiency of 98.8%.

Hitachi coordinates all aspects of highly reliable megasolar power generation systems that feature the highest levels of efficiency available in Japan. This extensive support includes manufacturing the PCSs and other core components used in megasolar power generation systems, providing assistance with gaining the necessary permits prior to construction, construction work from design and fabrication through to commissioning, and a remote monitoring service after the plant enters service.

DEPLOYMENT OF MEDIUM-SIZED PHOTOVOLTAIC POWER GENERATION SYSTEMS

The period since the introduction of the FIT scheme in 2012 has seen a stream of new entrants to the photovoltaic power generation business from many different industries, together with considerable activity in the construction on unused land of medium-sized photovoltaic power generation systems in the 1-MW to 2 MW range. In response to this new demand, Hitachi has developed its photovoltaic power generation system packages, which provide the key equipment needed for power generation, and which are designed to maximize annual power generation.

Because photovoltaic power generation operates under constantly changing conditions (including the weather), with good power output only possible on a small number of days each year, it is important to consider how to increase total annual production efficiently to allow sale of electric power. This package not only reduces the work associated with equipment selection during system configuration, it is also designed to allow the trouble-free construction of systems with a variety of desirable features, including highly efficient operation and low standby power consumption.

Specifically, the standard configuration, which includes photovoltaic panels, PCS, amorphous transformer, and switchgear, is available in 1-MW and 2-MW models. These have panel capacities of 1.3 MW and 2.6 MW, respectively. Based on the relation between sunlight levels and annual power generation, the systems are designed to maximize power generation under conditions in Japan, making maximum use of operating ranges in which the PCS and amorphous transformer are most efficient.

PCS

A PCS is an inverter that converts the DC power generated by the photovoltaic panels to AC power and supplies it to the grid. A characteristic of photovoltaic panels is that their output current varies depending on factors such as the incident sunlight and terminal voltage. These same factors also cause the output power (the product of the terminal voltage and current) to vary. To improve generation efficiency, the PCS includes a maximum power point tracking (MPPT) function that adjusts the voltage across the photovoltaic panel terminals to maximize the output power for different levels of sunlight (see Fig. 2).

In addition to these functions, the heavy-duty PCSs used by megasolar power generation systems also require grid stabilization functions. Through work that includes the NEDO research project referred to earlier, Hitachi has developed and commercialized a number of

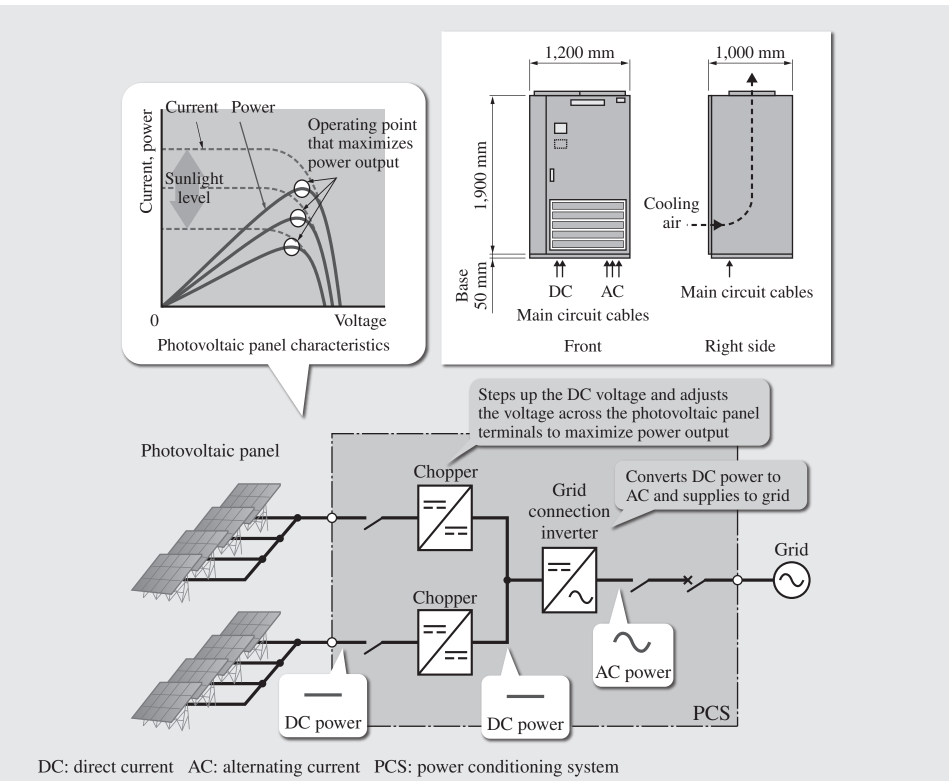


Fig. 2—PCS for Photovoltaic Power Generation Systems.
The PCS adjusts to the sunlight conditions to perform efficient conversion of the DC power generated by the photovoltaic panels to AC power.

such functions, including those for minimizing voltage fluctuations, maintaining operation through short-duration voltage drops, and suppressing harmonics.

Hitachi initially supplied PCSs in Japan and overseas that used two-level pulse-width modulation (PWM) inverters and achieved small size and high efficiency through features that included a transformer-less configuration and high output voltage (400 V). Hitachi then went on to develop and commercialize PCSs designed for even greater efficiency, and is currently releasing a new high-efficiency model with a maximum DC input voltage of 1,000 V to complement the previous model, which has a maximum input voltage of 660 V.

Use of Three-level PWM Inverter

Conventionally, three-level PWM inverters have only been used in applications that require the suppression of harmonics or a higher converter voltage, such as in railway rolling stock and large motor drives. However, insulated-gate bipolar transistor (IGBT) modules for three-level inverters in the 600- to 1,200-V class have become commercially available in recent years, thereby allowing three-level inverters to be implemented without requiring a significant increase in the component count. Accordingly, Hitachi has gone ahead with the commercialization of next-generation PCSs that use three-level PWM inverters to improve conversion efficiency further.

The anticipated benefits of using three-level PWM inverters include lower switching loss, the ability to use smaller and lighter filter reactors with lower losses, less high-frequency electrical noise, and quieter operation. These lower losses are expected to make a major contribution to increasing annual power output (see Fig. 3).

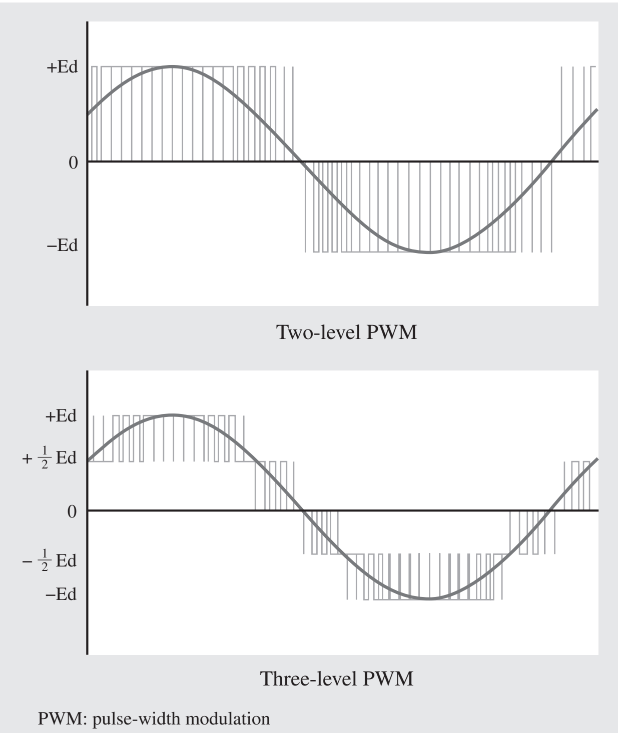


Fig. 3—Comparison of Two-level and Three-level PWM.
Compared to two-level PWM, the three-level PWM waveform is closer to a sine wave and therefore allows use of a smaller AC filter.

Features of HIVERTER NP203i (500-kW)

The HIVERTER NP203i combines a transformer-less, three-level PWM inverter with a step-up chopper input circuit that enables MPPT control to be performed over a wide range of voltages (DC230 V to 600 V). It features enhanced conversion efficiency in the DC400 V to 500 V range. The step-up chopper consists of two circuits, each of which has an input capacity of 250 kW and supports MPPT operation (see Fig. 4 and Table 1).

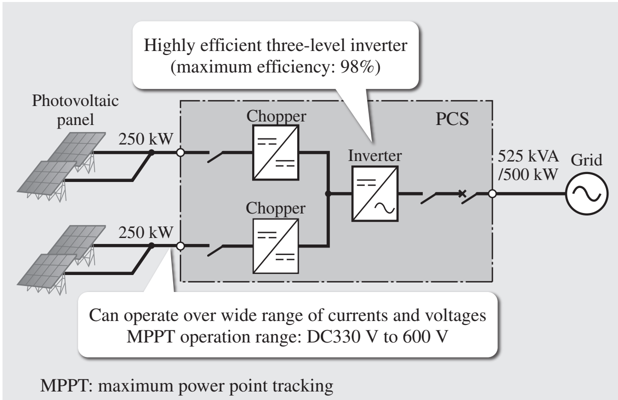


Fig. 4—Single-line Wiring Connection Drawing for PCS (HIVERTER NP203i).
The HIVERTER NP203i has a step-up chopper input circuit to perform MPPT control over a wide range of voltages.

TABLE 1. HIVERTER NP203i Specifications
The table lists the main HIVERTER NP203i specifications.

Parameter	Specification
Maximum output	500 kW/525 kVA
Maximum DC input voltage	660 V
Operating DC voltage range	DC 230 V – 600 V
Rated AC output voltage	AC 420V/440V (±10%)
Rated frequency	50/60 Hz (±6%)
Conversion efficiency	98% (max.) (DC 500 V, AC 420 V, PF = 1.0)
Dimensions (mm)	1,200 (W) × 1,000 (D) × 1,900 (H)
Weight	1,350 kg

PF: power factor

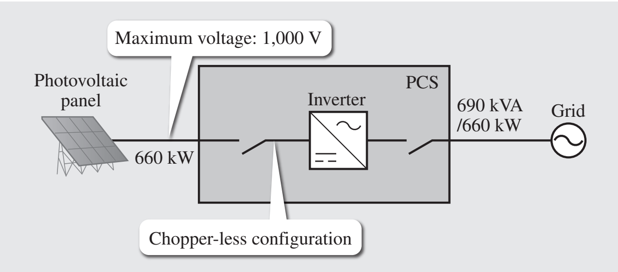


Fig. 5—Single-line Wiring Connection Drawing for PCS (HIVERTER NP213i).
The HIVERTER NP213i has a maximum DC input voltage of 1,000 V and achieves maximum conversion efficiency of 98.8%.

Features of HIVERTER NP213i (660 kW)

Based on the 550-kW HIVERTER NP201i intended for the global market, the HIVERTER NP213i is designed for higher output. It features a chopper-less design and a three-level PWM inverter with a maximum input voltage of 1,000 V (see Fig. 5) to deliver a maximum conversion efficiency of 98.8%, giving it world-leading performance for a PCS in its class*. It is designed for small size and light weight, with efficiency characteristics that ensure high efficiency across the entire operating range (see Fig. 6 and Table 2).

Outdoor PCS Package

The HIVERTER NP203i/NP213i product range includes outdoor packages suitable for large photovoltaic power plants (see Fig. 7). The ability to deliver the outdoor package to an installation site with two or three PCSs already fitted helps shorten installation time because it means that on-site setup work can be performed efficiently. The outdoor package isolates the PCSs from the external atmosphere and ensures that the PCSs operate reliably by using multiple air conditioning units to perform efficient internal cooling.

HITACHI'S SOLUTION BUSINESS

Large photovoltaic power generation projects require the plant operator to overcome a wide range of challenges, including not only equipment selection and design, but also permit procedures, power company grid connections, and operation and maintenance. In addition to the know-how it has built up in large photovoltaic power generation systems, Hitachi can also call on the comprehensive capabilities of the Hitachi Group to supply everything needed for these large systems to local governments or companies that are considering the construction of such projects on unused or under-used land.

Specifically, in addition to the selection and supply of the key equipment used in large photovoltaic power generation systems, including the photovoltaic panels and also ancillary systems such as highly efficient PCSs, transformer and distribution systems, and

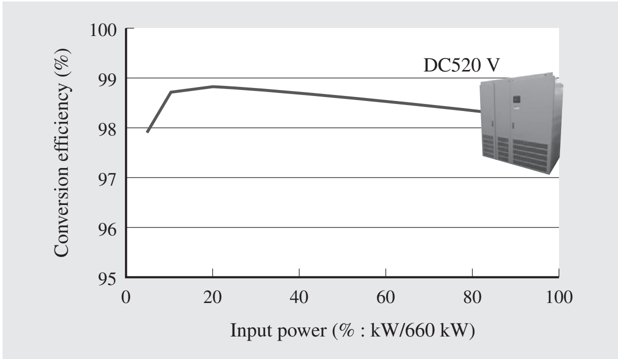


Fig. 6—PCS Conversion Efficiency Characteristics (HIVERTER NP213i).
The PCS helps maximize power production by delivering high conversion efficiency across the typical operating range for photovoltaic power generation.

TABLE 2. HIVERTER NP213i Specifications
The table lists the main HIVERTER NP213i specifications.

Parameter	Specification
Maximum output	660 kW/690 kVA
Maximum DC input voltage	1,000 V
Operating DC voltage range	DC 520 V – 900 V
Rated AC output voltage	AC 360V (±10%)
Rated frequency	50/60 Hz (±6%)
Conversion efficiency	98.8% (max.) (DC 520 V, AC 360 V, PF = 1.0)
Dimensions (mm)	1,400 (W) × 1,000 (D) × 1,900 (H)
Weight	1,400 kg

Fig. 7—PCS Outdoor Package.
The outdoor package can be fitted with up to three PCSs. Reliable long-term operation is facilitated by efficient cooling of the interior, which is isolated from the external atmosphere.

* PCSs for large photovoltaic power generation systems in the 500-kW class. Based on Hitachi research as of October 2012.

remote monitoring systems, Hitachi can also handle permit procedures, power company grid connections, and also 20-year operation and maintenance plans arranged in conjunction with Hitachi Capital Corporation or other organizations.

Hitachi is also constructing a 1.8-MW photovoltaic power generation system on approximately 2 ha of land it owns in Hitachi City, Ibaraki Prefecture. By constructing and operating its own large system, Hitachi aims both to improve equipment quality and reliability and also to enhance its ability to assess business viability.

To achieve a major boost in generation efficiency over a wide range of sunlight levels (sunny and cloudy days), the system configuration will include a highly efficient PCS that went on sale in FY2013 (maximum voltage: 1,000 V, rated capacity: 660 kW, conversion efficiency: 98.8%) and an amorphous transformer with high efficiency at low load. Hitachi intends to sell all of the electric power generated by the system under the renewable energy FIT scheme. Work started in August 2013, and the plant is scheduled to commence generation in April 2014.

Hitachi has received turnkey orders (EPC contracts) for a considerable number of large photovoltaic power generation systems, including the large 82-MW photovoltaic power generation system for Oita Solar Power Co., Ltd. and the Ohgishima Solar Power Station (output: 13 MW) for Tokyo Electric Power Co., Inc. Hitachi's extensive experience also includes the supply of Megakits; ancillary equipment, particularly highly efficient PCSs, that contribute to cost savings; and remote monitoring systems.

CONCLUSIONS

This article has described Hitachi's involvement and experience with large photovoltaic power generation projects along with PCSs and other core components. Through the comprehensive use of these core components and other technologies in the renewable energy sector, and by working in collaboration with overseas production and engineering facilities, Hitachi believes it can supply solutions that suit regional needs, including for regions outside Japan.

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An Anomaly Detection System for Advanced Maintenance Services

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Hideaki Suzuki

OVERVIEW: Combining maintenance service expertise with data mining technology, Hitachi has developed an anomaly detection system to make appropriate diagnoses in accordance with equipment status changes. The system enables automation of equipment status diagnoses that previously required engineers with specialist knowledge. The system's highly accurate anomaly detection helps prevent losses from unexpected production facility shutdowns, and improves availability. Carrying out maintenance appropriately in line with equipment status can also lower the time and cost of maintenance management. Expanding the scope of application of the system is expected to enable advanced maintenance services.

INTRODUCTION

NOW that recent advances in information and communication technology (ICT) are making it easy to collect and store massive amounts of operation records data and sensor data, such log data are being saved for a large number of devices and systems. But in many cases, the saved electronic data are not being used effectively. The large volume of saved data (big data) contains various types of information about the devices and systems that the data came from. Effective use of this data can provide advance knowledge of device status changes and problems, and create highly reliable operation.

Seeking to enable more advanced maintenance services, Hitachi Power Solutions Co., Ltd. has developed the anomaly detection system, a system designed to provide advance knowledge of changes to abnormal hardware statuses by using data mining technology to extract significant information from among big data.

This article provides an example of how this big-data-driven anomaly detection system was applied to compact gas engine generators (see Fig. 1), and discusses future applications of the system.

ANOMALY DETECTION SYSTEM FUNCTIONS

The developed anomaly detection system automatically gathers data from dozens of sensors for parameters such as temperature, pressure, and engine speed. It stores the data in a database, then automatically executes a diagnosis process using two functions—a remote monitoring function and a data mining function. The diagnosis result can be communicated to maintenance service personnel using a list screen of color-coded statuses for each piece of equipment (see Fig. 2).

The remote monitoring function is a physically based diagnosis function that detects status changes after upper/lower threshold values and rate-of-change evaluation criteria for each sensor signal gathered from the equipment have been set from operator experience and knowledge. Evaluations are made by setting an abnormal detection threshold value for each sensor. Each sensor signal has a single evaluation threshold value and vice versa, making it easy to explain generated errors and failures, but making it difficult to detect status changes involving multiple sensor signals. When there are seasonal variations or differences in equipment installation environments, separate settings are also needed for each of the changing conditions. When there are many different failure types, each will

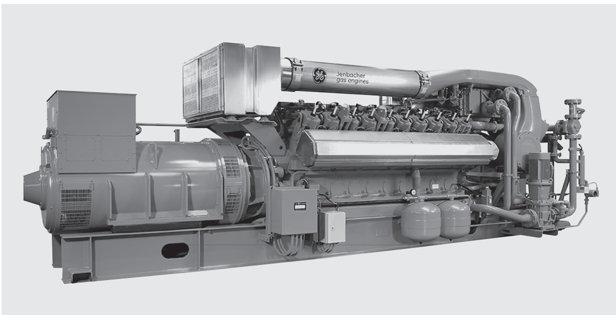

Fig. 1—Compact Gas Engine Generator.
A type of generator used in facilities such as offices, hospitals, and shopping malls, with a generation output of 300 to 2,400 kW.

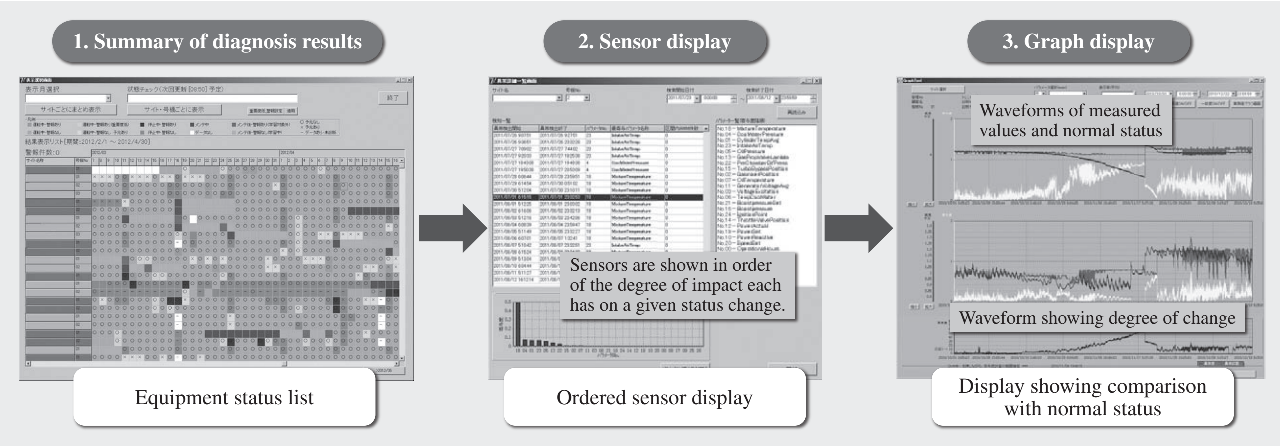

Fig. 2—Checking Status from Diagnosis Result Display.
Color-code displays show various equipment statuses giving the user a visual representation of them.

have a different occurrence frequency, so it may not always be possible to determine the optimum setting value. Another difficulty is that even among failures of the same type, the process leading to the failure or the cause of the failure might be different in each case, making it impossible to determine a single setting value for each failure type.

The data mining function is an example-based diagnosis function that is trained with normal-status data to learn statistical reference points. It detects equipment status changes on the basis of the distance between the measurement point in the statistical data space, and the reference point. The data mining function has higher sensitivity than the remote monitoring function, so could enable early detection of status changes. But a drawback of conventional data mining functions is that causes are difficult to explain when diagnosis results are derived from complex sensor signal correlations. This system has been designed to assist status monitoring and cause analysis by outputting an ordered list of the sensor signals responsible for a detected status change.

Configuration Overview

The anomaly detection system consists of a data gathering unit that receives sensor signal data from the equipment (a pre-existing data gathering mechanism can be used if present), a data storage unit that stores the gathered data, a diagnosis process unit that analyzes the stored data, and a display unit that outputs the analysis result (see Fig. 3).

Since the equipment in this example did not necessarily require a large computer system, the entire system was constructed using a computer to handle all three functions (data gathering, diagnosis, and storage).

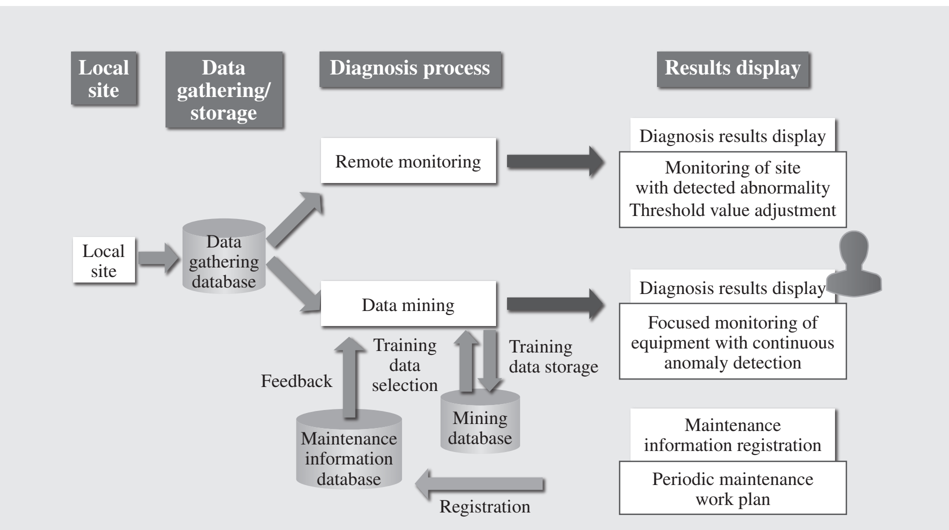

Fig. 3—Anomaly Detection System.
The anomaly detection system gathers and stores data, executes diagnosis processes, and displays the results. It enables early discovery of status changes, assisting inference of causes.

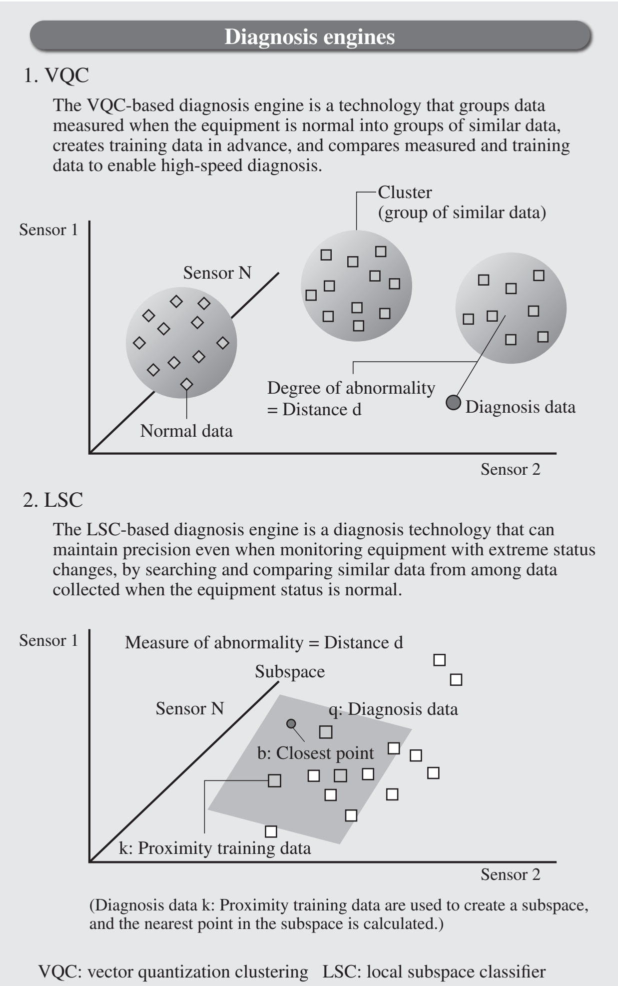

Fig. 4—Data Mining Algorithms.
Equipment operation statuses and sensor signal movements are used to select the optimum diagnosis algorithm, and mount it in the system.

Diagnosis Engines (Algorithms)

Two data mining technologies are used as anomaly detection algorithms—vector quantization clustering (VQC), and local subspace classifier (LSC) (see Fig. 4). Both of these diagnosis engines perform machine learning on normal-status sensor data, create indicators of differences between the data to be monitored and the learned normal data group, and evaluate whether the result is normal (same as the normal data) or abnormal (different from the normal data).

Since the developed diagnosis engines are non-parametric methods, they are resistant to statistical restrictions on sensor data. Methods such as the Mahalanobis-Taguchi (MT) system can only be applied when sensor data has a normal distribution, but the developed diagnosis engines are resistant to being affected by the data distribution. Since the algorithms are model-free, they can respond flexibly without the need for modelconstruction or simulations for each status change, even when there is a major change in a device or system operation status.

The optimum system configuration can be created by using each diagnosis engine separately according to the device or system to be monitored, or to the characteristics of the abnormality to be detected.

SYSTEM EVALUATION AND OPERATION

The Onuma Works of Hitachi Power Solutions (located in Hitachi, Ibaraki prefecture) performs remote monitoring of compact gas engine generators throughout Japan. We evaluated the system by applying it experimentally to about 100 of these monitored generators to verify its effectiveness. We have now increased the number of generators to 120, and perform daily diagnoses of about 30 different sensor signals measured in 30-second cycles. Here we describe an example anomaly that was actually detected by the data mining function (see Fig. 5).

This example is an anomaly that the system started to detect on October 11, and which subsequently continued to increase in degree of abnormality. The abnormality detection interval sensor signal was analyzed. As shown in Fig. 5, the result indicated that Sensor X contributed the most to the abnormality, and the anomaly detection system detected a drop in its measured value. The progress of the abnormality in the equipment was subsequently monitored, and parts were replaced on October 22. A pattern of decreasing Sensor X values led to the estimate that without this corrective action, the equipment would have experienced a trip (sudden shutdown) after about three

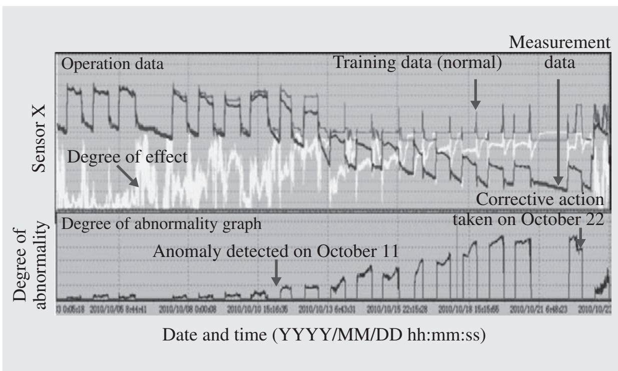

Fig. 5—Anomaly Detection Example.
When monitoring many equipment items, manually checking each output from every sensor is very difficult. The anomaly detection system can automatically diagnose device statuses that are different from the normal data, and notify the monitoring operator of the sensors responsible.

days, and an evaluation by experts also concluded that the system succeeded in detecting the anomaly about 10 days in advance.

Before the anomaly detection system, problems were handled by after-the-fact maintenance once failures had occurred. This approach requires time to coordinate the schedules of the field engineers dispatched to the site and time to allocate replacement parts, leading to adverse effects on equipment availability factors.

Since the use of the anomaly detection system enables steady monitoring of equipment anomaly detection results, the approach to compact gas engine generator maintenance service has now radically changed. Specifically, system diagnosis results are checked daily and also subjected to expert evaluations. The need for maintenance and its appropriate timing are then studied. While not completely comprehensive, this approach enables condition-based maintenance (CBM) in accordance with equipment status before failures occur and enables appropriate allocation of replacement parts (see Fig. 6). Since the system also provides visualization of equipment statuses, it has changed the awareness among maintenance service personnel, and data gathered daily are being used effectively.

ANOMALY DETECTION SYSTEM APPLICATIONS

The anomaly detection system uses sensor data to monitor (visualize) the daily operation statuses of devices and systems, and determines whether each is normal (the same as the normal data) or abnormal (different from the normal data) on the basis of abnormality measurement indicators. It can therefore be used to solve various problems (see Fig. 7).

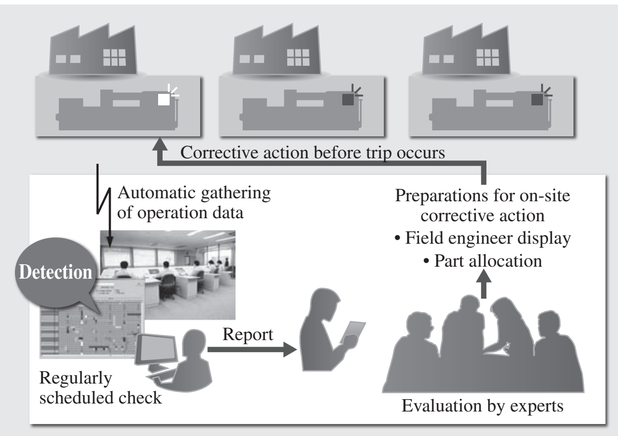

Fig. 6—Operation of Anomaly Detection System.
By checking anomaly detection system results daily, after-the-fact corrective actions can be replaced with advance corrective actions.

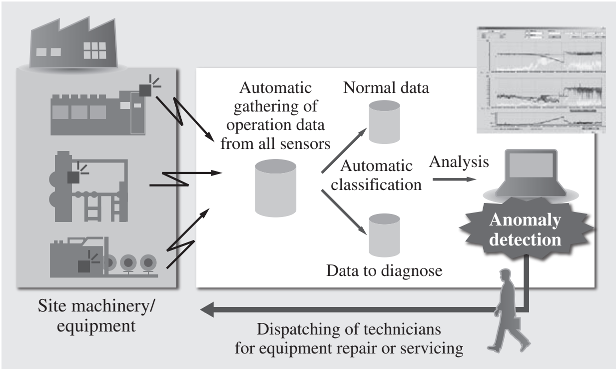

Fig. 7—Avoiding Unplanned Shutdowns of Important Equipment.
Data gathered and analyzed daily can be used to identify statuses that are 'different from always' and take corrective action without waiting for periodic maintenance.

(1) Problems encountered in preventing unplanned shutdowns

(a) The user has signed a maintenance agreement and makes efforts to maintain equipment. Maintenance is done periodically, but the user does not know whether the maintenance cycle and replacement parts are appropriate.

(b) The user puts time and effort into coordinating production and carries out periodic maintenance, but has overlooked failures and coordination errors, and sudden shutdowns have occurred directly after maintenance.

(c) When the user spots failures early on, repairs are just quick-fix part replacements.

(d) The user is unaware of equipment statuses, so daily operations are done with the anxiety of not knowing when a shutdown could occur.

(2) Problems encountered in using gathered data effectively

(a). The user gathers operation data and sensor data for important equipment items, but feels reassured just by gathering the data, and doesn't use it.

(b) The user does not know how to analyze data.

(c) Data are analyzed manually, imposing a large burden on workers.

(d) Data are used for cause analysis when accidents occur but not for preventive maintenance.

(3) Problems encountered in transferring skills and assuring quality

(a) The user relies on highly experienced veteran operators for equipment inspections and failure detection, and skills are not passed on to others.

(b) The user is forced to rely on individual ability for evaluating abnormalities.

(c) Only specific equipment items can receive abnormality evaluations.

(d) The user starts production without noticing that incorrect parameters or conditions have been entered, and produces a large volume of inferior products.

(e) Inferior products are generated even when the production process is the same.

The anomaly detection system greatly helps to solve these problems, and by storing information gathered during maintenance (type of sensor indicating an abnormality, failure cause, replacement part, corrective action) in a maintenance information database, it can provide guidance on the action required (hypothesized cause, possible replacement parts, corrective action) when a previously encountered anomaly is detected. These benefits improve maintenance work efficiency. They should also enable further use of data mining (effective data extraction) to acquire information needed for applications such as optimum part ordering and inventory management driven by replacement-based consumable part management, and needed for repairs and improvements done by identifying frequent failure locations and parts.

CONCLUSIONS

This article has presented an example of how a big-data-driven anomaly detection system was applied to compact gas engine generators, and discussed how its range of applications could be expanded in future.

In future, this system will be used with advanced maintenance technology to grow the O&M (operation and maintenance) service business. The anomaly detection system could also be used to create advanced maintenance services spanning a wide range of areas.

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Development of New Technology for Fukushima Daiichi Nuclear Power Station Reconstruction

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OVERVIEW: Since the accident at Fukushima Daiichi Nuclear Power Station of the Tokyo Electric Power Co., Inc., remediation work at Fukushima has needed to deal with high radiation environments and has demanded new techniques. This requires the development of remote-controlled robots along with radiation measurement, water treatment, and other technologies, as well as ways of utilizing these technologies in tandem. It is also necessary to conduct a site survey (including radiation measurement, visual assessment, and the identification of access routes), formulate a cleanup plan for decontamination and the removal of rubble, and to use remote-controlled equipment for performing essential tasks. Similar enhancements are also needed for treating the contaminated water produced by reactor cooling (removing the radioactive material).

INTRODUCTION

IN addition to work on instruments for measuring radioactivity and remote-controlled robots for conducting surveys and taking measurements in a highly radioactive environment, work is currently in progress on the use of robots to remove rubble at the Fukushima Daiichi Nuclear Power Station of the Tokyo Electric Power Co., Inc. Various systems and robots are also seen as necessary, to support the planning of decontamination based on measurement data, and to perform decontamination work to clean up the site.

In response to these disaster site requirements, Hitachi has developed radiation detection techniques; a remote-controlled decontamination system; a remote monitoring robot system that uses wireless communications; and the small double-arm, heavy-duty robot. Hitachi is also working on developments that will enable work at the disaster site to proceed from site surveys to rubble removal and cleanup. Meanwhile, other developments that will contribute to the cleanup involve the treatment of contaminated water produced by reactor cooling.

This article describes technologies that have been developed and applied to date for radiation measurement, decontamination, remote-controlled robots, and the treatment of contaminated water.

DEVELOPMENT OF RADIATION DETECTION TECHNIQUES

The accident at the Fukushima Daiichi Nuclear Power Station has left walls, floors, ceilings, and other parts of the reactor buildings in particular contaminated with radioactive materials. For decommissioning work to proceed smoothly, these contaminated sites need to be cleaned up. Decontamination consists of five main steps: (1) Radiation measurement to assess contamination, (2) Decontamination plan, (3) Decontamination, (4) Verification, and (5) Transportation and storage of radioactive waste. To provide the radiation detectors required for decontamination to proceed efficiently and effectively, Hitachi has developed a gamma camera that provides a broad visualization of contamination, and a plastic scintillation fiber (PSF) that provides an ambient dose distribution along the fiber. It has also developed, a radiation field mapping software that helps in a decontamination plan by using the large amounts of radiation data obtained by the detectors.

Development of Radiation Detection Techniques

Gamma Camera[1]

Fig. 1 shows the vehicle-mounted gamma camera. To allow measurements to be made in the highly radioactive environments inside the reactor buildings, Hitachi has made the gamma camera better than previous cameras at minimizing radiation background effects (through better shielding of the camera body and the addition of a shutter mechanism), and has added a remote control function for taking measurements remotely and a tilt function to better assess contamination inside the building.

Gamma camera images were taken at about five locations in each of reactor buildings 1 to 3. The

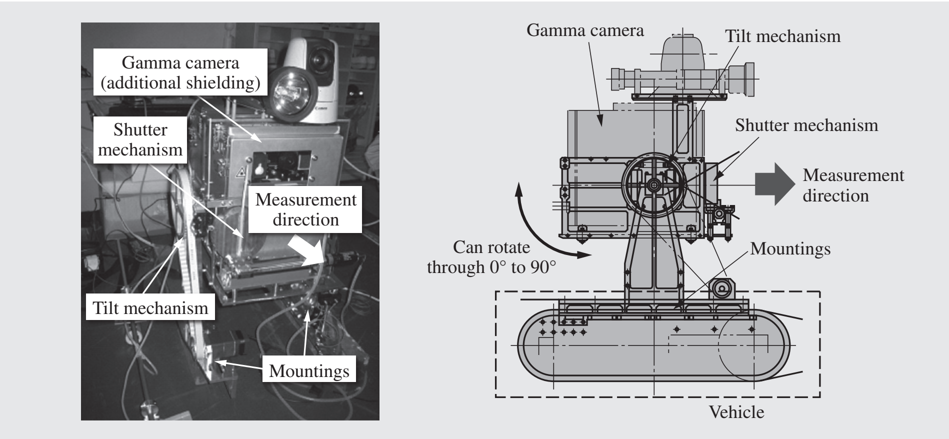


Fig. 1—Vehicle-mounted Gamma Camera.
The system consists of the gamma camera itself together with a tilt mechanism, shutter mechanism, and mounting. The tilt mechanism allows measurements to be performed up to a vertical angle of 90°, and the shutter mechanism improves accuracy.

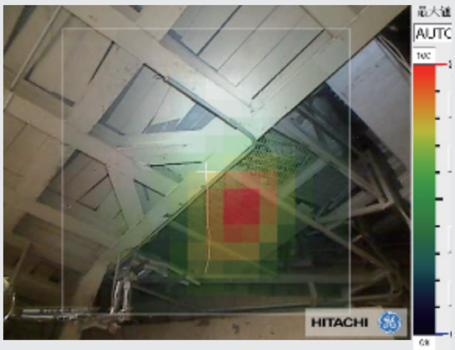
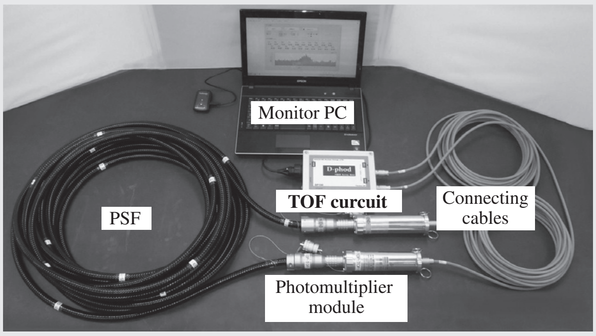


Fig. 2—Image Taken Using Gamma Camera.
This image of the exterior of the containment vessel in reactor building 3 was taken from the heavy equipment access door. It shows the location of hot spots (ports in the containment vessel).



PC: personal computer PSF: plastic scintillation fiber TOF: time of fight

Fig. 3—PSF System.
The PSF system consists of the PSF, photomultiplier module, TOF circuit, personal computer (PC) for displaying results, and connecting cables. It can be used outdoors and in the absence of an external power supply.

ambient dose equivalent rates at the image locations were in the range 10 mSv/h to 100 mSv/h. As shown in the Fig. 2 example, hot spots could be detected from all of these locations.

PSF system(2)

Fig. 3 shows the PSF system for measuring ambient dose equivalent rates using a time of flight (TOF) technique. A characteristic of the system is that the radiation distribution along the fiber can be obtained in roughly the same time and with the same accuracy as a scintillation survey meter. The system consists of the PSF, photomultiplier module, TOF circuit, personal computer (PC) for displaying results, and connecting cables. It is designed to be more sensitive, smaller, lighter, and more robust than previous models, and it can be used in the absence of an external power supply.

The system was used to measure dose equivalent rates at a total of 31 locations in the building surroundings, car park, and grounds in an area of roughly 80 × 60 m. The displayed radiation map provides a clear indication of the contaminated areas (see Fig. 4).

Fig. 4—Measurement of Dose Equivalent Rate Using PSF system.
The data measured by the PSF system is displayed on a digital map to provide an accurate indication of the contaminated areas and to facilitate efficient and effective decontamination.

Hitachi has made improvements to allow its use where radiation levels are high, and also has plans to adapt it to the measurement of dose equivalent rates on the surfaces of walls, floors, and ceilings in the reactor buildings.

Software for Preparing Decontamination Plans(3)

Hitachi has developed a computer system for producing maps of dose equivalent rate distribution. To do this, it is able to rapidly calculate the dose equivalent rate at any point in space by using data on the attenuation of radiation by air or concrete pre-determined using three-dimensional Monte Carlo N-Particle Transport Code 5 (MCNP5); measured dose equivalent rates for wall, floors, ceilings, and other surfaces; and data on hot spots identified by the gamma camera. Its most important feature is the ability to estimate the reduction effect in ambient dose equivalent rate that will be achieved by measures such as decontamination or shielding.

Fig. 5(a) shows a dose equivalent rate map produced by the above system for the reactor 3 building at Fukushima Daiichi Nuclear Power Station. Fig. 5(b) shows the dose equivalent rate distribution after decontamination of walls and floors and the installation of shielding at specific locations. This provides an easy way to assess the extent of contamination and predict how well decontamination will work, allowing a decontamination plan to be formulated that will achieve the target dose equivalent rate.

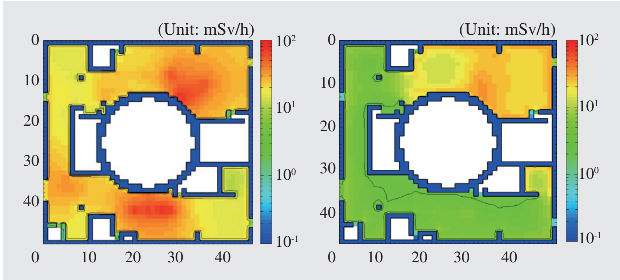


Fig. 5—(a) Indoor Dose Equivalent Rate Distribution Produced by Software for Preparing Decontamination Plans, (b) Prediction of Decontamination Effectiveness.
Using actual radiation level measurements as its input, the software can calculate the ambient dose equivalent rate for any specified location and produce a map of radiation level distribution.

DEVELOPMENT OF DECONTAMINATION TECHNIQUES

In response to the need to reduce exposure of the workforce while decontaminating the site of a nuclear accident, Hitachi has developed a remote-controlled decontamination system.

Overview of Remote-controlled Decontamination System(4)

The remotely operated system uses high-pressure water to clean up various different forms of contamination from the interior of reactor buildings.

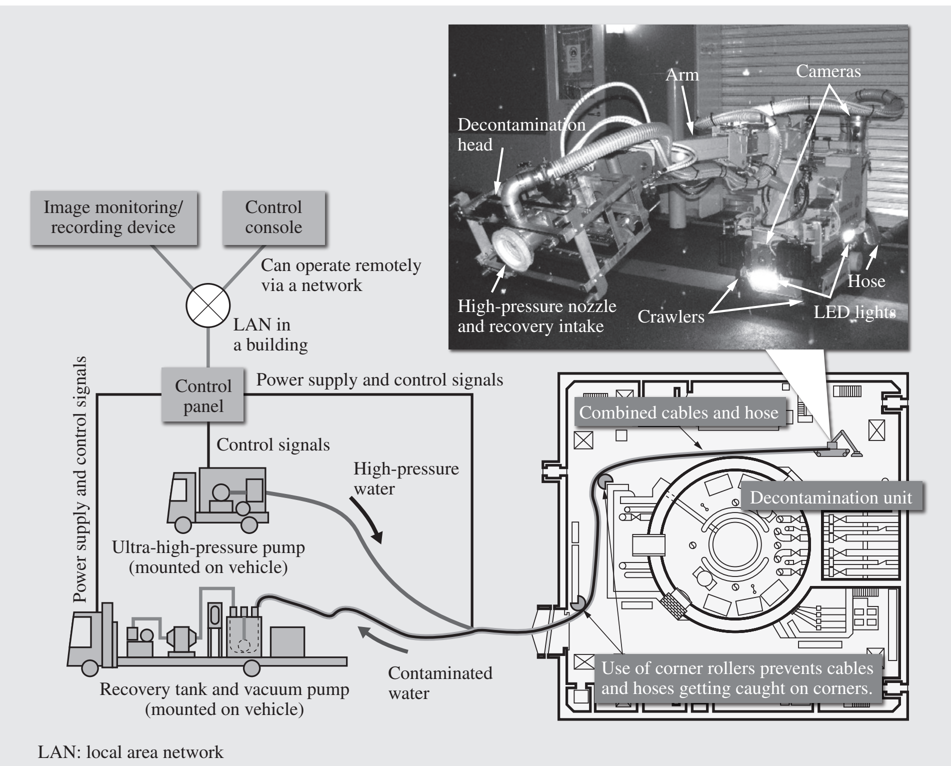


Fig. 6—Remote-controlled Decontamination System and its System Configuration.
The pumps and other decontamination equipment can be operated from a remote control room. This system decontaminates floors and walls by simultaneously spraying them with water supplied at high pressure and recovering the sprayed water.

Fig. 6 shows a photograph and block diagram of the system.

Developed by Hitachi, a remote-controlled robot system removes and collects radioactive material that has adhered to floor or wall surfaces. It can clean up the interior of a building and also prevent the dispersal of contaminated cleaning water. To make it suitable for a wide range of decontamination work inside reactor buildings, Hitachi designed the decontamination unit to be small and incorporated an arm mechanism that presses the head used to spray and recover the high-pressure water up against the floor or wall surface.

System Features

(1) Water pressure control to suit different uses

The ability of the decontamination system to vary the water pressure in the range 25 MPa to 200 MPa allows it to be selectively configured for surface cleaning, paint stripping, or chipping of surfaces. Accordingly, it can be used in a variety of situations, extending from the cleaning of surfaces that can be decontaminated by removing surface deposits through to cleaning concrete into which contaminants have penetrated.

(2) Full recovery of all cleaning water

The system has a decontamination head that simultaneously sprays and recovers the high-pressure water. The head produces the high-pressure water spray internally. Hitachi has optimized the brushes around the edges of the head to recover all of the cleaning water (high-pressure spray) and contaminated water.

This ensures that decontamination is performed reliably without spreading contaminants in the process.

DEVELOPMENT OF TECHNOLOGY FOR REMOTE-CONTROLLED ROBOT

Work at the Fukushima Daiichi Nuclear Power Station proceeds by incorporating information collected at the site into subsequent work plans. Furthermore, because of the high levels of radioactivity at the site, this also requires the use of remote-controlled robots to collect this information and to carry out other tasks inside the buildings.

Monitoring Robot System[5] for Conducting Surveys

To provide remote-controlled robots for this purpose, Hitachi is working on the development and deployment of a monitoring robot system that uses wireless communications for remote-controlled operation.

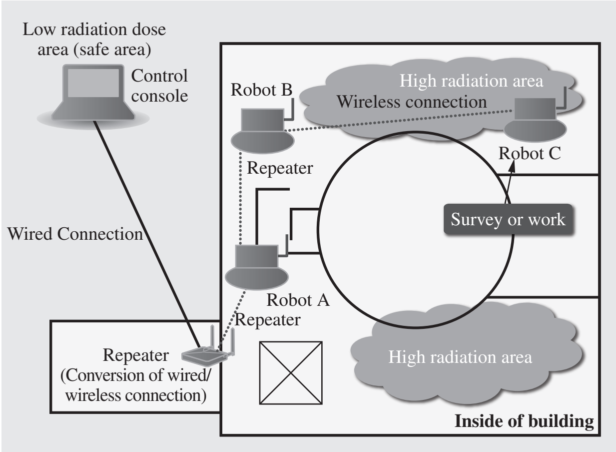


Fig. 7—Configuration of Remote-controlled Robot System.
Because the three remotely controlled robots can relay wireless communications between each other, a system can be configured to conduct surveys deep inside buildings, even when no communications infrastructure is available.

System Configuration

Fig. 7 shows a block diagram of the remote-controlled monitoring robot system. The system can operate three robots from a single console, with each robot able to relay signals to the others. Use of this wireless relay technique allows the robots to survey highly radioactive areas that are too dangerous for people to enter, and to do so even if the disaster site lacks communications infrastructure or has poor reception inside buildings.

Robot System Features

(1) Each console can operate multiple robots

Fig. 8 shows the system's control console. The user can switch the control screen between the different

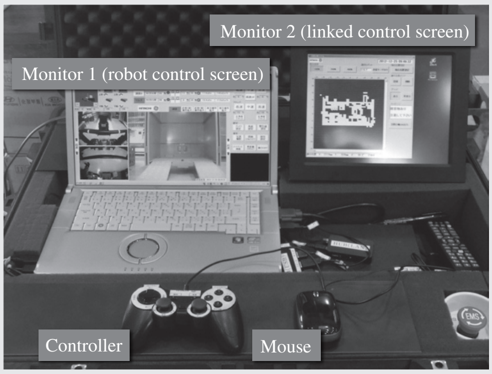


Fig. 8—Control Console.
The system configuration allows three robots to be operated from a single console. The map screen (linked control screen) displays the robot position and information about nearby obstacles.

robots to display the monitoring camera and front and rear bird's eye camera images from the selected robot. Using the monitor, the user controlling the robot can also select which of the multiple camera images available to observe as they do so. To monitor conditions at the robots' locations, sensor information (radiation level, temperature, and humidity) from three robots is displayed continuously.

(2) Map function

The mobile robots used by the system are fitted with laser rangefinders to collect measurements on their surroundings as they move, and to determine their location. This self-location data is then combined with a map of the area to avoid collisions with obstacles or other robots.

The map displayed on the console's operation screen is overlaid with a mesh. To help identify robot position and obstacles, and to make operation easier for the operator, whether or not the robot is able to pass can be specified for each square of the mesh.

Double-arm, Heavy-duty Robot[6]

To provide remote-controlled robots for use at disaster sites, Hitachi is working on the development and deployment of a heavy-duty robot with two arms that has been designed for use in nuclear accidents.

Overview of Robot

To provide flexibility for working indoors, a heavy-duty robot developed by Hitachi has a compact body (980 mm wide) and two arms. The two arms can reach up to 2.5 m high. The arms can lift 150 kg each and 300 kg in tandem.

Furthermore, the tools at the ends of the arms can be swapped to suit different tasks. Fig. 9 shows a heavy duty robot in operation using its two arms.

This robot uses radio control and was designed for tasks such as removing rubble from the reactor buildings.

It also has good operating characteristics, with extensive functions provided to assist remote control by the operator.

Robot System Features

(1) Swappable tools

To enable the robot to perform a wide range of tasks, the ends of the two arms can be fitted with gripping or cutting tools, rotating tools, or an extension arm that incorporates a camera.

To provide the flexibility to deal with conditions at the site, these tools can be swapped remotely.

The provision of two arms, the ends of which can each be fitted with different tools, allows the robot to perform delicate indoor rubble removal and dismantling work. When removing rubble, for example, one arm can be used to hold material while the other performs cutting.

(2) Use for making site measurements

In addition to cameras, the robot is also fitted with a radiation dosimeter, sensors for temperature and humidity, sensors for oxygen and hydrogen concentration, and an infrared camera. The sensor information is constantly updated on the remote control console to provide monitoring of the conditions inside the building at the robot locations.

(3) Support functions for remote control

This robot is operated via radio control from a remote control console. The console can display five monitor images at a time selected from the six camera feeds provided by the robot. Each of these six cameras is fitted with light-emitting diode (LED) lighting to facilitate rubble removal and other tasks in the dark interior of the reactor buildings at the disaster site. Fig. 10 shows the remote control console.

DEVELOPMENT OF TECHNOLOGY FOR TREATING CONTAMINATED WATER

Water treatment systems are being used at the Fukushima Daiichi Nuclear Power Station to remove radioactive cesium (Cs) from the high-level radioactive waste water that has collected inside the turbine buildings and other locations, and to help prevent corrosion of the reactor by removing salts that originally came from seawater (see Fig. 11). Hitachi

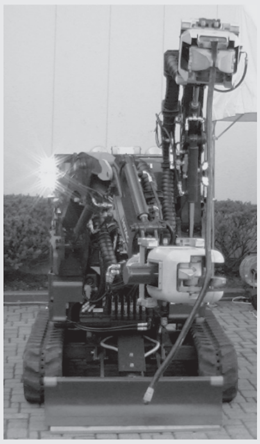


Fig. 9—Small Double-arm, Heavy-duty Robot.
Different attachments can be fitted to the end of each arm. This allows the robot to perform delicate tasks that take advantage of its two arms, using one arm to hold material while the other cuts it, for example.

Fig. 10—Remote Control Console.
This robot is operated by the four joysticks at the center. The console can display five camera images selected from the six camera feeds from the robot.

was given the job of installing reverse osmosis (RO) membrane systems and evaporative concentrators at the site, and has also been helping ensure that the RO membrane systems operate reliably.

However, because the current systems remove only Cs, Hitachi has also set out to develop a technique for removing strontium (Sr) in particular. Due to the use of seawater to cool the reactors in the immediate aftermath of the disaster, and the flooding of buildings with groundwater that contained seawater, the concentration in the contaminated water at Fukushima of non-radioactive Sr originating from this seawater is an order of magnitude greater than the concentration of radioactive Sr (seawater contains about 8 ppm of Sr). This means that the adsorbent used to remove Sr needs a high level of adsorption to also collect all of this seawater-derived Sr.

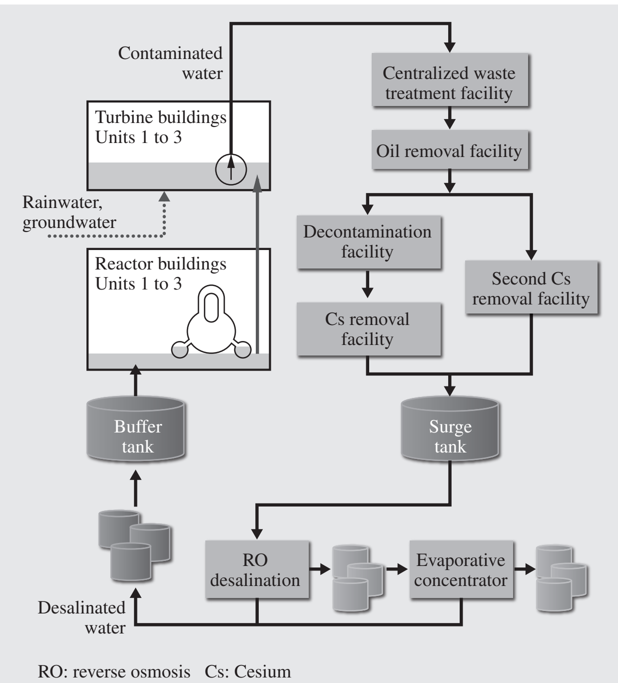


Fig. 11—Treatment of Water Contaminated with High Levels of Radioactivity.
Water contaminated with high levels of radioactivity that has collected inside the reactor, turbine, and other buildings due to flooding by the tsunami or reactor cooling water is treated and then reused as reactor cooling water for removing the decay heat from the fuel still inside the reactor (operation commenced on June 27, 2011).

Development of Adsorbent for Both Cs and Sr

Hitachi-GE Nuclear Energy, Ltd. and the Hitachi Research Laboratory have developed an adsorbent for both Cs and Sr that adsorbs Sr in sufficient quantities to make it suitable for use on the contaminated water at Fukushima(7).

Cs is an alkali metal and Sr an alkaline earth metal. The two have different ionic valences and radii in aqueous solution. For these reasons, the conventional practice for removing these elements has been to use separate Cs-specific and Sr-specific adsorbents. The advantage of using this single adsorbent is that it simplifies the equipment design.

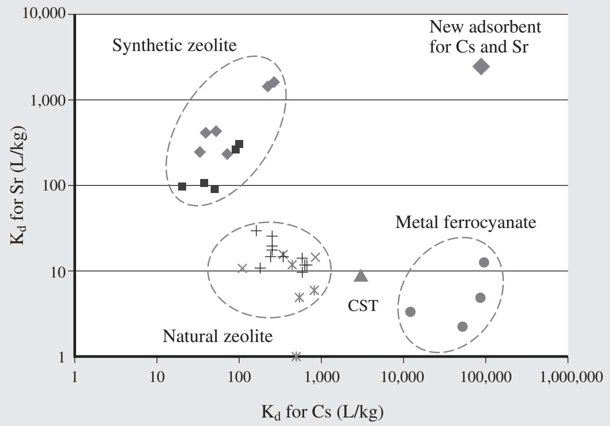
The following describes how the distribution coefficient (K_d) provides a way of comparing the amount of material adsorbed by the new adsorbent compared to Cs-specific and Sr-specific adsorbents.

The adsorbent was dipped into artificial seawater to which Cs-137 and Sr-85 had been added, and K_d was obtained according to the following formula.

$$K_d = C_0 = C_t / C_t \times V/m$$

Where, C_0 is the concentration of Cs-137 prior to inserting the adsorbent, C_t is the concentration of Cs-137 after one week, V is the volume of the solution, and m is the mass of adsorbent. Accordingly, the higher the value of K_d, the greater the amount of material adsorbed.

The results for the new adsorbent were then plotted on a graph along with those for the Cs-specific and Sr-specific adsorbents (see Fig. 12). The values for the latter materials were taken from data reported by a group associated with the Atomic Energy Society of Japan(8). The horizontal and vertical axes represent the K_d values for Cs and Sr, respectively. Note that the K_d values for particular adsorbents are different depending on factors such as their composition and shape. The graph shows that the new adsorbent is suitable for adsorbing both Cs and Sr, with a high K_d for both elements.



Sr: strontium K_d: distribution coefficient
CST: crystalline silico titanate

Fig. 12—Performance of Newly Developed Adsorbent for Cs and Sr.
The graph plots the distribution coefficients (K_d) measured for the case when nuclides were added to artificial seawater. The horizontal and vertical axes represent the K_d values for adsorption of Cs and Sr respectively. A high value of K_d indicates a high level of adsorption. K_d values for other adsorbents are shown for reference.

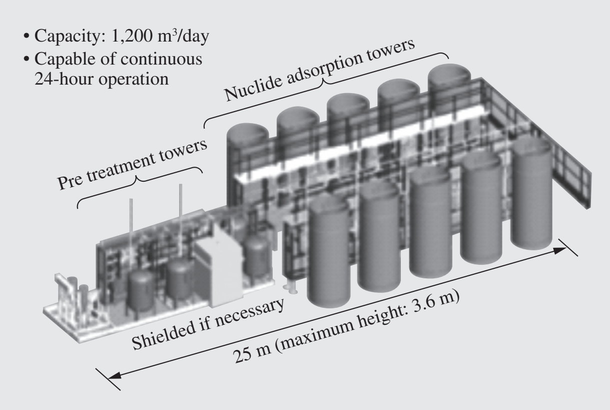


Fig. 13—Sub-drain Water Treatment System.
The system includes a number of adsorption towers to allow various different adsorbents to be used for the different nuclides contained in contaminated water. Through the adoption of the new adsorbent for Cs and Sr together with pre treatment (filters for removing soil, colloids, and other similar material), Hitachi succeeded in building a compact nuclide removal system with fewer adsorption towers (operation to commence in September 2014).

Development of System for Treating Contaminated Water

This section describes a sub-drain water treatment system that uses the Cs/Sr adsorbent to treat contaminated water.

The water from sub-drains located around the buildings has been found to contain antimony (Sb) as well as Cs and Sr. In addition to the new adsorbent described in this article, the system also uses a number of other adsorbents to deal with any other radioactive nuclides that may be present in the sub-drain water (see Fig. 13). Another feature is that, along with the adsorbents, the system also includes pre treatment equipment with conventional filters and a filter that can remove colloids. This equipment can ensure that the concentration of nuclides in the sub-drain water is below the permitted level for discharged water. Hitachi is contributing to the treatment of contaminated water at Fukushima Daiichi Nuclear Power Station by ensuring the reliable operation of this sub-drain water treatment system along with existing equipment.

CONCLUSIONS

This article has described technologies that are essential to decontamination work, including the gamma camera, PSF, Software for Preparing Decontamination Plans, and the remote-controlled decontamination system, which are used for radiation measurement, to support decontamination planning, and as remote-controlled decontamination equipment. It is anticipated that these technologies will make a major contribution to improvements in the efficiency and precision of tasks that extend from accurately determining the level of contamination before starting decontamination through to identifying which areas need decontamination, performing the work by remote control, and assessing the results once decontamination is complete. Hitachi has been working on preparations for cleanup work, extending from surveying building interiors to rubble removal, by developing remotely operated technologies for use at the Fukushima Daiichi Nuclear Power Station, namely a monitoring robot system and a double-arm, heavy-duty robot.

In terms of technology for treating contaminated water, Hitachi has also been developing an adsorbent for both Cs and Sr, and a treatment system for contaminated water.

In addition to deploying these technologies it has developed at the Fukushima Daiichi Nuclear Power Station, Hitachi also intends to continue working towards its remediation.

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Efforts to Improve Safety of Nuclear Power Plants

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OVERVIEW: Progress is being made on safety measures at Japan's nuclear power plants in preparation for their restarting operation, with new regulatory standards being implemented in July 2013 based on the lessons from the March 11, 2011 accident at the Fukushima Daiichi Nuclear Power Station of Tokyo Electric Power Co., Inc. Hitachi has been striving to improve the reliability, safety, and economics of nuclear power plants since its involvement in the construction of Japan's first BWR nearly 40 years ago, and has participated in the construction of more than 20 plants during that time. Drawing on this extensive experience and the lessons from the accident at the Fukushima Daiichi Nuclear Power Station, Hitachi is contributing to the operation and construction of safer and more reliable nuclear power plants by actively working toward the supply of plants with even higher levels of safety along with improvements to the safety of existing plants.

INTRODUCTION

THE great East Japan Earthquake in March 2011 and the accident at the Fukushima Daiichi Nuclear Power Station of Tokyo Electric Power Co., Inc. inflicted major damage on Japan. Taking the consequences of this accident to heart, Hitachi is fully involved in the recovery and rehabilitation of the affected regions and the Fukushima Daiichi plant, while also working to rebuild trust in nuclear power.

Hitachi has a track record of striving to improve the reliability, safety, and economics of boiling water reactors (BWRs), having participated in the construction of more than 20 such plants. In what can be seen as a culmination of this work, Hitachi's advanced BWR (ABWR) is the only generation III+ reactor (as defined by the U.S. Department of Energy) to have entered operation.

Progress is being made on safety measures at Japan's nuclear power plants in preparation for their restarting operation, with new regulatory standards being implemented in July 2013 that draw on the lessons from the Fukushima Daiichi Nuclear Power Station and include countermeasures against serious accidents, natural disasters, and man-made threats (terrorism). To enhance safety margins at existing plants in Japan, Hitachi has formulated and proposed optimal safety margin improvements that take account of the specific circumstances at these existing plants, and is participating in the design, manufacture, and installation of the associated equipment while also providing other assistance, including a variety of analytical methods for the quantitative evaluation of these measures. Hitachi is also responsible for key equipment at ABWRs currently under construction and is assisting with further safety improvements to ensure compliance with the new standards.

This article describes the core strategies underpinning safety measures based on the lessons from the Fukushima Daiichi accident, and the implementation of safety measures associated with compliance with the new regulatory standards, and provides an overview of the specific safety equipment being deployed at existing Japanese nuclear power plants.

In general, the safety measures being deployed at existing Japanese plants will also be incorporated into plants constructed outside Japan. One such overseas project is the Visaginas Nuclear Power Plant Project in the Republic of Lithuania. Following on from the November 2012 completion of Hitachi's purchase of Horizon Nuclear Power Limited, a nuclear power development company in the UK, the entire Hitachi Group is also currently working together on the design of an ABWR with enhanced safety and on coordination with the regulatory authorities in the UK with the aim of constructing ABWRs in the UK.

CORE STRATEGIES UNDERPINNING SAFETY MEASURES

The following sections describe the thinking behind safety measures that draw on the lessons from the Fukushima Daiichi Nuclear Power Station, and the factors to be considered in their implementation.

Core Strategies

From the experience of the accident at Fukushima Daiichi Nuclear Power Station and the lessons learned, Hitachi has identified the following three core strategies for safety measures that take account of the potential for a large earthquake or tsunami to cause widespread damage at the site.

The first is to protect important safety equipment from loads caused by external events that do not exceed design assumptions. Examples include seawalls, watertight doors, and physically dispersed location of equipment for dealing with a loss of all alternating current (AC) power.

The second is to have portable equipment available that can respond flexibly (respond to external events that exceed design assumptions) if the safety equipment is compromised. It is also important to improve the robustness of the reactor containment vessel to prevent leaks of radioactive material.

The third is to put measures in place to ensure a coordinated on-site and off-site response to a major external disaster by preparing simple and practical measures that take account of the likelihood of damage across the entire site.

These concepts can also be applied to a defense-in-depth approach to ensuring plant safety. Table 1 gives an overview of the five layers of civil defense when the defense-in-depth approach is applied to safety at a nuclear facility.

The aforementioned first policy for ensuring safety amounts to adopting an approach of closely reviewing equipment designs to select appropriate assumptions for the loads imposed by an external event (layer 1), and to allow the layer 2 and 3 countermeasures to be implemented appropriately. Similarly, the second policy is related to the layer 4 response, whereby internal measures are put in place at the facility to deal with accidents that exceed the plant equipment design assumptions set for layers 1 to 3. The third policy consists of measures that straddle the boundary between layers 4 and 5 by also making effective use of off-site resources.

In this way, the core strategies of the safety measures that draw on lessons from the accident at Fukushima Daiichi Nuclear Power Station strengthen each layer of the "defense-in-depth" approach, including the boundaries between layers.

Table 1. Defense-in-depth Approach to Ensuring Plant Safety
In the case of a nuclear power facility, the three layers (preventing problems, preventing escalation, and minimizing impacts) are augmented by an additional two layers for dealing with severe accidents.

	Description
Layer 1	Prevent problems or faults from occurring
Layer 2	Prevent problems or faults from escalating into an accident
Layer 3	Minimize the impact of accidents
Layer 4	Internal countermeasures against accidents that exceed design assumptions
Layer 5	External countermeasures against accidents that exceed design assumptions

Equipment Design Requirements

Safety equipment installed to cope with events in accordance with design standards achieves reliability both by taking a conservative approach to setting assumptions and through measures such as diversity and redundancy. A risk analysis of a plant fitted with this safety equipment can then be conducted to identify vulnerabilities and implement countermeasures (accident management measures). Through this process, it is possible to provide measures that will maintain effective functionality in the event of a simultaneous loss of safety equipment functions, for example. However, because a major external event that exceeds design assumptions by a significant margin is likely to also damage this pre-installed equipment, countermeasures in the form of the second type of policy are also required that are designed to provide a flexible response to a widespread loss of safety functions. That is, these are countermeasures that give operators more diverse and flexible options for how to respond. Examples of accident management measures are listed below.

(1) Alternative control rod insertion method
(2) Additional means of tripping recirculation pumps
(3) Means of releasing reactor pressure under extreme circumstances
(4) Reallocation of power supply from alternative power sources
(5) Alternative water supply equipment
(6) Primary containment vessel (PCV) vent
(7) External access to means of releasing reactor pressure
(8) Alternative water supply using portable equipment
(9) Alternative PCV spray using portable equipment

Because the accident management measures are provided for the case when safety equipment designed to auto-initiate fails to operate, the core strategy is to provide diversity and flexibility through manual operation. However, considering the amount of time available, automatic operation has been selected for measures such as (1) to (3) that deal with events that unfold rapidly.

On the other hand, in the case of situations that last over a certain amount of time, such as measures for dealing with decay heat removal and a damaged core, because of the high degree of uncertainty in the accident sequence up to that point, and because attempting to deal sensibly with all possibilities may be unrealistic, it is important not to compromise accessibility and mobility of operation. This can be achieved by, for example, not requiring design conditions of enveloping nature regarding excessively comprehensive scenarios of failures and by not making conservative environmental assumptions. To this end, in the case of measures (6) to (9) and depending on the objective, it is appropriate to take account of practicality and ensure that actions can be taken quickly by providing equipment based on realistic rather than conservative assumptions.

Accordingly, it is desirable that design requirements make realistic assumptions that are based on the characteristics of the measure concerned.

CONSIDERATION OF NEW REGULATORY STANDARDS

The new standards were prepared with consideration of both major accidents and accidents within design assumptions. In the core strategies underpinning safety measures, meanwhile, the purpose of the first strategy is to minimize the impact of accidents that are within design assumptions, whereas the second and third strategies are intended to deal with major accidents. The facilities for dealing with major accidents referred to in the new standards include both fixed and portable equipment intended for this purpose and also for dealing with major accidents of a specific type. In addition to using the portable and other equipment referred to above, it is also possible to comply with all aspects of the standards by incorporating the concept of a backup building[1].

Of particular importance when considering these standards is to reduce overall risk by striking a balance in the equipment design between providing equipment for dealing with major accidents that focuses on plant vulnerabilities and preventing this additional equipment from having a negative impact on the equipment provided to deal with accidents within design assumptions. This demands a basic philosophy in which the priority placed on facilities for dealing with major accidents is raised to the minimum extent needed for the operation of equipment for dealing with major accidents, while still maintaining the priority of equipment for dealing with accidents within design assumptions. For example, while isolation functions are important, because of the concern that overzealous use of isolation functions will significantly degrade access to portable equipment connection points and leave the equipment unusable in an actual accident, it is necessary to adopt an approach that includes prioritizing portable water supply over isolation functions, but only to the extent necessary. In adopting this approach, Hitachi needs to pay careful attention to future debate over new regulatory standards.

USE OF SAFETY EQUIPMENT

This section describes how safety equipment that is designed considering the core safety measure strategies and the new regulatory standards is used in practice. It divides safety equipment into four main categories and gives an overview of equipment that can be enhanced to provide additional safety measures. Note that not all listed equipment needs to be installed. Rather an appropriate selection is made based on the resilience of each plant.

(1) Equipment for dealing with accidents within design assumptions

To enhance equipment for dealing with accidents within design assumptions, Hitachi has identified specific equipment based on an assessment of the impact of events such as internal fires, internal spills, or external events (volcano, tornado, or external fires). The two main enhancements to equipment for dealing with accidents within design assumptions are as follows.

(a) Measures for dealing with internal fires

Provide equipment that can prevent safety being compromised by an internal fire.

(i) Use of non-flammable or fire-retardant materials
(ii) Install fire detection sensors
(iii) Install firefighting equipment
(iv) Use of firewalls to contain fires, and so on.

(b) Measures for dealing with internal spills

Provide equipment that can prevent safety being compromised by an internal spill.

(i) Install watertight doors
(ii) Install dams
(iii) Install leak detection sensors, and so on ...

(2) Equipment for dealing with major accidents (permanent equipment)

Permanent equipment is provided to ensure that its functions will be available for quick deployment, to prevent problems such as serious damage to the reactor core or rupture of the containment vessel, and also to inhibit release of radioactive material and minimize its dispersion. The following are some examples of key equipment.

(a) Alternative low-pressure water supply

Install an alternative low-pressure water supply for responding to accidents within design assumptions that provides additional options for low-pressure water supply, and that can also help prevent damage to the reactor core by injecting water into the core in the event of an accident that exceeds design assumptions.

(b) Install filter vents

Install equipment for venting the containment vessel externally to remove heat and protect against overpressure. Because this results in the external release of gases from the containment vessel, install filter vents in the exhaust flow path to reduce the amount of released radioactivity by trapping the radioactive aerosols contained in the vented gas.

(c) Containment vessel sprayer

Install equipment for spraying coolant inside the containment vessel to prevent damage by cooling the containment vessel (removing heat). Because spraying coolant inside the containment vessel does not need to start immediately, it is possible to use portable water pumps for this purpose. In this case, provide two separate connection point locations outside the building to provide physical separation, and use permanently installed fittings to supply the containment vessel sprayers from these external connection points so as to reduce the work required by operators to use the system.

(d) Indoor passive autocatalytic recombiner (PAR)

Install a PAR in the reactor building to keep the concentration of hydrogen below the ignition point when there is the potential for hydrogen gas released into the containment vessel following damage to the core to have leaked into the reactor building. Utilize three-dimensional flow analysis to select an appropriate location for the PAR.

(e) Reactor well water supply

Install a water supply to irrigate the reactor well to remove heat from the containment vessel and prevent damage to heat-sensitive non-metallic components such as gaskets by cooling the upper part of the containment vessel. Because supplying water to the reactor well does not need to start immediately, use portable water pumps for this purpose. Also, provide two separate connection point locations outside the building to provide physical separation, and use permanently installed fittings between these external connection points and the reactor well so as to reduce the work required by operators to use the system.

(f) Water supply to the lower part of the containment vessel

To prevent rupture of the containment vessel when the core has suffered serious damage, install equipment for irrigating the lower part of the containment vessel to cool a melted core that has flowed to the bottom of the vessel. Because supplying water to the lower part of containment vessel does not need to start immediately, it is possible to use portable water pumps for this purpose. Also, provide two separate connection point locations outside the building to provide physical separation, and use permanently installed fittings between these external connection points and the lower part of containment vessel so as to reduce the work required by operators to use the system.

(g) Water supply and sprayers for spent fuel pool

To provide equipment for cooling the spent fuel pool that operates differently to the equipment provided for dealing with accidents within design assumptions, install a system for topping up the water in the spent fuel pool to ensure that the pool is kept cool and to prevent fuel damage. Because spent fuel pool cooling does not need to start immediately, it is possible to use portable water pumps for this purpose. In this case, provide two separate connection point locations outside the building to provide physical separation, and use permanently installed fittings between these external connection points and the spent fuel pool so as to reduce the work required by operators to set the system up for use. Also, to allow for situations in which the level of damage is difficult to predict, such as terrorist attacks, adopt a configuration that allows both water supply and spraying to operate simultaneously by installing sprayers in the spent fuel pool for discharging water so that water can be sprayed over the fuel.

(h) Alternative high-pressure water supply

The reactor core isolation cooling system (RCIC) is intended for dealing with accidents within design assumptions when the reactor core has been isolated. To provide an alternative to this system and prevent core damage, install an alternative high-pressure water supply so that water cooling can still be performed when the reactor is at a high pressure.

(i) Equipment for enhancing operation of main steam safety relief valves (SRVs)

Enhance the opening mechanisms of main steam SRVs to deal with events that exceed design assumptions by providing backups for the nitrogen gas cylinders used to operate the valves and raising their operating pressure so that valve opening will work better, and by enhancing the power supplies required for valve opening. Work is also proceeding on the development of equipment that will allow main steam SRVs to be opened using nitrogen gas as the sole driving force without the need for an electric power supply.

(3) Equipment for dealing with major accidents (portable equipment)

Additionally to the permanent equipment, provide portable equipment for dealing with major accidents to prevent problems such as serious damage to the reactor core or rupture of the containment vessel, and also to inhibit release of radioactive material and minimize its dispersion. In using portable equipment, it is a prerequisite that the objective of the system (such as preventing core damage) should be able to be achieved even though the system will not be available for use until after the time required to set it up, including transportation and installation.

The following are two key examples of portable equipment for dealing with major accidents.

(a) Alternative auxiliary reactor cooling water system

The auxiliary reactor cooling water system is provided for dealing with accidents within design assumptions. As a backup to this system, provide an alternative auxiliary reactor cooling water system on a trailer that includes pumps, heat exchangers, and other equipment that can be used in place of the auxiliary reactor cooling system.

(b) Water tankers

Provide water tankers to transport water to the reservoirs used to supply equipment for dealing with major accidents, namely containment vessel sprayers, reactor well water supplies, and spent fuel pool water supplies and sprayers.

(4) Equipment for dealing with specific types of major accident

Install equipment that provides functions required to deal with major accidents or other events related to terrorist acts such as deliberately crashing a large aircraft into a reactor building.

In general, these are dealt with by providing a backup building that houses the reactor water supply equipment, containment vessel sprayers, equipment for reducing reactor pressure, spent fuel pool water supplies and sprayers, power supplies, and instrumentation.

The next section describes details of key permanent equipment for dealing with major accidents.

Filter Vents

A number of measures are planned to ensure the integrity of the containment vessel during a major accident even if the core is damaged, including maintaining the vessel's water supply and cooling, along with the power supplies they require. Filter vents are provided for the case when control of the containment vessel pressure becomes difficult despite these measures being implemented. Filter vents reduce radioactivity by filtering out radioactive aerosols contained in gases that pressure control has released from the containment vessel to reduce the pressure inside it.

Hitachi has adopted wet filter vent technology from AREVA SA and is working diligently to design, manufacture, and install filter vents for use in boiling water reactors in Japan.

Fig. 1 shows the structure of a filter vent. The filter vent combines two types of filters in an upright cylindrical housing made of stainless steel. The first filter stage consisting of venturi nozzles (scrubbers) traps relatively coarse aerosols contained in the gas released from the containment vessel. Further filtering of finer aerosols is then performed in the second filter stage (metal filters).

The following points were considered as a result of lessons learned from the accident at the Fukushima Daiichi Nuclear Power Station.

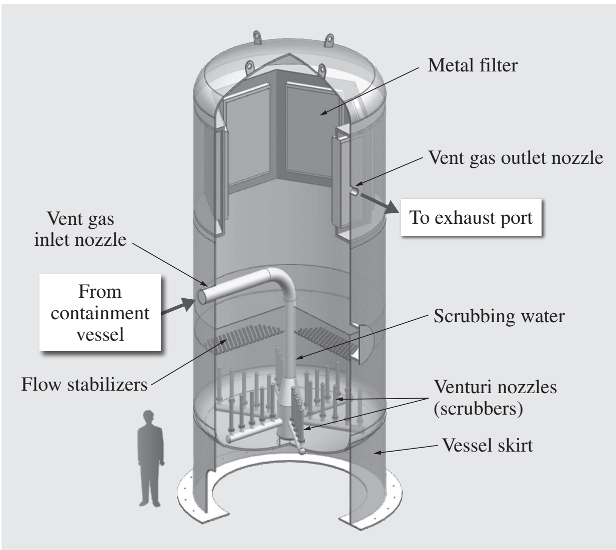

Fig. 1—Structure of Filter Vent.
A filter vent contains venturi nozzles (scrubbers) and metal filters, which together efficiently trap aerosols. The scrubber enhances the adsorption of aerosols by forming a gas-liquid mixture by circumferentially injecting tiny droplets of scrubbing water into the fast-moving gas in the venturi nozzle.

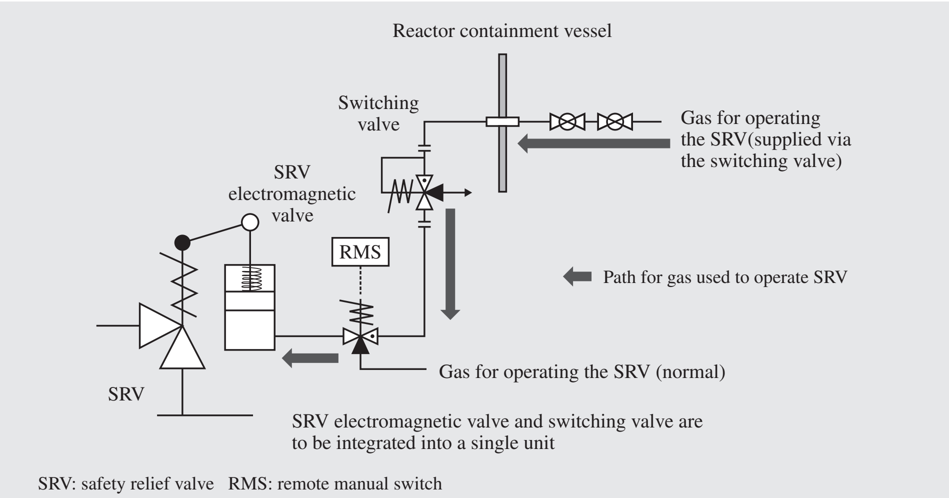

Fig. 2—Example System Configuration of Pressure Relief Mechanism for Reactor Pressure Vessels that Uses Switching Valve.
The SRV can be forcibly opened without an electric power supply by supplying gas for operating the SRV to the drive supply line connected to the switching valve in order to pressurize the SRV cylinder via the switching valve and SRV electromagnetic valve.

(1) Improvements to operation

To ensure that the filter vents will still be able to operate even if all AC power has been lost, valves driven pneumatically or by direct current (DC) are used for the isolation valves, and the valves are able to be operated manually in place through a shielding wall. To allow for monitoring, passive devices are used for the instrumentation around the filter vents required for plant operation.

(2) Preventing hydrogen explosions

The interior of the filter vents is filled with nitrogen to ensure that any hydrogen that gets in during venting does not ignite.

Functional Enhancements for Main Steam SRVs

If a major accident or other event results in all power being lost, including DC power supplies, electromagnetic valves used to operate relief valves to directly relieve pressure in the primary reactor system will not be able to be used. This makes it difficult to reduce the pressure in the primary reactor system, a prerequisite for supplying large quantities of coolant to the core. As having portable DC power supplies or other backup power supplies available for this key equipment is an effective way of dealing with the problem directly, it is being installed or planned. Meanwhile, to provide another way of dealing with situations like this, Hitachi has developed a switching valve mechanism that can operate without a power supply and act as a relief valve for the main steam SRVs used to reduce pressure in the primary reactor system.

These switching valves have two outlets that share a common inlet. They work by using the force of the inlet pressure to automatically close the common inlet or one of the outlets. Specifically, the normally open outlet of a switching valve is connected to outlet-side of the SRV electromagnetic valve and the other outlet is left open to the atmosphere so that gas for operating the SRV can be supplied to the common inlet. By using this switching valve to supply the gas that operates the SRV, this design provides a way for the SRV to function even when its electromagnetic valve cannot be energized due to loss of all power, including DC power. Fig. 2 shows the system configuration of a pressure relief mechanism for reactor pressure vessels that uses this switching valve. In addition to SRVs, the switching valve can also be used as a way of forcibly opening pneumatic valves that have failed.

Enhancements for High-pressure Water Supply

RCIC systems have conventionally been used to supply high-pressure water during a station black out (SBO) in which all AC power is lost. RCIC systems avoid the need for AC power by using steam from the reactor to run turbine-driven pumps.

As with RCIC systems, alternative high-pressure water supply systems that use turbine-water-lubricated (TWL) turbine-pumps also use turbine-driven pumps and are added as backups to the RCIC system (see Fig. 3). Hitachi is collaborating with its partner, GE Hitachi Nuclear Energy, on studying and proposing an optimum configuration for a system for dealing with severe accidents that takes account of the lessons from the accident at the Fukushima Daiichi Nuclear Power Station.

A feature of TWL turbine-pumps is that the turbine and pump are both integrated into the same housing, making them smaller than previous RCIC turbine-

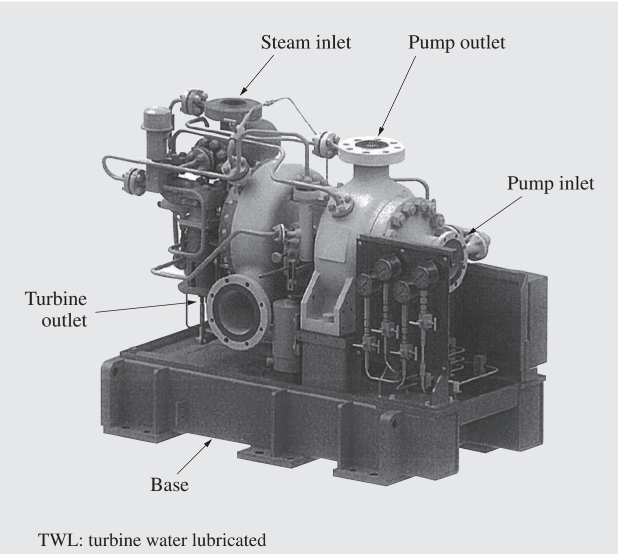

Fig. 3—TWL Turbine-Pump.
The TWL turbine-pump is contained in an integrated housing. Use of water-lubricated bearings and mechanical seals eliminates the need for a lubricating oil system and gland seal unit.

pumps. They are also made more compact by not requiring a gland seal unit (condenser, vacuum tank, and vacuum pump) which is due to use of mechanical seals in the turbine gland (see Fig. 4). Use of water-lubricated bearings also eliminates the need for a lubricating oil system, making it easier to find space for their installation.

The flow rate and pump head under high-pressure conditions are similar to or better than those of RCIC pumps. The pump also reduces control power consumption because it uses an internal mechanical mechanism to adjust the discharge flow rate of the pump and does not have an electrical control system.

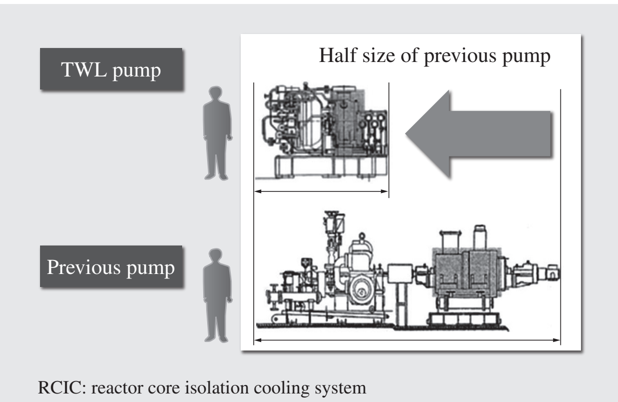

Fig. 4—Relative Sizes of TWL and Previous RCIC Pumps.
TWL turbine-pumps are smaller than the RCIC pumps used in the past, making it easier to find space for their installation.

TWL turbine-pumps have been selected for use as RCIC pumps at the Lungmen Nuclear Power Plant in Taiwan, and Hitachi plans to use them as RCIC pumps at future overseas ABWR plants.

CONCLUSIONS

This article has described compliance with the new regulatory standards and the core strategies underpinning safety measures based on the lessons from the Fukushima Daiichi accident, and has given an overview of the specific safety equipment being deployed at existing Japanese nuclear power plants.

Hitachi believes that nuclear power plants represent an important part of a reliable energy mix that will strengthen Japan's energy security. It intends to draw on the lessons learned from the accident at the Fukushima Daiichi Nuclear Power Station to supply nuclear power plants with even higher levels of safety. Furthermore, the technologies described here will support the safe restarting of existing plants and contribute to the operation and construction of plants that are safer and more trusted.

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extra notes

Power Transmission & Distribution

Yukiyoshi Yanagisawa

Emerging economies have an urgent need to augment their power transmission infrastructure to meet vigorous growth in energy demand, while developed economies need to upgrade their aging power transmission infrastructures. Around the world, stronger wide-area or transnational interconnections are being created using UHV or HVDC power transmission. Several countries are adopting renewable energy which makes the power grid unstable, and looking to bring stabilization technology to the power grids. Hitachi will work to meet these global needs in the power T&D sector.

WORKING ON LOCAL PROBLEMS FROM GLOBAL BASES

HITACHI'S global power transmission & distribution (T&D) bases were created to draw on resources such as engineering, overseas production, and procurement to provide appropriate solutions to various local problems. Bases in North America provide the switchgear and transformers needed to upgrade aging facilities, while also working on grid stabilization systems and energy storage battery systems. Bases in Asia bring together engineering bases and transformer and switchgear production bases to meet demand for various power T&D infrastructure. Bases in China are contributing to create China's domestic power transmission network mainly through production of ultra-high-voltage (UHV) gas-insulated switchgears (GISs).

In 2013, Hitachi signed a cooperation agreement with Russian grid for technical cooperation on the modernization and stabilization of electric power T&D

Katsunori Sone

President & CEO, Hitachi HVB, Inc.

Established in 1977 through a joint venture between Hitachi Ltd. and GE, Hitachi High-Voltage Breaker Inc. has since become a wholly owned subsidiary of Hitachi. Located about 30 miles northwest of Atlanta, the company manufactures and sells high-voltage (HV) and extra-high-voltage (EHV) circuit breakers (VCBs/GCBs), and sells generator main circuit breakers (GMCBs) and gas-insulated switchgears (GISs). It has delivered over 8,000 GCBs in the USA nationwide, including fifty-five 800 kV GCBs delivered or manufacturing for American Electric Power Company, Inc (AEP), and has the top share of the US domestic market. It has also delivered GISs to about 30 sites, including Mott Haven 345/138-kV S/S in New York City for Consolidated Edison (Con Ed). In July 2013 Hitachi HVB started selling transformers.

With demand expected to grow in North America, Hitachi HVB will continue providing the products and services to this market.

Fig. 1—Engineering Bases and Production Bases.
Hitachi will work with overseas engineering bases to propose solutions to the various problems of local regions.

infrastructure, and also signed cooperation agreement on power generation and T&D area with Mongolia Ministry of Energy and Sumitomo Mitsui Banking Corporation. In the years ahead, Hitachi will further improve and expand global systems rooted in local regions, while helping to solve problems unique to each area (see Fig. 1).

The Americas

Demand for upgrading of existing facilities and the application of renewable energy are expected to create growth in the markets of the Americas. In 1977, Hitachi partnered with GE to create joint-venture Hitachi HVB and begin manufacture and sales of high-voltage switchgear in the USA. Hitachi HVB has since become a wholly owned subsidiary of Hitachi and is one of the five largest manufacturers of switchgear in the US market. It added transformers to its sales lineup in July 2013.

To meet demand for grid stabilization needed with the application of renewable energy, Hitachi is also providing wide-area grid protection/control systems and energy storage systems.

Asia

In the Association of Southeast Asian Nations (ASEAN) region, an organization of power providers known as Heads of ASEAN Power Utilities/Authorities (HAPUA) is leading construction of the ASEAN Power Grid, a power transmission network linking the ten member nations. Among these nations, Thailand has started work on grid expansion and implementing a modernization plan driven by GIS upgrading of aging power transmission facilities, while Indonesia is working on a plan for direct current (DC) interconnection facilities between Java and Sumatra along with generator facility upgrading work.

Along with power T&D engineering bases in Singapore and Indonesia, Hitachi has the ASEAN region's only production base capable of 500-kV GIS

Shinji Nogami

President & CEO, Hitachi T&D Systems Asia Pte. Ltd.

Operating mainly in Southeast Asia, Hitachi T&D Systems Asia Pte. Ltd. (HTDA) engineers, procures, and constructs transformers, circuit breakers and other hardware and systems vital for substation equipment. In addition to substation equipment for power companies, HTDA also deals with industrial electric equipment such as substation equipment for overseas plants and railways system. Maintenance is another main business area, and expanding business to Singapore, Hong Kong, Thailand, Bhutan, and Saudi Arabia in which Hitachi has delivered substation equipment. Hitachi also constructs solar generation facilities, and has delivered a 1.2-MW megasolar facility to Brunei and a solar facility for Petroliam National Berhad (Petronas), Malaysia's state-run oil company.

PT. Hitachi Asia Indonesia (HAS-IDN) does business mainly in Indonesia. It sells, engineers and markets products for power and substation systems, civil/industrial systems, and information and communication systems.

With the demand for power infrastructure equipment in Southeast Asian countries expected to continue, HTDA is aiming to improve and coordinate its accumulated engineering expertise and provide system solutions for total grid optimization.

manufacture (located in Indonesia), which will help Hitachi meet the demands of the ASEAN nations. Hitachi has also created a new transformer plant in Taiwan that can produce equipment with capacities of up to 500 kV, 600 MVA, and will meet transformer demand from all over the world. To meet demand for grid stabilization needed with the application of renewable energy in India, Hitachi has created a research and development base that provides functions such as grid analysis.

China

While power generation is primarily coal-fired thermal generation, renewable energy sources such as hydroelectric and wind power, as well as nuclear power sources are being developed as a means of protecting the environment and reducing global warming.

Amid China's vast land area, coal and hydroelectric resources are centered in the center and western part of the country, while demand is centered along the southeast coastal region. Construction is underway to create power transmission and substation facilities for low-loss, long-distance transport of power from large thermal and hydroelectric power plants in the central and western parts of the country. Construction of UHV power transmission networks for low-loss, long-distance transport has been particularly active recently.

Fig. 2—SDEE Hitachi High-Voltage Switchgear (Left), UHV GIS Exterior (Right)
UHV GISs were developed for the world's first commercial 1,100 kV UHV alternating current (AC) power transmission project.

SDEE Hitachi High-Voltage Switchgear Co., Ltd. is a local company located in China's Shandong province created with SDEE which is subsidiary of State Grid Corporation of China. It can produce UHV GISs (see Fig. 2) and many other types of GISs (with capacities ranging from 110 to 1,100-kV). Hitachi will use this base to contribute to the power transmission network in China.

Middle East, Africa

Recent economic growth and growing populations

Kenji Annou

President & CEO, PT. Hitachi Power Systems Indonesia

PT. Hitachi Power Systems Indonesia (HPSI) is the Indonesian manufacturing subsidiary of the Power Systems Company, Hitachi, Ltd. Since its establishment in 1995, it has served as an ASEAN-region manufacturer of extra-high-voltage (EHV) power transmission equipment, producing GISs and GCBs. To meet demand for augmented power transmission and distribution networks in Indonesia, the ASEAN region and the Pacific Rim region, the company completed construction work to increase production capacity in June 2014, and started manufacturing Indonesia's first 500-kV-class GISs.

The growing populations of Indonesia and the ASEAN and Pacific Rim regions are expected to create growing demand for thermal power facilities and other main-line power plants, and for natural energy facilities such as wind and solar power facilities. This will lead augmentation of transmission and distribution networks, and HPSI will work on meeting these needs as a major base in the global value chain for the power systems industry.

are expected to result in major growth in demand for power in the Middle East and Africa. Indoor GIS substations are the focus in this region of harsh natural environments.

Hitachi has been constructing GIS substations in countries such as Saudi Arabia and Kuwait since the 1970s. Hitachi's transformer technology has been highly praised by the Saudi Electricity Company (SEC), and Hitachi has a near-monopoly in providing step-up transformers for recently constructed large thermal power plants.

Drawing on its high-reliability hardware and ability to successfully complete projects, Hitachi plans to continue helping the power transmission market in this region.

Europe

Nowhere in the world has championed renewable energy more actively than the EU, as seen in its '20-20-20' environmental targets and the efforts of several member countries to introduce various systems and create funds. As the region works to adopt large-scale renewable energy, problems such as shortages of power transmission facilities and grid instability have been coming to light. This environment has generated aggressive investment in DC power transmission for connecting remote power plants or upgrading power transmission facilities, grid stabilization using flexible alternating current transmission system (FACTS) devices, higher-speed monitoring using phasor measurement units (PMUs), and smart grids.

Hitachi has worked on smart grid verification projects such as verifying stabilization of power distribution voltages in the UK, and verifying the mass-introduction of electric vehicles (EVs) in Spain. Hitachi has also signed a cooperation agreement with Russian Grid to modernize and stabilize its power transmission and distribution network, and have studied the potential applicability of storage battery systems and grid stabilization solutions.

BECOMING A MAJOR GLOBAL PLAYER

In the years ahead, there will be increasing demand for system solutions combining hardware and IT, such as wide-area interconnections among different power grids, grid stabilization to prevent major power failures, industrial energy-saving, and high-reliability environmentally friendly power receiving/transforming equipment. Through the bases in the USA, China, Singapore, Indonesia, Taiwan, and elsewhere, Hitachi will work on providing solutions more closely tailored to the needs of each region.

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extra notes

Renewable Energy

Yasuo Takashima Tsuyoshi Koizumi Norihisa Wada

The adoption of renewable energy on a large scale is an international trend. Hitachi is working on core technologies for maintaining and improving the reliability and competitiveness of photovoltaic and wind power generation. Hitachi is also conducting research and development of future forms of renewable energy, including in particular gas turbine systems that utilize solar heat. Internationally, Hitachi is also marketing new energy and smart grid systems designed for conditions in different countries such as the Russia.

LARGE-SCALE PHOTOVOLTAIC POWER GENERATION

HITACHI has received turnkey orders [engineering, procurement, and construction (EPC) contracts] for a large number of megasolar power plants, including an 82-MW megasolar power plant for Oita Solar Power Corporation. It also supplies its Megakit photovoltaic power generation system packages and ancillary equipment, particularly power conditioning systems (PCSs) that help increase power generation. Overseas activities include a 1.2-MW megasolar project for Mitsubishi Corporation in Brunei, and the supply of PCSs to the Thailand.

Hitachi initially supplied highly efficient PCSs in Japan and overseas that used two-level pulse width modulation (PWM) inverters and were designed for small size and high efficiency. Hitachi then went on to develop and commercialize PCSs designed for even greater efficiency that used three-level PWM inverters. In addition to its current HIVERTER-NP203i model, which has a maximum input voltage of 660 V, Hitachi has released the new HIVERTER-NP213i model with a maximum input voltage of 1,000 V and a maximum conversion efficiency of 98.8%, which represents world-leading performance for a PCS in its class* (see Fig. 2).

Fig. 1—82-MW Megasolar Power Plant for Oita Solar Power Corporation.
This megasolar power plant scheduled to commence operation in 2014 will be Japan's largest.

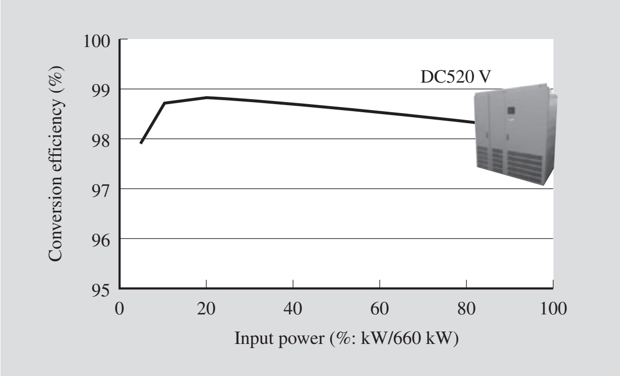

Fig. 2—PCS Conversion Efficiency Characteristics (HIVERTER-NP213i).
Hitachi is helping maximize the amount of power generated by providing high conversion efficiencies in the actual operating ranges used for photovoltaic power generation.

WIND POWER GENERATION

The downwind configuration of the 2-MW-class HTW2.0-80 wind turbine means that the rotor is located on the downwind side of the tower. The downwind configuration applied to 2MW HTW2.0-80 locates the rotor downwind of tower. This

* PCSs for large photovoltaic power generation systems in the 500-kW class. Based on Hitachi research as of October 2012.

Fig. 3—Wind Power Generation System with Downwind Configuration.
This wind power generation system is used by the Fukushima Floating Offshore Wind Farm Demonstration Project (Fukushima Forward). (Photograph courtesy of Fukushima Offshore Wind Consortium)

configuration, which lowers wind load, can simplify foundation work and reduce its cost, and can improve generating efficiency in hilly areas where updraft wind generally blows.

This model also features a high level of tolerance for lightning to withstand intense winter thunderstorms that occur in Japan.

Because the benefits of a downwind configuration are particularly applicable to offshore sites, Hitachi is also working on the development of a 5-MW-class downwind offshore wind power generation system. To facilitate progress on this work, a HTW2.0-80 turbine has been installed off the coast of Fukushima by the Fukushima Floating Offshore Wind Farm Demonstration Project (Fukushima Forward) funded by the Ministry of Economy, Trade and Industry (see Fig. 3). Trial operation of this system together with an offshore substation also supplied by Hitachi has already commenced. Trial operation of a HTW2.0-80 wind turbine has also commenced off the Goto Islands in Nagasaki Prefecture in a Floating Offshore Wind Turbine Demonstration Project run by the Ministry of the Environment (the first such project in Japan on a commercial scale).

RAPID ENGINEERING TOOLS

Extracting maximum performance from large-scale photovoltaic and wind power generation requires advanced core technologies that can be used in the associated engineering work. Hitachi has developed rapid engineering tools for both photovoltaic and wind power.

Fig. 4 shows a rapid engineering tool for large photovoltaic power generation systems. This megasolar design tool is used for the processes from project planning to estimation. By combining and linking programs that perform calculations for such things as power output and mounting structures, the tool reduces the time required for data input, automates the generation of drawings for submission to the customer during each process, and allows these drawings to be managed in a standardized format.

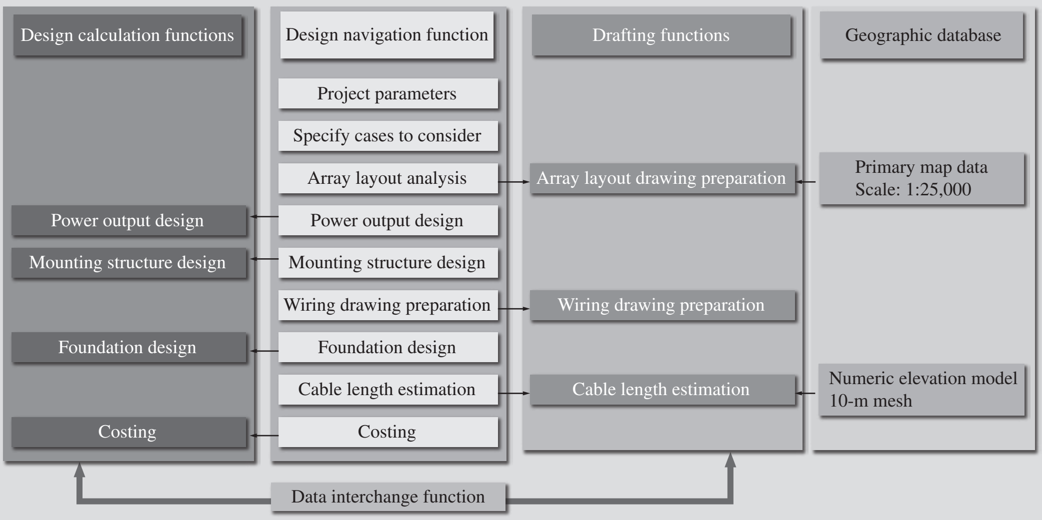

Fig. 4—Configuration of Rapid Engineering Design System for Megasolar Projects.
The interchange of data between design tools avoids data entry errors and saves time by reducing the volume of manual data entry.

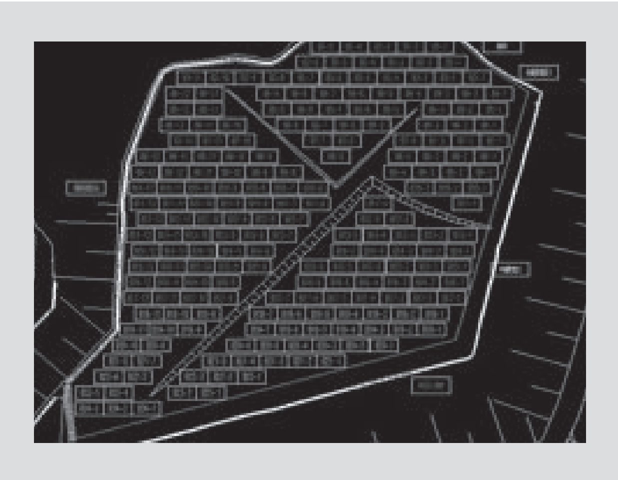

Fig. 5—Automatic Generation of Array Layout.
The system uses map data to determine the layout of the photovoltaic panels automatically. This layout can then be used to evaluate the cable routing.

The tool can automatically estimate annual power generation using a database of sunlight levels around Japan that was published by the New Energy and Industrial Technology Development Organization (NEDO), use map data to determine how to arrange the photovoltaic panels to maximize their number, determine the optimal mounting structures for the photovoltaic panels, and determine the shortest cabling layout (see Fig. 5).

Advanced numerical analysis techniques are essential for the development of wind turbines, which require a high level of reliability. A downwind turbine configuration means that each rotor blade passes through the tower wake at each rotation. Accordingly, Hitachi has developed its own numerical analysis model that considers the tower shadow effect caused by aerodynamic interference between the tower wake and rotor (see Fig. 6). Numerical analysis techniques are also utilized for development tasks such as estimation of blade and tower strength and multi-objective optimization of blade shape.

DEVELOPMENT OF SYSTEM USING SOLAR HEAT

A new system for exploiting renewable energy is a gas turbine system that uses solar heat. Once the thermal energy is collected, solar thermal power generation can use the same technology as conventional thermal power generation. It can also achieve higher generation efficiencies than photovoltaic power generation. The main limitations are weather conditions and the large area of land required for the solar collectors that generate the high-temperature steam.

Hitachi has developed a new gas turbine system that uses solar heat and that reduces the land area required per unit output for solar collectors to one-tenth or less that of previous solar thermal power generation methods (see Fig. 7).

A characteristic of gas turbines is that their output falls during the summer, for example, because the lower air density when air temperatures are high reduces the mass flow of air drawn into the compressor. A technique that has been implemented to overcome this is to spray water into the gas turbine intake to cool the incoming air. Unfortunately, this technique has failed to mitigate the drop in output sufficiently because of the potential, if the spray droplets are large, for it to cause erosion of the compressor blades. This limits the amount of sprayed water to no more than

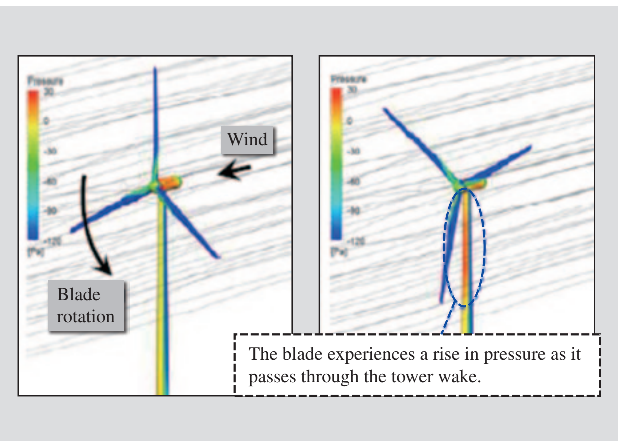

Fig. 6—Calculation of Tower Shadow.
This analysis considers the pressure fluctuations that result from the tower wake that is a feature of downwind turbines.

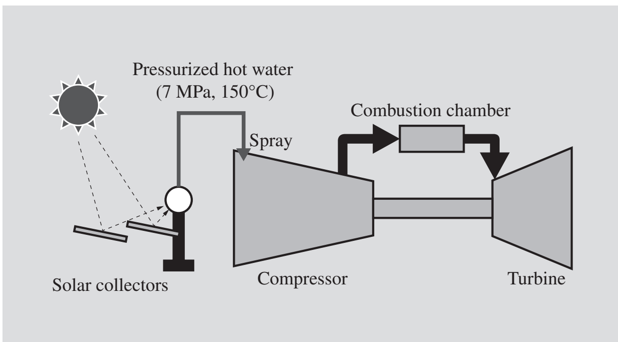

Fig. 7—Concept of Gas Turbine System Utilizing Solar Heat.
Solar heat is used to produce pressurized hot water that is then sprayed into the gas turbine intake. When the water flash boils on exposure to atmospheric pressure, it takes latent heat from the intake air, thereby cooling the air.

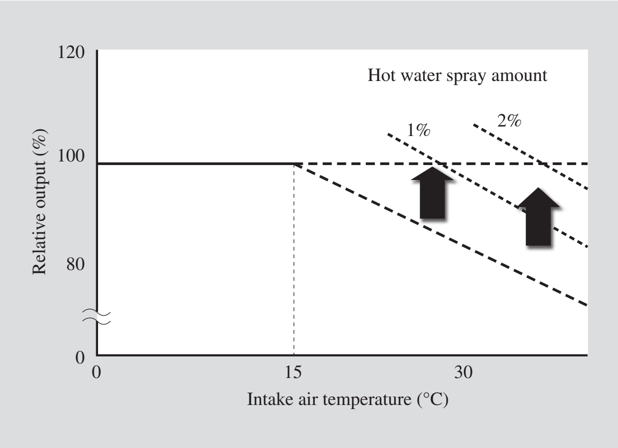

Fig. 8—Predicted Restoration of Gas Turbine Output through Spraying Pressurized Hot Water.
At an air temperature of 35°C, a gas turbine can be restored to its rated output by spraying water equivalent to 2% of the intake air by mass.

about 0.5% of the intake air by mass.

Hitachi has now developed a new system that operates with a water spray pressure of 7 MPa and uses solar heat to raise the water temperature to 150°C (conditions under which water is still a liquid). This pressurized hot water is sprayed into the intake where it instantaneously flash boils (vaporizes) on exposure to atmospheric pressure. At the same time, the droplet size also shrinks due to internal boiling. The heat of vaporization is taken from the surrounding air, efficiently cooling it, and the technique also prevents erosion of the compressor blades by water droplets. It is seen as providing an effective way of using solar

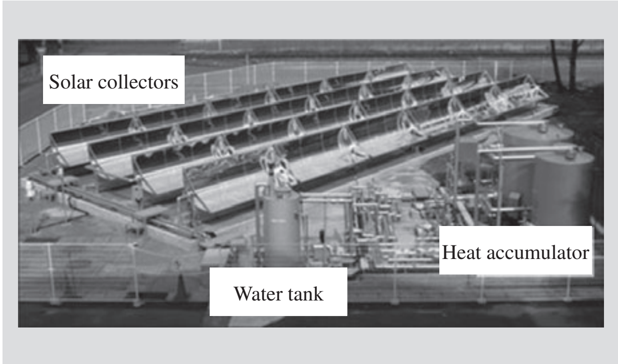

Fig. 9—Experimental System at Hitachi.
Trough-shaped solar collectors are used to collect solar heat.

heat during summer when the loss of gas turbine output is at its most severe (see Fig. 8).

The viability of this principle has been verified on an experimental system installed at Hitachi (see Fig. 9), with demonstration trials on actual gas turbines planned in the future.

OVERSEAS PARTNERSHIPS

Because the renewable energy business is influenced by different national policies, it is essential to establish partnerships with overseas institutions and customers. Hitachi has established such partnerships in the fields of renewable energy and smart grids from an early stage. Currently, this includes initiating approaches to public and private power companies in the Russian Federation and elsewhere with the aim of proceeding through win-win collaborations.

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extra notes

Nuclear Power

Takashi Masui Takao Kurihara

While nations around the world have revised their nuclear power policies subsequent to the accident at Fukushima Daiichi Nuclear Power Station, Tokyo Electric Power Company, Incorporated, there is demand for the construction of new nuclear power plants in emerging economies and elsewhere. Based around its alliance with GE, Hitachi works with a variety of partners to deliver the best possible solutions to suit the needs of different nations. Energy security, environmental protection, and economic performance are challenges that many nations have in common. Hitachi seeks to meet the demand for nuclear power generation capable of overcoming these challenges.

CIRCUMSTANCES SURROUNDING OVERSEAS NUCLEAR POWER BUSINESS

THE Nuclear Regulation Authority, Japan was established as an independent committee in response to the accident at the Fukushima Daiichi Nuclear Power Station, Tokyo Electric Power Company, Incorporated caused by the Great East Japan Earthquake on March 11, 2011. Also, new safety regulations were introduced in July 2013. Overseas, meanwhile, while some nations have turned away from nuclear power, there remain a large number of countries, particularly emerging economies that have a need for Japanese nuclear power technology (see Fig. 1).

To meet the world's need for nuclear energy, Hitachi entered into an alliance with the General Electric Company (GE) of the USA, establishing GE-Hitachi Nuclear Energy Americas LLC in the USA in June 2007 and Hitachi-GE Nuclear Energy, Ltd. in Japan in July 2007. From these platforms, Hitachi and GE are jointly proceeding with global operations

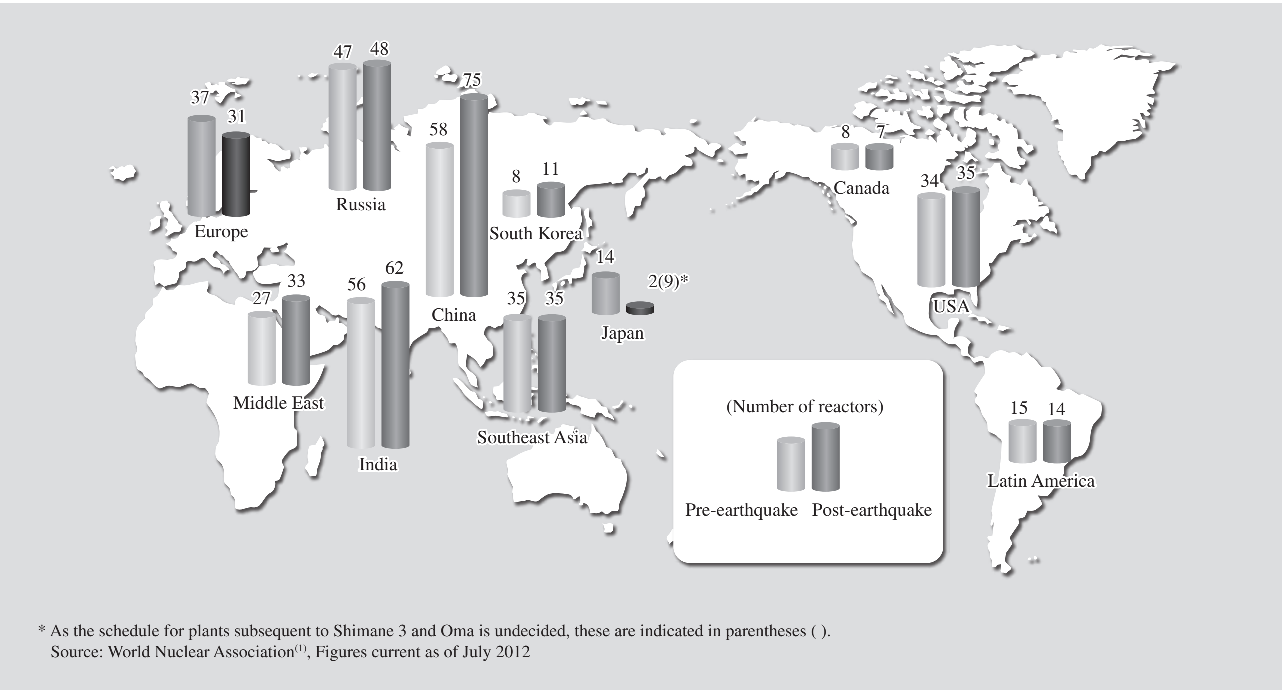

Fig. 1—New Plans for Nuclear Power in Key Regions.
A comparison of plans for new nuclear power plants before and after the Great East Japan Earthquake shows notable increases in emerging economies such as China and India, but little change in other parts of the world.

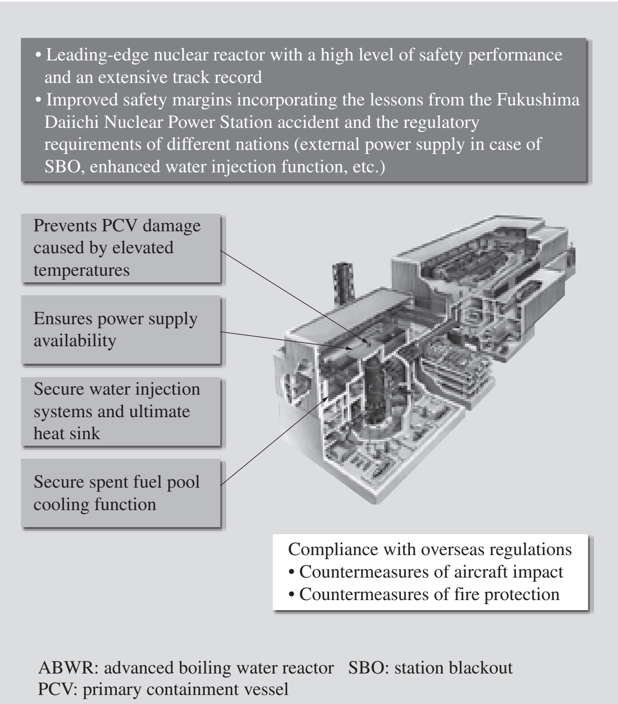

Fig. 2—Safety Enhanced ABWR.
The Safety Enhanced ABWR is a leading-edge nuclear reactor with a high level of safety performance and an extensive track record. It incorporates the lessons from the Fukushima Daiichi Nuclear Power Station accident and the regulatory requirements of different nations to improve safety margins.

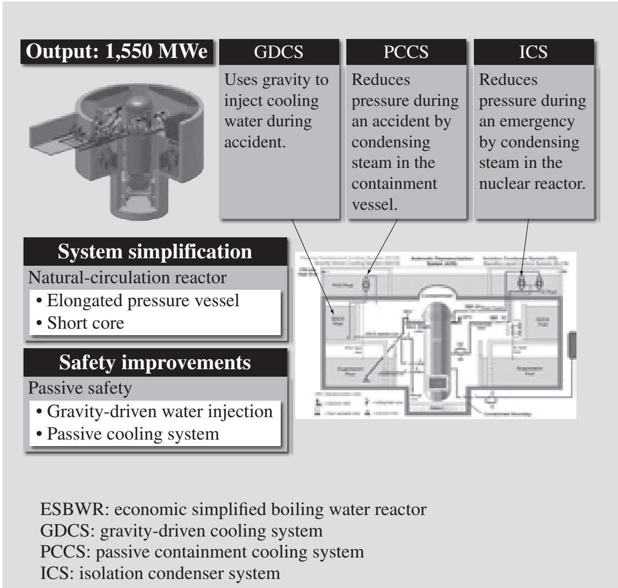

Fig. 3—ESBWR.
The main features of the ESBWR are its use of a natural-circulation reactor to simplify system design and its use of passive safety to improve safety.

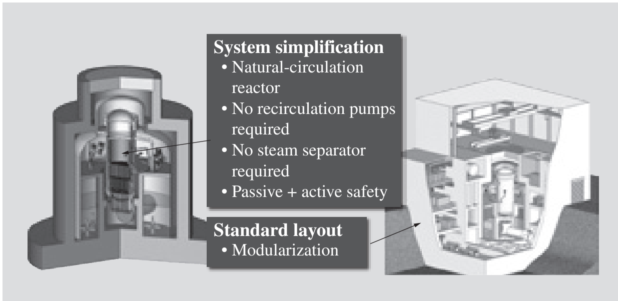

Fig. 4—Small or Medium-sized Reactors.
These small or medium-sized reactors feature modularization to provide a standard equipment layout and a simplified system design.

as the world's largest manufacturer of boiling water reactors (BWR) with products that extend from supply of nuclear fuel through to plant construction and maintenance services.

GENERATION SYSTEM PRODUCT RANGE

Hitachi can supply the following generation systems to meet demand from around the world (see Figs. 2, 3, and 4).

(1) Safety Enhanced ABWR (Advanced BWR)
To improve safety margins, Hitachi has incorporated the lessons from the Fukushima Daiichi Nuclear Power Station accident and the regulatory requirements of different nations into the ABWR, which has excellent safety performance and an extensive track record.

(2) ESBWR (Economic Simplified BWR)
Along with improved safety margins achieved through the use of passive safety systems, the ESBWR also features easier maintenance. Acquisition of design approval in the USA is planned in the near future.

(3) Small or medium-sized reactors
These are based on the modular simplified & medium small reactor (DMS) developed under contract to The Japan Atomic Power Company. An agreement to conduct joint development was signed with the Saskatchewan Power Corporation (SaskPower) of Canada in 2011.

INVOLVEMENT IN OVERSEAS NUCLEAR POWER MARKET

Hitachi segments the numerous nations or regions that are considering the installation of new nuclear power plants based on factors such as: How clearly they have defined their plans, whether or not they have regulatory standards in place, and whether financing is required. Collaboration with a variety of partners is necessary when preparing specific proposals for these nations or regions based on this segmentation. In the case of an emerging economy, for example, collaboration with the power company is needed to provide operational and maintenance support. Collaboration may also be needed with engineering companies, construction companies, or financial partners who are familiar with the circumstances of the nation concerned. Based around its alliance with GE, Hitachi utilizes these collaborations to ensure that services can be provided throughout the life cycle of the nuclear power plant, which comprises approval, design, equipment manufacturing, procurement, construction, operation, and maintenance.

SUMMARY OF EUROPEAN PROJECTS

Republic of Lithuania

The Republic of Lithuania is one of the three Baltic states. When gas imports from the Russia are included, approximately 80% of the nation's domestic energy consumption is reliant on the Russia. With the aim of resolving this energy security problem, the Republic of Latvia, Republic of Estonia, and Lithuania agreed in 2006 to the construction of the Visaginas Nuclear Power Plant at a nearby site with a view to future energy market integration (see Figs. 5 and 6).

In 2009, the Visaginas Nuclear Power Plant was incorporated into the Baltic Energy Market Interconnection Plan (BEMIP), an energy market integration plan agreed by eight nations abutting the Baltic Sea.

When tendering to be appointed as a strategic investor (SI) in 2011, Hitachi proposed a 1,300-MW ABWR with additional safety features incorporating countermeasures to the accident at the Fukushima Daiichi Nuclear Power Station and was awarded preferred bidder status. Subsequent developments included the government of the Lithuania and Hitachi concluding a concession agreement (in March 2012), followed in June 2012 by approval of the related laws and the conclusion of parliamentary debate. However, following a change of government in October 2012 and the results of a referendum, a review of energy strategy by a special committee of the Lithuanian parliament was requested.

The current status of the Visaginas Nuclear Power Plant construction project is that a report submitted at the end of April 2013 by a government working group (WG) set up to look at comprehensive energy strategies (and approved by parliament) has proposed that the project proceed subject to conditions. In the future, the Lithuanian government intends to debate the project further in a joint committee established with the governments of the Estonia and the Latvia.

As an SI, Hitachi has been involved along with investment partners in the Baltic region in debate about how to proceed with the project, with agreement having been reached on a joint position paper at the end of September.

Fig. 5—Proposed Site of Visaginas Nuclear Power Plant.
Construction of the Visaginas Nuclear Power Plant is planned for a site in the northeast of the Lithuania, one of the three Baltic states.

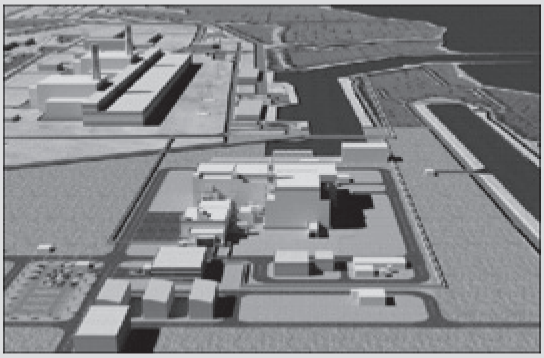

Fig. 6—Artist's Impression of Completed Visaginas Nuclear Power Plant.
This artist's impression shows the completed Visaginas Nuclear Power Plant.

UK

In 2011, the UK government demonstrated its support for commercially based nuclear power plant construction by selecting eight sites for new plants (see Fig. 7). The UK government recognizes nuclear power as a low-carbon source of energy and is proceeding with legislation for a feed-in tariff scheme for low-carbon energy as part of its electric power market reform policies. The first round of laws for the electric power market reform was passed in December 2013.

In November 2012, Hitachi purchased all shares in Horizon Nuclear Power Limited, a nuclear power business development company in the UK. Established

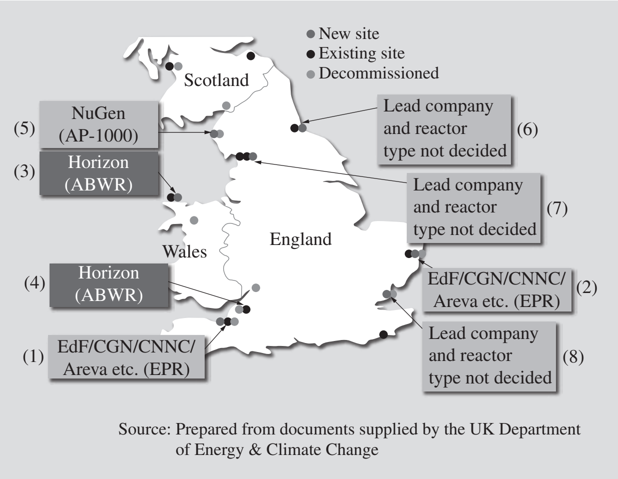

Fig. 7—Plans for Construction of New Nuclear Power Plants in UK.
Two of the planned new plants for the UK, (3) Wylfa and (4) Oldbury, are projects of Horizon.

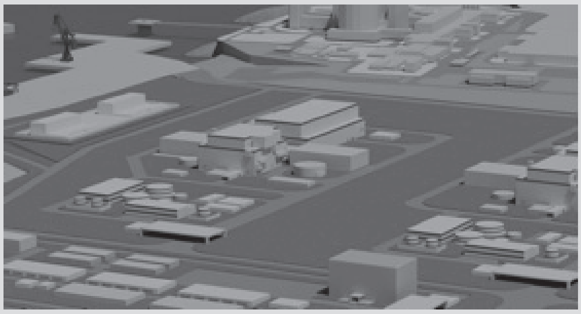

Fig. 8—Artist's Impression of Completed Wylfa Newydd Nuclear Power Station.
This artist's impression shows the planned Wylfa Newydd Nuclear Power Station. The aim is for operation to commence in the first half of the 2020s.

in January 2009 by the UK subsidiaries of German power companies E.ON SE and RWE AG (E.ON UK plc and RWE Npower plc, respectively), Horizon is planning the construction of nuclear power plants at two sites in the UK (Wylfa and Oldbury). The subsequent decision by E.ON and RWE in March 2012 to sell their stakes in Horizon came as a result of Germany adopting a policy of shutting down nuclear power generation. Horizon was then purchased by Hitachi.

Horizon intends to obtain all licenses and approvals needed from the UK government for the initial project at Wylfa Newydd by 2018, and to have the first nuclear reactor operating by the first half of the 2020s (see Fig. 8). To proceed with the engineering, procurement, and construction (EPC) plan for the Wylfa site, Horizon and Hitachi-GE Nuclear Energy, Ltd. signed a front end engineering and design (FEED) contract in May 2013.

In December 2013, Her Majesty's Treasury, Horizon, and Hitachi agreed to cooperate in future on obtaining external financing for the Wylfa Newydd project. This allows the project to consider utilizing the UK government's infrastructure guarantee scheme that supports the securing of external financing for social infrastructure projects.

Along with the railway business that it already operates in the UK, Hitachi believes that the nuclear power business will provide an opportunity to make an even greater contribution to the development of that nation's social infrastructure, including job creation.

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