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ADVANCE

Latest Trend of Power Systems

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Latest Trend of Power Systems

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Technical Reports

Precis

Mitsubishi Electric equipment and systems in the field of power systems are known for their high level of reliability, durability and safety by customers worldwide.

This paper describes the developmental background and future prospects of power generation systems, and introduces the latest products used in the field of the generation, transmission and distribution systems.

Transition of Power Generating Systems and Future Prospects

Author: *Naohiro Nakano**

1. Introduction

Electric power systems, which constitute vital infrastructure for supporting society and economic activities, consist of three main subsystems: the power generating subsystem that produces electric power; the power transmission subsystem that converts voltage at a substation for transmitting the electric power to various destinations; and the distribution subsystem that supplies the electric power to various consumers (Fig. 1).

The main types of power generating systems include:

- hydroelectric power generation, which utilizes the energy of the head of the water stored in a dam;
- thermal power generation, which utilizes the energy resulting from the combustion of fossil fuels such as petroleum, coal and natural gas; and
- nuclear power generation, which utilizes nuclear energy.

In recent years there has been a focus on power generation using renewable energy such as solar and wind power, but most of the power generated in Japan comes from thermal, nuclear, and hydroelectric power.

In the early twentieth century, hydroelectric power systems were the main source of power in Japan. To cope with the subsequent growing demand for electric power, large-capacity hydroelectric systems were constructed.

Around the middle of the twentieth century, the main type of power generation shifted to thermal power, and thermal power systems spread and their generation capacity became larger.

In the late twentieth century, thermal power facilities expanded and their generation capacity became even larger to meet the growing demand for electric power during the period of high economic growth.

To break away from the dependence on petroleum after the oil shocks in the 1970s, both hydroelectric and thermal power generation were made more efficient by using systems such as pumped-storage power generation and combined-cycle generation. Also, nuclear power plants were constructed and their operating rate was improved. As the combination of power generation systems changed, a stable supply of electric power using the best mix of thermal power, nuclear energy and hydroelectric power was promoted. The generation of electric power using renewable energy such as solar and wind power was also promoted.

This paper describes the technical transition, the latest technology, and future prospects of thermal power, nuclear power, and hydroelectric power as power generating systems as well as turbine generators.

2. Transition of Technology for Power Generating Systems

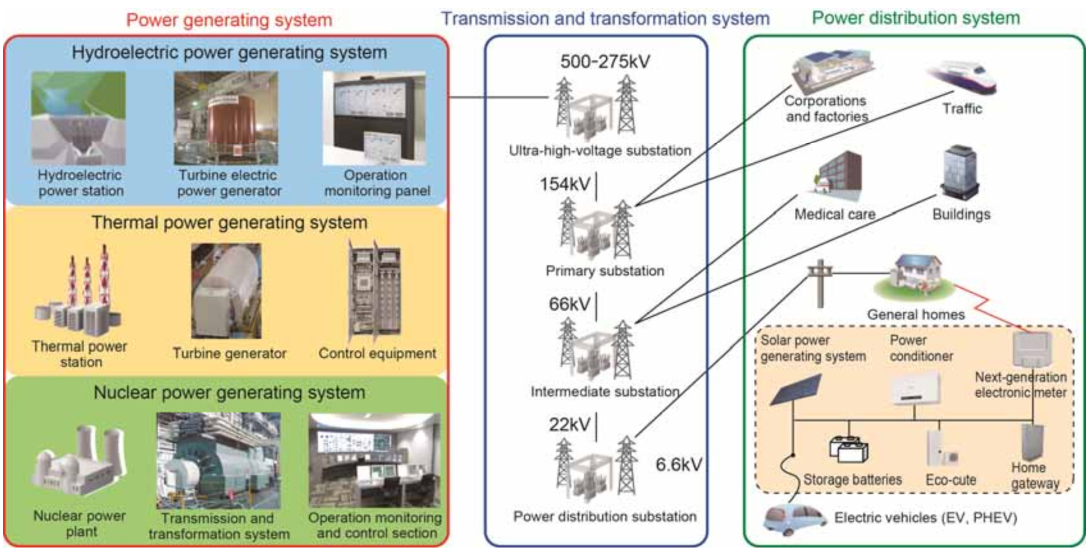


Fig. 1 Electric power systems

* *Power Distribution Systems Center (Former Energy Systems Center)*

2.1 Thermal power generating systems

In the history of increasing scale and efficiency of thermal power generating systems, not only steam-powered but also combined-cycle power generating systems came into widespread use. Monitoring control systems have also become more sophisticated in order to cope with changes in the power generation methods and customer requirements. The transition of monitoring control systems for thermal power generating systems, and the future trends (Fig. 2), are described below.

2.1.1 Transition of thermal power generating systems

In the 1960s, electric power generation shifted mainly from hydroelectric power to thermal power. Accordingly, more thermal power generating facilities and systems were constructed, and they also became larger in scale. In the 1980s, Japan entered the era of supply and demand adjustment type thermal power generation. In line with this, combined-cycle power generation, which uses both gas turbine and steam turbine power generation, was more widely adopted, and the demand for facilitating load variation and starting and stopping increased.

2.1.2 Transition of monitoring control systems

During the 1950s, system operation was local manual operation using pneumatic measuring instruments. From the 1960s, however, electronic analog measuring instruments and electronic computers were introduced, and in 1963 the MELCOM330 was delivered as the first data logging unit for use with thermal power generating systems.

With the advent of the 1970s, large-scale thermal power generating systems were constructed, buoyed by the high economic growth, and significant progress was made in electronics technology such as the birth of the microprocessor. Mitsubishi Electric also developed the MELCOM350-30 and -50 series of computers, which used microprocessors. These computers were used not only for data logging, but also for direct digital control (DDC) of turbines and boilers.

In the 1980s, demand arose for flexible plant operation such as daily startup and shutdown (DSS), and advanced functions such as automation in monitoring control systems. To meet these needs, we developed the MELSEP700/500 digital control units that used 16-bit microprocessors, thus improving controllability, reliability and maintainability.

The role of computers grew, leading to the development of the MELCOM350-60 series. This led to high-speed computing performance and enhanced real-time operation, thus saving labor and enabling flexible plant operation through automation.

In the 1990s, with widespread computerization, there was an increasing need for monitoring operations using a cathode ray tube (CRT) instead of the control console panel for boiler turbine generator (BTG), resulting in the development of the MELSEP2000 CRT operation unit and also the MELSEP500PLUS control unit. This resulted in a more substantial man-machine interface, and greatly increased the range of applications for digital technology in high-speed networks and other applications.

The 2000s saw an increasing demand for reduction of the environmental burden, and new demand for downsizing and openness of specifications. Regarding control equipment, we developed the MELSEP550, which reduces the number of panel faces by 30 to 50%. Regarding the computer/CRT operation equipment, we developed the MELSEP2000S/C, which

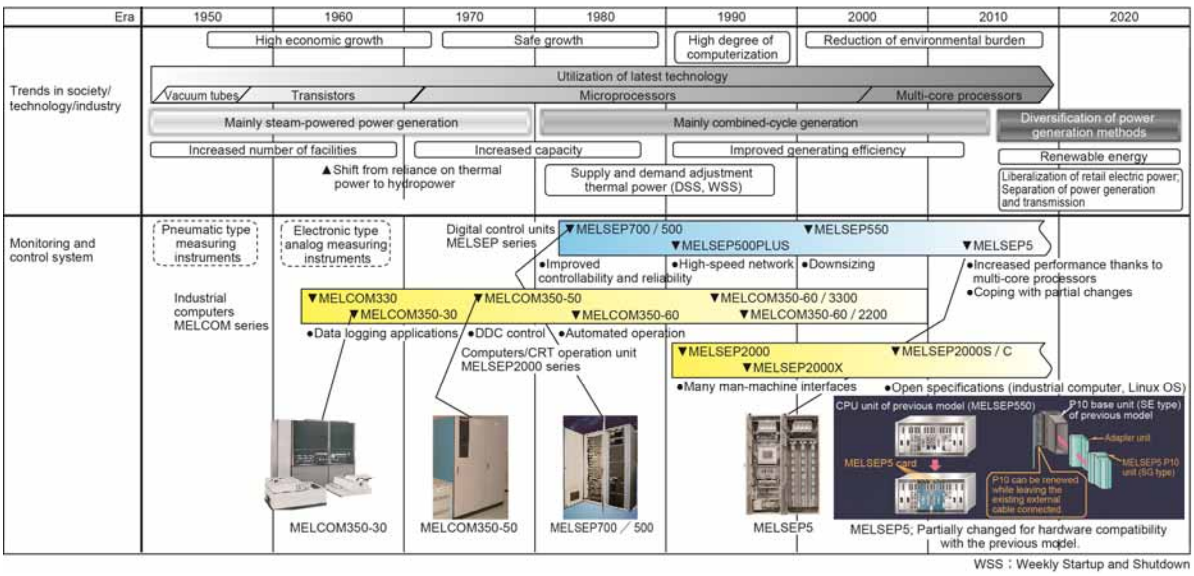


Fig. 2 Transition of technology for thermal power generating systems

is intended for industrial PCs and uses the Linux[1] OS. These have been combined into a system to meet the needs of the market.

2.1.3 Latest technology

The MELSEP5, which is the latest model of control equipment, meets a wide range of needs for reducing the environmental load and saving labor, such as high performance using a multi-core processor, stronger collaboration with CRT operation equipment, the adoption of universal design, and hardware compatibility with previous models.

2.1.4 Future trends

Thermal power generation is likely to remain the main source of electric power, although the types of electric power generation will diversify with the expanding use of renewable energy sources. With the deregulation of retail electric power and the separation of generation and transmission, there will also be an increasing need for optimum utilization of the entire power system by controlling supply and demand and energy storage. Regarding monitoring control systems as well, the changing needs for higher operability, controllability and labor saving will be met by utilizing our extensive know-how and the latest electronics and IT technologies.

2.2 Nuclear power generating systems

To meet social needs for safe and reliable pressurized water reactor (PWR) type nuclear power plants, as the Mitsubishi Group, we have been continuously developing technologies with a particular focus on the electrical and instrumentation & control fields since the dawn of nuclear energy in the 1960s. We also, with Mitsubishi Heavy Industries, have carried out joint research with domestic utilities on this field and have delivered numerous products to power stations.

The following sections describe the transition of our technology and our future work. (Fig. 3).

2.2.1 First generation: Import and domestic production

The electrical and instrumentation & control systems applied for the initial nuclear power plants, such as reactor coolant pump motors, control rod drive mechanism control system, electrical penetration and radiation monitoring system which are all specific to nuclear power plants, are mainly consisted of imported items from the U.S.

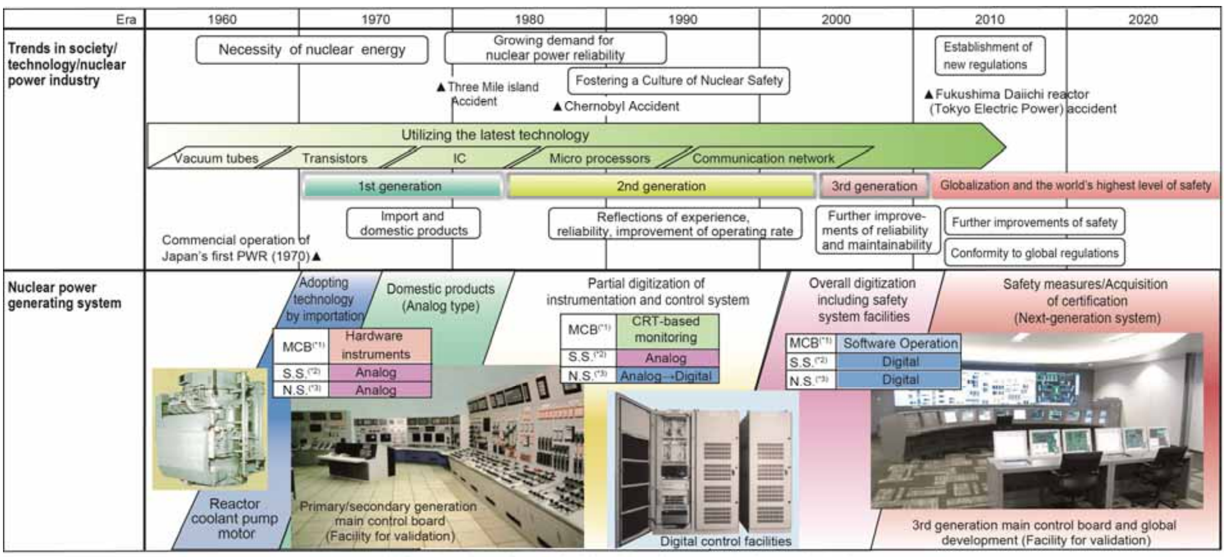
In the next step, we developed our own technologies and improved the design such as miniaturization for subsequent plants.

In those days, the control and protection system and other units consisted of box-type measuring instruments and analog cards. Computers were used not for monitoring the entire plant, but rather for partial assistance of monitoring and supplementary applications such as performing calculations.

2.2.2 Second generation: Standardization, reliability and operating rate improvement

At this stage, we utilized our accumulated experience in plant construction and operation to design and manufacture electrical instrumentation equipment.

We also promoted the latest technology, standardization of electrical instrumentation equipment



(*1) MCB : Main Control Board (*2) S.S. : Safety System (*3) N.S. : Non-Safety System

Fig. 3 Transition of technology for nuclear power generating systems

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1 Linux is a registered trademark of Linus Torvalds.

and improvement of reliability.

In instrumentation and control equipment, we improved the reliability of the system and started introducing digital equipment as follows.

- Adoption of a double-hold system for the control rod drive mechanism and multiplex detectors for the rod position indication system
- Adoption of digital system for auxiliary equipment
- Expanding the scope of CRT-based monitoring

Next, we improved the man-machine interface and operating rate as follows.

- Expansion of automated operation by digitization of the reactor control systems, radiation monitors, etc.
- Improvement of reliability and maintainability by introducing multiplex system technology, distributed control system and self-diagnostic functions
- Improvement of ease of identifying important alarms by using the above functions

Regarding electrical equipment, we reduced the number of transformers and strengthened the power receiving system by utilizing generator load break switches (GLBS).

2.2.3 Third generation: Additional improvement of reliability and maintainability

In the third generation, we achieved total digitization including the monitoring, operation, control and protection systems, by applying microprocessor technology, high-speed data transmission, and equipment with improved electromagnetic compatibility (EMC).

In this fully digital system, we digitized the safety system by applying the following technologies:

- High reliability software technology
  Rigid execution without interrupt and fixed-cycle operation
  All white-boxed software
- Verification and validation technology (V&V technology)
  Step-by-step and rigorous verification system

In addition, by using the following digital technology, we were able to make the most of the reliability, information transmission and maintainability advantages:

- Integration of various facilities
- Interconnection between equipment via the communication system
- Unified management of information
- Prevention of human errors and reduction of operator workload based on task analysis
- Man-machine interface verified by nuclear power plant operators (all software operation)

By using these latest technologies, we were able to improve the function, performance and reliability of new and existing nuclear plants.

Regarding electrical equipment, we upgraded the generator capacity, enhanced power saving and downsized uninterruptible power supplies (UPS) and switch gear.

2.2.4 Approach to globalization and the world's highest level of safety

Based on technologies developed in Japan, we are now acquiring certification from the United States Nuclear Regulatory Commission (NRC) for safety system platforms.

As of June 2014, we have delivered 14 sets of this safety system to China CPR (China PWR) plants.

Also, to implement safety measures which meet the latest Japanese regulatory guidelines, and to achieve the world's highest level of safety, we are conducting development in response to the diversification of power supplies, reinforcement of seismic resistance and security, and functions for severe accidents.

Additionally, in the field of nuclear power generation, we will continue global development as a comprehensive supplier of electrical and instrumentation facilities that conform to the regulations of various countries.

2.3 Turbine generators

The history of our turbine generators was commenced in 1908 when a 2-pole 625 kVA generator was manufactured at the Mitsubishi Shipyard in Nagasaki as the central power generating station for the shipyard. Subsequently, a technical agreement was signed with Westinghouse Electric, resulting in significant technical progress to meet the rapidly increasing demand for electric power during the postwar restoration and high economic growth period. The technology trends of turbine generators, which have developed along with the changes in society and economy (Fig. 4), are described below.

2.3.1 Transition of technology

(1) Increase in facilities to match the increased demand for electric power (1950s and 1960s)

Generators that used hydrogen gas as a coolant started spreading throughout the market in order to cope with the increased demand for electric power after the end of the war. Basically, hydrogen gas has high cooling performance compared to air. Particularly, with the development of the direct cooling system in which ventilation tubes are installed inside the coil (inner-cooling), the maximum capacity of the generator continued to increase. Subsequent to manufacturing our first hydrogen inner-cooled generator in 1959, which had a capacity of 208 MVA, we manufactured record-breaking generators one after the other, and from

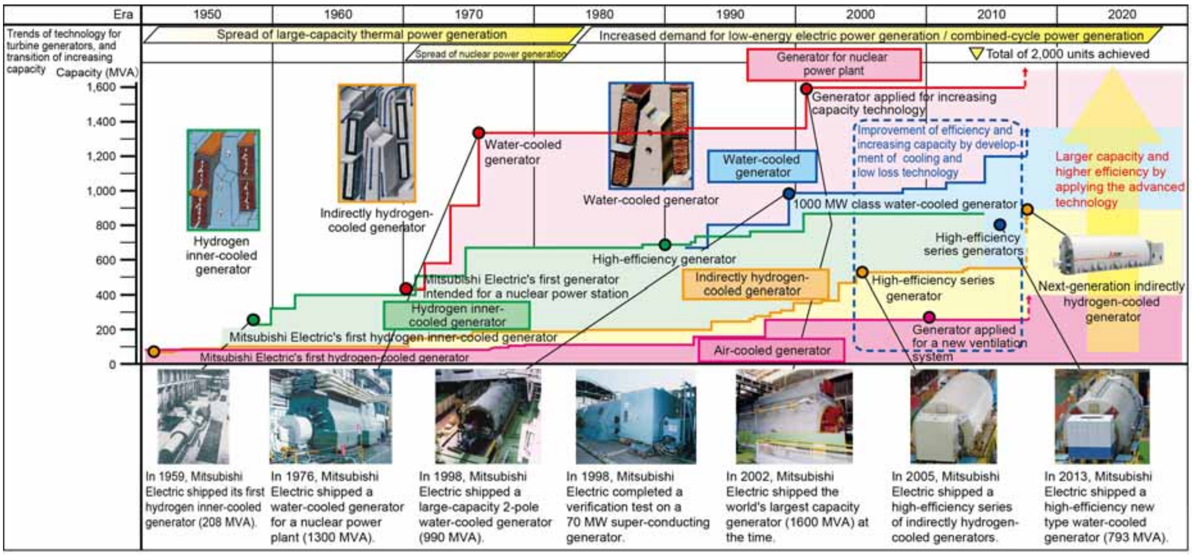


Fig. 4 Transition of technology for turbine generators

around 1965 we were manufacturing large-capacity generators of between 400 and 500 MVA.

(2) Increase in capacity of generators for thermal/nuclear power generation (1970s and 1980s)

Following the oil shocks, the construction of nuclear power plants kicked into gear, and so we developed generators for these plants. As a result, the capacity of our turbine generators for nuclear power plants more than tripled from the conventional 400 MVA to 1300 MVA. Among the factors responsible for the dramatic increase in generator capacity, the use of water for cooling the stator coil was particularly important. High-quality water-cooling technology was established while issues such as corrosion of the flow path and water leakage were resolved by repeatedly performing trial manufacture and verification. Subsequently, water-cooling technology which was applied to large-capacity generators for nuclear power plants was also applied to turbine generators for thermal power plants, thus the unit capacity of the generator was increased markedly.

As public demand for energy conservation increased, we focused on manufacturing more efficient turbine generators. With advances in the performance of computers, more sophisticated mathematical processing of electromagnetic fields and ventilation became possible. Consequently, technology for optimizing the structure of the rotor cross-section as well as ventilation and cooling system was developed, and in 1989 we manufactured a 670 MVA water-cooled generator incorporating new technology that resulted in 0.2% higher efficiency than that of conventional generators.

(3) Improved economy and efficiency of electric power generating facilities (1990s and 2000s)

Even after the collapse of the bubble economy, overseas demand for electric power remained robust, so we developed large-capacity generators, as well as high-strength shaft materials and retaining rings, and we also manufactured larger-diameter rotors, thus greatly improving capacity. In the case of 2-pole generators for thermal power plants, we manufactured a 990 MVA generator in 1998, and in the case of 4-pole generators for nuclear power plants, we manufactured a 1600 MVA generator in 2002.

Meanwhile, the combined cycle power generation using a gas turbine (GTCC), which has high thermal efficiency, spread throughout the world, and the development of large-capacity, high-efficiency, indirectly hydrogen-cooled generators were progressed. These generators featured a simple ventilation system that was highly efficient. However, in terms of cooling, they were inferior to generators that used inner-cooling, so we improved the cooling performance and increased the capacity of indirectly hydrogen-cooled generators by using a high-performance insulation system, high-efficiency fans, and so on. In addition, we used electromagnetic field and fluid analysis using the 3-dimensional finite element method (FEM) to create a low-loss structure. We also adopted low-loss bearings and other parts, boosting efficiency by 0.2% compared to a conventional generator of the same rated capacity.

(4) Latest technology

The maximum capacity of generators has increased, and designs have been completed for water-cooled 2-pole 1400 MVA class and 4-pole 2000 MVA class generators, and also for air-cooled 350 MVA class generators. In 2013, we manufactured and shipped a new type of high-efficiency water-cooled generator that applies the same simple ventilation system for an indirectly hydrogen-cooled generator. This generator was realized not only by using high-strength materials, but also by the improvement in cooling performance using high-performance insulation and also the improved cooling system by ventilation. In addition to these technologies, we use advanced high-performance insulation with improved thermal conductivity. Consequently, we completed the development and commercialization of high-efficiency 900 MVA class indirectly hydrogen-cooled generators in 2014.

2.3.2 Future trends

To further improve efficiency and capacity, we are developing high-performance insulation systems and advanced element technologies. We are also using IT (information technology) to develop manufacturing technology, condition monitoring technology, and preventive maintenance technology. We will continue to offer products and services that meet the needs of society and also the demands of our customers, while keeping in mind the application of our superconducting generator technology.

2.4 Hydroelectric power generating systems

We have a history of more than 100 years. Hydroelectric power generating systems, which were previously the main source of electric power in Japan, have recently gained attention again because they are a clean renewable energy. Already, pumped-storage power stations are acting as electricity storage facilities, and have contributed to smoothing out the variable demand load for electric power. In an adjustable-speed pumped-storage generating system, the high-speed power control function used for system stabilization is particularly effective. The following section describes the trends of technology for hydroelectric power generating systems developed to meet a wide range of needs (Fig. 5).

2.4.1 Trends in technology for hydroelectric power generating facilities

In order to comply with the limitations on construction sites for power stations and also to reduce construction costs, since 1980 we have been developing various element technologies to increase the speed and capacity of hydroelectric generators, regardless of whether they are normal or pumped-storage. Some of these technical innovations are described below.

(1) Generators

It goes without saying that the strength of the rotor must be increased in order to build a large-capacity, high-speed generator. However, the key issues are to improve the bearing reliability and develop a suitable cooling method.

1) Plastic bearings

Among the various parts of a generator, the bearings require very high reliability. We have developed a technology in which PEEK (polyetheretherketone) plastic[2] is used for the sliding faces of bearings, resulting in superior wear resistance, anti-seize performance, and high-temperature mechanical strength, and also lower sliding friction coefficient, compared to conventional white metal. In 1999, starting with the application of plastic bearings to medium-capacity generators, we gained experience with small-to-medium normal hydroelectric generators. In 2003, we used plastic bearings in pumped-storage generator/motors.

2) Cooling technology

Along with the move to greater capacity, the most important element that determines the manufacturing limit is the cooling of the stator and rotor. Based on analysis, we developed a self-cooling ventilation cooling method in which a radial fan and a rim duct were

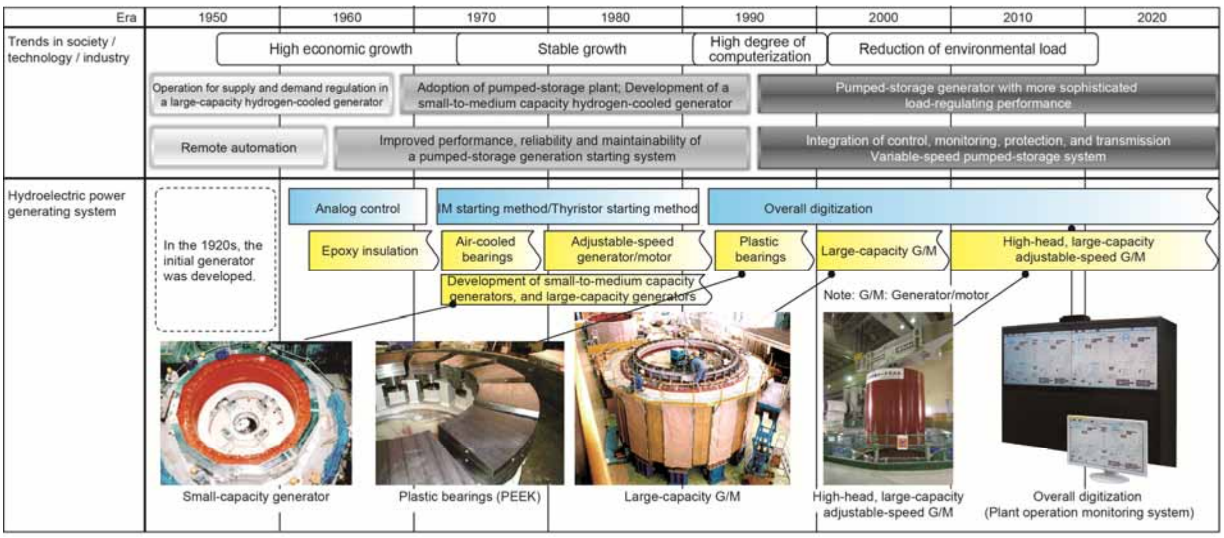


Fig. 5 Transition of technology for hydroelectric power generating systems

2 PEEK is a registered trademark of Victrex Manufacturing Limited.

optimally combined. In 2000, we used this cooling method in a pumped-storage generator/motor to significantly increase the capacity and rotational speed compared to conventional generators.

(2) Monitoring and control units

Monitoring and control units are digitized, and in recent years they have made it possible to monitor operations from a remote location by using a control network and an operator station (OPS). Also, these units are becoming increasingly compact, power saving type and have superior reliability and high functionality (easier maintenance), thus reducing the environmental burden and enabling high performance plant control.

2.4.2 Trends of technology for adjustable-speed pumped-storage generating systems

Adjustable-speed pumped-storage generating systems are attracting attention as electric power generating systems that can contribute to the stability of electric power systems by maintaining the system voltage and suppressing variations in system frequency, amid the increasing amount of wind and solar power generation in recent years. On the other hand, compared to a normal hydroelectric system, more facilities are required, so greater economy by increasing the capacity is needed. In addition, compactness through higher speed is a technical issue.

The rotor of an adjustable-speed pumped-storage generator/motor differs from the salient pole rotor of a normal generator/motor even though it uses the same 3-phase windings as that of the stator. However, because centrifugal force is proportional to the square of rotational speed, it is difficult to secure adequate strength at the coil ends as the speed increases. For this reason, in 1994 we developed a coil support structure using binding wire, which was intended for high-speed generators, and we delivered two machines of the world's highest speed class of 600 r/min in 2009 and 2011, respectively, in Japan, and also a third machine in 2010 overseas.

2.4.3 Future trends

We believe that hydroelectric power generating systems will continue to play an important role in the "best mix of power sources" in the future.

We are promoting the adoption of an adjustable-speed pumped-storage system that improves system stability and is more compact. We are also working on extending the life of power stations and making maximum use of water resources, by updating the existing generators to the latest high-efficiency generators.

3. Future Prospects

Since the Great East Japan Earthquake in 2011, a stable supply of electric power is increasingly pursued and efforts are being accelerated for developing new energy sources, starting with a review of electric power supply. As indicated by the increased use of power generation from renewable energy sources, energy sources have diversified and there is increasing awareness of the effectiveness of dispersed energy systems. In the power market, there is strong demand for new solutions such as energy supply and demand management tailored to regional characteristics and improved operation of the entire electric power system that supports such supply and demand management.

Together with the transition of power generation systems, we have been increasing the capacity and compactness of electric power generators, the main circuit facilities, and so on, using sophisticated technology that supports these power systems, and have been ensuring the stable operation of generation systems and energy saving through the latest

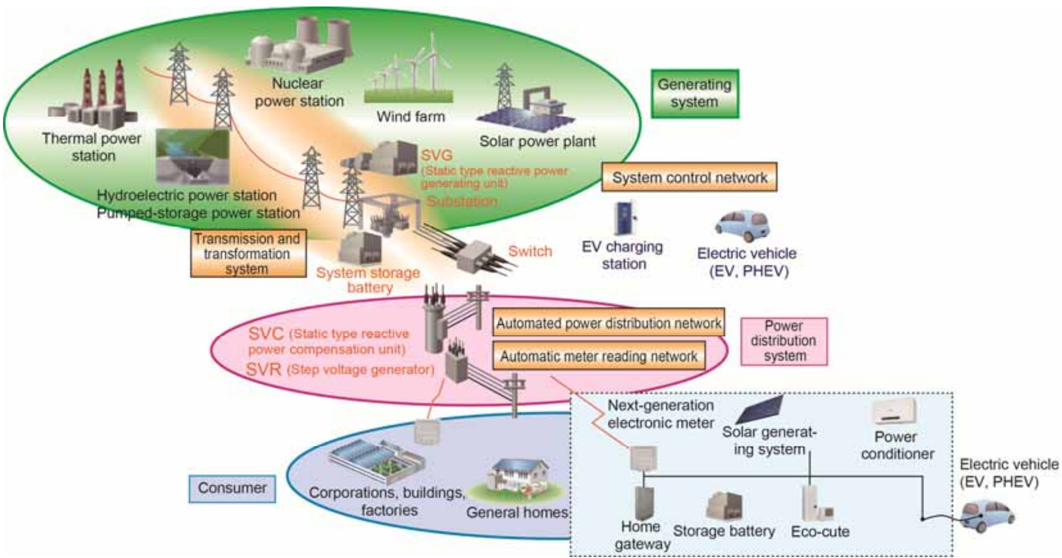


Fig. 6 Future Prospects of electric power systems

monitoring control technologies. In recent years, in line with the trend toward increased capacity of power generators, we have been supplying high-efficiency, environmentally-friendly electrical machinery by developing static-type starting units utilizing power electronics which are indispensable for starting up gas turbines, which are becoming more widely used. In this way, we have been helping to create the optimum power generating system.

4. Conclusion

While using thermal, nuclear energy or hydroelectric power generating systems as the core of the power generating system, Mitsubishi Electric will meet the demands from and contribute to a diversifying society by:

(1) meeting the demand for optimum operation of new energies, which are increasing amid the liberalization of the electric power market such as by combining sophisticated technologies for monitoring control, information communications and information processing; and

(2) developing and manufacturing electrical machineries that are supported by sophisticated technologies for electric generators, main circuit facilities and other units required for thermal, nuclear energy or hydroelectric power generation.

Completion of World's First 900-MVA-Class Turbine Generator Applied Indirectly Hydrogen-Cooling

Authors: *Masahiro Kondo** and *Kiyonori Koga**

1. Introduction

Against the background of global warming due to CO_2 emissions, and the world's increasing demand for electric power, there is an urgent need to improve energy efficiency, and to develop turbine generators with higher output and higher efficiency than existing ones. Mitsubishi Electric manufactured its newly developed 900-MVA class generators applied indirectly hydrogen-cooling. This output is the world's highest for an indirectly hydrogen-cooled generator. This paper outlines the latest technologies used in this developed generator, and also the results of factory tests carried out on the generator.

2. Specifications of a Developed Verification Generator

Figure 1 shows the exterior of the developed verification generator, and Table 1 shows its specifications. By applying the advanced technologies, which are described later, we achieved a world's first 900-MVA-Class and 99% efficiency world's highest level for an indirectly hydrogen-cooled generator. The generator is achieved not only this high output but also high output density by approx. 20% increased and compact design by approx. 20% reduced compared to conventional indirectly hydrogen-cooled generator. Incidentally, this high output density was realized by the enhanced cooling performance and this compact design was also realized by the optimum layout structure, thus the transportability has been improved and installation space can be saved.

Fig. 1 870 MVA turbine generator used for verification test

Table1 870 MVA turbine generator (verification model)

Maximum output	870 MVA
Power factor	0.90 (lagging)
Rotating speed	3600 min^{-1}
Frequency	60 Hz
Number of poles	2
Efficiency	99%
Cooling system	Indirectly hydrogen-cooling

Figure 2 shows the lineup of generators classified according to cooling method. Mitsubishi Electric's lineup comprises three types of generators: air-cooled, indirectly hydrogen-cooled, and water-cooled. We selected the optimum cooling method according to the generated output. As a result of developing cooling technologies, it became possible to use indirectly hydrogen-cooling up to the 900-MVA class high-output region, previously this region could only be covered with applying a water-cooling method. The indirectly hydrogen-cooling method does not require auxiliary equipment such as a stator cooling water supply unit, making maintenance much easier.

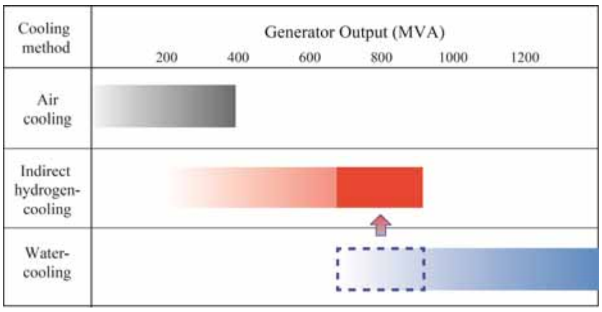


Fig. 2 Lineup of two-pole turbine generators

3. Technologies Applied to Developed Generator

3.1 Technologies for realizing high-output generators

3.1.1 Increasing the performance of the stator coil insulation

In the indirectly hydrogen-cooling method, heat generated in the copper conductors of the stator coils is

*Energy Systems Center

cooled by hydrogen gas via the main insulation, In order to achieve a high output for indirectly hydrogen-cooled generator, it is important to improve the thermal conductivity of the main insulation of the stator coil.

The main insulation of the stator coil mainly consists of glass cloth, mica layers, and thermosetting resin. Of these component materials, thermosetting resin has the lowest thermal conductivity. To improve the thermal conductivity of main insulation, a filler with high thermal conductivity has been usually added to the thermosetting resin. However, in the conventional manufacturing method, the filler flowed out during the resin impregnation process, leaving insufficient filler. To overcome this, we optimized the manufacturing process, and successfully reduced the outflow of filler. As a result, we achieved high thermal conductivity of the main insulation, without changing the component materials of the insulation, which have a proven track record.

As a result of measuring the thermal conductivity of the main insulation, which were acquired using the verification tested generator and also a life-size model coil, it was confirmed that the thermal conductivity of developed coils main insulation was at least 10% greater than that of convention insulation.

3.1.2 Optimization of form of the ventilation paths

Figure 3 shows a schematic diagram of the ventilation flow used in an indirectly hydrogen-cooled generator. For the developed verification generator, we continued using this highly reliable flow system, which has a proven record in conventional-type generators. This cooling method features simple ventilation in the radial direction of the stator.

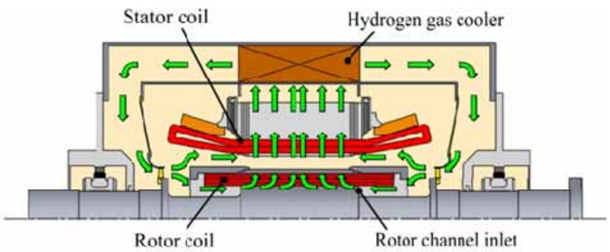


Fig. 3 Flow diagram of hydrogen gas in generator

The shape of the ventilation paths for cooling was optimized based on computation fluid dynamics analysis and wind tunnel tests of section model, consequently, the pressure loss was decreased and the cooling performance was improved. Figure 4 shows one example of optimizing to the rotor channel inlet. As a result of this form optimization, it was confirmed by computation fluid dynamics analysis and wind tunnel tests of section model that the pressure loss at each part was reduced by approximately 60% compared to the conventional form.

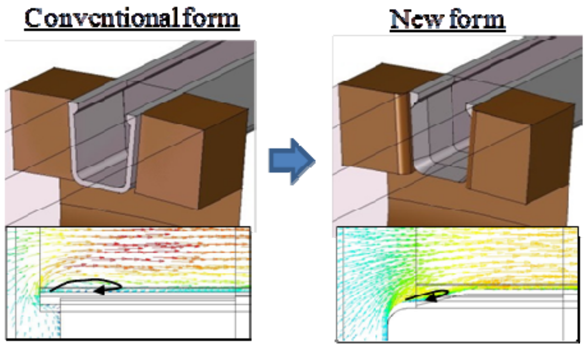


Fig. 4 Optimized form of rotor channel inlet

The ventilation valance at each part was adjusted using ventilation and thermal network analysis calculation to obtain a uniform temperature distribution inside the generator. In the factory verification tests, the temperature and ventilation valance were measured at each part, and it was confirmed that the measured values agreed well with the design values and also satisfied the standards criteria.

3.1.3 Loss and temperature analysis technology at the stator core end

By improving cooling performance for coils, the output density was increased by approx. 20% compared to that of conventional generators. Not to mention, loss due to leakage flux at the end of the stator was increased by increasing of the output density, thus overheating of the core end had to be prevented. Consequently, loss and temperature were evaluated by three-dimensional electromagnetic and thermal analyses, taking eddy current into consideration. Figure 5 shows an example of the analysis results. The precision of this analysis was confirmed by comparison of core end temperatures between the analyzed values and the measured values of the verification tested generator under three-phase short-circuit. In addition, the temperatures at the core end were confirmed to be lower than the permissible temperature under leading power factor operation by this analysis.

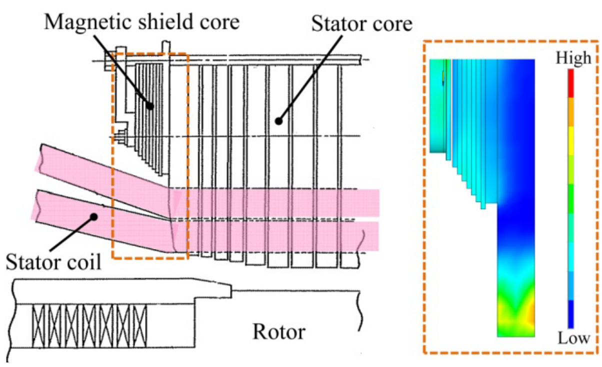
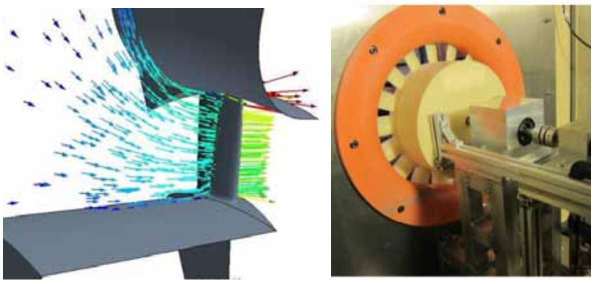


Fig. 5 Thermal analysis at stator core end under 3-phase short circuit test

3.2 Technology for high efficiency

3.2.1 Low-loss fan

The windage loss is divided into fan drive power loss, pressure loss and friction loss occurring in the ventilation path. In the developed verification generator, the efficiency of the fan was improved by optimizing the shape of the fan blades and also by optimizing the form at the fan inlet zone by computation fluid dynamics analysis. As a result, the efficiency was improved by approx. 10 points compared to the conventional fan. After the appropriateness of the fan design was verified by the wind tunnel test of scale model fan (Fig. 6), the fan was applied to the verification tested generator.



CFD analysis Wind tunnel test

Fig. 6 Computation fluid dynamics (CFD) analysis and wind tunnel test of fan

3.2.2 Low-loss bearings

Conventionally, the direct lubrication tilting pad bearings, which equipped oil feed nozzles to supply lubrication oil directly to the journal and which have excellent vibration characteristics and relatively low loss, have been applied to the generator. In the developed verification generator, the number of pads on the tilting pad bearings was optimized, thus bearing loss was reduced by approx. 30% compared to the conventional tilting pad bearings. It was confirmed that the measured bearing loss agreed with the design value and also that the shaft vibration characteristics was good in the test using developed verification generator.

3.3 Technology for compact package

A compact design is essential for turbine generators in order to avoid limitations on railway transportation and also to reduce the installation area. In the case of the developed verification generator, the performance of the fins on the hydrogen gas cooler was improved by approx. 30% compared to conventional one thus the size of the hydrogen gas cooler could be reduced. In addition, the layout of the hydrogen gas cooler was optimized, thus the outer diameter of the stator frame was reduced by approx. 20% (Fig. 7). During the design of the stator frame, the structure was optimized by large-scale finite element method (FEM) analysis. The soundness of strength and vibration characteristics for the stator frame was confirmed in the tests using developed verification generator.

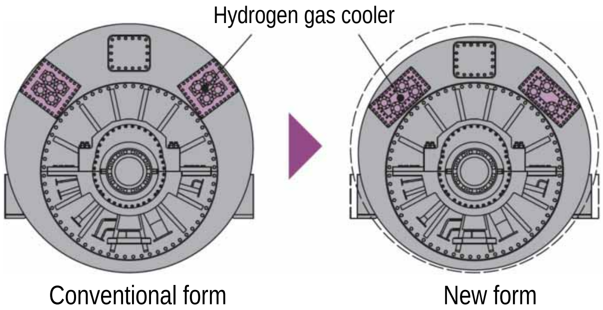


Fig. 7 Downsizing of stator frame

4. Actual Generator Verification Test Results

An outline of the factory tests results about the developed verification generator is shown below. All results were satisfactory.

1) No load saturation characteristics

We measured the field current during no-load open-circuit operation and also during three-phase short-circuit operation, and confirmed that the measured values agreed well with the design values.

2) Loss and efficiency

We measured each loss and confirmed that they agreed with the design value. The efficiency of this generator exceeded 99%.

3) Temperature

The temperature at each part was measured during the equivalent heat run operations. We confirmed that all determination values of temperature at rated output condition had an adequate margin to the standard criteria, and that the measured temperatures agreed with the design values.

4) Rotor vibration characteristics

We confirmed that the variation of vibration was sufficiently small when the rotation was speeded up and down, that the vibration of vibration was sufficiently small when the rotor coil temperature was equivalent to that of the rated operation.

5) Noise and vibration of stator frame, coil end and core

We confirmed that the vibration value at each part and also the measured noise level was lower than the design criteria.

5. Conclusion

We carried out factory tests on a 900-MVA class indirectly hydrogen-cooled turbine generator, which was world's highest output, and confirmed that the performances of the generator agreed with the design values. Based on this achievement, we are currently developing a lineup of high output and high efficiency generators to be supplied to the market.

Reference

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Development of 420 kV Gas Insulated Switchgear

Authors: *Masahiro Fujioka** and *Daisuke Yoshida**

The latest 420 kV gas insulated switchgear (GIS) with one-break spring-operated gas circuit breaker (GCB) has been developed to reduce the costs imposed on utilities during installation, operation and maintenance. Application of the developed 420 kV GIS delivers the following benefits:

1) Reduced installation period

Compact design using one-break GCB and convergent configuration enables reduction of installation work by 30% in comparison with existing GIS using two-break GCB. Transportation of a single package per unit can reduce site construction work by 30% of that for existing GIS that require five separate packages per unit. Compactness also reduces the installation footprint of switchgear to 60% of that for existing switchgear, and results in the reduction of land cost for the whole substation.

2) Reduced maintenance work

Single access direction for maintenance is considered by applying a convergent configuration for the operating mechanism. The flexible linkage system for the disconnectors (DS) and earthing switches (ES) enables convergent configuration of all operating mechanisms located in front of the GIS unit.

3) Reduced environmental impact

SF_6 gas is reduced to 60% compared to existing GIS because of the compact design of the developed GIS. The use of material and number of parts can also be reduced to 50% and 70%, respectively.

1. Introduction

Reduction of life-cycle cost of high-voltage electric equipment including installation and maintenance costs is an increasing need for electric power utilities as the construction of substations is continuing to accelerate due to global urbanization.

The latest 420 kV gas insulated switchgear (GIS) has been developed to meet the growing demand for substation construction together with the demand for reduced installation and maintenance costs.

One-break gas circuit breakers (GCB) and disconnectors (DS) / earthing switches (ES) with flexible linkage are applied. The key features of the developed 420 kV GIS are described.

2. Basic specifications and structure

International standards are considered in determining the specifications of the 420 kV GIS. Table 1 shows the major ratings for the GIS, determined in accordance with IEC-62271-100, 102 and 203.

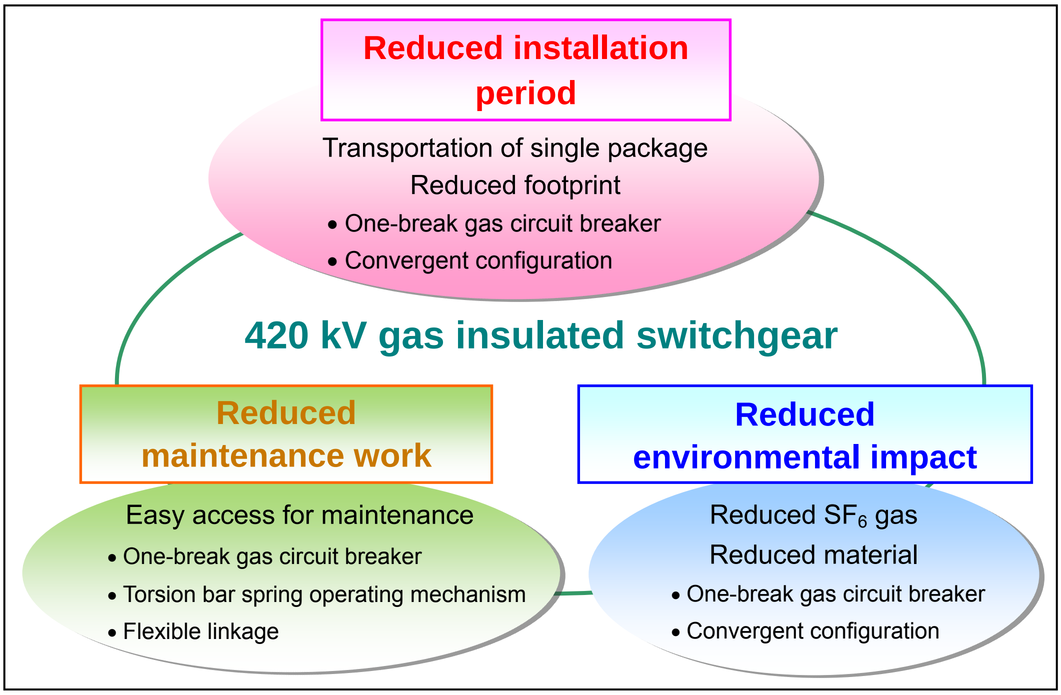

Fig.1 Features of the latest 420 kV GIS

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Table 1 Ratings of 420 kV GIS

GIS	Rated voltage		420 kV
	Rated normal current		Up to 5000 A
	Rated short time withstand current		63 kA
	Rated frequency		50 / 60 Hz
	Dielectric	Lightning impulse voltage	1425 kV
		Switching impulse voltage	1050 kV
		Power frequency voltage	650 kV
	Rated pressure of SF_6 gas		GIS: 0.6 MPa-g GCB: 0.7 MPa-g
GCB	Rated breaking current		63 kA
	Rated breaking time		2 cycles
DS	Busbar transfer current switching		20 V / 1600 A
Fast Earthing Switch (FES)	Electromagnetically induced current switching		10 kV / 160 A
	Electrostatically induced current switching		20 kV / 18 A

Application of the one-break GCB and convergent main busbar configuration enables the structure of the GIS to be made compact. Figures 2 and 3 compare the outline and cross-sectional structure of the existing GIS and the developed GIS, respectively. The reduced size of GCB contributes to the convergent configuration of the primary circuit connected to both sides of the GCB. The operating mechanism for the GCB is placed

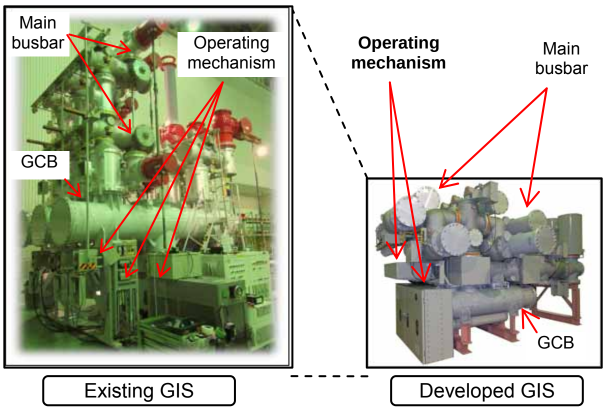

Fig. 2 Comparison of outward appearance of existing and developed GIS

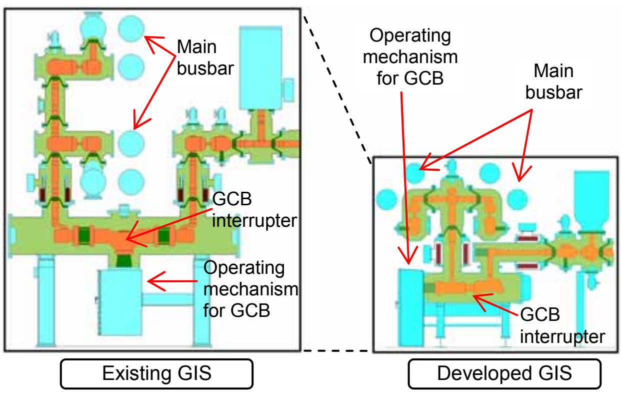

Fig. 3 Comparison of inside structure of existing and developed GIS

horizontally to the GCB interrupter, which results in a lower height of the GCB than that for existing GIS. The three-phase double main busbar that is arranged vertically in existing GIS is rearranged horizontally in the developed GIS to reduce the total height of the GIS.

Table 2 compares the footprint, cubic volume and total height between the existing GIS and the developed GIS. These values are reduced to 50%, 30% and 50%, respectively.

Table 2 Comparison of typical size of existing and developed GIS

	Existing GIS	Developed GIS
Footprint	100%	50%
Cubic volume	100%	30%
Height	100%	50%

3. Features of developed 420 kV GIS

3.1 Reduced installation period[1]

Site construction work can be minimized because the whole unit is transported as a single package, whereas for existing GIS each unit must be divided into five packages. Figure 4 shows the difference between the existing GIS and the developed GIS in transportation packages for one unit; as a result, the on-site installation period can be reduced to 70%.

The compact structure reduces the land and building costs for the substation. Figure 5 shows a top view of the typical whole switchgear construction for the substation when using existing GIS or the developed GIS. The footprint of the total construction can be reduced to 60%.

3.2 Reduced maintenance work

3.2.1 Torsion bar spring mechanism[2][3][4]

Spring operating mechanisms have been used to develop higher interrupting capabilities while also providing the benefits of increased mechanical reliability and reduced maintenance work.

A spring operating mechanism stores mechanical energy in the solid spring. Since the operating

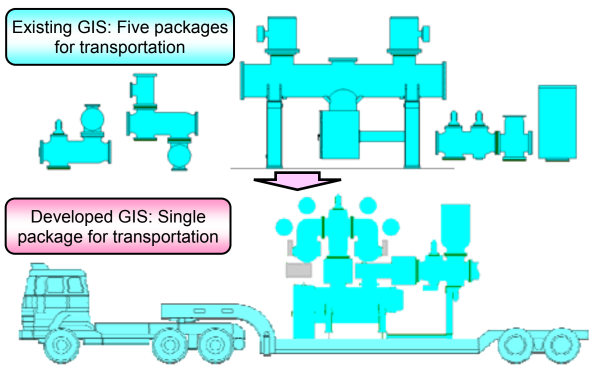

Fig. 4 Transport configuration

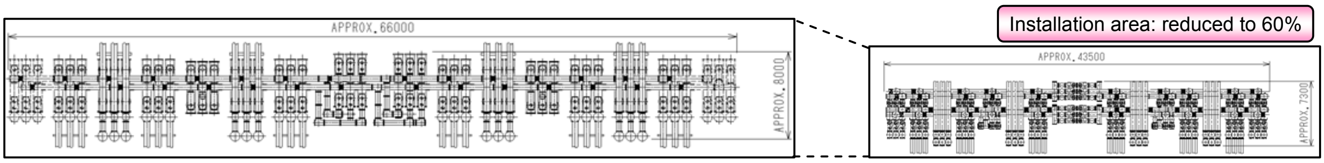

Fig. 5 Reduced substation footprint

characteristics of a spring operating mechanism are less affected by changes in ambient temperature and loss of mechanical pressure, which often occur in hydraulic mechanisms due to hydraulic leakage, spring mechanisms are inherently superior in long-term reliability compared with pneumatic or hydraulic operating mechanisms. Lubricating material, such as sulfur molybdenum, is thermally applied on the sliding parts to optimize long-term mechanical performance by reducing friction and preventing rust.

The use of a torsion spring divided into two bars makes it possible to design a compact operating mechanism with large stored energy. A photo of a torsion spring operating mechanism is shown in Figure 6. The mechanisms have been verified by extensive testing programs. The programs include the normal mechanical endurance tests of 2,000 operations where the stored energy is 120% of the normal value, special mechanical endurance tests to confirm the change in operating characteristics when grease is removed, as well as extended mechanical endurance tests of up to 30,000□50,000 operations. A high-speed motion analyzer was also used to detect any changes during these mechanical endurance tests.

Fig. 6 Torsion bar spring mechanism

3.2.2 Improved accessibility to operating mechanism

Concentration of the mechanisms for the GCB, DS and ES at the front of the GIS unit enables easy access during maintenance. Introducing a one-break GCB makes it possible to place the operating mechanism in front of the GIS vertical to the GCB interrupter. All the operating mechanisms for DS and ES can also be located in front of the GIS thanks to the application of a flexible-linkage system. Figure 7 shows the structure of the linkage system for DS and ES in the existing GIS and the developed GIS together with the access direction for maintenance. All maintenance can be done in front of the developed GIS. Detailed construction of the flexible linkage system is also shown in the figure. Metallic wires are used to transmit operating force from the operating mechanism to the moving parts of DS or ES, and enable the operating mechanism to be flexibly located. Since all maintenance can be done on the mechanism side where the motor is located, the convergent configuration of the mechanism location is essential to reduce the time for maintenance work. In contrast, maintenance for existing GIS needs to be done in three places because the rigid linkage system limits the location of the mechanism.

3.3 Reduced environmental impact

Reduction of SF_6 gas and reduced use of materials are achieved thanks to the compact design of the developed GIS. Table 3 shows a summary comparison of the environmental impact between the existing GIS and the developed GIS. Use of SF_6 gas, material and parts is reduced to 60%, 50% and 70%, respectively.

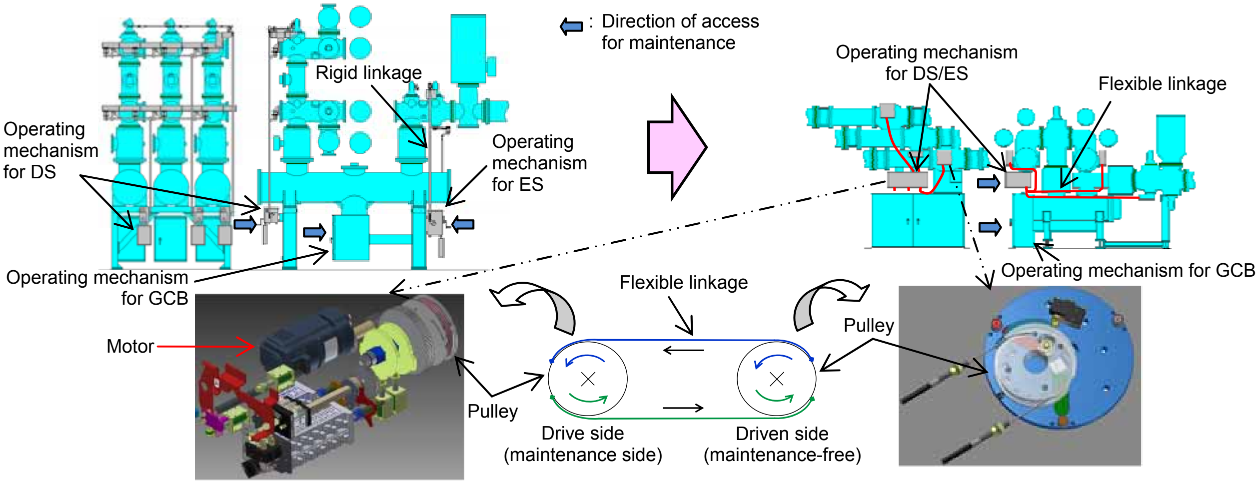

Fig. 7 Cross-section of flexible linkage

Table 3 Reduction of environmental impact

	Existing GIS	Developed GIS
SF_6 gas weight	100%	60%
Material weight	100%	50%
Number of parts	100%	70%

4. Testing

Type tests to verify the performance of the developed GIS were carried out in accordance with IEC 62271-100, 102, 203 and other related standards. Table 4 shows the performance verified with the test items. Figures 8, 9 and 10 are photos of the dielectric test, short circuit making test and interruption test with the prototype GIS. All tests finished with successful results.

Table 4 Test items in accordance with IEC

Performance	Items
Dielectric strength	Lightning impulse voltage tests
	Switching impulse voltage tests
	Power frequency voltage tests
	Partial discharge tests
Current carrying	Temperature rise tests
	Short time withstand current and peak withstand current tests
Mechanical endurance	Transportation tests
	Seismic analysis
Making and breaking current	Bus transfer current switching tests
	Induced current switching tests
	Short circuit making tests
	Bus charging current switching tests
Operation	Satisfactory operation at temperature limits tests
	Satisfactory operation and mechanical endurance tests
Interruption	GCB interruption tests

Fig. 8 Prototype 420 kV GIS under dielectric test

Fig. 9 Prototype 420 kV GIS under short circuit making test

Fig. 10 Prototype 420 kV GCB under interruption test

5. Conclusions

The latest 420 kV GIS with one-break GCB has been developed to reduce the costs for utilities during installation, operation and maintenance, and offers the following benefits:

1) Reduced installation cost

Transportation of a single package per unit reduces on-site construction work. The compact structure reduces the substation footprint, thus reducing land and building costs.

2) Reduced maintenance cost

Maintenance work and replacement of parts are reduced by the application of one-break GCB. The location of the convergent mechanism in front of the GIS unit enables easy access and reduces time for maintenance.

3) Reduced environmental impact

Reduction of SF_6 gas and reduced use of materials are achieved thanks to the compact design of the developed GIS.

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12 kV Vacuum Circuit Breaker For Overseas

Author: *Takeaki Yamanaka**

1. Introduction

A circuit breaker passes load current, and if a circuit or load device faults, it can safely turn on the power and break the current, which may range from the rated value of the circuit or load device to several dozen times the rated value. It is an indispensable switch for the stable supply of electrical energy.

Arc quenching media for circuit breakers include SF_6 gas, oil and vacuum. Among the various types of circuit breakers, vacuum circuit breakers (VCB), which use vacuum valves, have many features such as high insulation performance, isolation performance, maintainability, and safety. Consequently, they are used in a wide range of fields extending to high-voltage. Also, subsequent to the Third Conference of the Parties to the UNFCCC held in Kyoto in 1997, SF_6 gas has been specified as a greenhouse gas. It is thus necessary to reduce the reliance on SF_6 gas, and so SF_6 gas circuit breakers (GCB) are rapidly being changed to VCB. Accordingly, the range of applications of VCB is expanding.

In addition to the basic required performances such as operability, reliability and safety, a VCB must also have a lower environmental burden as well as the LCC, to help protect the global environment and create a low-carbon society. Also, in recent years, internal arcing tests are being upgraded and standardized to conform to the IEC62271-200 international standard that covers switchgear-containing circuit breakers. VCBs require a structure that takes safety into full consideration.

This paper outlines the environmental and technological trends concerning circuit breakers in recent years, and the 12-kV-rated Type 10-VPR-32D/40D (hereafter called "Type 10-VPR-32D/40D VCBs") as an example of such a circuit breaker. The Type 10-VPR-40D (GV) circuit breaker intended for GCB renewal, which uses the circuit breaker of the Type 10-VPR-40D VCB as the base unit, is also described.

2. Rating Items for Type10-VPR-32D/40D Vacuum Circuit Breakers

Table 1 lists the rating items and Fig. 1 shows the external appearance of the Type 10-VPR-32D/40D VCBs.

Table 1 Rating items of Type 10-VPR-32D/40D VCBs

Type	10-VPR-32D	10-VPR-40D
Compliance standards	JEC2300, IEC 62271-100	
Rated voltage (kV)	12	
Rated short-circuit breaking current (kA)	31.5	40
Rated normal current (A)	630/1250, 2000, 3000/3150	
Rated frequency (Hz)	50/60	

Fig. 1 Appearance of Type 10-VPR-32D/40D VCBs

3. Reduced Environmental Burden

To comply with the EU RoHS Directive and REACH regulations, we developed a new type VCB with a rated voltage of 12 kV, which does not use any of the six specified substances. We abandoned the use of hexavalent chromate treatment used in the zinc plating of bolts, pins and screws, and adopted trivalent chromate treatment instead. Before introducing the new treatment process, we carried out various tests to evaluate corrosion resistance, and so on, and confirmed the long-term reliability.

We also indicated the name of each type of material used in the main resin parts, thus facilitating the sorting of the various materials during recycling or disposal.

Figure 2 shows the transition of the vacuum valves (12 kV, 40 kA) used in a VCB. These vacuum valves use copper-based contacts, reducing the trip force when the contacts weld together while the power is turned on and current is passing through them, as well as improving the voltage resistance and interruption performance, and reducing the size and operating force

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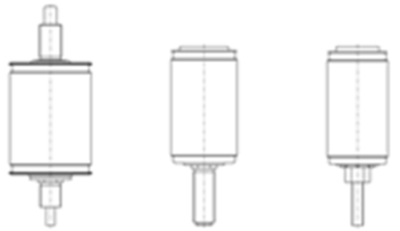
thanks to the development of the optimum electrode structure based on arc behavior analysis.



	1983	1997	Current type
Volume	100%	66%	55%

Fig. 2 Transition of miniaturization of vacuum valves for 12 kV and 40 kA

4. Safety

As safety measures required for switchgear, tests that simulate internal arcing accidents and methods for evaluating the results are covered by the IEC62271-200 standard, and consideration is given to operation and worker safety. We commercialized products through external withdrawal operation that complied with this standard, and operated the insertion/withdrawal handle with the switchgear door closed, thus making it possible to move the VCB from the test position to the connecting position (Fig. 3).

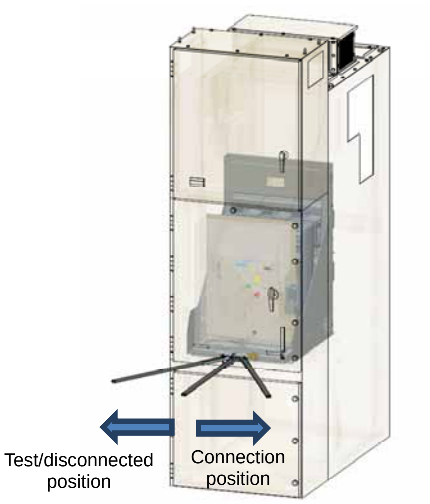


Fig. 3 External withdrawal operation method

To prevent shorting accidents caused by the entry of small animals into live sections of the main circuit, we used a cylindrical insulation molded construction and made live exposed sections as small as possible to increase the safety. In addition, we used a structure that inhibits the entry of dust and water droplets, and also considered environmental protection. We also performed a thermic fluid analysis, and based on the results, designed a cylindrical internal structure that efficiently dissipates heat, enabling self-cooling up to the rated normal current of 3150 A (based on our evaluation criteria). Figure 4 shows an example of thermic fluid analysis.

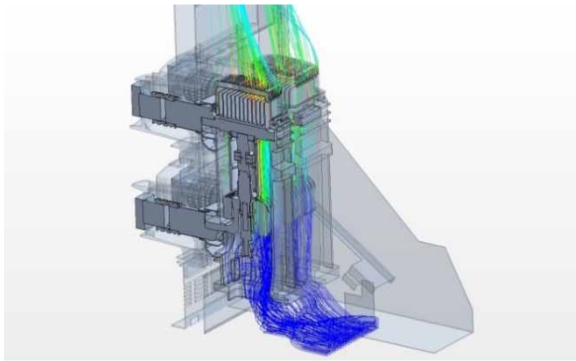


Fig. 4 Example of thermic fluid analysis

In addition, we employed UL94 (V-0) grade flame retardant resin for the main insulation parts used in the vicinity of live parts such as protective covers, to prevent the spread of fire.

5. Labor Saving in Maintenance and Inspection

When the operation mechanism of a circuit breaker is being driven, a malfunction may occur due to deterioration of the grease over time. For this reason, it is necessary to periodically lubricate the sliding parts of the operation mechanism as part of the maintenance and inspection of the circuit breaker. However, there is a need for more efficient maintenance and inspection for reducing the LCC. Therefore, we performed the 3-dimensional mechanism simulation shown in Fig. 5 to improve the motion reliability, and also used long-life grease and PTFE-based non-lubricated bearings that do not require grease for the bearings of parts driven by small force. As a result, stable operation characteristics were realized, and the lubrication interval was increased from the normal three years to six years.

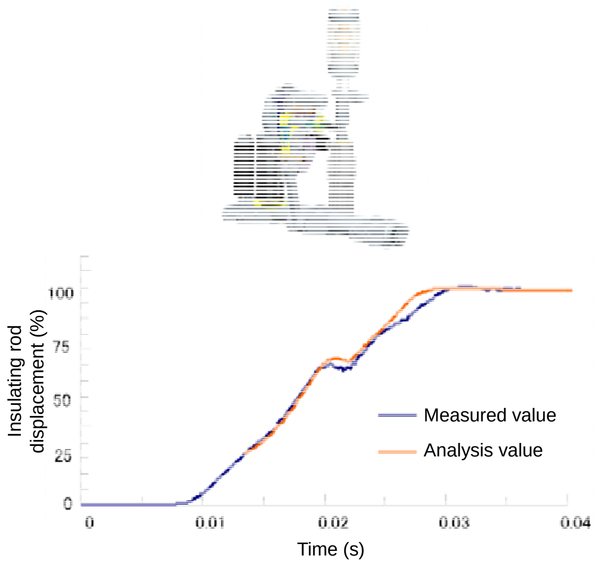


Fig. 5 Example of 3-dimensional mechanism simulation

6. Many Options

We are increasing the range of options by offering various safety devices such as a key interlock, trip coil duplication, monitoring of wire breaking, earthing switches, and an additional auxiliary switches, in order to meet various needs. Particularly, overseas demand for earthing switches is increasing, to improve safety during maintenance and inspection. Table 2 lists the rating items and Fig. 6 shows the external appearance of the earthing switch for the Type 10-VPR-D VCB.

We can provide an interlock function that enables opening/closing of the earthing switch for the first time when the VCB is in the test/disconnected position, and we can safely open and close it from the front panel of the power distribution board using the operation handle

Table 2 Earthing switch rating items

Type	10-ESV-M40D
Compliance standard	IEC62271-102
Rated voltage (kV)	12/15
Rated frequency (Hz)	50/60
Rated making current (kAp)	104
Rated short-time withstand current (kA)	40 (3 s)
Number of short-circuit applications	5 (class E2)

Fig. 6 Appearance of earthing switch

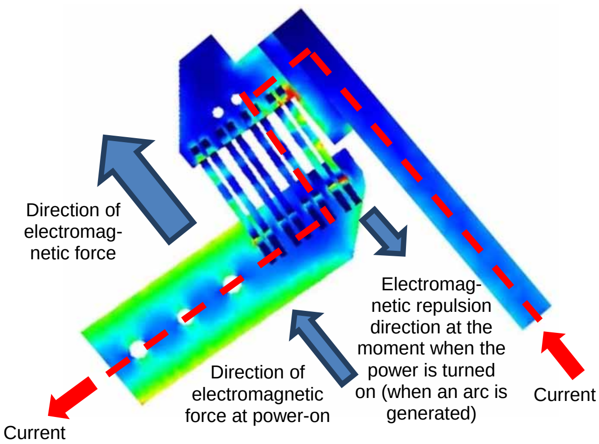


Fig. 7 Example of electromagnetic force analysis

provided. We must also ensure that the earthing switch can withstand short-circuit currents. We have modified the current flow path so that an electromagnetic force is generated in the same direction as that when the power is turned on, thus overcoming the arc electromagnetic repulsion force generated at that time. By analyzing the 3-dimensional electromagnetic force shown in Fig. 7, we studied the optimum layout, and acquired the best class, E2, in which the short-circuit current can be made to the circuit breaker five times in succession.

7. Upgrading to a Retrofit for GCB

The GCB was the main type of circuit breaker in the 1970s. More than 30 years later, these will now need to be replaced. However, in view of lower environmental burden, SF_6 gas treatment, and cleaning of the interruption part, it is desirable to change over to the VCB.

Accordingly, we developed the retrofit Type 10-VPR-40D (GV) VCB, which is based on Type 10-VPR-32D/40D VCBs.

7.1. Rating items

Table 3 lists the rated items and Fig. 8 shows the external appearance of the Type 10-VPR-40D (GV) VCB.

Table 3 Rating items of Type 10-VPR-40D (GV) VCB

Type	10-SFG-40 (To be renewed)	10-VPR-40D (GV) (VCB for renewal)
Compliance standards	IEC 56 JEC2300	IEC 62271-100 JEC2300
Rated voltage (kV)	12	
Rated short-circuit breaking current (kA)	40	
Rated normal current (A)	630/1250, 2000, 3000/3150	
Rated frequency (Hz)	50/60	

Fig. 8 Appearance of Type 10-VPR-40D (GV) VCB

7.2. Product features

The Type 10-VPR-40D (GV) VCB has the following features in addition to those of the 10-VPR-D VCB.

(1) Greatly reduced renewal time to secure compatibility

By using the same connection method as that of the GCB to be renewed, renewal is possible simply by inserting and withdrawing the circuit breaker, thus eliminating the need for a prolonged power interruption. In addition, as shown in Fig. 9, one type of VCB has a surge absorber installed in order to suppress the switching surge and protect the load. Even for a circuit that requires surge suppression, renewal can be carried out without modifying the panel.

(2) Reduction of maintenance costs

The VCB eliminates maintenance items such as gas treatment and cleaning of the interruption part which are required for a GCB, thus reducing maintenance costs.

(3) Reduction of environmental burden

SF_6 gas, which has a high global warming effect and is used as an arc quenching medium in a GCB, is not needed in a VCB, thus contributing to environmental conservation.

Fig. 9 Surge absorber

8. Conclusion

Circuit breakers, which perform an important role in power distribution facilities, have certain requirements such as safety, improved reliability, reduction of environmental burden, and reduction of LCC, which are becoming increasingly important in the global market. In this paper, we introduced the Type 10-VPR-32D/40D VCBs and also Type 10-VPR-40D (GV) circuit breakers that correspond these needs. The needs of customers both in Japan and overseas will continue to become more diverse and sophisticated. We will correspond those needs by reducing the maintenance work on electrical facilities and also the environmental burden.

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