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ADVANCE

Technological Innovation for Strengthening the Global Presence of Our Electrical Business

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Changes for the Better

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Technical Reports

Precis

Demand for equipment and systems for use in electric power systems is expected to grow in view of the social need for minimizing environmental impact and energy consumption increasing across the world.

This issue looks at Mitsubishi Electric Corporation's recent accomplishments in electric power systems, management strategies for the electric market, service technologies for generators aiming at global launch, nuclear power instrumentation control systems, and AC field winding brushless excitation systems.

Overview

Author: *Koichi Orito**

Management Strategy in the Power Market

Electricity demand in Japan has steadily risen along with rising living standards and other developments in society. Mitsubishi Electric Corporation has provided nuclear, thermal and hydroelectric power generation systems, power transmission and transformation equipment, and power network control systems, thus contributing to the stable supply of power. The electric power industry, however, has reached a major turning point in the wake of the Great East Japan Earthquake in 2011. In addition, electricity liberalization and other system reforms have substantially changed the power market. By taking these opportunities for further growth, we will help customers to expand the business infrastructure that such reforms may involve, while strategically shifting our focus to growth areas.

(1) New business

The Japanese government is fully liberalizing retail electricity sales and introducing legal unbundling of the power transmission and distribution sectors. To date, we have supplied customers with equipment and systems that play central roles in the reforms of the electricity system. By leveraging this track record and integrating various field data analysis methods and other new technologies as well as our experience, we will serve as a core system integrator in the drastically changing power market for information and communication technology (ICT). Moreover, by utilizing the core technologies we have cultivated, we will promote development in the global market.

(2) Existing business

In the nuclear power generation field, we will focus on entering the nuclear back-end markets, such as those of decommissioning and intermediate storage facilities, in addition to the construction work required for introducing additional safety measures for the restarting of domestic power plants. Outside of Japan, various countries (Turkey, Russia, United States, China, etc.) are planning to construct new plants or replace/upgrade facilities amid the trend toward extending the life of plants. We will accelerate business development by concentrating on selectively using our strengths, such as safety system certification. In the thermal power generation field, severe competition on performance and price continues in Japan and overseas alike. In addition to maintaining the scale of new plant business, we will focus on the power generation service business by identifying customers' needs which change as the market environment changes; the power-generating solution business including fuel supply and demand optimization systems by using power plant operation and maintenance technology; and systems for remote supervision and monitoring of abnormal signs for the purpose of preventive maintenance. We will also improve our after-sales service, such as the planning of equipment repair plans by using generator inspection robots, as well as the development of high-output, highly-efficient, small-sized, and cost-competitive new models of power generator that can meet various needs of society for effective energy use, etc.

We will strive to provide Japanese and overseas markets with products that optimally combine existing technologies, applied technologies, and newly-developed elemental technologies, thus helping society to use energy most efficiently.

**Group Senior Vice President,Energy & Industrial Systems Group*

After-Sales Service Technologies for Generators and Ancillary Electrical Equipment

Authors: *Naoto Niki** and *Shoichiro Yamada**

The power generation business of Mitsubishi Electric Corporation is increasingly focusing on enhancing after-sales services. Meanwhile, overseas services are facing severe competition, making it important to differentiate ourselves from competitors by leveraging our knowledge as an original equipment manufacturer (OEM) to offer unique maintenance plans and other services. In addition to increasing the number of orders for conventional large-scale rehabilitation (refurbishment) of generators including for extending generator life, it has become imperative to understand customer needs and establish a new service menu of service technologies that include sophisticated periodical inspections, additional installation of equipment and partial upgrade for improving reliability and functionality, as well as Long Term Service Agreements (LTSAs). Accordingly, we are taking action to expand and improve our range of services.

1. Internal Robotic Inspection of Turbine Generators

1.1 Background and characteristics of the internal robotic inspection

It is important for stable operation of a power generator to perform daily inspections and periodical maintenance. Among the main components, the stator core, stator wedge and the surface of the rotor in particular require periodical inspections. When inspecting these parts in detail, the rotor needs to be taken out from the generator. Conventionally, when any abnormality is detected during a detailed inspection with pulling out the rotor, it is difficult for engineers to complete the repair work for the abnormality; they may be forced to terminate the work even partway through due to an unavoidable schedule, or to seek an extension of the outage.

The internal inspection robot (Fig. 1), which is first inserted into the vacant space (air gap) between the stator and rotor to be attached to the stator core by the attraction of the magnet mounted on the robot, and which then moves in the axial direction, enables: (1) visual inspection through a camera, (2) inspection of stator wedge tightness and (3) EL-CID testing without demounting the generator components. This robot also can improve the minor inspection performed prior to conducting a full inspection with the rotor pulled out from the generator (Fig. 2).

If an abnormality is detected beforehand through the minor inspection, the need for promptly conducting a full inspection by taking the rotor out can be considered. This will allow the necessary repair materials to be prepared before conducting the inspection mainly on the area of concern, and allow repair work to be carried out more quickly.

1.2 Details of the internal robotic inspection

(1) Visual inspection

The inspection robot's built-in camera can visually detect abnormalities such as scratches and marks of

Fig. 1 Appearance of the inspection robot

Fig. 2 Internal robotic inspection

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overheating on the stator core and rotor surface, shift in the position of structures inside the stator and rotor slots, and wear debris (Fig. 3).

Fig. 3 Typical robotic inspection result (using a remote camera)–damage on a stator core

(2) Wedge tightness inspection

The inspection robot has a built-in hammer and acceleration sensor. The hammer taps the stator wedge and the acceleration sensor detects vibration of the stator wedge to quantify the looseness of the wedge and thus measure the distribution of looseness. In addition, inspection results can be accumulated to manage the tendency of looseness and assess the soundness of the structures in the slots. By mapping stator wedge looseness, which is classified into three levels of (1) hard, (2) slightly loose and (3) loose, the tendency of looseness can be managed (Fig. 4).

(3) EL-CID inspection

A multicore cable is wound around the stator, and a direct current is applied to excite the stator core. If the stator core has an interlayer short circuit, abnormality of the stator core can be detected by the Chattock coil attached to the robot, which senses a current in the short circuit.

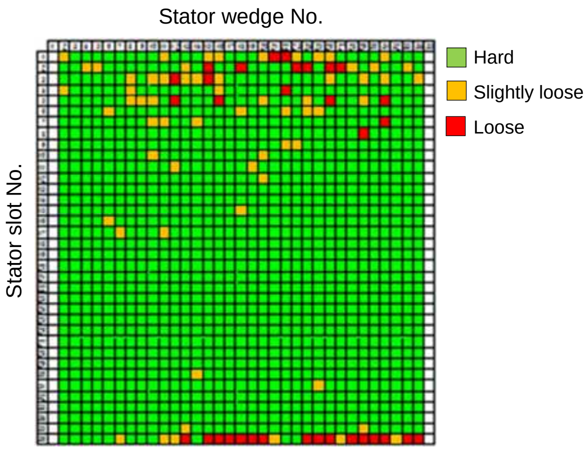


Fig. 4 Typical robotic inspection result (wedge tightness inspection)

2. Online Partial Discharge Monitoring (PDM) System

2.1 Characteristics of the online PDM system

When a voltage is applied between electrodes, a discharge that occurs in the insulation material between electrodes and one that occurs between an electrode and a dielectric are called partial discharges. It is known that in the case of a turbine generator, partial discharge occurs at the stator windings to which a high voltage is applied, and that partial discharge lasting for long term may deteriorate the insulation. As the ground wall insulation deteriorates due to thermal, electric, environmental, or mechanical stress, partial discharge of the stator windings of a turbine generator tends to increase as the deterioration progresses. Thus, it is possible to learn the state of deterioration of the ground wall insulation by periodically measuring partial discharge.

The online PDM system assesses the insulation deterioration and monitors the tendency of insulation deterioration by constantly monitoring the partial discharge while the generator is in load operation. As shown in Fig. 5, this system consists of microstrip antennas, cable connectors, partial discharge (PD) detectors, monitoring PCs, monitors, cables of various types, etc.

The microstrip antennas, which are small and light-weight, can be easily and quickly installed without pulling out the rotor from the generator, and can detect with high sensitivity a partial discharge occurring throughout the stator windings.

2.2 Obtaining partial discharge data and actions in case of detecting abnormality

Data that can be obtained using this online PDM system can be broadly classified into two categories: phase characteristics and trend of magnitude. Partial discharge is assessed using these data.

(1) PD phase characteristics

As shown in Fig. 6, the partial discharge signals that the microstrip antennas receive contain information on the magnitude and phase. Phase characteristics can be obtained by plotting all signals in a certain time period.

(2) PD magnitude trend

The trend graph of partial discharge magnitude shown in Fig. 7 is prepared using partial discharge data that have been repeatedly obtained and arranged in chronological order. By monitoring this trend for a long term, information necessary for trend management, such as whether the level of partial discharge is constant or rising, can be obtained.

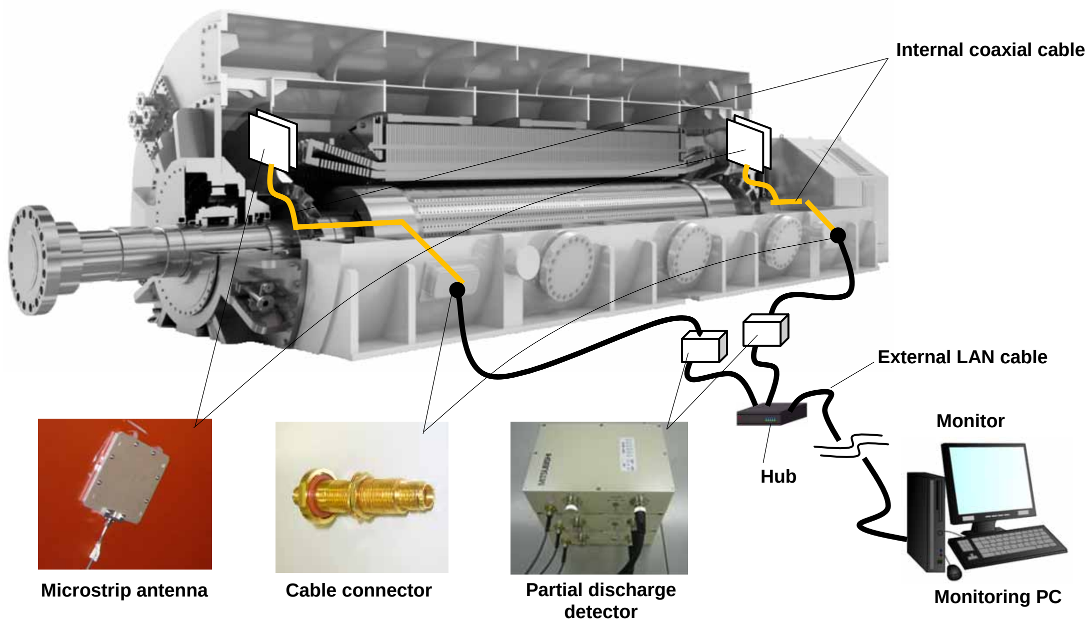


Fig. 5 Schematic view of the configuration of the online partial discharge monitoring system

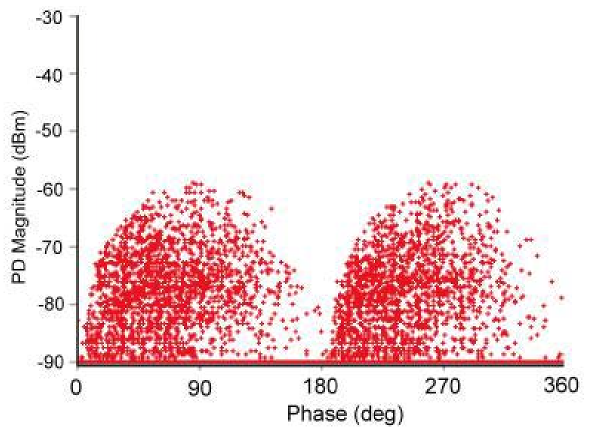


Fig. 6 PD phase characteristics (typical measurement result)

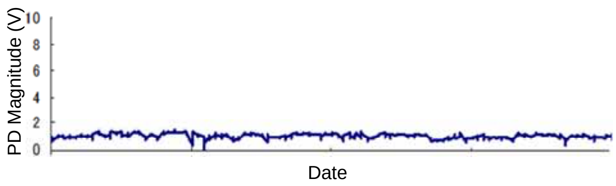


Fig. 7 PD magnitude trend (typical measurement result)

2.3 Action to be taken upon detecting a sign of abnormality

When a sign of abnormality is detected, the generator must be stopped and the stator windings checked for abnormality by conducting: (1) a visual inspection of the stator end-windings, (2) visual and hammering inspections of the wedge and (3) electrical tests for insulation diagnosis. If necessary, repair work is performed to prevent an accident.

3. Partial Replacement of Existing AVRs (with the MEC700U digital AVR unit)

An automatic voltage regulator (AVR) is installed inside the excitation system of a turbine generator. It serves to maintain the voltage of a synchronous generator at a constant level during steady operation. When the load changes, the AVR maintains the voltage and improves dynamic stability; when the voltage suddenly changes, it promptly restores the voltage to the level before the change. AVRs are equipped with these features in order to suppress a voltage increase when the load is cut off, improving the transient stability.

As shown in Fig. 8, we have been manufacturing AVRs since 1944. Since releasing the first digital AVR in 1990, we have continued manufacturing upgraded models. The latest model, the MEC700 digital AVR module (Fig. 9), employs cutting-edge digital technologies, offers more functions and is more compact than past models.

The expected service lives of electrical products including this latest AVR is about 15 to 20 years, although there are slight differences depending on the components used in individual products. We have conventionally recommended that customers replace the entire unit with a new one. However, this requires disconnecting the existing external cables, removing the existing equipment, carrying in and installing new equipment, connecting the existing external cables again, testing the new equipment, etc. This prolongs on-site installation work, increases the replacement cost, etc., which is particularly problematic for customers outside Japan.

The MEC700U digital AVR unit is a retrofitting model for partial replacement of only the main components used in existing generator equipment of a brushless excitation system: the existing analog AVR unit (model number: VRG-PMH-IV) and digital AVR unit (model number: DVRG) (Fig. 10). The existing analog AVR unit and the digital AVR unit contain thyristor element units for full-wave rectification, in addition to an AVR. The MEC700U unit has the same configuration as the existing AVRs in terms of appearance (outside dimensions and external interface connection) and functions (AVR module, THY module, etc.), which allows partial replacement (Fig. 11). The renewal of a system by replacing existing AVRs with the MEC700U unit makes it possible to continue using existing equipment including the panel and cable interface. It also reduces the time and cost of on-site installation/replacement work, while upgrading to the latest model.

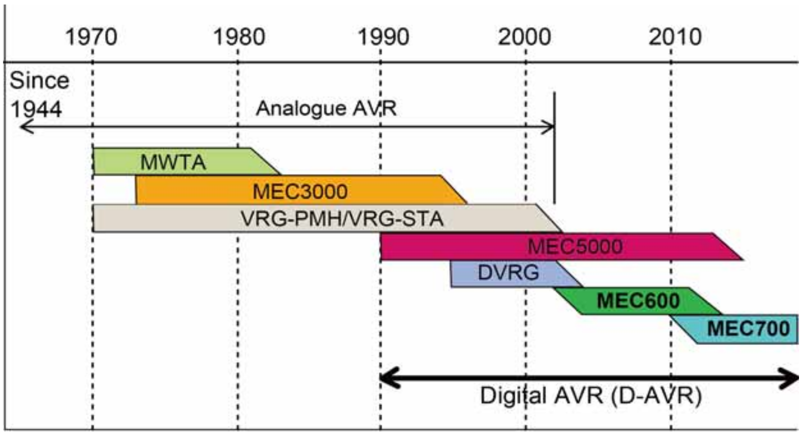
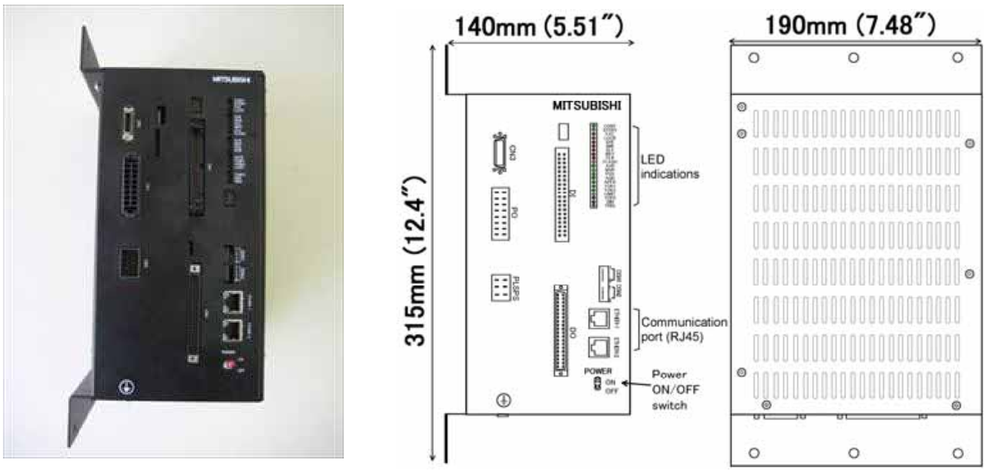


Fig. 8 History of MELCO's AVR



(a) Appearance (b) Front view (c) Side view

Fig. 9 Appearance of the latest digital AVR (MEC700) module

(a) Previous digital AVR (DVRG) (b) Latest digital AVR (MEC700U)

Fig. 10 Previous/Latest digital AVR units

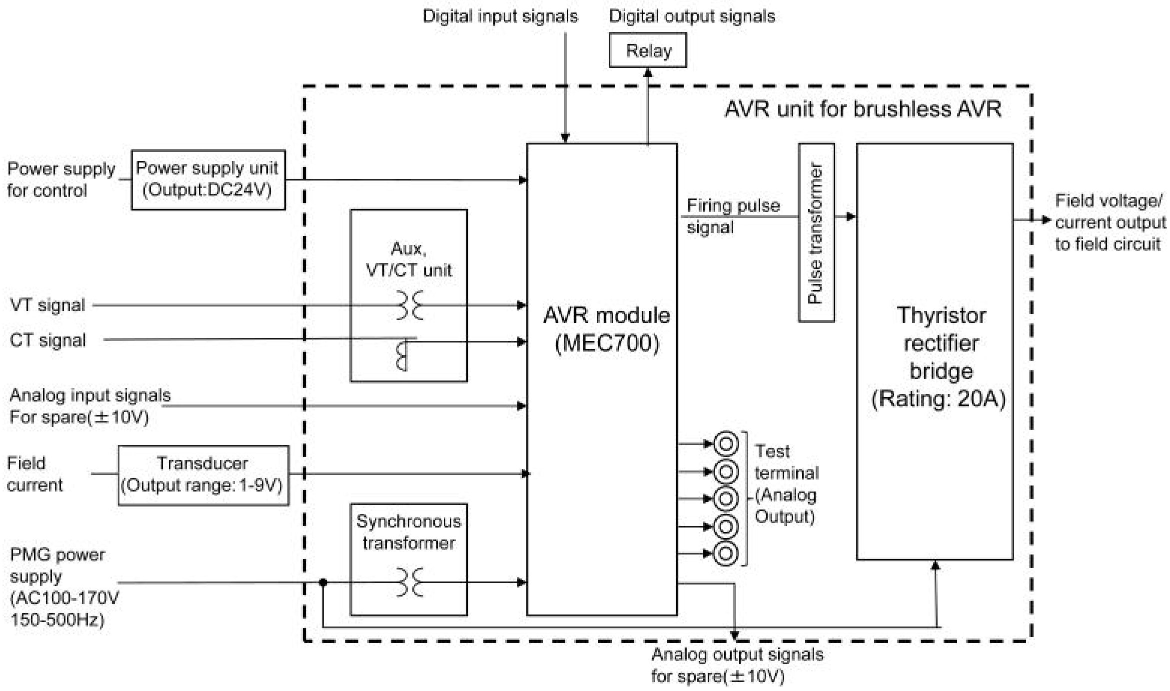


Fig. 11 System configuration of MEC700 digital AVR unit

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Product Development of Instrumentation and Control Systems for Overseas Nuclear Power Plants

Author: *Tadaaki Nagai** and *Hiroki Okamoto**

For over 50 years, we have provided instrumentation and control (I&C) systems for nuclear power plants (NPPs) in Japan, China, and other countries, while promoting initiatives involving the design certification of I&C systems for NPPs in the United States. Using our technologies developed domestically and abroad, we are currently developing new NPP I&C system for the international market that can improve the safety and reliability of NPPs to be constructed in emerging countries.

1. Proven Track Record and Initiatives for Global Expansion

1.1 Domestic/overseas proven track record

Throughout our long history in the field of nuclear power generation, we have consistently engaged in the development, design, manufacture, and testing of our own I&C systems that require high safety and reliability. With our strength the flexibility to a wide range of needs and long term support, our I&C systems have been further improved to satisfy various regulations, reactor type classifications, and customer requirements.

In Japan, our I&C systems have been provided to 24 NPPs over the past 50 years. In addition, in order to improve the reliability and safety of the I&C systems, we have implemented the digital upgrade of existing systems, full plant digital upgrade, and building of new full digital I&C systems.

Outside Japan, we have implemented design certification initiatives in the United States and supplied our I&C systems in China. For US-APWR design certification in the United States (joint effort with Mitsubishi Heavy Industries, Ltd.), the draft Safety Evaluation Report (SER) was issued for the human factors engineering (HFE) design (including HFE verification and validation (V&V) by operators) and I&C system design, which were reviewed per the U.S. Standard Review Plan,. (See reference (1).) For CPR1000 in China, we supplied the I&C system that satisfied the safety evaluation of China's National Nuclear Safety Administration (NNSA). (See reference (2).) Furthermore, as an overseas company capable of manufacturing safety I&C systems, we have obtained HAF604 certification.

1.2 Further initiatives for global expansion

For deployment of our I&C systems to other countries based on our achievements in China and the United States, the following requirements must be met.

(1) Conforming to overseas regulations (international regulations and standards)
(2) Adapting to different reactor types
(3) Meeting different customer engineering scope

In order to move towards global deployment of our I&C systems, we have taken the following actions (Fig. 1).

Regulations—Requirement (1)

In order to conform to the regulatory requirements in many countries, we will ensure that the I&C systems meet the CE marking criteria, functional safety standard (SIL: safety integrity level), and the new International Atomic Energy Agency (IAEA) requirements for plant emergency, which are European regulations that must be satisfied in addition to the US regulations (Chapter 3).

Reactor type—Requirement (2)

In order to ensure adaptability to the reactor types used overseas, we will prepare a lineup of reactor I&C systems, based on the reactor types. At the same time, we will expand the open protocol communication function to allow network connection with systems of other I&C vendors (Chapter 4).

Customer requirements—Requirement (3)

We will develop a concise, user-friendly engineering environment for the plant monitoring and control systems including screens, database, etc., so that the customer in emerging countries can conduct maintenance of the I&C system after its installation (Chapter 5).

2. Conformance with European Regulations

2.1 CE marking

For providing products to countries using the European regulations, it is necessary to indicate that

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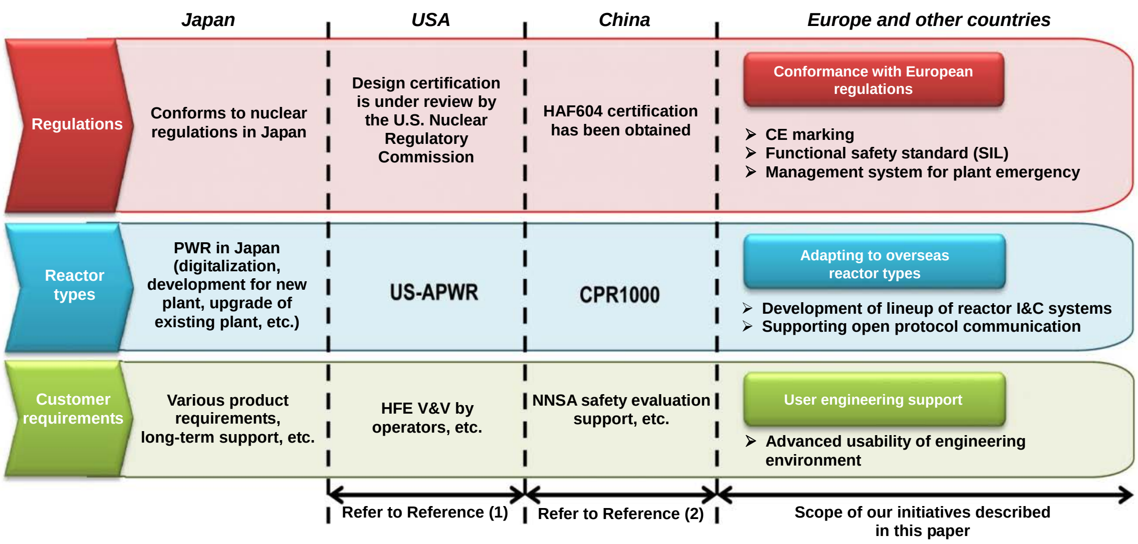

Fig. 1 Summary of activities for globalization

the I&C systems conform to the EMC / low voltage / machinery / RoHS Directives for acquisition of the CE marks.

Specifically, the confirmation of conformity to warning signs, contact prevention of charged and movable parts, etc., as stipulated by the low voltage directive and machinery directive, is underway for the prevention of accidents causing bodily injury. For the EMC Directive, conformity to the radiation noise provisions is being checked. Starting in 2017, industrial monitoring and control instruments will be covered by the RoHS Directive. Therefore, electronic circuit parts, coatings, etc. have been reviewed and the appropriate production lines have been established.

As we described in this paragraph, we have developed CE marking complied I&C systems to make it to supply.

2.2 Functional safety standard (SIL)

Business operators of various plants including power generation plants now require to use equipment that conforms to the functional safety standard based on IEC61508. Particularly in Europe, the SIL of turbine island heavy components is a mandatory condition as an objective index of equipment reliability. The SIL classifies the probability of activation failure of the safety function into levels SIL1 to 4, and objectively and quantitatively evaluates the system safety when the hardware or software fails. Specifically, SIL3, which satisfies the failure probability requirement of 10^{-3} to 10^{-4} upon actuation of the safety function, is required for a main turbine protection system.

We have developed a compact system with capabilities that include output using voting logic, and a quadruplex computing system, to ensure the aforementioned reliability level (Fig. 2). The safety standard assessment covers each process of planning, design, and validation. To maintain objectivity, we are conducting certification activities through a third party certification body.

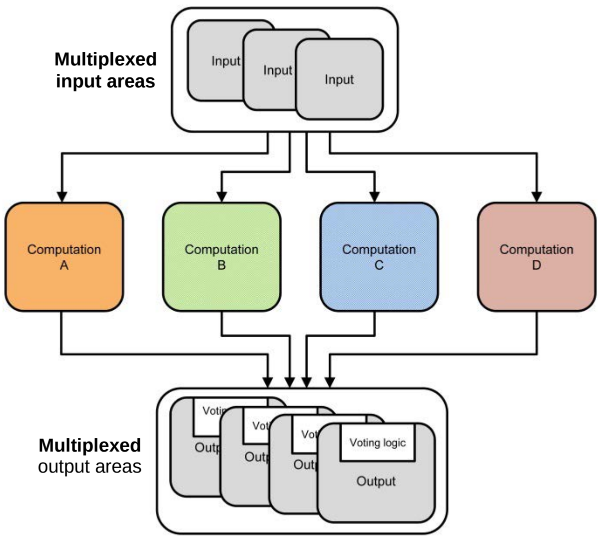

Fig. 2 Typical SIL3 system configuration

2.3 Management system for plant emergency

Considering the lessons learned from the Fukushima 1 NPP accident and the International Commission on Radiological Protection (ICRP) recommendation, the IAEA announced the General Safety Requirements (GSR7) in November 2015 to reinforce "Emergency Preparedness and Response (EPR)" for a nuclear hazard.

Going forward, to meet IAEA GSR7, we anticipate an increased need for a plant management system to immediately and accurately control and operate the plant during an emergency. We have developed a management system that allows for real-time sharing of information on work progress in the event of an accident and resources for equipment and personnel at multiple locations including the power plant concerned, national/local governments, etc. This system supports appropriate decision-making by providing prioritized information in order of importance.

In addition, for optimizing this system, we will coordinate with nuclear power utilities to identify their needs and reflect them in the plant operation.

3. Adapting to Reactor Types Used Overseas

3.1 Development of a lineup of reactor I&C systems

Reactor I&C systems constitute a direct interface with the detector and the control rod drive mechanism (CRDM) directly linked to the reactor vessel, for operating, monitoring, and protecting an NPP (Fig. 3). It is a system that depends on the reactor vessel and core design. Since the design varies depending on the reactor type, we have prepared a lineup of reactor I&C systems that meet different reactor types.

As an example of our initiatives to develop a lineup of components, we introduce the following two systems in this paper.

(1) In-core Instrumentation System

(2) Control Rod Drive Mechanism Coil

(1) In-core Instrumentation System (ICIS)

At Japanese NPPs, constant load operation is performed using generated nuclear power as the base load power. In contrast, at overseas NPPs, load following operation is becoming the norm. In order to achieve load following operation, it is necessary to measure and monitor the neutron flux distribution of the reactor core in detail, both in the axial direction and horizontal direction. Therefore, the FID (fixed in-core detector) type ICIS, which can always measure the neutron flux distribution in the reactor in detail by fixing a neutron detector in the reactor vessel, is widely used. In the FID type ICIS, an SPND (self-powered neutron detector) is used as the detector.

However, the current range from an SPND may be wide (10^{-9} to 10^{-6} A) depending on the material used to detect neutrons. In addition, the output signals are minute current signals compared to signals output by the detector (ionization chamber) used at NPPs in Japan which are about 10^{-3} A.

We have improved the S/N ratio by separating the analog / digital circuits in the signal processing unit and optimizing the component layout. This has allowed the development of a signal processing unit that can accurately measure minute current signals over a wide range, and its commercialization is moving ahead.

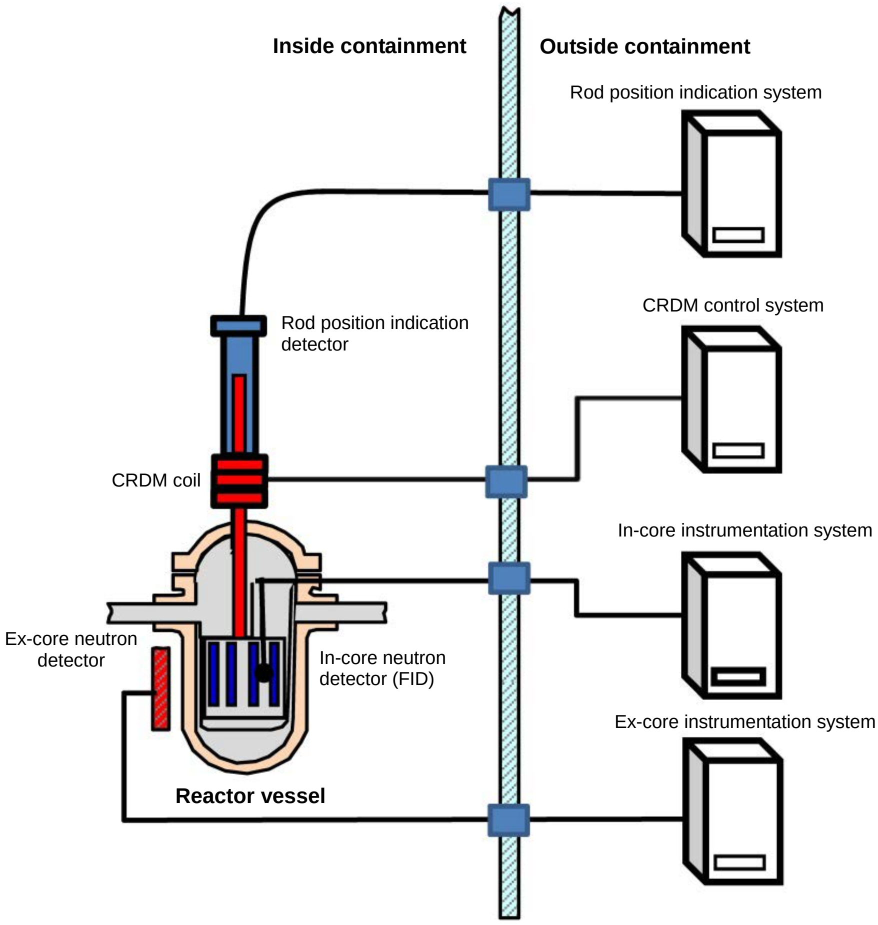

Fig. 3 Reactor I&C systems

(2) Control Rod Drive Mechanism Coil

The CRDM coil is a component of the CRDM for operating the control rods. The CRDM is installed at the upper part of the reactor vessel. Outside Japan, NPPs with various types of reactors have been built. As the core specifications are determined depending on the reactor type, each specification has a suitable CRDM.

We devised new methods for selecting the materials and manufacturing the CRDM coil based on the expertise acquired through working with NPPs in Japan, thereby making it possible to flexibly manufacture CRDM coils of different specifications. This has increased the types of CRDM coils, providing support not only for NPPs in Japan but also for CRDM of other reactor types.

3.2 Supporting open protocol communication

Considering the use of I&C systems for safety systems, and not just for non-safety systems, we have developed and applied a control network using a proprietary protocol that gives consideration to licensability. Since equipment from multiple I&C vendors are likely to be connected to the non-safety system network, it is necessary to allow interoperability between these systems and devices.

For this reason, in addition to our proprietary protocol, the I&C systems support open protocols, which allows connection to equipment of other I&C vendors. We are adding more interfaces based on market share and customer interest (Fig. 4).

4. User Engineering Support

4.1 Usability enhancement in the engineering environment

As we undertake all software production processes for our customers in Japan, we are involved in design, production, and testing of screens, databases, etc., related to plant operation.

Our engineers specializing in software have combined specific tools for the screens, databases, etc., to facilitate flexible build-out of new systems and large-scale software modification. The configuration and functions of the I&C engineering environment used in Japan reflect this background (Fig. 5).

Outside Japan, non-MELCO engineers will be modifying the software after installation of the I&C system. Given this situation, optimization of the engineering environment and development of a universal design are currently underway, so that engineers who have less experience may easily make appropriate selections even for the settings that required our skilled engineers in Japan. We are developing an integrated GUI in the engineering environment and user operation guidance through the introduction of a navigation wizard, in order to simplify engineering operations and shorten the time required for users to acquire the engineering operation skills.

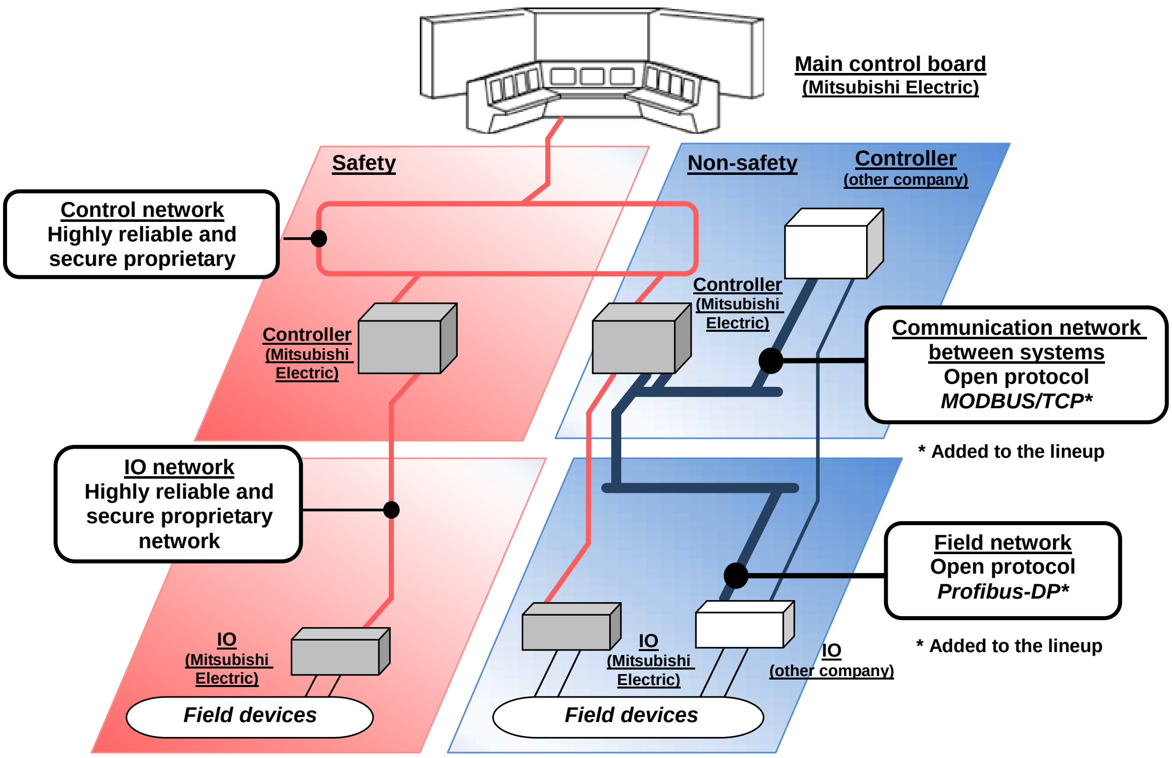

Fig. 4 Typical network configuration

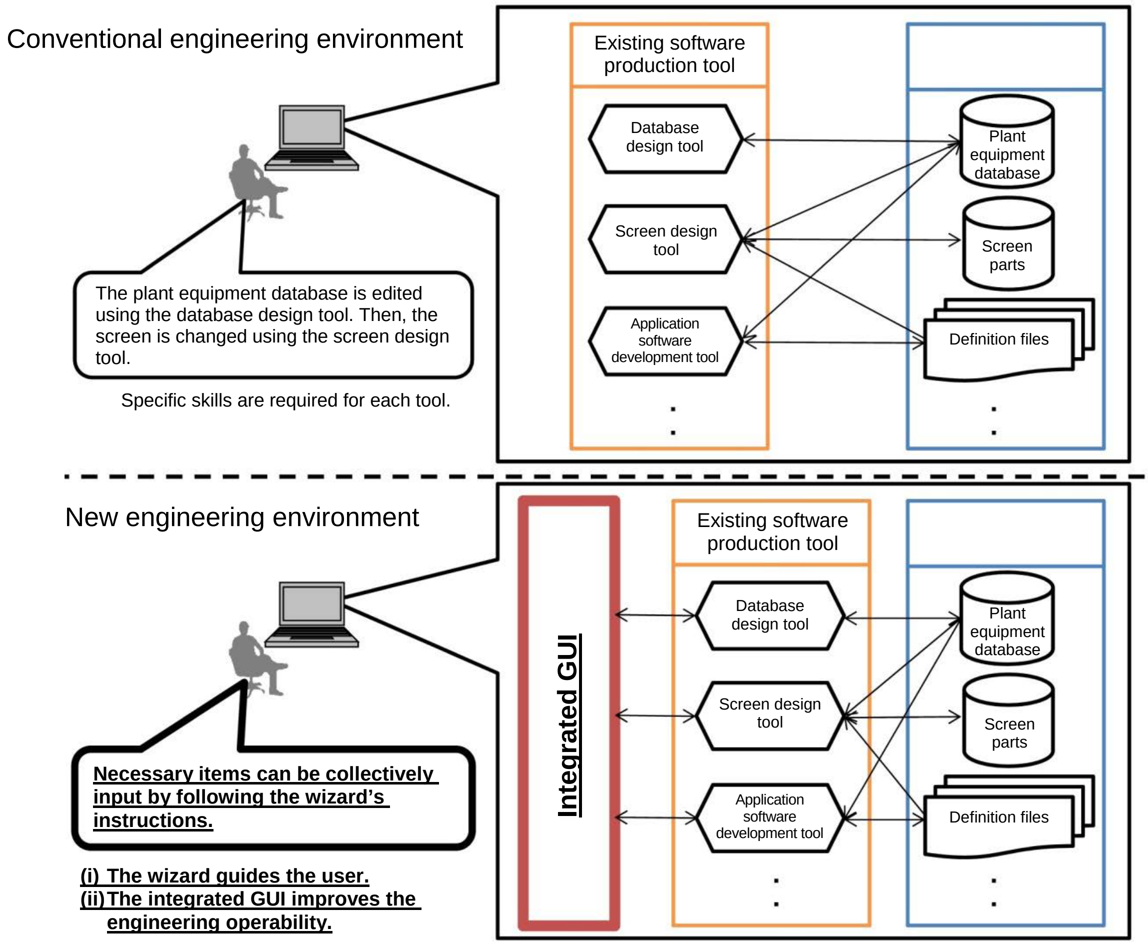

Fig. 5 Overview of software engineering environment

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AC Magnetic Field Brushless Excitation System for Thermal Power Plants

Authors: *Michio Kataoka** and *Ryoji Miyatake**

With the increasing demand for power as well as reduction of impact on the global environment, the demand for power generation plants using gas turbines (GTs) is expected to grow. Since a GT cannot be started by itself, a starter system is required. Mitsubishi Electric Corporation has developed a 500 kW-class AC magnetic field brushless excitation system (power generation capacity of 250 MVA) with which SFC starting is enabled by using AC magnetic fields for the brushless exciter. Compared with conventional thyristor static excitation systems, the new system has a small footprint, maintenance is simple, no excitation transformer or bus duct is required, and brush replacement is not necessary.

1. Existing Systems and the Purpose of Development

1.1 Turbine generator excitation system

Currently, the following two excitation systems are mainly used for power generators.

(1) Brushless excitation system

Figure 1 shows a schematic view of the equipment configuration of the brushless excitation system. Armature windings of the AC exciter, a rotating rectifier, and a permanent magnet generator (PMG) are installed on the same shaft as that of the rotor of the generator. The armature winding of the AC exciter is connected to the generator field winding through a rotating rectifier. The AC output from the armature winding of the AC exciter is converted to direct current, rectified by the rotating rectifier using a three-phase bridge, and supplied to the generator field winding. As the direct current that is required by the generator magnetic field is generated at the rotary part, brush or slip-ring is not necessary.

The excitation energy of the generator is supplied by the generator, AC exciter and PMG rotated by GTs. For this reason, the thyristor rectifier capacity of the brushless excitation system is an excitation capacity scaled to the magnetic field loss of the AC exciter, and is smaller than the capacity of the thyristor excitation system described later.

Furthermore, in the brushless excitation system, as voltage is applied to the generator field windings via the AC exciter, the response time of the AC exciter causes the response time to be longer than that of thyristor excitation systems. However, by using high initial responsive excitation, the voltage response time of the excitation system can be 0.1 second or less.

(2) Thyristor static excitation system

Figure 2 shows a schematic view of the equipment configuration of the thyristor static excitation system. The thyristor static excitation system receives power from the grid through an excitation transformer, converts AC to DC with a thyristor static exciter, brings the carbon brush into mechanical contact with the steel slip ring on the rotor shaft of the generator, and

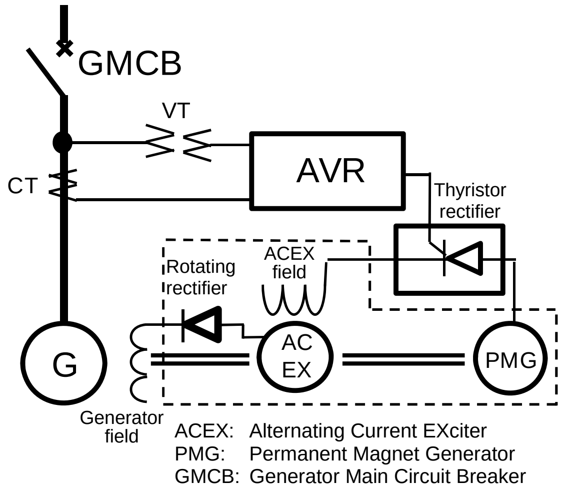

Fig. 1 Brushless excitation system configuration

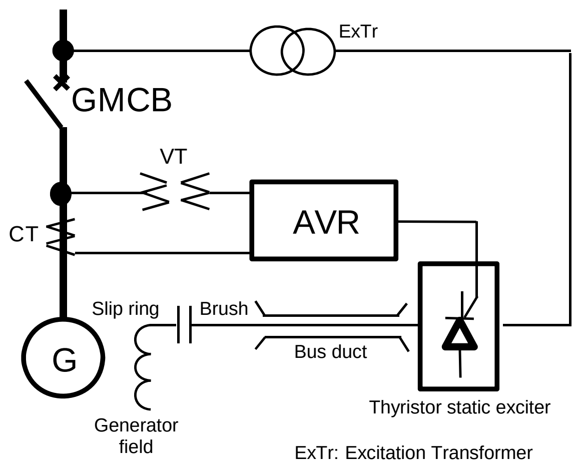

Fig. 2 Thyristor static excitation system configuration

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performs DC excitation of the field windings of the generator. In this way, the thyristor static excitation system receives energy from the grid power supply at start-up, and can thus provide the necessary excitation current to the field windings of the generator regardless of the rotational speed. However, the thyristor static exciter, excitation transformer, and bus duct need to have sufficient capacity to compensate for the generator magnetic field loss, and so the equipment requires more space. Moreover, since a slip ring and brush are required, regular maintenance such as brush replacement, carbon dust cleaning, etc. is essential.

Table 1 summarizes the description above.

Table 1 Comparison between the two excitation systems

Item	Brushless excitation system		Thyristor static excitation system	
Brush maintenance	Not required	○	Inspections and replacement work are required.	△
Equipment space	Small	○	Large (requiring excitation transformer, bus duct, and thyristor static exciter)	△
Response time of the excitation system	Standard response: 0.5–2 seconds High-initial response: 0.1 second or less	△	Approx. 0.05 seconds	○

(○: Advantageous △: Disadvantageous)

1.2 Gas turbine starting system

Currently, the following two systems are used for starting gas turbines that exceed 100 MW.

(1) Motor starting system

The motor starting system has the configuration shown in Fig. 3. The speed of GT shaft rotation is controlled using a fixed speed induction motor and torque converter to start the GT. Both brushless excitation and thyristor static excitation can be performed; normally, brushless excitation is used.

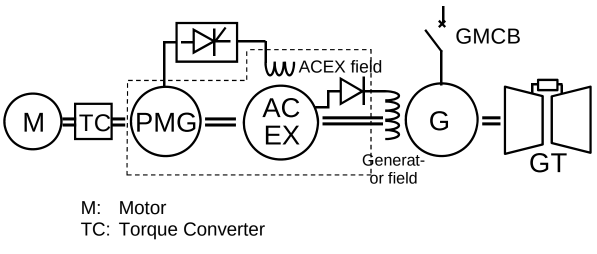

Fig. 3 Motor starting system

(2) SFC starting system

The SFC (Static Frequency Converter) starting system has the configuration shown in Fig. 4. The generator is operated as a synchronous motor using an SFC to increase the rotational speed of the GT shaft. When the GT is started, the SFC is connected to the armature windings of the generator. AC is supplied from the SFC to the armature windings of the generator to supply the necessary energy for rotation. When the generator is operated as a synchronous motor, the generator field current is controlled by an AVR and the thyristor static exciter.

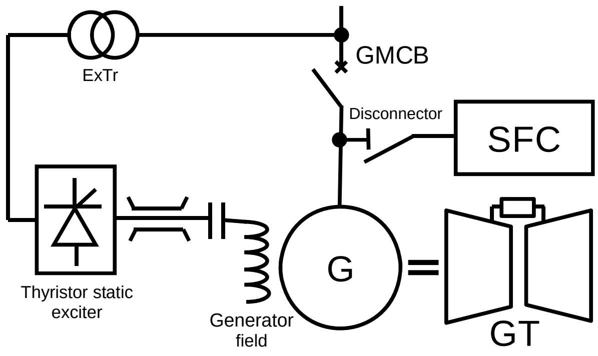

Fig. 4 SFC starting system

Figure 5 shows the behavior of the generator field voltage (Vf) and the terminal voltage (Vgen) at the start of a GT using SFC, and Table 2 shows the modes of the SFC control and excitation control. When the rotational speed is 0 to 20% of the rated speed, the generator field voltage for the excitation is controlled to be constant, and the generator terminal voltage is proportional to the rotational speed. When the rotational

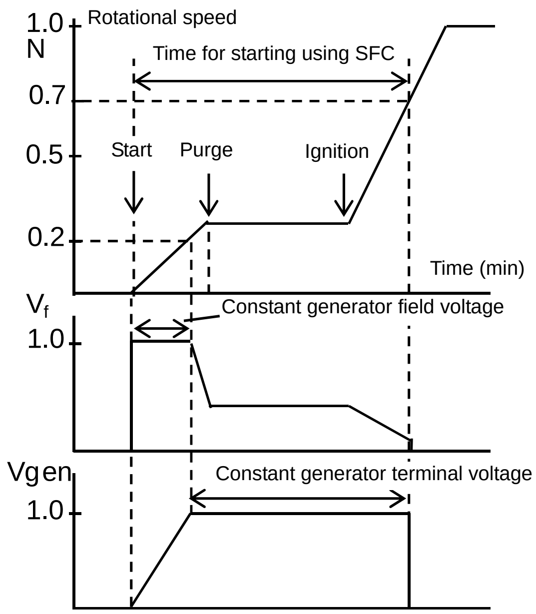

Fig. 5 Generator field voltage and terminal voltage when a GT is started using an SFC (example)

Table 2 Control modes for starting a GT using an SFC (example)

Rotational speed	SFC control	Excitation control	Generator terminal voltage
0 to 20% of rated speed	Constant torque	Constant generator field voltage	Proportional to rotational speed
20 to 70% of rated speed	Constant output	Constant generator terminal voltage	Constant

speed is 20 to 70% of the rated speed, the generator terminal voltage for the excitation is controlled to be constant, and the excitation voltage is decreased as the rotational speed increases.

As mentioned above, in order to start a generator using an SFC and operate the generator as a synchronous motor, it is necessary to supply DC equivalent to the rated no-load voltage to the field windings of the generator from 3 rpm after the start of the GT. In a conventional brushless excitation system, the required DC cannot be supplied for generator field winding at such a low speed of rotation. Therefore, we are using the thyristor static excitation system when performing with the GT started by an SFC.

1.3 Purpose of the development

Table 3 shows the results of comparing combinations of the GT start systems with the excitation systems described previously. The motor can be started by either thyristor static excitation or brushless excitation. The thyristor static excitation of combination A has no advantage in terms of maintenance and space, and relatively few such systems have been delivered to customers. The brushless excitation of combination B has the advantages of no need for brush maintenance or space used for an excitation transformer and bus duct, and has a proven track record of deliveries to customers.

Table 3 Comparison between combinations of starting and excitation systems

Combina-tion	Starting system	Excita-tion system	Maintainability		Space		Remarks
			Brush	Motor	Shaft length	Equip-ment	
A	Motor	Thyristor	△	△	△ △	△	Limited track record regarding DC magnetic field
B	Same as above	Brushless	○	△		○	Solid track record regarding DC magnetic field
C	SFC	Thyristor	△	○ (No motor)	○	△	DC magnetic field of Mitsubishi Electric current standard
D	Same as above	Brushless	○	○ (No motor)	○	○	AC/DC magnetic fields as developed

In the SFC starting system, we currently use the thyristor static excitation of combination C as the standard as mentioned above. No starting motor or torque converter is used, and the shaft length can be short, enabling the building to be smaller. The other advantages include start-up of multiple GTs using one SFC.

This development allows for a brushless excitation system that is capable of starting up GTs using an SFC by using an AC excitation inverter and brushless exciter that can be used for AC magnetic field as a brushless excitation system for generators. This balances both the advantages of the brushless excitation system and the SFC starting system as indicated by combination D of Table 3.

2. AC Field Winding Brushless Excitation System

2.1 System configuration

During the development, the 500 kW-class AC field winding brushless exciter and AC excitation inverter were prototyped and system tests were conducted in the factory. The details of the AC field winding brushless excitation system are described below.

(1) Configuration

Figure 6 shows a schematic view of the SFC starting circuit by AC field winding brushless excitation. The AC field winding brushless excitation system requires: (i) a brushless exciter with two-phase field windings for the d-axis and q-axis, (ii) an AC excitation inverter that performs AC-excitation of field windings of the AC exciter during the start-up process using an SFC, (iii) an AVR/thyristor rectifier that perform DC-excitation of field windings of the AC exciter during the load operation of the generator, (iv) an excitation switchover circuit that is responsible for the connection shift involving the field windings and excitation devices.

(2) Operation

In the GT starting system using an SFC, the SFC, AVR/thyristor rectifier, and AC excitation inverter operate the generator as a synchronous motor according to the command of the upper plant control system.

Regarding the excitation control, AC excitation control is performed by the AC excitation inverter during the start-up process using the SFC, while DC excitation control is performed by the conventional AVR/thyristor rectifier that output DC after the excitation switchover circuit performs connection shift for the field windings and excitation devices, once the rated rotational speed is reached.

(3) Features of the system

The features of the AC field winding brushless excitation system are as follows.

(i) Assured reliability as an excitation system

Depending on the operation status of the generator, the excitation devices are switched. When GTs are started using the SFC, the system performs AC excitation using the AC excitation inverter, while during the rated load operation, the system performs DC excitation using the conventional AVR/thyristor rectifier. This allows the use of the conventional AVR/thyristor rectifier, which has a proven track record for rated load operation, thereby ensuring the reliability of the

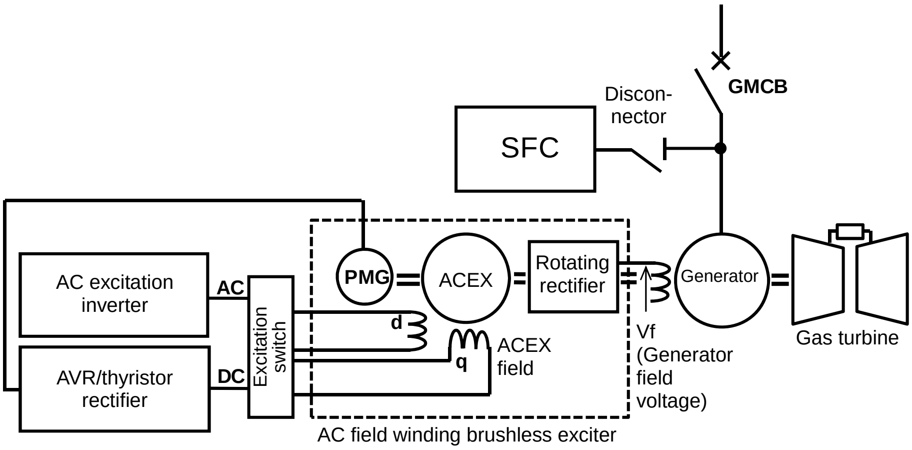

Fig. 6 Circuit of the SFC starting and AC field winding brushless excitation system

excitation system.

(ii) Brushless exciter that allows DC output when rotation is stopped, and excitation device

The magnetic field component of the AC exciter is changed from the DC windings to AC winding so that DC output can be made from 3 rpm after the start of the GTs using the SFC. Furthermore, an insulated gate bipolar transistor (IGBT) inverter is used as the excitation device to allow for AC excitation. This also allows the brushless exciter to output DC directly even when the GTs are not rotating, making it possible to supply DC necessary for the generator field windings.

(iii) Generator field voltage sensor-less control

As shown in Table 2, in the SFC starting system, the generator field voltage is controlled to be constant when the rotational speed is 20% or less of the rated speed. In the case of the brushless excitation, as shown in Fig. 6, the generator field voltage (Vf) is on the rotor and cannot be directly detected. Therefore, we have developed a method for controlling the generator field voltage in which Vf on the rotor is estimated from the output voltage/current of the AC excitation inverter and the rotational speed, and this estimated value is used as a feedback value. This method allows sensor-less generator field voltage control without having to detect the generator field voltage when it is being maintained constant.

2.2 AC field winding brushless exciter

In order to implement the AC field winding brushless excitation system that supports the SFC starting system, we developed an AC field winding brushless exciter (hereinafter referred to as “AC field winding BL”). The basic specifications and results of verification tests are described below.

(1) Features

Similar to conventional brushless exciters, an AC field winding BL consists of an AC exciter, rotating rectifier, and PMG. For the SFC starting system, the necessary DC supply to the generator field windings is required from 3 rpm after the GTs are started using the SFC. As shown in Fig. 7(a), the field windings of a conventional brushless exciter have DC salient poles, which makes it difficult to generate a rotating magnetic field from the field windings. Due to this, if an AC magnetic field is applied, conventional brushless exciters cannot supply the generator field currents necessary for the SFC starting from 3 rpm after the start of GTs using the SFC. Therefore, as shown in Fig. 7(b), we changed the shape of the field core of the AC field winding BL to the shape of a slot as with general rotor armatures. Moreover, the AC field winding BL was provided with two-phase AC field windings for the d-axis and q-axis. The d-axis field windings and q-axis field windings were AC-excited at the phase difference of 90°. When the rotation is stopped, the supply of generator field capacity necessary for the SFC starting was allowed.

Figure 8 is a photo of a prototype taken after the rotor was inserted. The field core and bearing are mounted on the exciter base plate. The field core has a structure in which circular silicon steel sheets are laminated for generating a rotating field, and the rotor is designed to be inserted in the axial direction toward the field core. Other armature windings and PMG of the

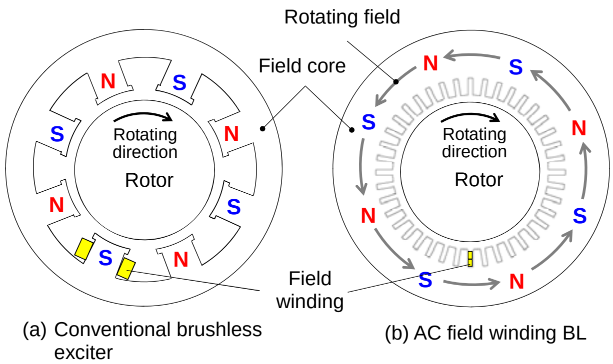

Fig. 7 Magnetic field structures of AC exciters

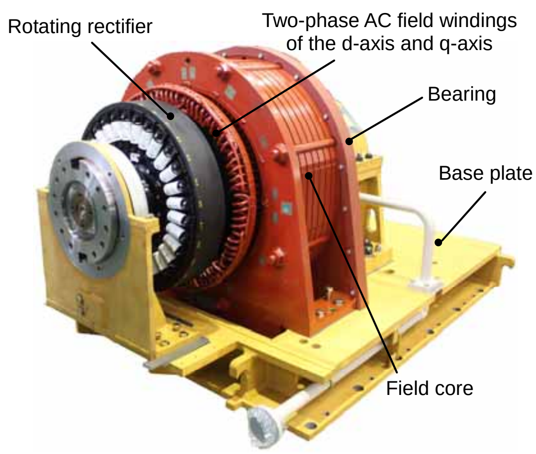

Fig. 8 Prototype of the AC field winding brushless exciter (after installation of the rotor)

rotating rectifier and AC exciter use the same structures as in various conventional brushless exciters that we have been manufacturing.

(2) Basic specifications

Table 4 shows the basic specifications of the AC field winding BL as developed. When it is combined with a 250 MVA turbine generator, the DC output necessary for the rated load of 3,600 rpm is 520 kW, and the DC output necessary for the SFC starting at 3 to 2,400 rpm is 60 kW. Considering a possible increase in the output of generators in future, the AC field winding BL and the AC excitation INV are designed to support the DC output of 85 kW at the start using an SFC.

At 3 rpm after the start of GTs using the SFC, the velocity electromotive force is low, and the AC exciter field current increases, affected by the magnetic saturation of the AC exciter. Therefore, we lowered the magnetic loading of the AC exciter in order to suppress the capacity of the AC excitation inverter. Furthermore, as a result of the increase of capacity of the PMG, the voltage response time as an excitation system is 0.1 second or less, and the voltage response speed is 3.3 pu/second or more during the rated load operation of the generator. These values show that the AC field winding BL has been designed to satisfy the high initial excitation requirement.

(3) Test results

Figure 9 shows the load characteristics of the AC field winding BL.

As mentioned in Section 1.2 (2), during operation at a rotational speed that is 20% or more of the rated rotational speed after the start of GTs using the SFC, DC output is not constant but decreases as the rotational speed increases. In order to confirm the load characteristics, a verification test was conducted under the conditions of DC output maintained constant at 85 kW at the rotational speed from 0 to 3,600 rpm. With respect to field currents Id and Iq and field voltages Vd and Vq, the design values closely matched the measured values, showing the adequacy of the design. It was also confirmed that under the conditions of DC output maintained constant at 85 kW, energy is supplied from the rotor shaft along with the increase of rotational speed, which causes a decrease in the field

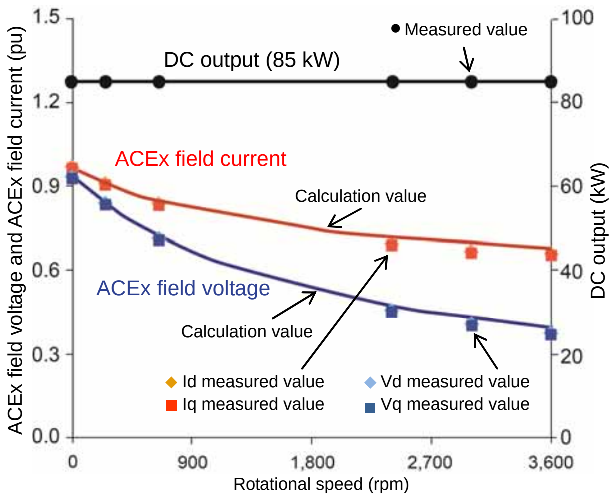

Fig. 9 Load characteristics of the AC field winding brushless exciter

Table 4 Basic specifications of the AC field winding brushless exciter

Target	Turbine generator		Rating: 250 MVA, 3600 rpm
Configuration	AC exciter	Stator	Two-phase AC field windings of the d-axis and q-axis
		Rotor	Three-phase AC armature windings
	Rotating rectifier		Three-phase full-wave rectifier
	Sub-exciter		Permanent magnet synchronous generator
Specification	Rated load	DC output	520 kW
		Rotational speed	3,600 r/min
		Excitation	DC excitation thyristor
	SFC starting	DC output	85 kW
		Rotational speed	3 – 2,400 r/min
		Excitation	AC excitation inverter
High initial excitation	Voltage response time		0.1 second or less[1]
	Voltage response speed		3.3 pu/second or more

[1] 0.1 second of voltage response time is as specified in IEEE421.1.

current and field voltage of the AC exciter. Regarding other verification items such as temperature, loss, and excitation response speed, the measured values almost matched the design values and complied with standards such as IEC and JEC, and were thus confirmed to be acceptable.

2.3 AC excitation inverter

In order to implement the AC field winding brushless excitation system that supports the SFC starting system, we developed an AC excitation inverter.

(1) Function

Figure 10 shows the external appearance of the developed AC excitation inverter. The AC excitation inverter controls the excitation of the generator in collaboration with the plant control system and the SFC when the GTs are started.

Fig. 10 AC excitation inverter

The AC excitation inverter consists of the converter, inverter, Scott transformer, and control circuit. The three-phase AC voltage input is converted to DC by the converter and performs pulse width modulation (PWM) switching for the IGBT device at the inverter to generate three-phase AC voltage. This three-phase AC voltage is converted to two-phase AC voltage by the Scott transformer to excite the two-phase field windings of the d-axis and q-axis of the AC exciter.

(2) Basic specifications

Table 5 shows the basic specifications of the developed AC excitation inverter. Based on the power capacity and the field voltage/current required by the field windings of the AC field winding BL, the rated output capacity was determined to be 212 kVA, rated voltage 1,520 V, and rated current 70 A.

(3) Control method

Figure 11 is a circuit block diagram of the internal configuration of the AC excitation inverter. The AC excitation inverter has two control modes necessary as

Table 5 Basic specifications of the AC excitation inverter

Configuration	Converter	Three-phase full-wave rectification
	Inverter	Three-phase two-level inverter
		600 A class IGBT
		Variable voltage constant frequency control (VVCF)
	Scott transformer	Three-phase input, two-phase (phase difference 90°) output
Specification	Output capacity	212 kVA
	Rated output	1,520V/70A
	Input voltage	Three-phase 400 V class; 50 Hz/60 Hz
Control	Field excitation control for SFC starting system	Generator field voltage estimation control
		Generator terminal voltage control

an excitation system when the GTs are started using the SFC. These two control modes are described below. According to the excitation control when the GTs are started using the SFC as shown in Table 2, the control mode is switched in the process of the SFC starting.

(i) Generator field voltage estimation control

As shown in the circuit diagram in Fig. 6, the generator field voltage (Vf) is on the rotation axis, which makes it difficult for Vf to be measured unless a slip ring and brush are used. Therefore, in the generator field voltage estimation control, using inverter output current Iinv, output voltage Vinv, and rotational speed information rpmE, the estimated generator field voltage is derived from the calculation formula based on an equivalent circuit of the AC field winding BL, and control using this estimation value as a feedback value is performed.

(ii) Generator terminal voltage control

In the generator terminal voltage control, the generator terminal voltage VT is used to perform feedback control. When the rotational speed is 20 to 70% of the rated speed, the generator terminal voltage is controlled to be constant, performing the same control as that of normal AVR controllers.

2.4 System test

(1) Equipment configuration used for the test

Figure 12 is a circuit diagram used for the factory system test of the AC field winding BL and the AC excitation inverter. The field windings of the d-axis and q-axis of the AC field winding BL are connected to the AC excitation inverter, and the DC output is connected to the resistor via the slip ring and brush that are used in the test. The shaft of the AC field winding BL is connected using a coupling to the testing drive motor, allowing variable speed operation.

As the generator terminal voltage signal, the signal of the generator simulator, which calculates the generator terminal voltage based on the rotating rectifier output voltage (Vf) and rotational speed information, was used.

(2) Test results

With the operation pattern similar to that when the GTs are started using the SFC, the AC field winding BL was variable-speed operated in order to check the control accuracy. The results were as follows.

(i) Generator field voltage estimation control

The generator field voltage estimation value on the rotor was calculated and a feedback control test was

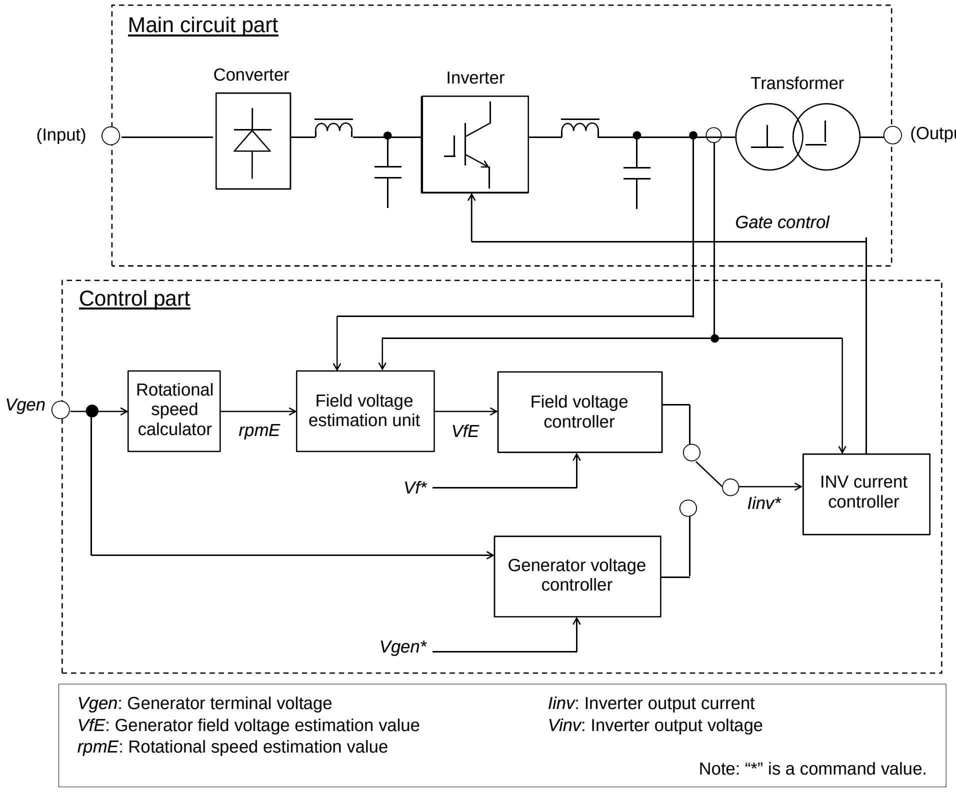

Fig. 11 Circuit block diagram of the inside of the AC excitation inverter

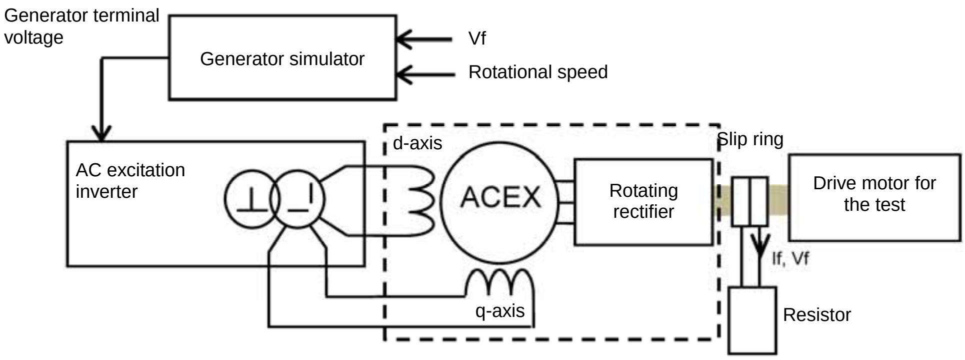

Fig. 12 Circuit for the assembly test

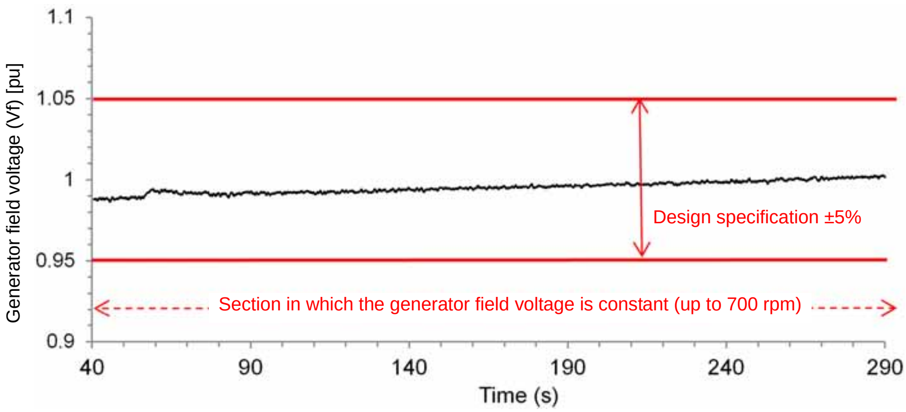

Fig. 13 Test results of the generator field winding voltage estimation control

conducted considering this value as a generator field voltage detection value. As shown in Fig. 13, the margin of error of the measured value is within ±2% compared to the control standard value of 1.0 pu. This satisfied the design specification to within ±5%, thus confirming that the control method is of practical use.

(ii) Generator terminal voltage control

As shown in Fig. 14, the margin of error of the measured value is within ±1% compared with the control standard value of 1.0 pu. This satisfied the design specification within ±2%, showing that the control method is of practical use.

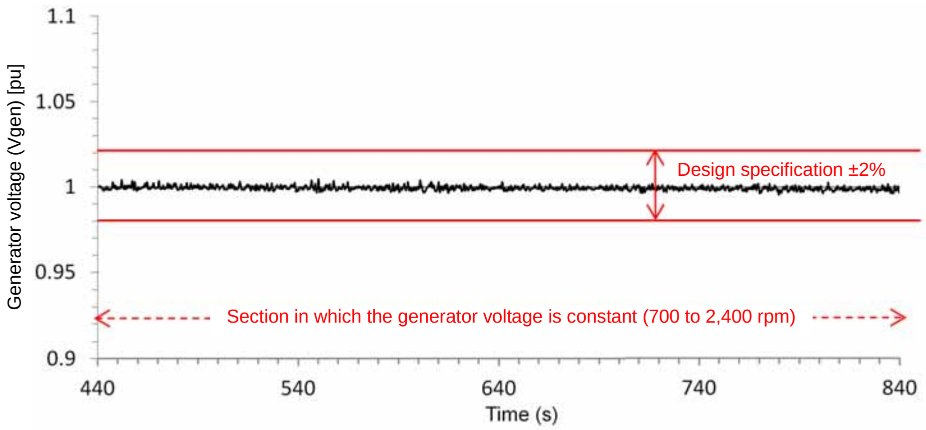

Fig. 14 Test results of the generator terminal voltage control

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