ISSN 1345-3041

Sep.2023 / Vol.183

Mitsubishi Electric

ADVANCE

Digital Energy

MITSUBISHI ELECTRIC
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Sep. 2023 / Vol. 183
Mitsubishi Electric ADVANCE

Digital Energy

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Mitsubishi Electric Advance is published on line quarterly (in March, June, September, and December) by Mitsubishi Electric Corporation.

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Precis

Mitsubishi Electric contributes to society through technology in a wide range of power-related situations, from power generation, transmission and distribution equipment and solutions to renewable energy and distributed energy sources.
This paper describes the grid control system for power distribution system, the "MELPRO-i" series edge device for advanced monitoring and control, a voltage sourced converter based HVDC system, and a cable switching breaker used for C-GIS for wind power system applications.

Introduction of Grid Control System for Power Distribution System

Authors: *Mitsuru Terawaki** and *Shunsuke Endo**

1. Introduction

To maintain a reliable supply of electricity, measures are in place to mitigate voltage drops throughout distribution systems, including Load Ratio Control Transformers (LRTs)—transformers for power distribution installed at substations—and Step Voltage Regulators (SVRs) that compensate for voltage drops across distribution lines.

In recent years, however, distribution systems have been experiencing increased voltage fluctuations and reverse power flows over both short and long-period cycles as more PhotoVoltaics (PV) systems are connected to the power grid. Distribution systems are also being affected by complex voltage fluctuations on the transmission system side, making it difficult for current LRTs and SVRs to maintain the constantly fluctuating supply voltage of distribution system in the optimum range.

To address these challenges, Chubu Electric Power Grid Co., Inc. has been working on the development and installation of next-generation voltage regulators and distribution panel LR control units at distribution substations as on-site equipment. Mitsubishi Electric developed Grid Control System (GCS) as the voltage control system for controlling this on-site equipment(1). The method used to control voltage with GCS allows setting values to be updated in a timely manner to achieve more precise voltage control. This also provides a greater voltage control range at each SVR, which is anticipated to be effective in limiting the increase in the number of SVRs installed.

GCS is a system developed to help maintain the appropriate supply voltage of distribution systems, by not only determining the setting value for the following day for the on-site equipment based on linked data acquired from automated distribution systems and high-low voltage load curve control systems, but also enabling values to be set remotely in real-time if there are sudden fluctuations in voltage. This paper provides an outline of the GCS system.

2. Central Voltage Control by System

When voltage regulation was required in the past, the process involved using general-purpose spreadsheet software to manually calculate the setting values for LRTs and SVRs from the voltage profile of the setting value of the past year. Workers then visited sites once or twice a year to manually update the setting values based on the calculated data.

The introduction of this GCS means setting values can be calculated automatically by the system from voltage profiles and other data of the past seven days—setting values can be remotely updated automatically every day, instead of requiring workers to visit actual sites (Fig. 1).

This is the first time[*1] in Japan that central voltage control by a system has been applied(2) to all distribution lines, and has successfully achieved “visualization of system voltage” and “automatic calculation of setting values.”

*1 June 10, 2021 press release, Chubu Electric Power Grid Co., Inc.

3. GCS

3.1 Characteristics

The voltage control functions of GCS have the two following key characteristics.

(1) Batch processing: Function that automatically updates the setting value at a specific time every day
(2) Real-time processing: Function that constantly monitors the distribution system voltage, and automatically updates the setting value if deviation from the optimum voltage is detected

In general, batch processing (Fig. 2) creates the optimal setting values (standard voltage and dead zone width) beforehand and updates them daily. In the event that there are unexpected voltage fluctuations and there is deviation from the optimum voltage range, real-time processing (Fig. 3) is used for further updates.

In this way, GCS provides a 2-stage approach to maintaining optimum voltage with batch processing and real-time processing.

3.2 Functions

Functions fall into the main categories of system analysis, system calculations, equipment data management, and links with other systems, as described below.

(1) System analysis

System analysis performs system locking,

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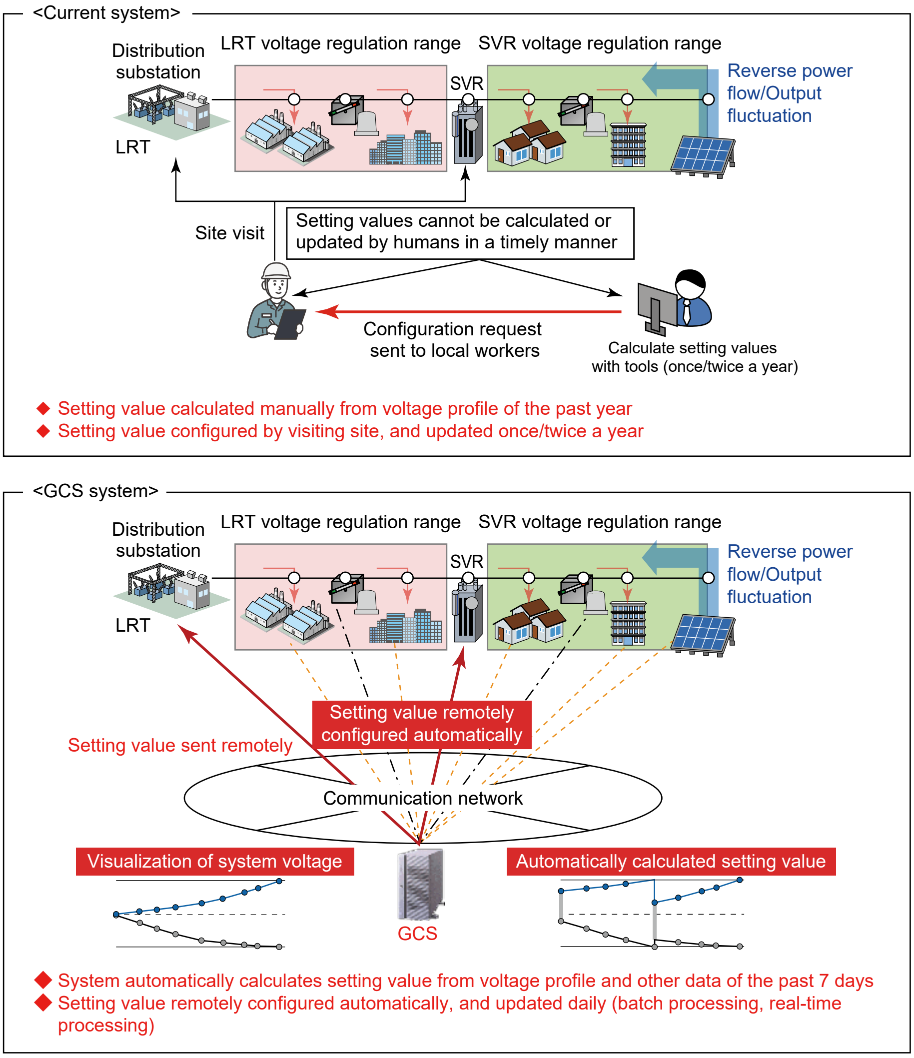

Fig. 1 Central voltage control by system

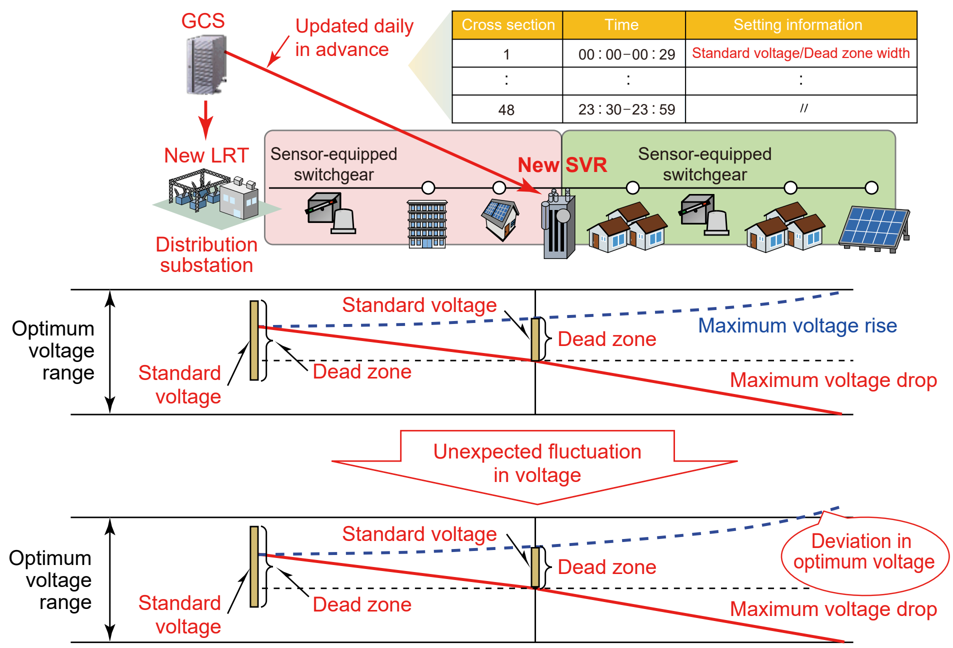

Fig. 2 Image of batch processing operation

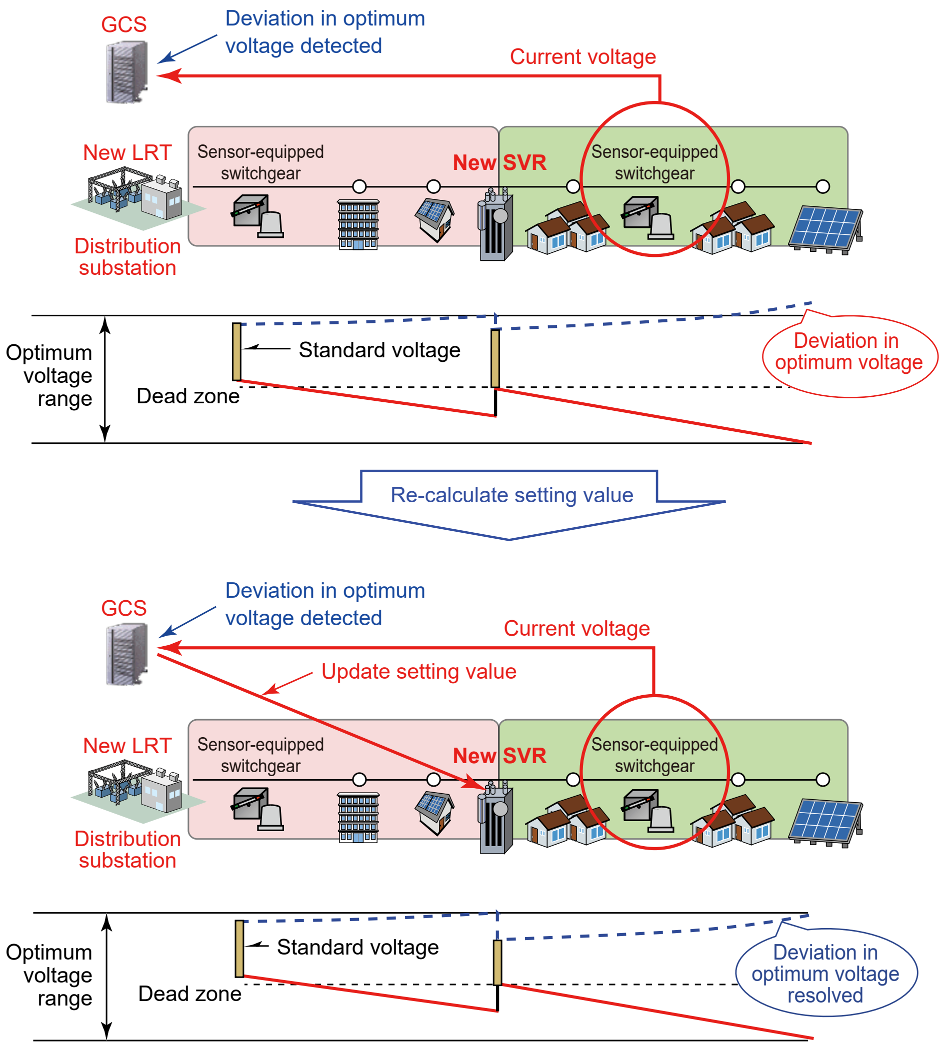

Fig. 3 Image of real-time processing operation

SuperVision (SV) analysis and TeleMeter (TM) analysis at 1-minute intervals. System locking acquires the current cross section of the SV (two-value data like on/off information of automatic switchgear) and TM (numerical information such as the current and voltage measured with on-site equipment) linked to the automated distribution system, and locks that as data for system analysis. With SV analysis, locked SV is assigned to the equipment data covered by GCS, while also acquiring details of the current system status. With TM analysis, locked TM is assigned to the equipment data covered by GCS, while also determining the validity of the TM value.

(2) System calculation

System calculation comprises ΔV calculation processing, real-time processing, batch processing, and local setting value calculation processing.

ΔV calculation processing is a function where the current distribution data is assigned to the equipment data covered by GCS and calculates the ΔV per segment between switchgears (amount of voltage rise or amount of voltage drop), while also calculating and storing the maximum voltage rise value and maximum voltage drop value within the voltage regulation range.

Batch processing estimates future voltage distribution and determines the LRT and SVR setting values to ensure that the it does not deviate from the optimum voltage range, based on past measurement data linked from high-low voltage load curve control systems. This calculates the setting value for equipment requiring calculation that is currently part of the distribution line for which ΔV is being created.

Real-time processing monitors the voltage deviation estimated from the amount of maximum voltage rise and amount of maximum drop between the voltage monitoring location and the end of the current system at 1-minute intervals. If ongoing voltage deviation is detected for a certain period of time, the setting value is calibrated so that the amount of deviation is kept within the LRT and SVR setting range. This operates after system analysis is performed to monitor the deviation in the measured voltage, and if a deviation continues to be detected, a new setting value is calculated to calibrate the LRT and SVR with that setting value.

Local setting value calculation processing calculates the future voltage distribution and determines the LRT and SVR local setting values to ensure that it does not deviate from the optimum voltage range, based on the annual maximum load and power generation data linked from high-low voltage load curve control systems. This calculates the setting value for equipment requiring calculation that is part of standard systems in distribution line for which ΔV is being created. The purpose of the local setting value is that it is used if the setting value for on-site equipment cannot be remotely updated automatically from GCS for some reason.

(3) Links with other systems

Links with other systems are performed for coordinating data with other systems such as automated distribution systems or high-low voltage load curve control systems, in order to collect data required for system analysis and system calculation.

This creates and manages a database required for system analysis and system calculation functions, based on equipment data information of distribution systems linked from automated distribution systems. GCS also updates equipment data with the same timing that equipment data is updated by the automated distribution system.

3.3 Data coordination with other systems

Central voltage control by the system is achieved by coordinating data between multiple systems (Fig. 4).

Visualization of the grid current distribution is required in order to calculate the setting value. First, current information of sensor-equipped switchgear is acquired by the automated distribution system to acquire details of the general current distribution per segment. The metered value of smart meters is also acquired from the smart meter control management system to acquire details of the amount of power generated from PV and other sources. This information is added up and the high-low voltage load curve control system calculates the amount of electrical energy per high-voltage customer and transformer. The measurement value of distribution substations and the measurement value of distribution system sensor-equipped switchgear are then used to calculate the current distribution throughout the entire distribution system. Current distribution comprises data for each 30-minute segment (48 cross sections per day), and the calculated current distribution is sent from the high-low voltage load curve control system to GCS. Batch processing is used by GCS to calculate the optimum setting value based on the linked current distribution. The calculated setting value is then sent twice a day to voltage regulators via the Automated distribution system.

GCS is constantly linking data with the automated distribution system. It monitors the optimum voltage deviation and calculates the setting value based on the measurement information of on-site equipment linked from the automated distribution system, and creates a database based on equipment information of linked distribution systems.

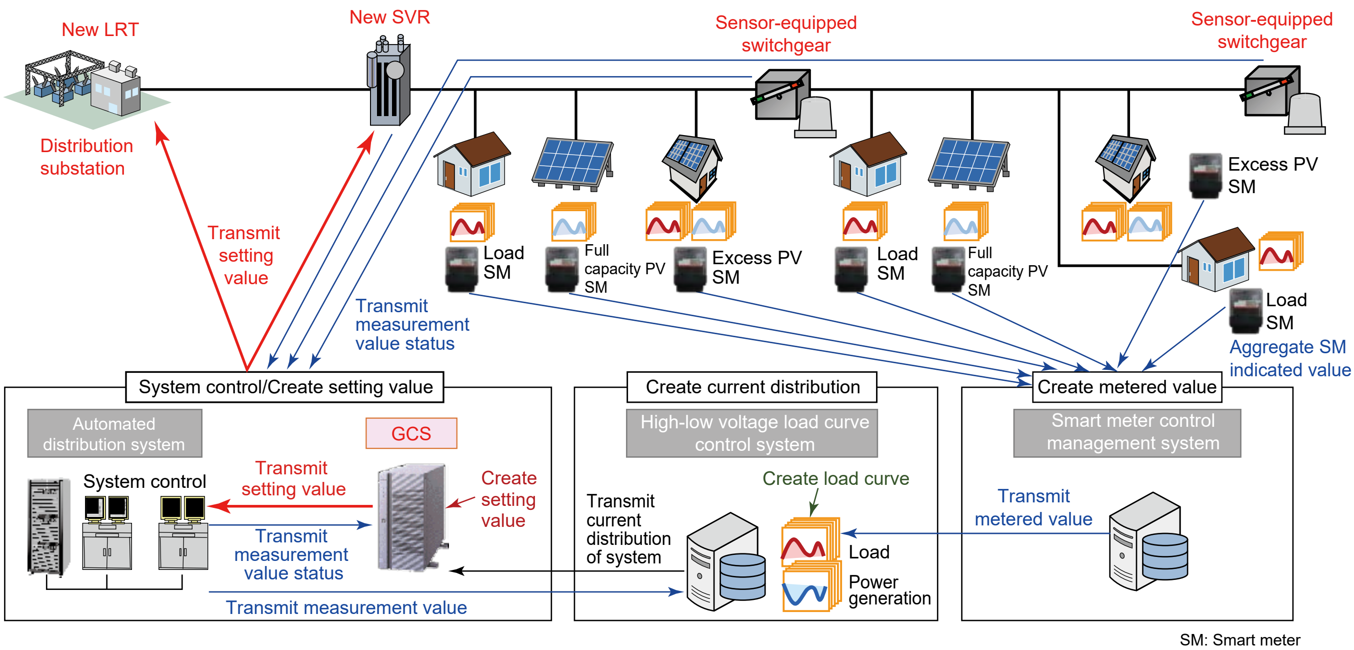

Fig. 4 Data coordination with other systems

3.4 Evaluation after starting system operation

In FY2021, results data stored within GCS was used for evaluation through actual data analysis in order to verify the effects of introducing GCS. The results data of 13 new SVRs that began operating with this system from June 2021 was the basis for the evaluation. A comparison of the number of tap operations before and after introducing the system indicated a reduction in the number of tap operations of all new SVRs covered by the evaluation. Analysis of data such as setting values updated with batch processing and real-time processing, measured voltage, occurrence of voltage deviations, and the results of real-time processing operations indicated that the optimum voltage is maintained by GCS using voltage control, with the expected effect being observed.

4. Conclusion

With the use of renewable energy sources like PV expected to increase further in the future, coupled with concerns about the impact that mass uptake of electric vehicles will have, the ability for distribution systems to maintain supply voltage within a suitable range is thought to become increasingly difficult. In addition to the detailed voltage control achieved with this GCS, systems to maintain and control optimum distribution voltage and power flow through the use of distributed energy resources (such as batteries and electric vehicles) connected to distribution systems will be required, and this is another field of development that is advancing. Mitsubishi Electric is working toward optimization of the entire system with the cooperative operation of centralized systems capable of large-scale control of distributed energy resources, and edge distributed terminals for smaller scale control(3). Mitsubishi Electric will continue advancing technical development for further enhancement of system operation, with a view to increasing the introduction of distributed energy resources in the future.

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"MELPRO-i" Series Edge Device for Advanced Monitoring and Control

Authors: *Takeo Hikita** and *Ryoya Yamamoto**

1. Introduction

Against the backdrop of introduction of a licensing system established by Japanese law with the aim of increasing the use of renewable energy and distributed energy resources with a view to achieving carbon neutrality, local production and local consumption of energy, and building communities with a high resilience against disasters. There is an anticipated increase in microgrid systems capable of supplying power in a self-sustaining manner using grids independent of electric utility companies in the event of large-scale power outages due to disasters or other causes. Meanwhile, there is a growing need in the field of electrical safety for more efficient and advanced (smart) service and maintenance operations associated with the aging deterioration of electrical facilities as well as the lower birthrate and aging population of society. MELPRO-i has been developed and released to meet these needs, complies with the IEC 61850 international standard for communication protocols and provides functions like edge AI, Programmable Logic Controller (PLC) and security.

This paper outlines the purpose of development of MELPRO-i, details of the factors behind development, and various use cases.

2. Aim of Development

Today's protection relays, also called Intelligent Electronic Devices (IEDs), are feature-rich products that include communication functions, PLC functionality and record functions. In addition to use cases as protection relays, there is an increase in use cases where IEDs are being applied for measurement and control devices for system data required for the operation of distributed energy resources and microgrids.

Mitsubishi Electric has already commercialized IEDs, but has developed and released MELPRO-i with the aim of further increasing use cases and achieving more advanced monitoring and control by including and expanding the following functionalities.

- Compliance with IEC 61850 Edition 2.0
- Include Mitsubishi Electric's Maisart AI technology
- Expanded PLC function
- Cybersecurity

3. Details of Development

3.1 Compliance with IEC 61850 Edition 2.0

The IEC 61850 communications protocol is already available to provide protective control for substations, and is currently transitioning to Edition 2.0. MELPRO-i complies with Edition 2.0, and also includes the following new communication services.

- Support for Select Before Operate with enhanced security (SBOes)
- Remote setting (change setting values within Setting Groups)
- Sending/receiving Value Generic Object Oriented Substation Events (Goose)
- Software updates (using File Transfer)

There is no definition for software updates in IEC 61850, but MELPRO-i uses defined communication services and object models to update its software.

3.2 Includes Mitsubishi Electric's Maisart AI technology

(1) Dedicated AI processing CPU

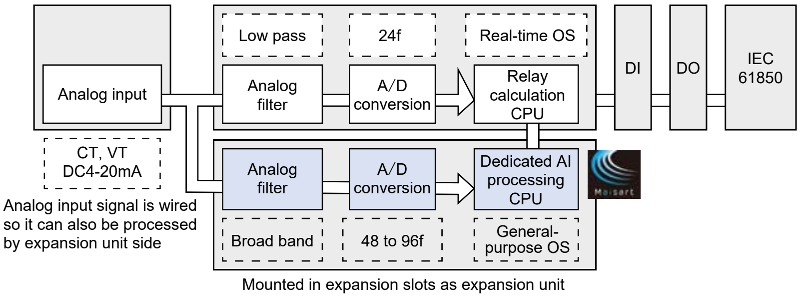
MELPRO-i features expansion slots that allow optional units to be mounted, and installing expansion units with dedicated AI processing CPUs in expansion slots allow the use of edge AI functions (Fig. 1). Analog input signals that are input for relay calculations are wired so that they can also be read by the expansion unit side—they are sampled at high speed (up to 5,760 Hz) via an analog filter with wider broadband frequency characteristics than those for relay calculations. MELPRO-i features a fanless design to take into account the installation environment, product life spans and other factors.

(2) Mitsubishi Electric's proprietary AI engine

The software configuration of edge AI is as outlined in Fig. 2. As described above, MELPRO-i features a fanless design and performs preliminary calculations to determine whether or not to launch the AI engine using the edge AI app—optimizing the execution of the AI engine helps to reduce power consumption.

Compatibility with Mitsubishi Electric's IoT platform INFOPRISM allows its proprietary AI engine to be used. AI engines that are currently available use technology for the recognition of similar waveforms[1].

*Transmission & Distribution Systems Center



CT: Current Transformer, VT: Voltage Transformer, DI: Digital Input, DO: Digital Output

Fig. 1 Edge AI hardware configuration

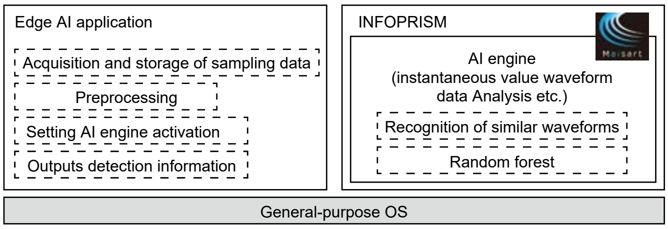


Fig. 2 Edge AI software configuration

Recognition of similar waveforms is a method used to determine the presence of faults (conditions that are different from normal). In the learning phase, score values (index that determines how similar the selected waveform is with other sections over the entire waveform) are calculated based on a learning waveform to determine the threshold for the score value. In the detection phase, score values (index that determines how similar the waveform is with the learning waveform) for the detection waveform are calculated, and if a value exceeds the threshold calculated in the learning phase, it is detected as a fault.

In the future, AI engines operating with random forest—a machine learning method used for applications like data classification (determination) and regression (estimation)—are anticipated to be used. Random forest is an algorithm that determines the feature amount (such as changes in frequency components or effective values) used for each data set, constructs a decision tree, and combines multiple decision trees—the classification output is determined by the results with the most trees. This application is anticipated to be used for cause estimation of accidents and faults.

3.3 Expanded PLC function

(1) PLC function

One feature of IEDs is the PLC function(2). Users can program sequence logic using programming language that complies with the PLC international standard IEC 61131-3. Programming sequence logic using PLC that had previously been achieved with the software or switchboard wiring incorporated within IEDs helps to reduce costs significantly.

(2) Extended PLC functions with Mitsubishi Electric's engineering tool MELGEAR

"MELPRO-D"(3), the base model used for development, enabled the use of the simplified PLC function using maintenance tool PC-HMI (Fig. 3). This meant programming is possible by selecting AND-OR logic for blocks available on the PC-HMI screen, making operation simple even for novice users. Yet this approach suffered from restrictions in the available logic functions and low programming capacity.

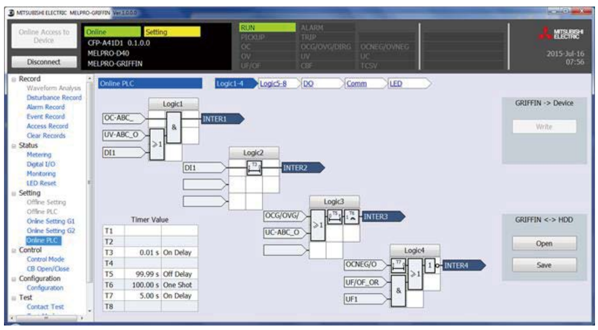


Fig. 3 PLC functions of PC-HMI

MELPRO-i resolves the PLC function issues of MELPRO-D, and the use of Mitsubishi Electric's engineering tool MELGEAR significantly expands the available PLC functions. MELGEAR allows the use of languages that comply with IEC 61131-3 like Function Block Diagram (FBD) and Structured Text (ST), and logic will be programmed by selecting the logic symbols and signals for required functions on the tool screen, as shown in Fig. 4.

Programmed logic can be converted to C and output, and after compiling is complete, a dedicated MELPRO-i software loader is used to load and run it in MELPRO-i (Fig. 5).

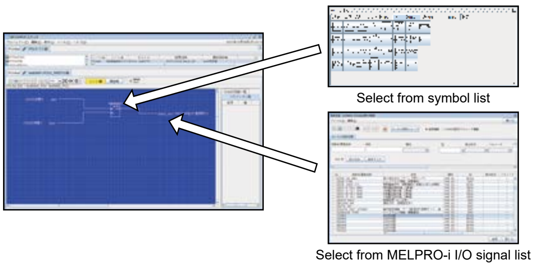


Fig. 4 Programming by MELGEAR

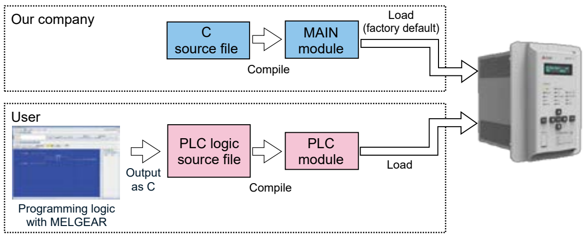


Fig. 5 Extended PLC functions of MELGEAR

Table 1 TOC of MELPRO-i

No.	Clause	Status
5.1.1	Electronic access control	Complies
5.1.2	Password defeat mechanisms	Complies
5.1.3	Number of individual users	Complies
5.1.4	Password construction	Complies
5.1.5.1	Authorization levels by password	Complies
5.1.5.2	Authorization using role-based access control (RBAC)	Complies
5.1.6	IED main security functions	Complies
5.1.7	Password display	Complies
5.1.8	Access timeout	Complies
5.2.1	Audit trail	Complies
5.2.2	Storage capability	Excluded
5.2.3	Storage record	Complies
5.2.4	Audit trail event types	Complies
5.3.1 to 5.3.6	Supervisory monitoring and control	Excluded
5.4.1	IED functionality compromise	Complies
5.4.2	Specific cryptographic features	Complies
5.4.3	Cryptographic techniques	Complies
5.4.4	Encrypting serial communications	Complies
5.4.5	Protocol-specific security features	Complies
5.5.1	Authentication	Complies
5.5.2	Digital signature	Complies
5.5.3	ID/password control	Complies
5.5.4.1	View configuration data	Complies
5.5.4.2	Change configuration data	Complies
5.6	Communications port access	Complies
5.7	Firmware quality control	Excluded

IEEE Std 1686TM-2013 (Revision of IEEE Std 1686-2007)

3.4 Cybersecurity

(1) IEEE 1686 compatibility

IEEE 1686 is defined as the security standard for IEDs, and IEDs available from international vendors are marketed with IEEE 1686 compatibility. While IEEE 1686 does not require all items of the standard to be met, it does require a Table of compliance (TOC) to be created to outline to users the compliance level of each item. The TOC being considered for MELPRO-i is shown in Table 1. Items not included in Table 1 do not meet one or more requirements defined in the standard.

(2) Role Based Access Control (RBAC) function

MELPRO-i provides protection for the front panel and locally connected PC-HMI with user IDs and passwords. Rights are also granted for each user ID, which applies limits access to each function depending on the level of rights. Four levels of rights are available, with fixed functions assigned to each level. Users will be able to configure the level of rights assigned to each user ID, and the same rights can be assigned to different user IDs.

(3) Communication encryption and communications port access

IEEE 1686 specifies that using remote access to transfer data, change settings or update software requires IEEE 1711-compliant data encryption for all ports used for remote access. MELPRO-i features an Ethernet(*1) port for IEC 61850 communications as the communications port, with encryption is planned to be available.

IEEE 1686 also specifies the use of a function in configuration settings for enabling/disabling all communication ports, whether physical or logical, and this setting is also planned to be available with MELPRO-i.

(*1) Ethernet is a registered trademark of the Fuji Film Business Innovation Corporation.

4. Use Cases

Use cases utilizing the IEC 61850 communication, edge AI, and other functions provided in MELPRO-i are introduced (Fig. 6).

4.1 Use cases utilizing IEC 61850 communications

(1) Distribution control(4)

In the event that an accident occurs along a distribution line, the current method of operation used for distribution lines temporarily interrupts power across the entire line after protection relays at the distribution substation are activated, in what is referred to as a sequential fault detection system. Switchgears starting from the closest to the distribution substation are then switched back on to restore power transmission—the segment with the accident can be identified when an accident occurs again. Power is then restored to other

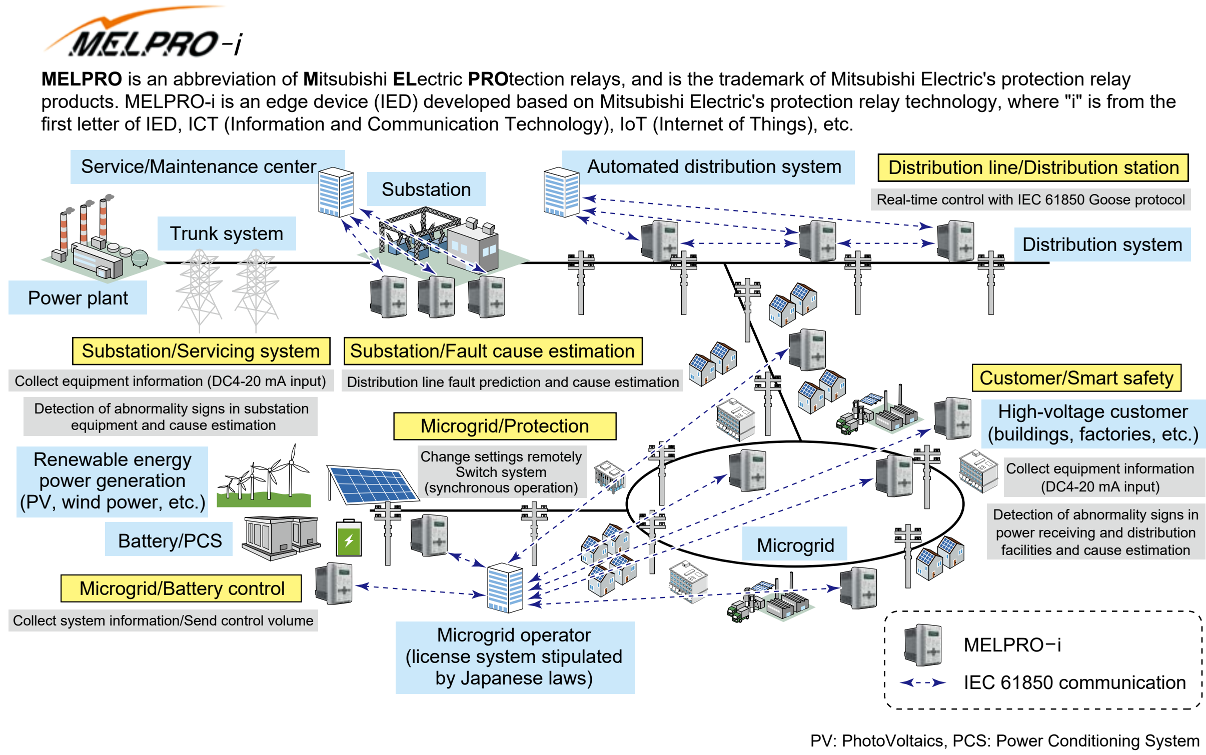


Fig. 6 Edge device "MELPRO-i" use cases

segments, but it takes several minutes to recover from the power outage.

Using MELPRO-i for distribution lines not only helps to detect accidents, but also exchanges information on detected accidents between adjacent MELPRO-i units using the IEC 61850 Goose protocol. This means affected segments can be identified and separated without interrupting the entire distribution line, as long as the fault is within the interruption capacity of switchgear.

(2) Microgrids

Efforts are being made in various areas to explore community microgrids utilizing renewable energy and distributed energy resources. Yet the configuration and scale of power systems when such communities are connected to electricity utility grids or operating their microgrids can vary significantly, which changes the scope of potential accidents. Addressing this may require changes to the setting values of protection relays installed at power plants and each customer before operating microgrids. To minimize power interruptions when switching from grid connections to microgrid operation, the setting value of each protection relay needs to be changed from remote sites via communications. MELPRO-i supports the IEC 61850 remote setting function, and caters to the requirements outlined above.

4.2 Edge AI use cases

The two following use cases are being considered as edge AI use cases.

(1) Distribution line fault prediction and cause estimation[4]

There are tens of thousands of kilometers of distribution lines installed around Japan. If power outages occur due to accidents or other causes, electricity utilities need to spend considerable effort identifying affected segments, determining the cause and restoring power transmission, and as such, there is strong demand for streamlining these operations.

MELPRO-i's edge AI records and analyzes distribution line signal waveforms like zero sequence current and zero sequence voltage, which allows predictive detection and fault cause estimation of accidents in distribution lines.

(2) Detection of abnormality signs in substation equipment and power receiving and distribution facilities

There is a growing need for more efficient and advanced (smart) service and maintenance operations associated with the gradual deterioration of electrical facilities and the lower birthrate and aging population. Equipment servicing and maintenance is becoming more sophisticated by installing various types of sensors on key equipment like circuit breakers and transformers, and utilizing the data acquired from those sensors.

In addition to zero sequence current and zero sequence voltage, MELPRO-i's edge AI reads DC4-20 mA input signals of sensor general-purpose interfaces, and records and analyzes signal waveforms for predictive detection and cause estimation of faults in various types of electrical facilities.

5. Conclusion

This paper outlined the purpose of development of MELPRO-i, details of the factors behind development, and various use cases. As communication infrastructure is put in place in the future and IEC 61850 communication is more widely adopted, use cases are expected to expand further. While edge AI currently has a shortage of available learning data (data on accidents and faults, data immediately before an accident or fault occurs), data will continue being acquired through demonstrations and other tests in each use case, to further advance prediction and cause estimation operations.

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Verification of Voltage Sourced Converter Based HVDC System

Authors: *Hitoshi Sadakuni*, Junya Ishiguro** and *Daisuke Yamanaka**

1. Introduction

Compared to line commutated converters, characteristics of voltage sourced converters include fewer restrictions on AC systems and reactive power control capability. Of the types of voltage sourced converters available, MMCs are suitable for HVDC applications because they are easy to operate at higher voltages, with characteristics like a smaller level of harmonics generated and being able to ensure redundancy(1). The application of HVDC using MMC (MMC-HVDC) has increased in recent years, and Mitsubishi Electric has also focused efforts on development in this field(2). To further these efforts, Mitsubishi Electric constructed a HVDC verification facility (Fig. 1) for verifying its HVDC-Diamond system, and ran a series of verification tests. This paper outlines the results of those verification tests.

2. HVDC Verification Facility

This verification facility was constructed on the grounds of the Transmission & Distribution Systems Center in Amagasaki City, Hyogo Prefecture, and began operation in November 2018. The purpose of construction of this verification facility is to run operational tests and store data of the entire MMC system using the same converters, control protection equipment and other equipment as production models. In-house verification tests have already been completed, and this facility is currently used for verifying equipment designed for use at external converter stations.

Details of the main circuit are shown in Fig. 2, and system parameters are shown in Table 1. The system includes two sets of converters, which are then connected to the AC grid via an interface transformer. The system uses a three-winding transformer to circulate transformer power between the primary and secondary windings, allowing 50 MW transmission tests to be run with only the HVDC verification facility system. These losses are covered by the factory's AC system supply.

Table 1 System parameters

Rated power	50 MW
Rated AC voltage (factory network side)	6.6 kV
Rated AC voltage (verification facility side)	21 kV (60 Hz)
Rated DC voltage	±21 kV
Rated DC current	±1,190 A

(a) Verification facility

(b) HVDC valve

Fig. 1 HVDC verification facility

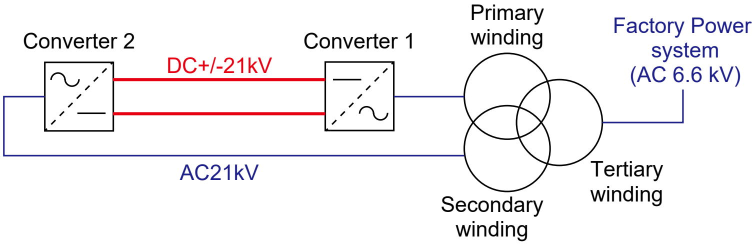

Fig. 2 Main circuit configuration

* *Transmission & Distribution Systems Center*

Fig. 3 shows the converter, which is comprised of multiple unit converter sub-modules connected in series. Mitsubishi Electric's high-withstand voltage, Insulated Gate Bipolar Transistors (IGBTs) are used as the switching elements, and reducing the number of sub-modules realizes a more compact converter station footprint with lower power loss.

The control protection equipment features a common HMI (console) for operating the devices and monitoring conditions, control device for controlling the converters, protective device, and optical repeaters for relaying signals between the converters and each device.

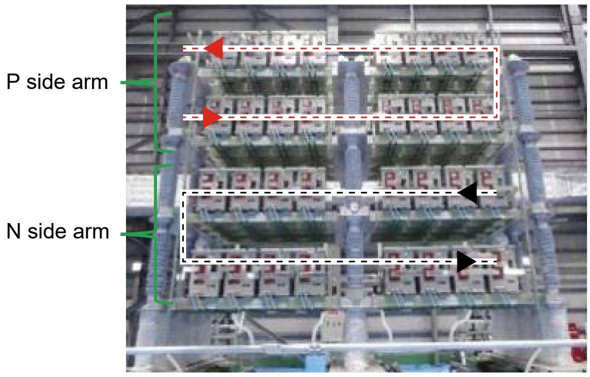

Fig. 3 Converter

3. HVDC System Verification

3.1 Start-up and stop tests[1]

Four types of tests confirmed the operation without any issues: normal start-up, normal stop, emergency stop, and black start.

The results of a typical black start test are shown in Fig. 4. In this test, the converter on the black start side is isolated from the transformer, and then the converter on the supplying system side is charged from the AC side, followed by (1) Control the supplying side converter to charge the DC circuit and blackout side converter, (2) Begin control of blackout side converter and after charging is complete, (3) Generate AC voltage with the blackout side converter, to simulate a black start.

3.2 Power interchange test[1]

Fig. 5 shows the results of a power interchange test which transmits active power and reverses power flow. The results indicated that up to 50 MW of active power can be transmitted reliably in accordance with a reference value.

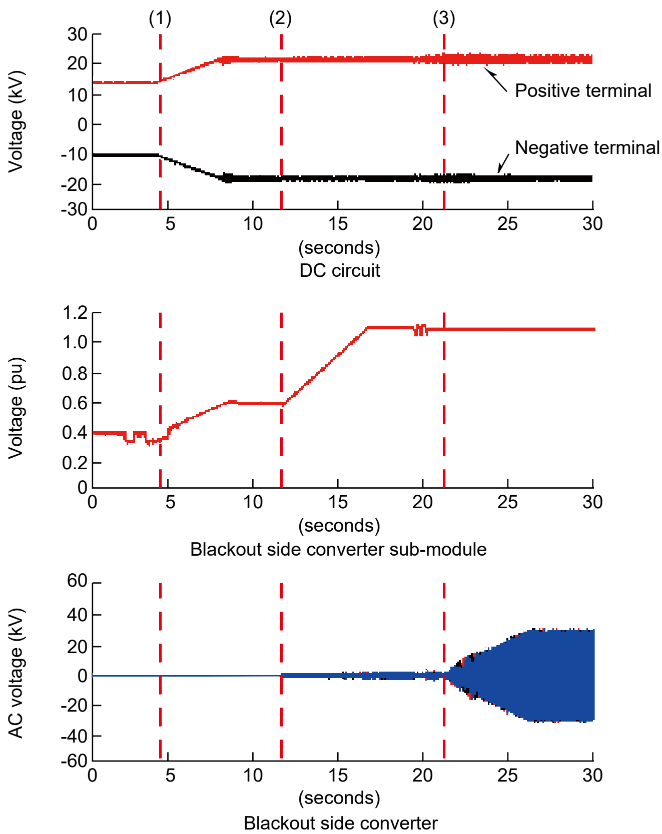

Fig. 4 Black start test

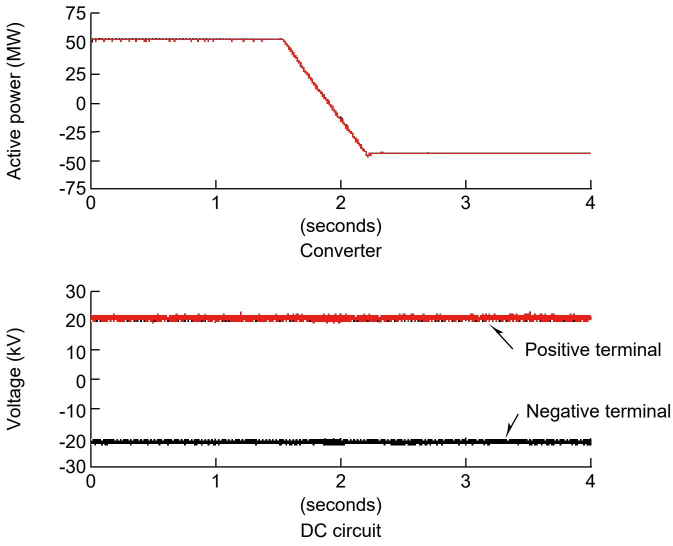

Fig. 5 Reverse power flow test

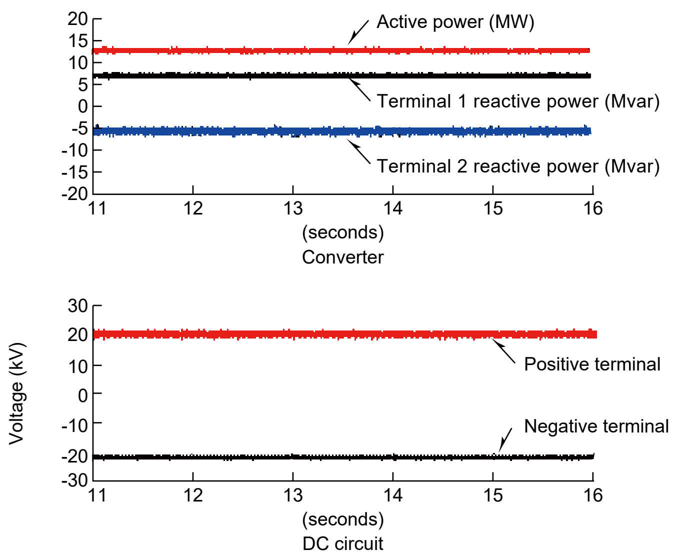

Fig. 6 Active/Reactive power simultaneous output test

3.3 Reactive power output test[1]

A STATCOM operating test and active/reactive power simultaneous output test were performed, indicating that reliable operation was possible in accordance with a reference value. Fig. 6 shows the results of the simultaneous output test with 13 MW active power and 7 Mvar reactive power.

3.4 Long-term stability test

A heat run test was performed that involves continually operating the equipment at the rated output until its temperature stabilizes. The equipment was energized constantly for 8 hours at 50 MW active power and 0 Mvar reactive power for the heat run test, and the temperature rise of the equipment was observed to be appropriate, without any faults caused by localized overheating (Fig. 7).

3.5 DC bus short circuit test

When short circuit faults occur in a DC bus, fault current continues to flow through antiparallel diodes in IGBT modules until AC-side circuit breakers are tripped, even if all IGBTs are gate locked. As the current flowing through the internal diode is much higher than the rated current, the junction temperature of the diode exceeds the given value over a short period (around one cycle), causing the diode to fail. To prevent this, an over-current bypass diode (Bypass Diode: BPD) is installed parallel to the IGBT internal diode as shown in Fig. 8 to divert current flow, which ensures that the BPD carries the fault

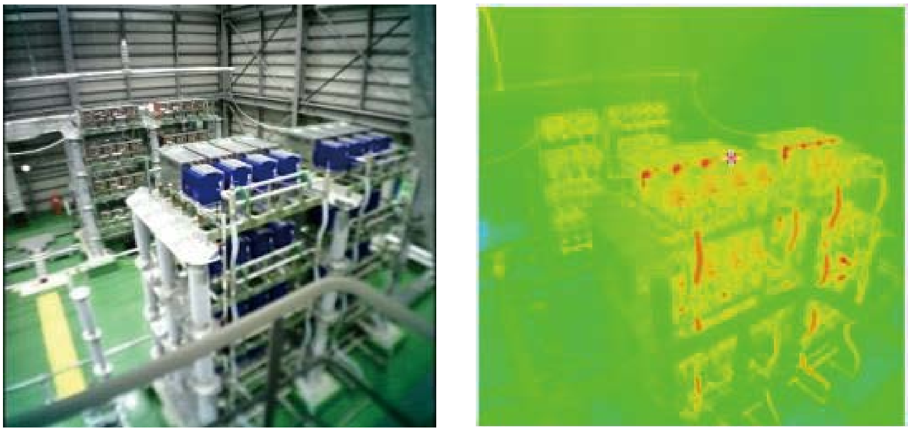

Fig. 7 Thermal imaging of converter during heat run test

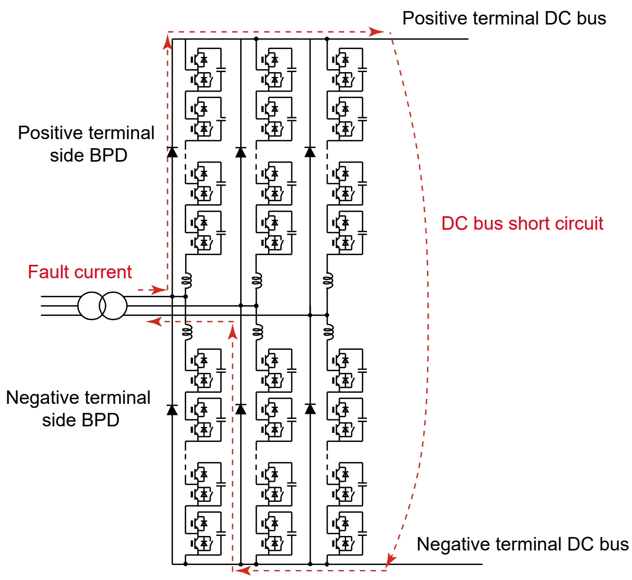

Fig. 8 Short circuit protection operating principle

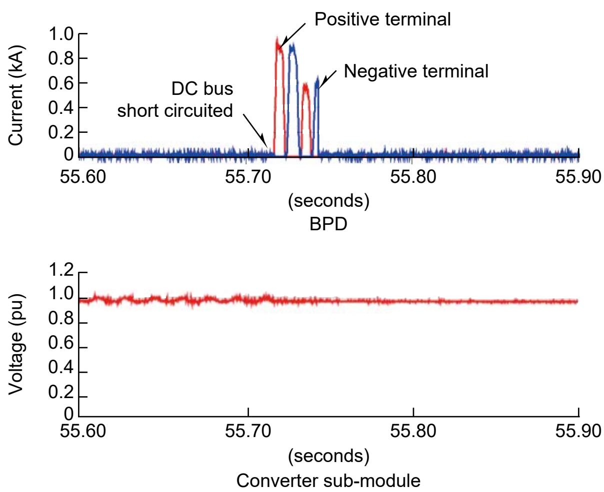

Fig. 9 DC bus short circuit test

current in the event of a short-circuit fault to protect the converter.

This test involves triggering a DC bus short circuit fault at the verification facility to verify that the BPD operates to protect the converter. It was confirmed that diverting the fault current to the BPD when a DC bus short-circuit fault occurs prevented the fault current flowing to the converter, as shown in Fig. 9, and also limited over-voltage generated at the converter's capacitor to provide normal protective action.

3.6 Radio noise test

Electromagnetic noise generated when a converter is operating includes various frequency components, and may adversely affect communications around the converter station. To address this, the verification facility was used to measure (with an antenna) the electromagnetic noise generated when the converter was operating. The results of electromagnetic noise measurements in the Japanese AM radio frequency bands when the converter was operating and stopped are shown in Fig. 10. No harmful level of noise was observed in these frequency bands.

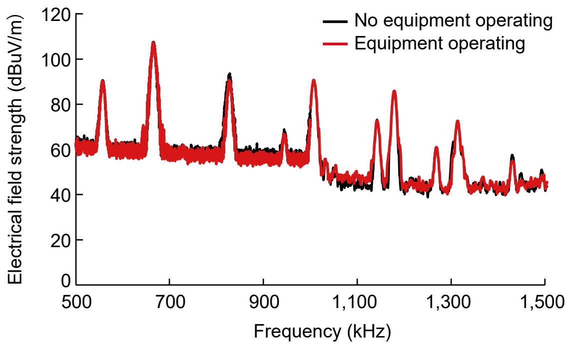

Fig. 10 Radio noise test

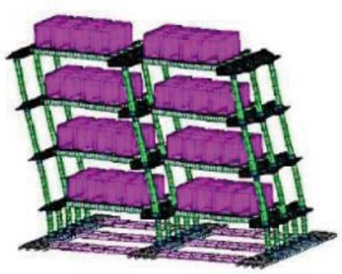

Fig. 11 Results of seismic analysis of converter (dynamic analysis)

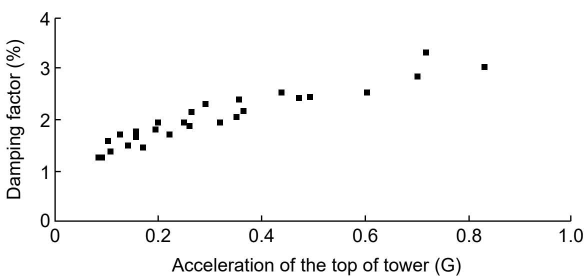

Fig. 12 Damping factor of converter valve tower

3.7 Seismic analysis

Converters suitable for HVDC systems are composed of series-connected sub-modules as shown in Fig. 3 to provide high voltage operation.

Stacking submodules can reduce the footprint of the converter, but the resulting higher center of gravity raises the issue of seismic performance.

In Japan, the required seismic specification is JEAG 5003 (Guideline for seismic design for electric equipment at substations, etc). Evaluation by dynamic analysis confirmed that this specification was met (Fig. 11). In this converter, polymer insulators were applied to the insulation supports using FRP (Fiber Reinforced Plastics) as a structural member. Data[3] on the damping factor of the polymer insulators obtained in the verification test equivalent to the actual equipment is applied (Fig. 12). The resonant frequencies of the converters were measured and the accuracy of the analysis was confirmed to be sufficiently high.

4. Conclusion

A verification facility was constructed to conduct a variety of tests for HVDC-Diamond, Mitsubishi Electric's HVDC system. This allowed data to be acquired on control (normal start-up, normal stop, emergency stop, black start, power interchange test, reactive power output test), long-term stability (heat run test), protection (DC bus short circuit test), practical performance (radio noise test and seismic evaluation), which indicated that the product can be supplied without any performance issues.

Based on these results, plans are being formulated for the development of more compact HVDC systems with even lower losses.

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C-GIS Cable Switching Breaker for Wind Power System Applications

Authors: *Toshihiro Matsunaga*, Koichi Kagawa*, Kenji Onishi** and *Yoshiki Yoshioka***

1. Introduction

With the increased use of renewable energy sources, the wind power industry embarked on full-scale construction of large offshore wind power plants from around 2010, particularly in Europe, and the uptake of wind power is anticipated to increase even further in the future in North America and throughout Asia.

As for construction of such large-scale offshore wind power plants, operation begins from wind turbines for which installation is completed, in order to maximize efficiency without losing power generation opportunities. Minimizing the loss of potential power generation opportunities, like with outages of wind turbine facilities due to inspections or other maintenance is also a key factor.

To operate a wind power system flexibly like this, Mitsubishi Electric has developed Cable switching breaker (CS) based on the conventional Disconnector (DS) with additional switching capability of cable charging current, and applied this technology to 72.5kV type C-GIS "HG-VG-A"(1) (below, "HG-VG-A type C-GIS") for offshore wind power system applications.

This paper provides an outline of CS and the technology that has been used.

2. Outline of CS for HG-VG-A type C-GIS

2.1 Roles of large offshore wind power plants and Cubicle-Type Gas Insulated Switchgear (C-GIS)

A diagram of the overall power system for large offshore wind power plants is shown in Fig. 1. Large offshore wind power plants feature around ten wind turbines that are connected in series with undersea cables to create an inter-array cable circuit. Power from multiple inter-array cable circuits is collected and converted to high voltage at the offshore substations and then transmitted to onshore substations in a tree-like configuration power system.

As shown in Fig. 2, power generated by each wind turbine is boosted to 72.5 kV by a transformer immediately beneath the wind turbine. Power then flows through Circuit breaker (CB) that protects the wind turbine by shutting off short circuit (earth fault) currents if there is an accident, and DS that connects or isolates the wind turbine and inter-array cable circuit, before being transmitted to undersea cables. HG-VG-A type C-GIS comprises the components within the dashed lines of Fig. 2, integrating CB and DS required for the operation of wind turbines, installed in the confined space within a wind turbine.

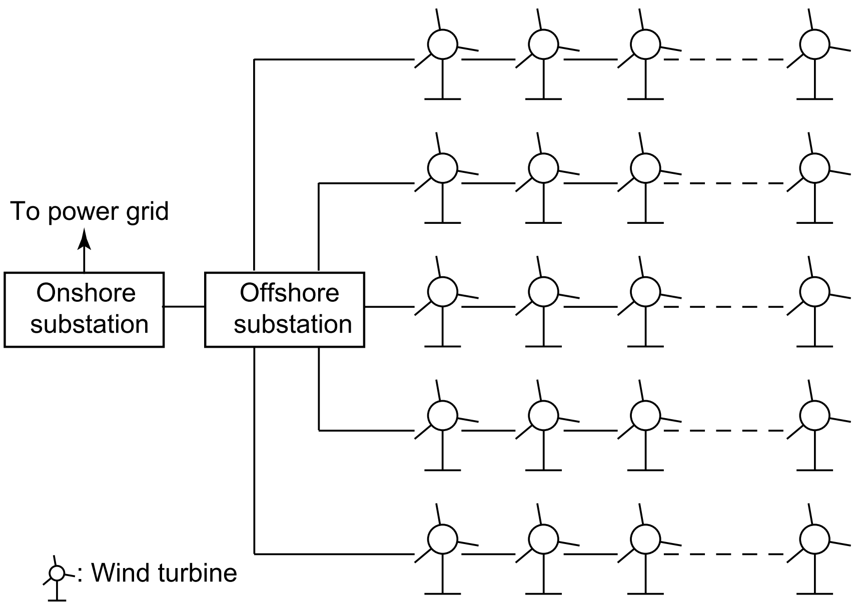

Fig. 1 Diagram of overall power system for large offshore wind power plants

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When a new wind turbine is constructed, DS is closed to ensure the turbine is connected to the inter-array cable circuit, then the CB is closed to begin transmitting power from the turbine. To stop power being transmitted from the turbine for inspections or other maintenance, the CB is opened and DS is isolated to disconnect the turbine from the inter-array cable circuit.

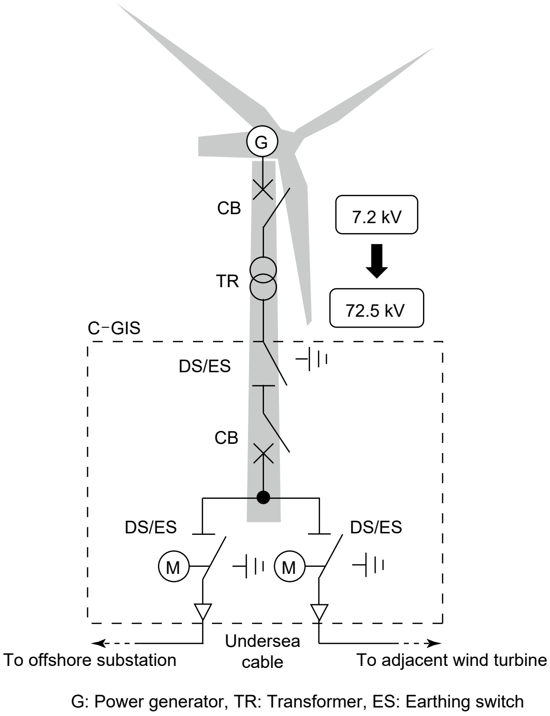


Fig. 2 Single-line diagram inside wind turbine

2.2 CS with switching capability of cable charging current

As DS itself does not have current switching capability while high voltage is applied, connecting or isolating the wind turbine from the inter-array cable circuit outlined above requires the CBs within the C-GIS for all other wind turbines on the same inter-array cable circuit to be opened to isolate the generators from the inter-array cable circuit. CB connected directly to the inter-array cable circuits in the offshore substation also need to be opened to isolate the entire inter-array cable circuit including the intended wind turbine from the power grid. Furthermore, as wind turbines are connected together with undersea cables, DS cannot be switched immediately after power transmission is stopped due to a charging current generated by the residual voltage corresponding to the capacitance of cable—DS can only be switched after waiting for the residual voltage to be discharged. Doing so affects a large area of the system for a long period of time, which implies that switching inter-array cable circuits results in a major loss of potential power generation opportunities (Fig. 3 (a)).

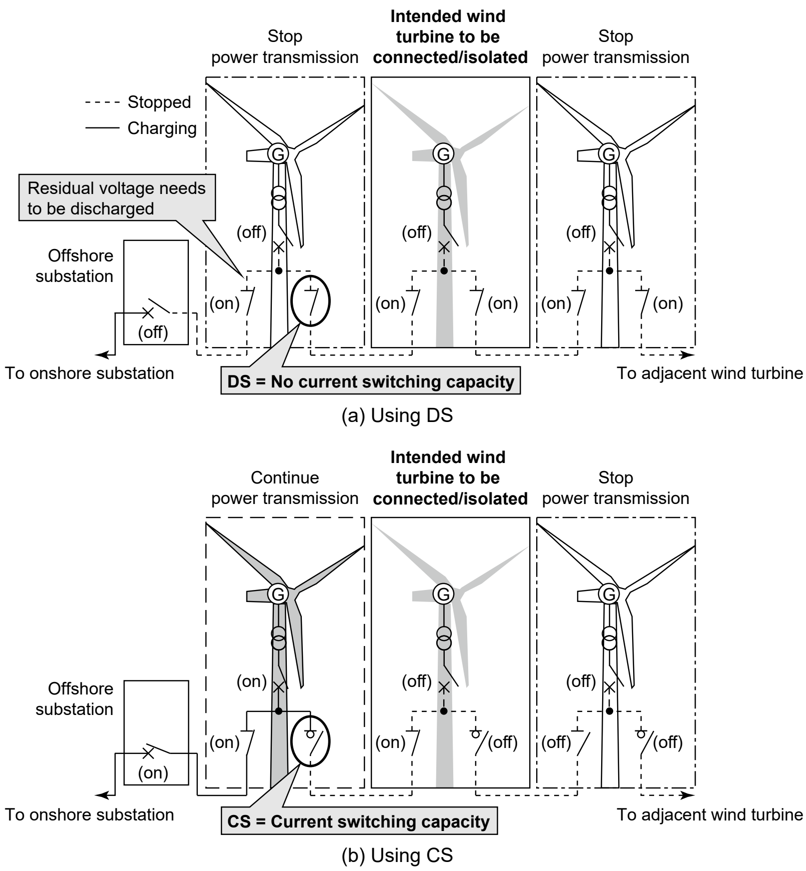


Fig. 3 Connecting and isolating wind turbines with/from inter-array cable circuits

Table 1 CS Ratings

Item		Specification
Standard Compliance		IEC 62271-104: 2020
Rated voltage		72.5 kV
Rated continuous current		1,250 A
Rated frequency		50 Hz
Rated lightning impulse withstand voltage		350 kV
Rated cable-charging current	Breaking current	40 A (class C1 switch)
	Making current	700 Apeak
Insulation medium		SF_6 (sulfur hexafluoride)
Rated gas pressure		0.05 MPa-G (at 20°C)

Equipment that provides more flexible operation is required in order to maximize power generation efficiency and achieve a stable supply of power, so Mitsubishi Electric has developed CS based on DS with additional switching capability of cable charging current (Table 1). To ensure that the external dimensions of C-GIS remains unaffected due to the space limitations for being installed within wind turbines, the CS was developed with added functionality based on the same structural layout as the conventional DS.

Replacing the conventional DS with a CS not only eliminates the need to wait for residual voltage in the cables to be discharged, but also negates the need to open the CB in the offshore substation. Simply stopping wind turbines upstream of the inter-array cable circuit allows the intended wind turbine and inter-array cable circuit to be connected or isolated (Fig. 3 (b)).

3. Technology underpinning CS for HG-VG-A type C-GIS

The highly technically challenging aspect of switching capability for cable charging currents is the opening operation, and this is due to the small capacitive current breaking. While the small capacitive breaking current is much smaller compared to the fault current during a short circuit, the small current means the current can be easily chopped and the recovery voltage rises immediately to peak after around half a cycle (around 10 ms for 50 Hz). As such, current switching generates a restriking of arc between the terminals if sufficient insulating distance cannot be achieved quickly during opening operation. The resulting over-voltage poses a risk of endangering the proper operation of devices. Accordingly, CS requires non restrike current interruption for the cable charging current.

The technology used to ensure CS has the capability of small capacitive current breaking is outlined as follows.

3.1 High-speed mechanism using mechanical latch

Fig. 4 shows the opening operation of the conventional DS installed within HG-VG-A type C-GIS. DS converts the rotational movement from the operating mechanism to linear movement with a trapezoidal screw installed inside the cylindrically shaped movable contact. The contact arm moves left from the terminal on the closing side toward the terminal on the disconnecting side, to disconnect the terminals.

This drive design is advantageous in that it achieves a long moving distance with a compact operating mechanism, but cannot achieve the required insulating distance quickly to withstand recovery voltage due to the relatively low opening speed of the contact arm that is dependent on motor rotation.

CS adds a drive spring and high-speed movable contact different from the main conducting contact arm within the terminal on the closing side at the opposing side of the terminal on the disconnecting side as shown in Fig. 5. This design engages the contact arm and

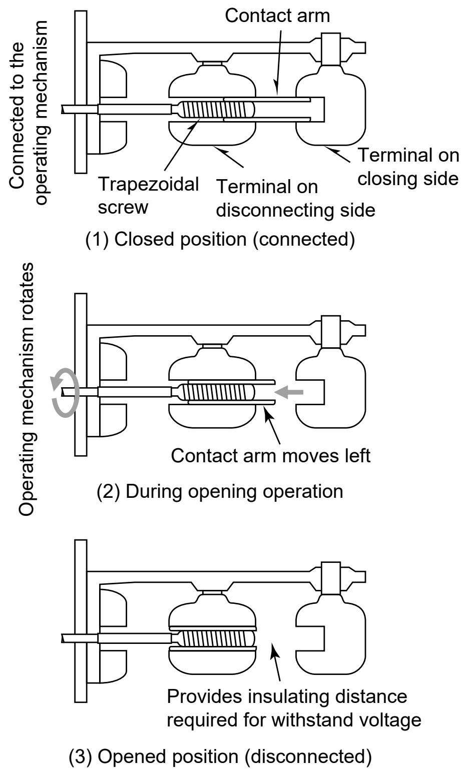


Fig. 4 Opening operation of DS

high-speed movable contact with a latch when the contact arm provides a connection between the terminals like with DS. During opening operation, the contact arm moves left and pulls out the high-speed movable contact while charging the spring. The latch opens when the high-speed movable contact reaches the terminal position on the disconnecting side, and the high-speed movable contact moves quickly to the right with the driving force of the charged spring to completely interrupt the current flow while quickly ensuring the required insulating distance.

3.2 Movable electrical shield

The required insulating distance to interrupt the current flow is affected by the electrical field strength. The electrical field strength of the high-speed movable contact is higher at the tip where the diameter is smaller—ensuring the high-speed movable contact moves quickly into the terminal on the closing side that has a large diameter relaxes the electrical field strength, which shortens the insulating distance required to interrupt the current flow.

Yet just like DS, CS also has withstand voltage requirements as disconnected poles between the terminals; a larger insulating distance is required at the opened position than when interrupting current flow, so the terminal on the closing side could not be designed closer to the terminal on the disconnecting side.

To overcome this issue, the terminal on the closing side of CS features a movable electrical shield that moves with the high-speed movable contact (Fig. 5). The shield is normally separated by a large distance from the terminal on the disconnecting side, but during opening operation it moves left with the contact arm and approaches the terminal on the disconnecting side. When the latch is released and the high-speed movable contact moves to the right into the terminal on the closing side, the shield subsequently moves to the right and returns to its normal position to disconnect the circuit, thus ensuring the insulating distance required for withstand voltage performance in the opened position.

3.3 Stiffness enhancement of terminal support

Compared to the slow opening speed of DS, CS suffers from significant shock in the direction of movement of the high-speed movable contact during opening operation. Whereas the terminal on the closing side of DS is secured with insulating support in one position at the top, CS features an additional insulating support at the bottom of the terminal on the closing side to enhance stiffness (Fig. 6).

3.4 Electrical interlock

When power is being transmitted from the wind turbine, load current corresponding to the generator capacity flows to the inter-array cable circuit via CS. The maximum value is set to the same 1,250 A rated current as that of the HG-VG-A type C-GIS, but adding switching capability of rated current to CS was expected to make it significantly larger. As such, CS was designed for switching the cable charging current under conditions where power transmission from upstream wind turbines has been stopped.

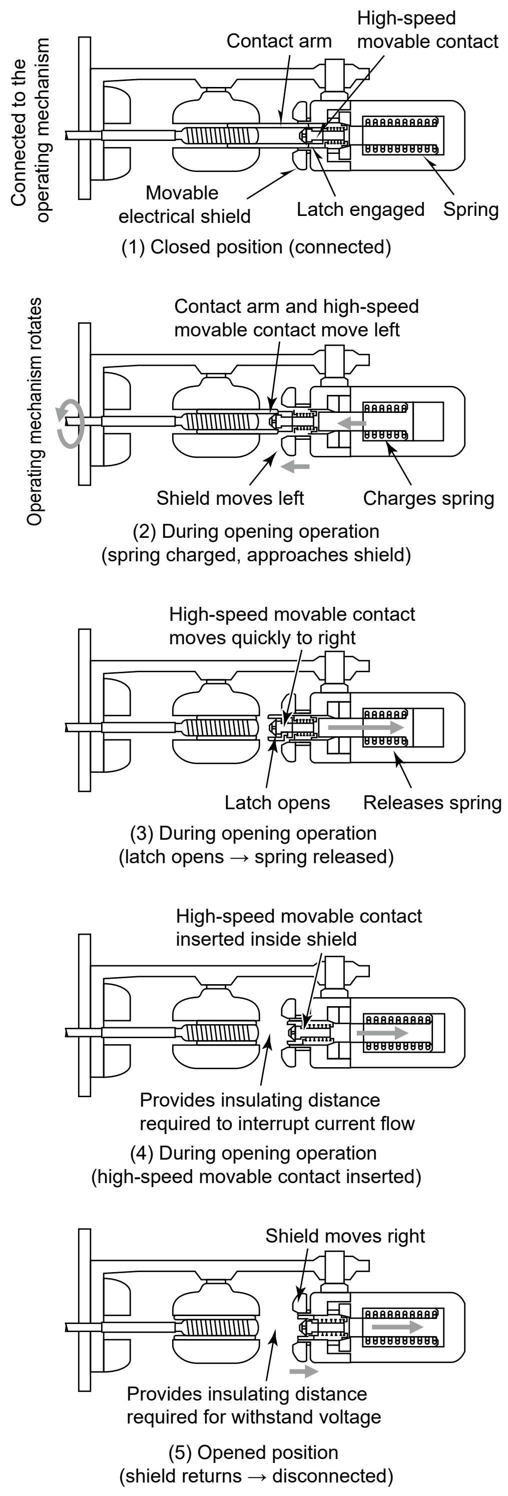
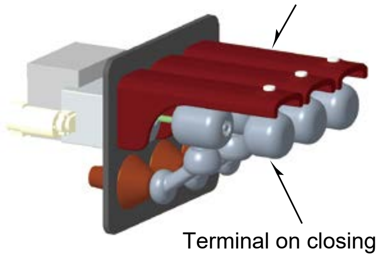
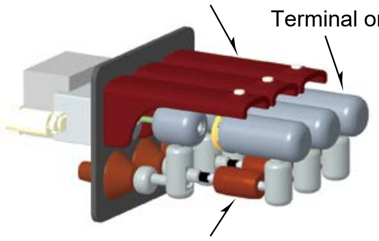


Fig. 5 Opening operation of CS



(a) DS unit



(b) CS unit

Fig. 6 Terminal supporting structure of DS unit and CS unit

In light of this, CS is only capable of interrupting the cable charging current (up to 40 A), and cannot interrupt currents that exceed the breaking current in Table 1, even with fault currents in the event of short circuits or load currents flowing through inter-array cable circuits under normal operations.

To address this, an electrical interlock featuring a combination of compact current transformer (CT) and current sensor has been installed in the cable—if the CT measures current that exceeds the breaking current, it blocks the operating signals so that the CS cannot be opened (Fig. 7).

Note that arc resistance material has been used for the tips of the contact arm and high-speed movable contact to allow switching of cable charging currents.

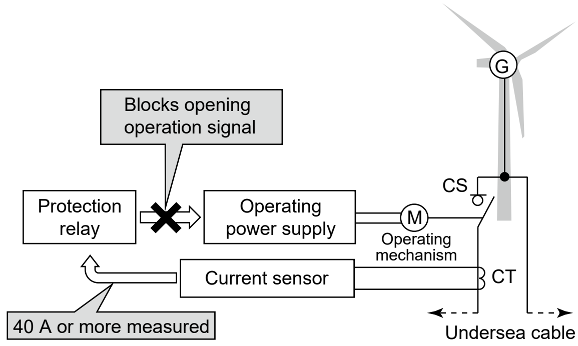


Fig. 7 Electrical interlock

4. Conclusion

This paper outlined the development of CS applied for HG-VG-A type C-GIS for offshore wind power system applications.

CS has been developed and applied that complies with IEC 62271-104 standards for switching capability of cable charging currents. It is based on the conventional DS and features such as a high-speed mechanism using mechanical latch so that it does not affect the external dimensions of HG-VG-A type C-GIS that have severe space restrictions for installing inside wind turbines.

The scope of application of CS will be expanded in the future in order to maximize the power generation efficiency of large offshore wind power plants and achieve flexible power system operation with minimal loss in potential power generation opportunities.

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