Technology of Digital Substation for Advanced Maintenance and Operation

ISHIGAMI, Yuta* SUGITA, Kohei* NOGAWA, Michio*

ABSTRACT

The aged substation facilities in Japanese electric power industry has created the growing need to replace many of them. When replacing substation facilities, it is required to improve construction work efficiency, save costs, increase equipment reliability, and enhance maintenance and operation. To meet these needs, Fuji Electric developed IEDs and MUs in accordance with IEC 61850, an international standard that stipulates the configuration of digitalized substations. Connecting IEDs and MUs via Ethernet, we have been developing an IEC 61850 fully digitalized substation by using oversampling techniques and examining protection performance (3-cycle breaking).

1. Introduction

The development of the Electricity System Reform has led to expansion in wide-area system operation across regions. As a result, some challenges and problems have emerged, such as issues related to how to seamlessly connect power companies, maintain system stability when a large number of distributed power sources are connected, cope with aging equipment, and perform maintenance while dealing with labor shortages. It is against this backdrop that power utilities are finding it necessary to improve efficiency in providing stable power supply and replacing facilities, while also reducing the cost of operations.

In particular, the aged substation facilities in the Japanese electric power industry have created the growing need to replace many of them. When replacing these facilities, it is necessary to improve construction work efficiency, reduce costs, increase equipment reliability, and enhance maintenance and operation. To meet these needs, digital substations based on digital technology are expected to achieve when renewing or replacing substation facilities. Digital substations are anticipated to reduce the hundreds of control cables installed in existing substations, streamline substation equipment and increase the efficiency of construction.

In this paper, we will introduce digital substation technology for achieving advanced maintenance and operation.

* Power Electronics Systems Energy Business Group, Fuji Electric Co., Ltd.

2. Trends in Substation Digitalization Technology

Figure 1 shows a configuration example of the information system in a digital substation. Up until now, research on the practical application of station buses has been advanced. In recent years, research on

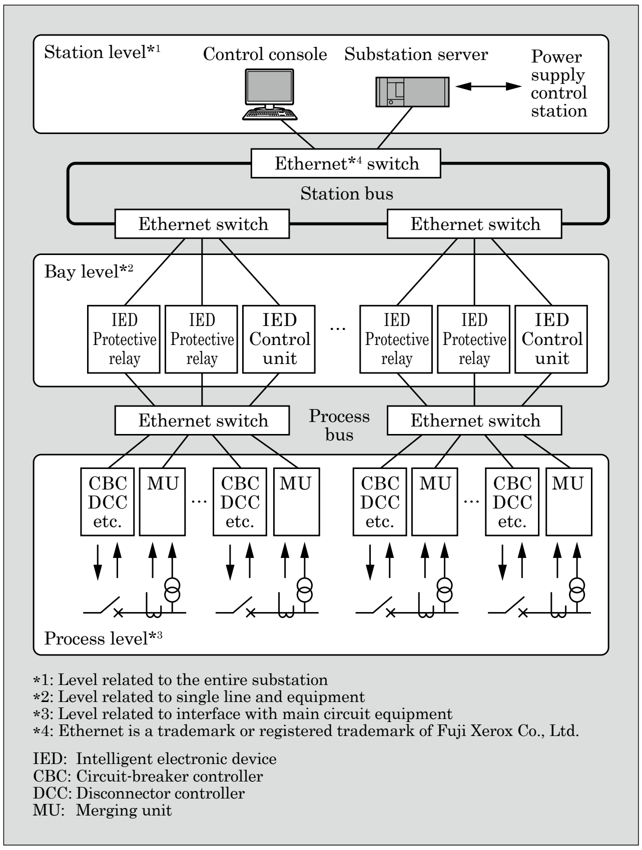

Fig.1 Configuration example of digital substation information system

the practical application of process buses has been actively conducted.

Digital substations outside Japan tend to adopt common information models (CIM) and abstract communication service interfaces (ACSI) for monitoring and control information specified in the international standard IEC 61850. In Japan, digitalization of substations is also being researched in accordance with IEC 61850[(1),(2)].

Hundreds of analog signal cables, such as for control signals, are installed in current substation systems. By using process buses that use optical fiber cables instead of analog signal cables, all information in substations can be digitalized. Process bus communications can be easily connected for equipment of various manufacturers via the ACSI specified in IEC 61850.

Analog signal cables currently connect lengthy distances between outdoor process-level field equipment and indoor bay-level equipment. The use of process buses will reduce the number of analog signal cables, decrease the size of on-site equipment through reduced wiring and achieve labor savings in construction. Furthermore, the use of process buses can also shorten construction periods and improve safety during construction and maintenance.

Moreover, sharing information via digitalization of information in the substations is expected to facilitate sophisticated monitoring and automatic control functions, stabilizing substation system operation and preventing failures. In addition, by accumulating and reusing various kinds of electricity measured data and equipment information measured in multiple substations over a long period of time, asset management is expected to be advanced for substation equipment.

3. Fuji Electric's Substation Digitalization Technology

Fuji Electric has been conducting research and development since 2011 for achieving practical application of digital substations, that is all information is digitalizes in substations. In the next section, we will describe the development status of the equipment that makes up digital substations.

3.1 IEDs and MUs based IEC standard

The main equipment that makes up digital substations includes intelligent electronic devices (IEDs) and merging units (MUs). IEDs are protection calculating devices that detect various failures occurring inside and outside substations and output trip commands to circuit breakers. MUs are input-output converters that convert voltage and current values and circuit breaker switching information measured in a substation into digital data to output to IEDs. The international standard IEC 61850 is generally used for communications between IEDs and MUs.

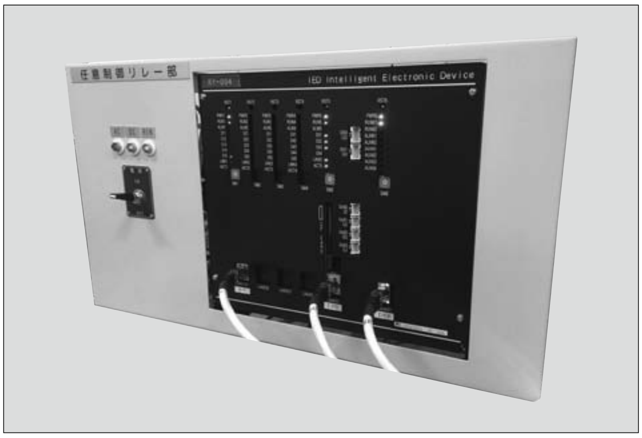

Fig.2 External appearance of IED

Input data from MUs to IEDs is digitalized, whereas analog input data has been used for voltage and current values and circuit breaker switching information in a substation measured with conventional protective relays. Therefore, all MUs need to output time-synchronized digital data using a common time.

On the basis of the above descriptions, Fuji Electric has developed new IEDs and MUs based IEC 61850. Figure 2 shows the external appearance of the newly developed IED. Communications between IEDs and MUs use the ACSI of IEC 61850. Sampled values (SV) in ACSI are used to communicate instantaneous voltage and current values and generic object-oriented substation events (GOOSE) are used as a communication method for notifying status changes to communicate circuit breaker switching.

Fuji Electric is currently working on the practical application of the time synchronization system described in Section 3.2 as a system that complies with the international standard IEC 61588. In addition, we are also working on the practical application of the time asynchronization system described in Section 3.3.

3.2 Model verification using a power system simulator

Fuji Electric has developed a power system simulator that simulates a power system compliant with IEC 61850 and IEC 61588 as a preliminary step to building a digital substation for use in the actual field. We built a digital substation model in this power system simulator. We verified the functions required by the digital substation through in-house testing and then delivered it to Chubu Electric Power Co., Inc. We describe the power system simulator in the following sections.

(1) System configuration of the power system simulator

Figure 3 shows the system configuration of the power system simulator.

The operation support system controls and monitors the status of circuit breaker models in the digital substation model built in the power system simulator.

The power system simulator connects multiple equipment models that simulate power distribution

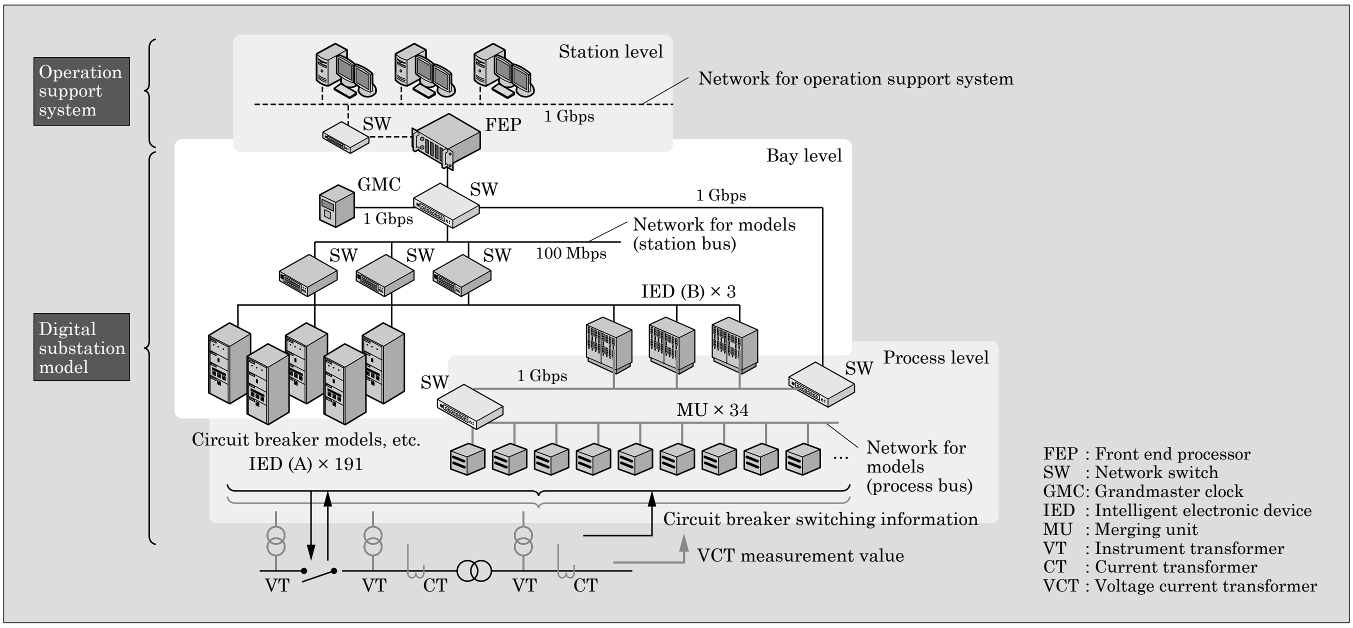

Fig.3 System configuration of the power system simulator

equipment on the basis of the system configuration in order to configure an equivalent abbreviated system (abbreviated model). These abbreviated models consist of analog models and hybrid models. In analog models, power distribution equipment, such as transformers and transmission lines, is represented by abbreviated models using R, L, and C elements. On the other hand, hybrid models digitally calculate the characteristics of synchronous generators, photovoltaic power generation systems, and utility customer loads and output analog current values according to the calculation results.

In order to build a digital substation in the power system simulator, information and communication equipment consist of the following three elements:

(a) MUs that sample instantaneous values of system voltages and currents
(b) Measurement control IEDs that control circuit breakers
(c) Protection control calculating IEDs that calculate protection control

(2) Overview of communications

This system uses the Ethernet*1 communication network. The operation support system is connected to the models of circuit breakers and other equipment in the digital substation model via the operation support system network. Control commands to the equipment models are converted according to the IEC 61850 protocol by a front end processor (FEP), which serve as the high level server in charge of the substation, and then sent to the IEDs in the equipment model. In contrast to this, real-time monitoring data transmitted by the IED in each equipment model is aggregated by the FEP and displayed in real time as a graph on the client PC of the operation support network.

(3) Types of IED and MU

Table 1 describes the types of IEDs and MUs. A total of 228 IEDs and MUs are connected to the network in the digital substation model (model network). A total of 191 measurement control IEDs (A) are connected to the station bus. A total of 3 protection control calculating IEDs (B) are connecting to both the station bus and process bus. In addition, a total of 34 instantaneous measurement MUs are connected to the process bus. Each IED and MU is interconnected using an Ethernet switch compliant with IEC 61850 and IEC 61588.

(4) Time synchronization and sampling synchronization

Accurately analyzing and evaluating the digital substation simulation results in the power system simulator need sampling synchronization; that is, the data measured by IEDs (A) and IEDs (B) distributed throughout the abbreviated system needs to be integrated without delay according to the sampling time. In addition, IEDs (B) for protection control calculation always perform protection control calculation using the instantaneous values of voltage and current sampled by multiple MUs that are time synchronized with high

Table 1 Types of IED and MU

Type	Name	Qty.
IED	IED (A): For measurement control	191
	IED (B): For protection control calculation	3
MU	MU	34
Total		228

*1: Ethernet is a trademark or registered trademark of Fuji Xerox Co., Ltd.

accuracy. Therefore, they always require highly accurate time-synchronized measurement data, in contrast to the method of acquiring measurement data only in a certain time interval by a preset trigger like typical general power waveform recorders. As a result, all IEDs and MUs in the abbreviated system must always perform measurement and control in synchronization with a single reference time. The grandmaster clock (GMC) is used as the reference time for the entire system.

In the network for the operation support system, time synchronization was performed using the network time protocol (NTP). In the network for models, time synchronization is performed using the precision time protocol (PTP) specified in the IEC 61588 to support highly accurate time synchronization. As a result, the IEDs and MUs in the network for models achieved time synchronization accuracy within ±1 µs relative to the GMC reference time.

By using the time synchronization technology described above, all IEDs in the abbreviated system acquired data with a time synchronization accuracy of 20 µs or less. This is a sufficient time synchronization accuracy for power system simulators.

(5) Custom control relay model

A custom control relay model (Ry model) for simulating the protective relay system in the digital substation is created with the combination of IEDs (B) and MUs as shown in Fig. 4.

The MUs in the Ry model measure the voltage and current of the abbreviated system from the input terminals of the voltage transformers (VTs) and current transformers (CTs) at a sampling frequency of 5,760 Hz. Furthermore, the MUs also acquire the circuit breaker switching information output from the contacts of the circuit breaker models in real time. The MUs send the system information to the process bus using SV and GOOSE, which are IEC 61850 ACSIs.

The IEDs (B) perform protection control calculation with the data received from the MUs via the process bus using SV and GOOSE. The breaking and closing commands generated by this calculation are transmitted to the IEDs (A) via the station bus. For the protection control calculations of the IEDs (B), users can create their desired control logic.

The IEDs (A) receive the breaking and closing commands to the circuit breakers from the IEDs (B) connected to the station bus using GOOSE to open or close the circuit breakers.

(6) Programmable functions with Simlink

The IEDs (B) come with a programmable functions that allow users, rather than IED manufacturers, to implement software applications. Users can program their desired control logic utilizing instantaneous values as input by using Simulink*2, a commercially available application software, installed in the operation support system of the power system simulator. Desired control logic can be developed by combining control blocks (see Table 2) prepared in advance on the Simulink screen.

This function can be used for users to verify the effectiveness of the introduction of large-scale systems through developing new protective relay control logic and verifying the control logic for new stabilization systems, in addition to analyzing and evaluating system operation results and system behavior.

3.3 Efforts to put digital substations into practical use

On the basis of the basic technology and achieve-

*2: Simulink is a trademark or registered trademark of The MathWorks, Inc.

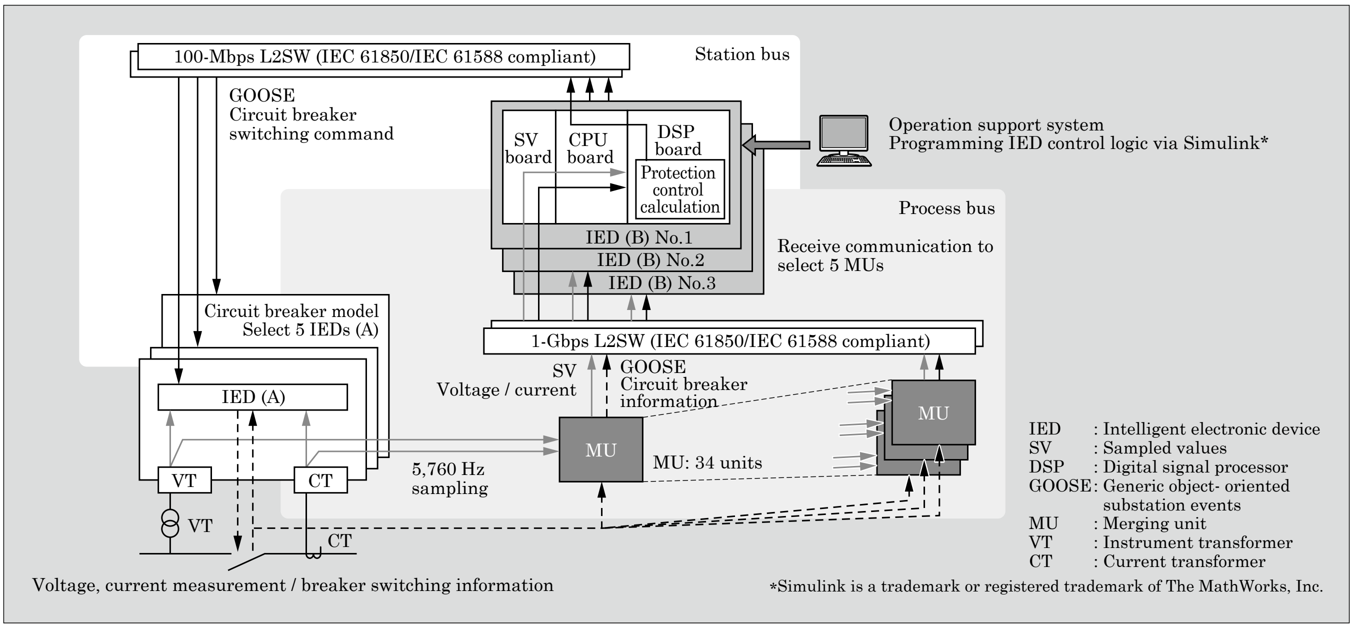

Fig.4 System configuration of the Ry model

Table 2 Blocks of protective relay elements

Facilities	Protection method	Protective relay element block
Power lines	PCM* current differential relay (direct grounding)	87P, 27S/G, 51G
	PCM current differential relay (resistance grounding)	87S/G, 64, 27B
	Line selection	50S/SA/G2/G3, 67GS, 64, 27
	Overcurrent	51, 51G, 64
	Short-circuit, ground fault distance (direct grounding)	44S/G, 27Gϕ, 51G
	Short-circuit, ground fault distance (resistance grounding)	44S, 51ϕ, 67G/GA, 64
Transformers	For Y-Y-Δ	87, 51, 87G, 67G, 51G, 64
	For Y-Δ	87, 51, 87G, 67G, 51G, 64
	For Y-Y	87, 51, 87G, 51G, 64

*PCM: Pulse code modulation

ments of the IEDs and MUs developed in the power system simulator, Fuji Electric has been working with Chubu Electric Power Co., Inc. in the research and demonstration of new methods using technologies that do not require time synchronization.

(1) Challenges facing practical use of digital substations

Communication networks for typical digital substations are built from communication devices, such as layer 2 communication switches (L2SW), and GMC for providing accurate time information to synchronize the time of those devices. However, if the GMC stops, there is a risk that differential relays, which operate on the assumption of sampling synchronization, will operate unnecessarily. Moreover, since a certain amount of knowledge is required when performing L2SW connection and setting work, there are challenges regarding how to prevent human error during operation maintenance and improving working efficiency.

Furthermore, to digitalize substation monitoring systems and protection and control equipment, it is necessary to consider the constraints of sampling time synchronization method of widely-adopted PCM current differential relays and the fault clearing time of super high-voltage substations.

(2) Adoption of oversampling method

An oversampling method uses sufficiently higher sampling frequencies for MUs and other devices than 5,760 Hz (in 60 Hz system) used in the existing substation system.

Operating these devices asynchronously sampling at the sampling frequency of existing substation systems can cause a time deviation. As a result, there could be performance degradation in detecting the failure of protective relays, which are premised on time synchronization. The timing deviation of sampling due to the asynchronous time decreases as the sampling frequency increases. Therefore, time synchronization can be eliminated when the sampling frequency is increased so as to coincide with the allowable range of the failure detection accuracy of the protective relay.

On the other hand, time differences that cannot be decreased by oversampling will vary due to the delay characteristics of each analog filter (AF) in the MUs and other devices. In order to suppress the impact of this variation in the processes performed by the device functions as shown in Fig. 5, the delay in processing until the IED receives data, processing(1) to (2), is kept within a certain range, allowing the sampling values from multiple MUs to be treated as same-time information.

(3) Ensuring protection performance (3-cycle breaking)

In addition to accuracy and reliability, protective relays need to have quick response to fault clearing. Even in digitalized substations, they are required to break within 3 cycles in the same manner as conventional protection systems. In other words, they need to clear faults within 50 ms for 60 Hz systems. Figure 5 shows the process sharing of each protection system

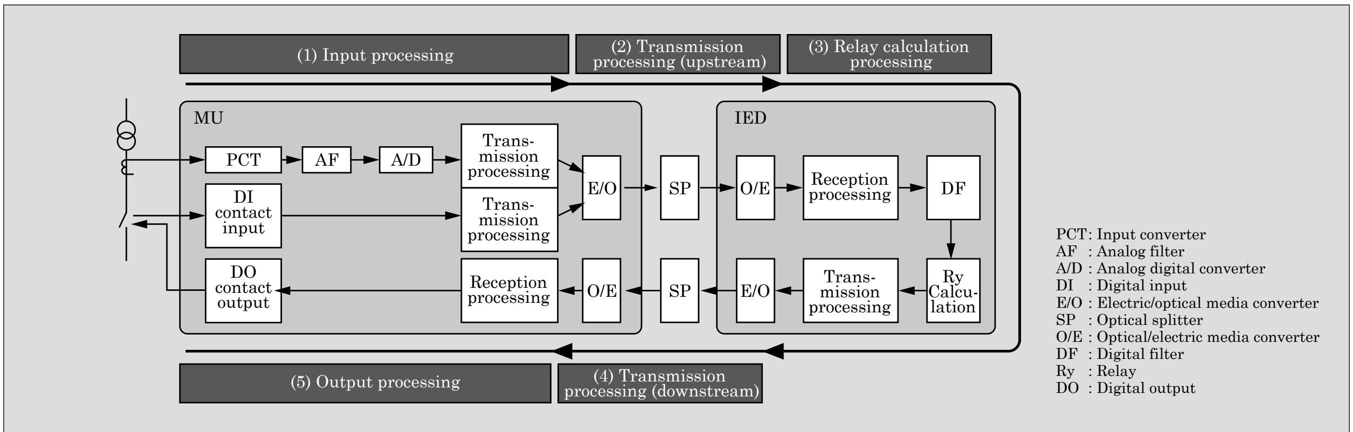

Fig.5 Process sharing of each function

function in a digital substation to satisfy the requirement for breaking.

In order to break within 3 cycles, it is necessary to contract the variation of the delay time and processing time required for the processes of each function, including (1) input processing, (2) transmission processing (upstream), (3) relay calculation processing, (4) transmission processing (downstream) and (5) output processing, as shown in Fig. 5. To achieve this, the following measures were implemented:

(a) Relay calculation and digital filter (DF) optimization
(b) Analog filter (AF) simplification (speed enhancement and characteristic uniformization)
(c) The suppression of delay and variation in transmission by employing optical splitters (SPs), which have responsiveness and higher reliability than L2SW.

Currently, we are prototyping a protective relay system based on these measures and are verifying the performance. We are also performing the development for achieving a digital substation capable of applying oversampling methods to power system facilities. Figure 6 shows a configuration example of a digital substation designed for practical use.

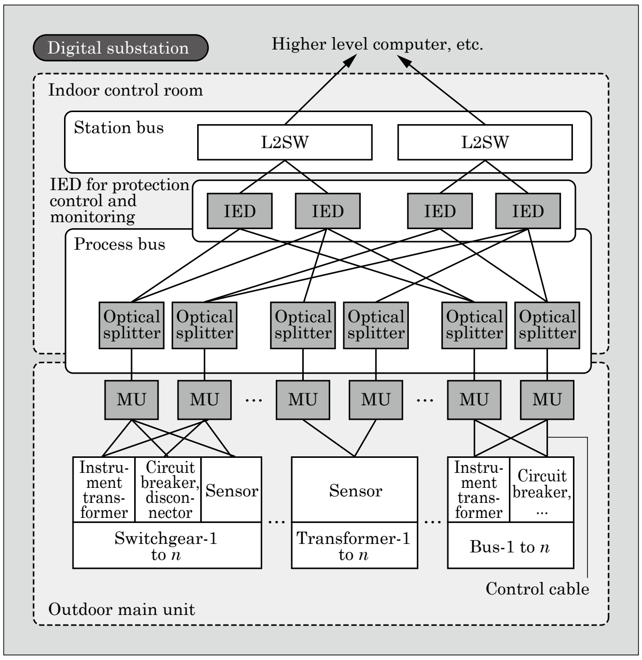

Fig.6 Configuration example of digital substation for practical use

4. Postscript

In this paper, we introduced digital substation technology for achieving advanced maintenance and operation.

We believe that these initiatives and their results will contribute to the practical application of digital substations, thereby creating new value and profits.

Devices such as IEDs and MUs and communication technologies specified in IEC 61850, which are used in digital substations, are being increasingly applied to various fields: distributed power sources, smart grids, storage batteries, wind turbine generation, hydroelectric power generation, thermal power generation, and EVs. In the future, we plan to work on the product development of these fields.

References

(1) "IEC 61850-5 Edition 2.0 Communication requirements for functions and device models". 2013.
(2) IEC 61850-9-2 Edition 2.0 Specific communication service mapping (SCSM) – Sampled values over ISO/IEC 8802-3". 2011.

Fuji Electric

Innovating Energy Technology