Large-Scale Power Conditioning System for Grid Storage Battery System with Redox Flow Battery Having World's Highest Capacity Class of 60 MWh

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ABSTRACT

Fuji Electric received an order from Sumitomo Electric Industries, Ltd. for a large-scale power conditioning system consisting of power conditioning equipment (2.5 MVA × 13 banks) and storage-bank control panels, which are part of a power system stabilization demonstration facility using a redox flow battery system having the world's highest capacity class of 60 MWh. We delivered the system to the Minami-Hayakita Substation of Hokkaido Electric Power Co., Inc. The power conditioning equipment is capable of governor-free equivalent control for quick charging and discharging in accordance with the frequency fluctuation in the power system, remote control from the central load dispatching center, and supplementary discharge control depending on the battery status. The bank controller panels control the statuses of as many as 65 power conditioning sub-systems to achieve large-scale and high-speed parallel operation.

1. Introduction

Wind power generation and photovoltaic power generation are prone to irregular output fluctuations because they depend on the weather conditions. With their increased introduction to power systems, there are concerns over the influence on power quality such as frequency. Considering this background, the Ministry of Economy, Trade and Industry has been promoting the "Large-scale Storage Battery System Demonstration Project" in order to suppress output fluctuations of renewable energies in power systems. One of the attempts is the power system stabilization demonstration project using redox flow (RF) batteries pursued jointly by Hokkaido Electric Power Co., Inc. and Sumitomo Electric Industries, Ltd. A demonstration test has been conducted on it since December 2015. This power system stabilization demonstration facility has the rated output of 15,000 kW, rated capacity of 60,000 kWh and consists of 13 banks*1. This facility offers the highest power storage capacity in the world.

As part of this demonstration system, Fuji Electric received an order for a large-scale power conditioning system from Sumitomo Electric Industries, Ltd. and installed it in the Minami-Hayakita Substation of Hokkaido Electric Power Co., Inc. in December 2015.

Currently in some areas, it is necessary to install a storage battery system in a wind or photovoltaic power generation plant in order to suppress output fluctua-

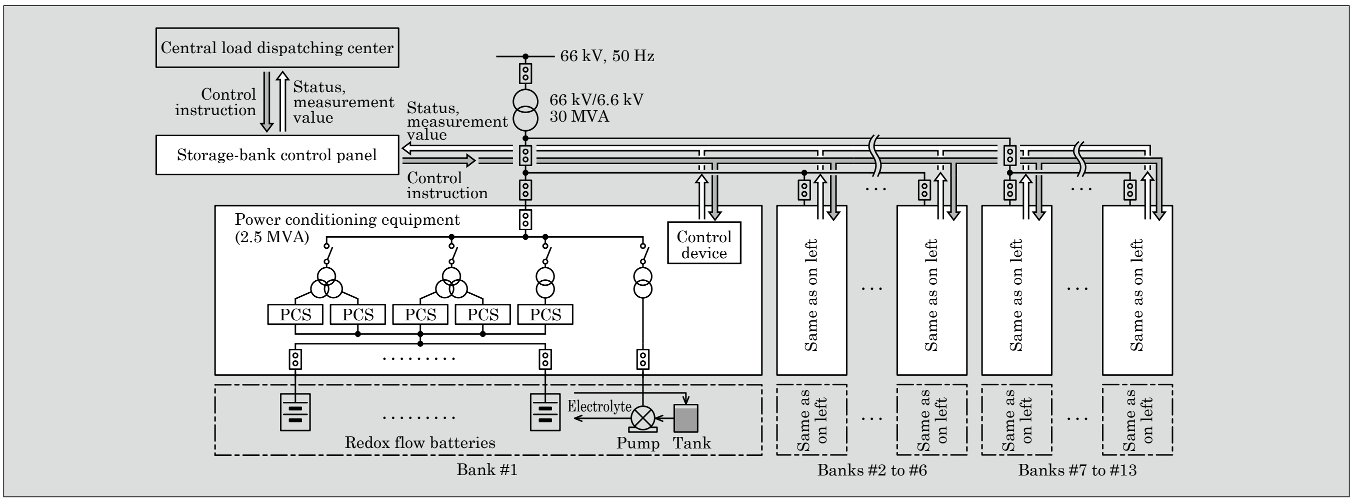

Fig.1 Overview of power conditioning system

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*1: Bank: In this paper, a "bank" is defined as a unit of the combination of power conditioning equipment and the storage batteries connected to it.

tions. As an alternative, we installed the power conditioning system in a substation to suppress the fluctuations in a large-scale power system.

This paper describes a large-scale power conditioning system for a grid storage battery system using redox flow batteries having the world's highest capacity class of 60 MWh.

2. Overview of Power Conditioning System

Figure 1 shows an overview of the power conditioning system. Although most conventional power conditioning equipment used for a storage battery system was small scale, up to 1 MVA capacity, this system offers high capacity with a maximum output of 30 MW. It consists of 13 banks, each of which contains power conditioning equipment with 2.5 MW capacity, and a storage-bank control panel that manages these banks. This configuration has achieved space saving as well as large-scale and high-speed parallel operation.

(1) Power conditioning equipment

The power conditioning equipment, which connects the RF batteries to an AC system, charges and discharges the batteries based on the governor-free equivalent control or the instructions from the central load dispatching center. The installation status is shown in Fig. 2.

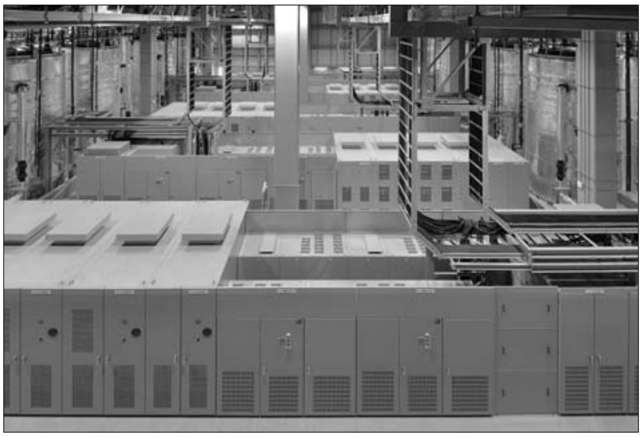

Fig.2 Installation status of power conditioning equipment

(2) Storage-bank control panel

The storage-bank control panel distributes control instructions from the central load dispatching center properly to the power conditioning equipment of each bank and controls the power conditioning equipment.

3. Configuration of Power Conditioning Equipment

Figure 3 shows the configuration of the power conditioning equipment in one bank, and Table 1 shows

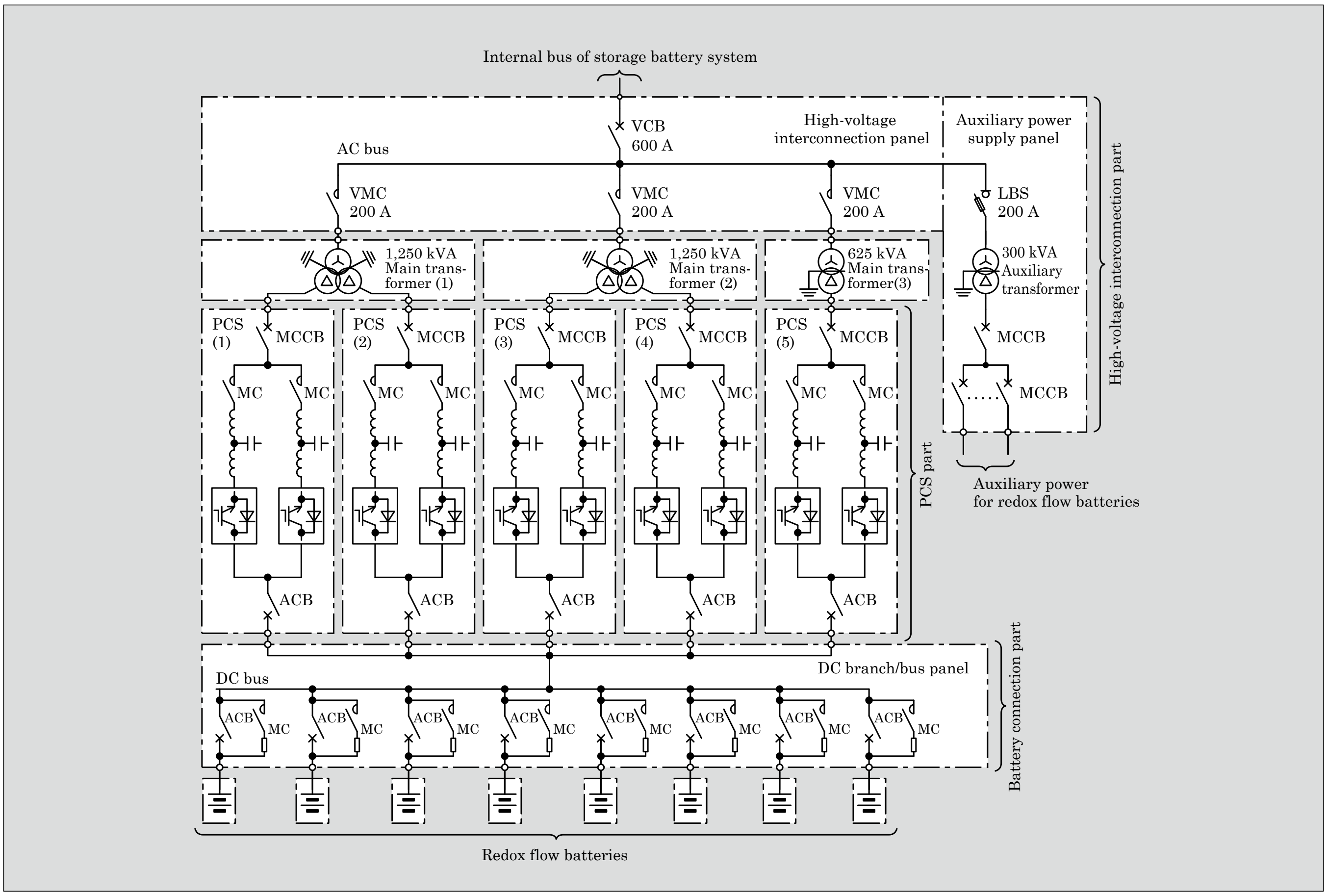

Fig.3 Configuration of power conditioning equipment (one bank)

Table 1 Major specifications of power conditioning equipment (per bank)

Item		Specification
Method	Main circuit/conversion method	Self-commutated voltage sine wave PWM
	Control system	Voltage type current control
	Operation method	System-linked
	Cooling system	Forced air cooling
DC input/output	No. of DC branches	8 branches
	DC voltage range	480 to 750 V DC
	Maximum DC current	Continuous 6,400 A (800 A × 8 in parallel)
AC input/output	Number of phases	3-phase 3-wire
	Rated voltage and fluctuation range	6,600 V±10%
	Rated frequency and fluctuation range	50 Hz±1 Hz
	Rated capacity at AC power receiving end	2,500 kVA
	Harmonic current content	Total: 5% or less, individual: 3% or less
	Power-factor	0.95 or more
Control response time		100 ms or less between −100% and +100%
Acoustic noise		70 dB or less
Dimensions		W15,233 × D2,920 × H2,870 (mm)

the major specifications. The power conditioning equipment consists of a power conditioning sub-system (PCS) part, a high-voltage interconnection part and a battery connection part.

3.1 PCS part

The PCS part has a structure of 5 units of the "PVI800-3/600" connected in parallel and is characterized by high efficiency, space saving and low noise. The PVI800-3/600 was developed for storage battery applications based on the "PVI750-3/500[1]," which is a mega solar PCS equipped with advanced T-type neutral-point-clamped (AT-NPC) 3-level insulated gate bipolar transistor (IGBT) modules. This part offers a system interconnection protective function, a fault ride through (FRT) function, a communication interface with upper systems through the "MICREX-SX" programmable controller (PLC) within the PCS, a high-speed response function to the control instructions from upper systems and an output suppression function for stable charging and discharging.

3.2 High-voltage interconnection part

The high-voltage interconnection part of the power conditioning equipment consists of (1) a high-voltage interconnection panel that integrates the AC output from 5 PCSs into an AC bus and connects it to the internal bus (6.6 kV) of the storage battery system, (2) a main transformer panel for boosting up the AC output from the PCS, and (3) an auxiliary power supply panel that supplies the auxiliary power for the RF batteries from the internal bus.

The high-voltage interconnection panel uses a high-voltage vacuum circuit breaker (VCB) for the connection between the internal bus of the storage battery system and the AC bus. It also uses a vacuum magnetic contactor (VMC), which is smaller than the VCB, for the circuit that integrates the AC outputs from the PCSs into the AC bus. These devices contribute to space saving.

For the main transformer panels, two 3-winding mold transformers are mounted to cover 4 PCSs. This has saved on the mounting space greatly compared with the case where 2-winding mold transformers are used. For the remaining PCS, an ultra-high-efficiency mold transformer is mounted. This combination enables high efficiency of the high-voltage interconnection part.

In addition to the high-voltage interconnection panel and main transformer panel, this part contains protection relays required for protecting the equipment for system interconnection and other functions in the high-voltage interconnection part and a programmable controller (PLC) that operates as the main controller of the power conditioning equipment. The PLC in the high-voltage interconnection part conducts governor-free equivalent control and works as the communication interface with the PLCs inside the storage-bank control panel and PCSs. All of these communication activities use Fuji Electric's "PE-link" high-speed data communication network to save on wiring and space and achieve high-speed control responses.

3.3 Battery connection part

The battery connection part of the power conditioning equipment consists of a DC branch panel that receive the outputs of the RF batteries in 8 branches and a DC bus panel that consolidates 5 branches into the DC bus and distributes common DC power to 5 PCSs. This part detects the current and voltage of the battery connection part with signal converters and inputs these measurement signals to the PLC of the high-voltage interconnection part.

The DC branch panel consists of low-voltage air circuit breakers (ACBs), circuits for RF battery initial charging [resistors and magnetic contactors (MCs)] and signal converters for DC current detection. The signal converter for DC current detection is mounted on each shunt as a measure for improving the control accuracy.

The DC bus panel has a main circuit configured with a bus bar passing 6,400 A DC, and the main circuit has DC ground fault detection equipment and signal converters for DC voltage detection on it.

This configuration of power unit and the layout of measuring and protective functions achieves a DC circuit suitable for the connection of high-capacity RF batteries.

4. Control Functions of Power Conditioning Equipment

The power conditioning equipment provides innovative control functions that allow the large-scale storage battery system to perform governor-free control conventionally used in thermal power plants or hydraulic power plants and the load frequency control based on the instruction from the central load dispatching center. It also conducts a long-period fluctuation suppression control that takes advantage of the characteristics of storage batteries.

4.1 Governor-free equivalent control

The governor-free equivalent control is a short-period fluctuation suppression control that detects the frequency of the power system (system frequency) in the power conditioning system and adjusts the output of the power conditioning equipment to restore the fundamental frequency. The controller calculates the amount of power change from the change in the system frequency and from the regulation rate, and generates governor instruction values every 10 ms from a PID controller to determine the output of the power conditioning equipment (see Fig. 4).

When the system frequency is lower than the fundamental frequency, supply is below demand in the power system. In this case, the controller generates governor instruction value to increase the system frequency. On the contrary, when the system frequency is higher than the fundamental frequency, supply is above demand in the power system. In this case, the controller generates the governor instruction value to decrease the system frequency. The output of the power conditioning equipment responds within 100 ms after the system frequency is detected.

In this way, the governor-free equivalent control by the power conditioning equipment adjusts the system frequency with high-speed in both charging and discharging directions.

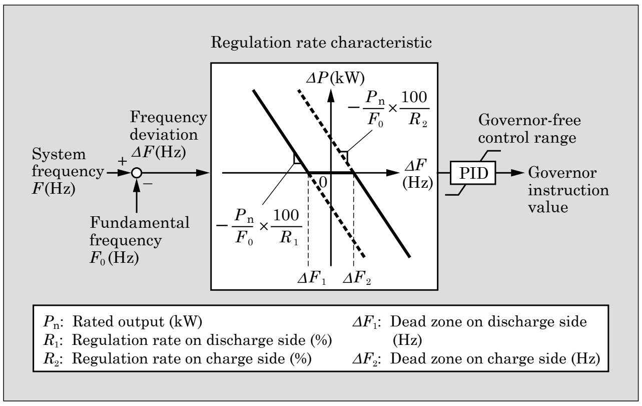

Fig.4 Block diagram for control logic of governor-free equivalent control

4.2 Remote control

The power conditioning equipment receives instruction signals from the central load dispatching center via the storage-bank control panel and remotely controls the charging and discharging of the RF batteries by the following control functions:

(1) Short-period fluctuation suppression control

This includes fluctuation compensation control to mitigate short-period fluctuations (cycle of 20 minutes or shorter) in the compound output of multiple wind and photovoltaic power systems and load frequency control to distribute imbalanced supply and demand in the entire system to hydraulic power plants or RF batteries.

(2) Long-period fluctuation suppression control

This is a control to mitigate long-period fluctuations (cycle of 20 minutes or longer) based on the output forecasts of wind and photovoltaic power systems.

(3) Operation control against insufficient lower control margin

This is a control to avoid generation of surplus power based on output forecasts and supply-and-demand planning.

(4) Short- and long-period hybrid control

This is a combination of the short-period and long-period fluctuation suppression controls to ensure optimum operation in the entire electric power storage system.

4.3 Supplementary charge and discharge control

The supplementary charge and discharge control detects the state of charge (*SOC*) of the RF battery and adjusts the *SOC* to a value within the target range based on the supplementary charge and discharge instruction value based on the supplementary charge and discharge characteristics (see Fig. 5).

If the *SOC* is lower than the setting value S_2, the supplementary charge and discharge instruction value for charging is issued. If the *SOC* is higher than the setting value S_3, the supplementary charge

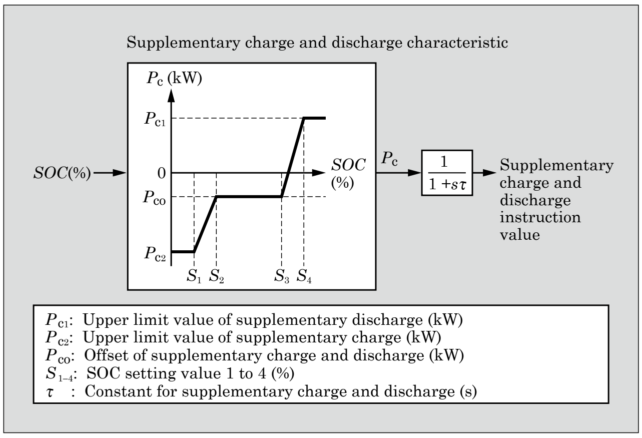

Fig.5 Block diagram for control logic of supplementary charge and discharge control

and discharge instruction value for discharging is issued. When the supplementary charge and discharge instruction value is combined with a power instruction value, such as of the governor-free equivalent control, and given to the PCS, allowing the *SOC* to be adjusted within the target range.

The temporal change of the supplementary charge and discharge instruction value can be adjusted not to affect the power system with the appropriate setting value τ.

4.4 Initial charging and maintenance control

Initial charging refers to the act of charging the RF battery from the power conditioning equipment when the battery's electromotive force is 0 V such as at delivery or during maintenance.

At the beginning of the initial charging, one PCS operates in the rectification mode of the DC voltage constant control and the remaining 4 PCSs operate in the system-linked mode. The outputs of the PCSs in the system-linked mode are connected to the RF batteries one by one via the initial charging circuits with resistance while being adjusted to reduce the charging power generated in the PCS in the rectification mode. This can reduce the inrush currents of the RF batteries and the PCS in the rectification mode to their allowable current values or lower.

Next, when the inrush current disappears, all of the electrical paths are switched from the initial charging circuits to the ACB circuits one by one, and then the PCS in the rectification mode is switched to the system-linked mode. Finally, all the PCSs are operated with constant power charging until the electromotive forces of the RF batteries increase to the specified amount to complete the charge.

Although applying low DC voltage to the RF battery with an electromotive force of 0 V can reduce the inrush current, a chopperless PCS cannot technically control low DC voltages. In contrast, power conditioning equipment can perform the initial charging by using a combination of several PCSs as described above and opening or closing the MCs and ACBs in the initial charging circuit designed with the optimum resistance.

The maintenance control is control of charging and discharging based on the setting values or operation signals input from the control panel of the RF battery in order to confirm the performance of the RF battery. It allows operations with the following operating characteristics:

(1) DC charge operation

This is charge operation with the characteristics of DC constant current, DC constant power and DC constant voltage.

(2) DC discharge operation

This is discharge operation with the characteristics of DC constant current, AC constant power and DC constant voltage.

(3) AC charge operation

This is charge operation with the characteristics of AC constant power and DC constant voltage.

(4) AC discharge operation

This is discharge operation with the characteristics of AC constant power and DC constant voltage.

5. Functions of Storage-Bank Control Panel

The storage-bank control panel manages the statuses of as many as 65 PCSs connected in parallel and still achieves high-speed optimum control. Based on the control information received from the central load dispatching center, the panel selects banks to operate, determines output values, then distributes the control instructions to the power conditioning equipment of 13 banks. The panel also collects and manages the operation information of the banks and sends it to the central load dispatching center.

In order to obtain a desirable response in the short-period fluctuation suppression control, such control information should be processed and exchanged quickly. Accordingly, for the storage-bank control panel, we selected the optimal methods for operations, in terms of the high speed performance, such as bank operating algorithm, the detection of control measurement signals, and the communication with the central load dispatching center and power conditioning equipment.

5.1 Bi-directional communication with central load dispatching center

The storage-bank control panel has a bi-directional communication function that uses a PLC to receive downstream control instructions from the central load dispatching center and send upstream information such as the measurement values and status signals of the power conditioning systems to the central load dispatching center. A special protocol is used for the communication between the central load dispatching center and the storage-bank control panel to enable the exchange of control information necessary for the power system operation using a high-capacity storage battery system.

5.2 Bi-directional communication with power conditioning equipment

The storage-bank control panel has a communication function that a PLC receives the measurement values and status signals of power conditioning equipment and sends control instructions such as power instruction values and operation instructions to the power conditioning equipment. PE-link is used for the communication between the power conditioning equipment and storage-bank controller, allowing the power conditioning system to achieve high-speed control responses as a power conditioning system.

5.3 Frequency measurement with high-speed frequency measuring device

A high-speed frequency measuring device in the storage-bank control panel determines the system frequency, which is the main factor of the governor-free equivalent control. This high-speed frequency measuring device is the customized “PowerSATELITE II” high-performance and versatile composite measurement terminal specifically to use for high-speed frequency detection. This device has also been adopted in the micro grid system intended for remote islands[(2)] and can detect a system frequency within approximately 30 ms in the 50-Hz system. Fuji Electric has improved the response performance of frequency adjustment by using the system frequency signals detected at high speed for the governor-free equivalent control conducted by the power conditioning equipment of each bank or for the governor-free equivalent control intended for the batch instruction operation described later.

5.4 Individual instruction operation

The individual instruction operation operates and controls the banks individually from the central load dispatching center.

The storage-bank control panel receives the load frequency control and other control instructions from the central load dispatching center and sends them to the power conditioning equipment of the bank specified by the central load dispatching center. This configuration allows the central load dispatching center to perform the remote control, governor-free equivalent control and supplementary charge and discharge control of the specified bank.

5.5 Batch instruction operation

The batch instruction operation handles the batteries of multiple banks as one high-capacity storage battery under the control by the storage-bank control panel to carry out the control instruction for the batch of banks from the central load dispatching center.

When the central load dispatching center specifies target banks for the batch instruction operation and a power instruction value for the batch of banks, the PLC determines the number of banks to operate according to the size of the power instruction value and select banks to start or stop based on a specific priority. The priority can be determined by selecting either of the following 2 modes:

(1) Schedule reference mode

The priority of banks is registered in a daily schedule in advance and the priority of the banks to be operated on the day is determined according to the schedule.

(2) Battery status reference mode

The priority of banks to operate is continually updated based on the battery condition of the RF batteries such as *SOC* of each bank.

Governor-free equivalent control with the power conditioning equipment supports individual instruction operation. On the other hand, the storage-bank control panel includes governor-free equivalent control for a batch instruction operation and can generate a batch governor instruction value.

The batch governor instruction value generated by the storage-bank control panel is combined with the power instruction value for the batch of banks from the central load dispatching center to make a composite instruction value for the batch of banks. The composite instruction value for the batch of banks is divided up according to the size of the *SOC* and other conditions of the RF batteries and distributed to the operating banks. If this power instruction value exceeds the output limit value of individual banks, it is redistributed to other banks. This is called interbank output distribution control. This instruction value is distributed with the PLC every 20 ms. Since the output of the power conditioning equipment follows the distributed power instruction value, the composite output of the power conditioning equipment always matches the composite instruction value for the batch of banks.

5.6 Measuring server

The measuring server uses the “MICREX-VieW PARTNER[(3)]” equipment monitoring system. This server performs unitary management to recognize the operating condition of the entire power conditioning system. It does this by collecting the upstream and downstream information exchanged with the central load dispatching center and the status and alarm signals, measurement values and control variables of the RF batteries and power conditioning equipment from the storage-bank control panel via Ethernet*2. The measuring server is capable of displaying a history of

Fig.6 Example of trend display of “MICREX-VieW PARTNER”

*2: Ethernet: Trademark or registered trademark of Fuji Xerox Co., Ltd.

status and alarm signals, 1-second trend display of measurement values and control variables and automatic saving in CSV data. Figure 6 shows an example of the trend display.

6. Postscript

This paper described a large-scale power conditioning system for a grid storage battery system using redox flow batteries having the world's highest capacity class of 60 MWh. The demonstration test confirmed several effects including frequency fluctuation suppression. The system is expected to work as a new adjustment measure against the output fluctuations of renewable energies.

To expand the introduction of renewable energies further, high-capacity power storage equipment is particularly indispensable for power systems and is expected to be introduced to many applications in the future. Fuji Electric will help to promote the introduction of renewable energies by aggressively acquiring capable technologies and providing optimally configured and controlled electric power storage systems.

In closing, we would like to express our deep gratitude to Hokkaido Electric Power Co., Inc. for the cooperation for the development, design and manufacturing of the large-scale power conditioning system.

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