Redox Flow Batteries for the Stable Supply of Renewable Energy

Toshikazu SHIBATA*, Takahiro KUMAMOTO, Yoshiyuki NAGAOKA, Kazunori KAWASE and Keiji YANO

Renewable energies, such as solar and wind power, are increasingly being introduced as alternative energy sources on a global scale toward a low-carbon society. For the next generation power network, which uses a large number of these distributed power generation sources, energy storage technologies will be indispensable. Among these technologies, battery energy storage technology is considered to be most viable. Sumitomo Electric Industries, Ltd. has developed a redox flow battery system suitable for large scale energy storage, and carried out several demonstration projects on the stabilization of renewable energy output using the redox flow battery system. This paper describes the advantages of the redox flow battery and reviews the demonstration projects.

Keywords: redox flow battery, energy storage, renewable energy, smart grid, wind turbine, photovoltaics

1. Introduction

The introduction of renewable energies such as solar power and wind power has recently been promoted to increase the use ratio of zero-emission power sources for the realization of a low-carbon society. Meanwhile, the "Green New Deal," which was released soon after Obama's inauguration as U.S. president in 2009, raised worldwide public concern over next-generation power supply networks (a smart grid, and so on). Since then, research and development of new electric power infrastructures and related electrical equipment have been promoted. Further, the March 2011 Great East Japan Earthquake and the subsequent accident at the Fukushima No. 1 nuclear power plant amplified the public's expectations for the construction of an electric power infrastructure that does not primarily depend on nuclear power generation and alternatively increases the use of renewable energies. However, the electric power generated by solar and wind depends on weather conditions, and therefore the output fluctuates. Connecting large numbers of renewable power plants to the electric power network without taking any measures against their unstable output will cause problems, including rise of voltage, frequency fluctuations, and surplus power generation. Various solutions to the above problems have been proposed. These proposals should meet the requirements for the construction and operation of (1) an environmentally conscious system, (2) a system that ensures a stable supply of high-quality power, and (3) a safe and efficient power supply system. "A technology that can interconnect zero-emission, safe solar and wind power plants efficiently at low cost with keeping the quality of electricity" is essential to realize these requisites against the above prevailing social background. Energy storage technologies, battery technologies in particular, are drawing attention as a solution to the above requirements. Storage batteries are expected to expand their use in the fields shown in **Fig. 1**. Sumitomo Electric Industries, Ltd. bigan to develope a redox flow battery[1] in the 1980s. Since then, Sumitomo Electric has carried out several demonstrations to confirm the usefulness of redox flow batteries in stabilizing the supply of renewable energy. This paper describes the outstanding features of redox flow batteries and reviews the demonstration test results.

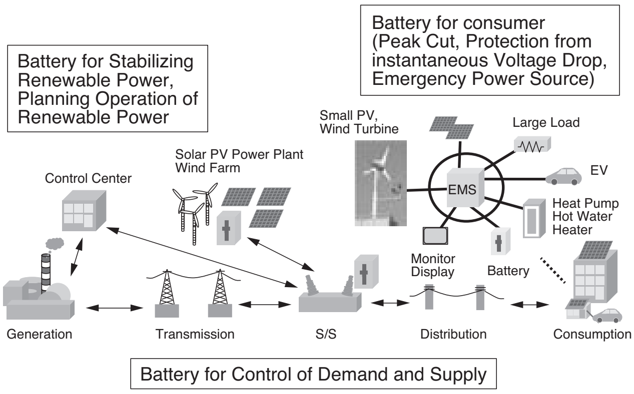

Fig. 1. Expected applications of batteries

2. Principle of a Redox Flow Battery

The principle of a redox flow battery with vanadium as active materials is shown in **Fig. 2**. As shown in this figure, a redox flow battery consists of flow type cells, electrolyte tanks, pumps and piping. The electrolytic reactions take place in the cell, while each electrolyte tank stores a solution of the active material (electrolyte). Each pump circulates the electrolyte between the tank and electrolytic cells. When an electric current is loaded to the cell, the battery reactions which change the valence of the vanadium occur in both the positive and negative electrodes as shown in **Fig. 2** and expressed by the following equations. The valence change moves protons through the membrane, charging or discharging the battery according to the above mechanism.

Positive electrode

$$VO^{2+} \text{ (tetravalent)} + H_2O \rightleftarrows VO_2^{+} \text{ (pentavalent)} + 2H^{+} + e^{-} \quad \cdots\cdots(1)$$

Negative electrode

$$V^{3+} \text{ (trivalent)} + e^{-} \rightleftarrows V^{2+} \text{ (bivalent)} \quad \cdots\cdots(2)$$

(→ : charge, ← : discharge)

A multi-layer structure of cells in which the above electrolytic reactions take place is called a cell stack. The typical structure of a cell stack is shown in **Fig. 3**. The voltage of a single cell is approximately 1.4 V. To obtain a serviceable voltage, multiple cells are connected in series to form a cell stack.

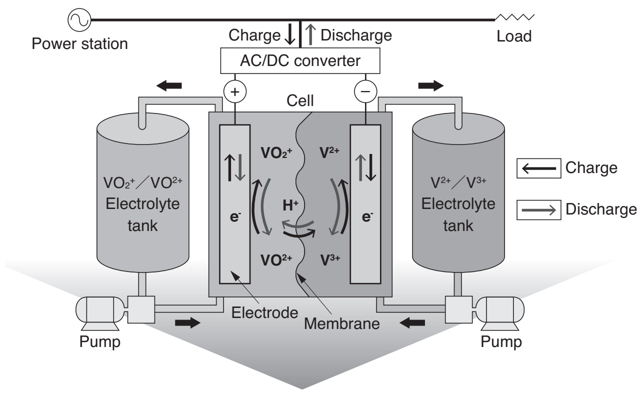

Fig. 2. Principle and configuration of a redox flow battery

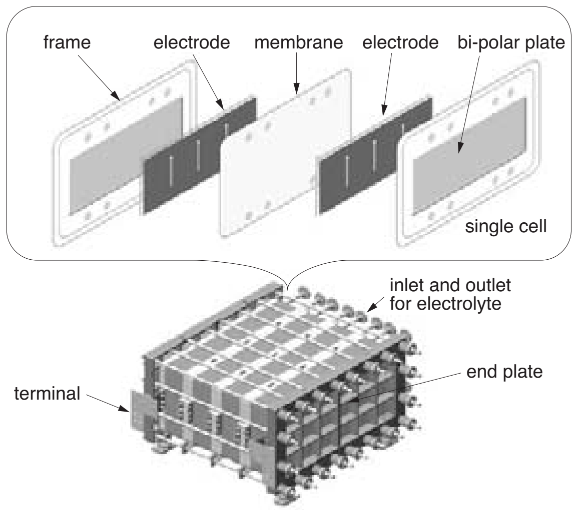

Fig. 3. Typical structure of a cell stack

3. Advantages of a Redox Flow Battery

In a vanadium redox flow battery, the battery reaction principle is simply the change of valence of the vanadium ions in the electrolyte without solid phase battery reactions. This principle gives the battery the following outstanding features: a long charge/discharge cycle service life is realized; the life of electrolyte is not susceptible to deep-discharge or complex charge/discharge pattern. In addition, redox flow batteries are safe by using an incombustible electrolyte. When applying storage batteries for the purpose of providing a stable supply of renewable energy, they are required to be (1) available for storing bulk energy (high output, large capacity), (2) available for state of charge (SOC) management, (3) highly responsive, and (4) available for short-term, high-output operations. Redox flow batteries meet all the above requirements as discussed in detail in the following sections.

3-1 Scaling up (Increasing output and storage capacity)

For a redox flow battery, the output specification and the capacity specification can be designed independently of each other, since the former depends on the number of cell stacks while the latter depends on the amount of electrolyte. Accordingly, the storage capacity can be increased easily by increasing the capacity of the electrolyte tanks (installing additional tanks). Furthermore, since the same electrolyte is supplied to individual batteries (cells), the characteristics of batteries (cells) connected each other can be equalized easily as detailed below.

Schematic illustrations of series-connected conventional batteries and redox flow batteries are shown in **Fig. 4**. In this figure, the SOC of each battery (remained energy in each battery) is shown schematically by shading. When series-connected batteries are operated continuously for long time, each battery may exhibit a different SOC because of the differences in internal resistance, self-discharge characteristics, aging deterioration, ambient temperature, and other factors. Difference in SOC destroys the balance of electromotive force between the batteries, and the resulting overvoltage may accelerate their deterioration. To avoid such an unfavorable condition in a large-scale battery system with conventional batteries, it is necessary to provide an additional system that continuously monitors the terminal voltage of each battery and discharges the battery as needed, or to maintain all batteries in an equalized charge condition by overcharging them. On the other hand, in a redox flow battery system a pump circulates electrolyte of

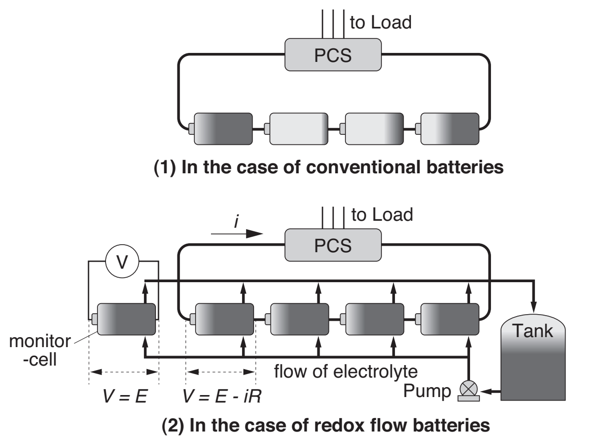

Fig. 4. Schematics of SOC variability between series-connected batteries

the same SOC from a single storage tank to each battery, thereby equalizing the SOC of all batteries. This means that it is easy to increase the storage capacity of redox flow batteries without complicating their configuration.

3-2 Measurement and management of SOC

Since the terminal voltage of a battery during charging/discharging is generally determined by summing the electromotive force and voltage drop attributed to the internal resistance of the battery, it is impossible to measure the electromotive force of a conventional battery as long as it is in operation. As for a redox flow battery system, the electromotive force can be measured even when it is in operation, by flowing the same electrolyte to the additional cell (a monitor-cell) which is electrically independent from cells under operation as shown in **Fig. 4**. When the electromotive force is given, the SOC of the battery can be determined from Nernst's equation as shown below. In this manner, the continuously-changing SOC of an operating redox flow battery can be measured on a real time basis.

$$E = E_0 + \frac{RT}{F} \ln \frac{[VO_2^+][V^{2+}]}{[VO^{2+}][V^{3+}]} \qquad \cdots\cdots\cdots\cdots\cdots (3)$$

where,

E : electromotive force, E_0: standard electromotive force,
R: universal gas constant, F : Faraday constant,
T: absolute temperature

In the operation of stabilizing output of renewable power plants, of controlling demand/supply in power network and so on, continuous complex charge/discharge operations are required. To perform these charge/discharge operations without causing over-charge/over-discharge, it is essential to continuously monitor the SOC of the battery and to control auxiliary charge/discharge using the SOC as a parameter. Redox flow batteries are ideal for these applications because such measuring and controlling can be realized.

3-3 High responsiveness

A high response speed is required for the operation of stabilizing renewable power and for controlling demand/supply. **Figure 5** shows the test result[(2)] for the responsiveness of a 6 MW redox flow battery used for stabilizing output of a wind farm, details of which will be described later. In this test, the wind farm's output was instantaneously dropped from 30 MW to 0 MW using a simulated signal when the redox flow battery was being charged at its rated capacity (6 MW) and the response time necessary for the battery to start discharging at its rated capacity (6 MW) by stabilizing operation was measured. When the response time was defined as the time necessary to reach 63% (1-1/e) of the target value, the response time was determined to be 57 msec. When the response time was defined as the time necessary to reach 90% of the target value, the response time was determined to be 170 msec. These response times were rate-controlled by a control system and signal measurement system. The test result confirmed that redox flow batteries have a sufficiently high response speed.

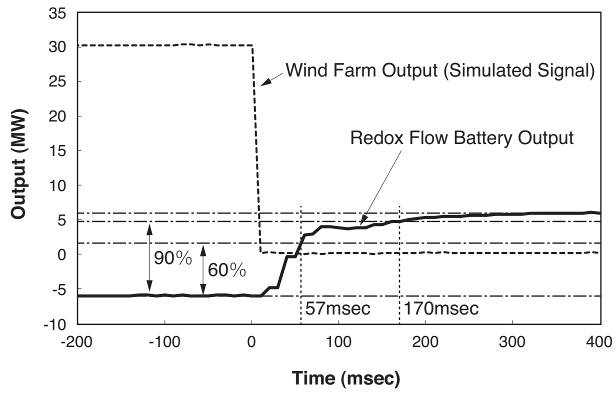

Fig. 5. The measurement results of response time of a 6 MW redox flow battery system

3-4 High-output power operation characteristics

For stabilizing the output of renewable power, the instantaneously necessary maximum output reaches several times of the average output. A battery that can instantaneously discharge electric power substantially higher than the rated output is cost effective for this purpose. **Figure 6** shows the length of time available for high power discharge, which was measured using a 1.1 kW × 1hour redox flow battery[(3)].

The dischargeable time of a battery depends on the internal impedance of its cells, the SOC of the electrolyte in its cells, and its capacity. As shown in **Fig. 7**, the equivalent circuit of a redox flow battery can be expressed as the sum of (1) the ohmic resistance of the component material and the reactive resistance at the electrodes with a time constant of less than several seconds, (2) a resistance that depends on the flow rate of electrolyte supplied to the cells with a time constant of less than several minutes, and (3) a

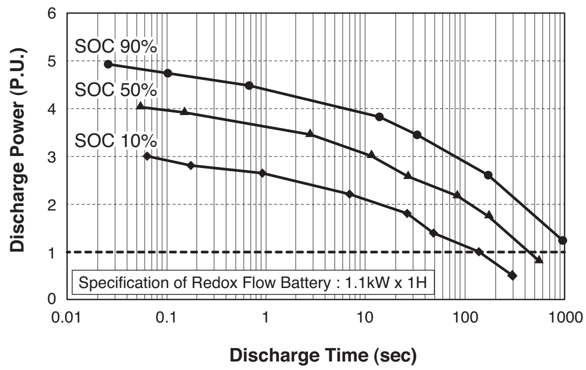

Fig. 6. High power characteristics of a redox flow battery

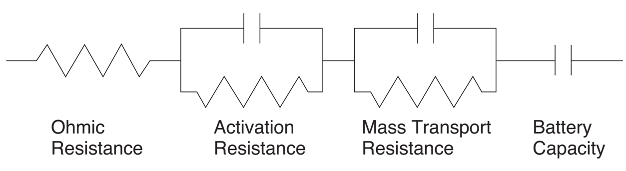

Fig. 7. Single equivalent circuit of a redox flow battery

capacitance that depends on the amount of electrolyte with a time constant of more than several minutes. According to electrical circuit theory, the above component (3) does not affect the instantaneous response of the battery. Therefore, a redox flow battery can instantaneously discharge electric power several times higher than its rated capacity.

These above advantages of the redox flow battery meet the conditions necessary for a storage battery suitable for the stable supply of renewable energy. On the other hand, redox flow batteries have a disadvantage that the energy density in their electrolyte is relatively small. As a result, the overall footprint of redox flow batteries is larger than that of conventional batteries of the same capacity.

4. Control Principle for Stabilizing Output of Renewable Power

An electric power supply system is required to follow the supply/demand balancing rule. Electric power companies usually conform to this rule by controlling the output of their power plants. Although the power generated using renewable energy sources such as wind and solar is clean, the output is difficult to estimate and fluctuates greatly since it depends on wind conditions and solar radiation. Therefore, unlike thermal and other power generation systems, renewable energy power generation systems cannot be operated systematically unless a suitable measure is implemented. In addition, photovoltaic systems and wind turbines themselves cannot control the supply/demand balance; rather they disturb the balance. As a result, the amount of power that can be connected to the commercial power network is limited. A means of stabilizing these outputs is essential to expand the use of renewable energies. Storage batteries are expected to provide a means of absorbing the fluctuations in power generation output.

Taking a wind farm as an example, an algorithm for stabilizing the fluctuations in power generation output is described below. The control flowchart for stabilizing the short-period fluctuations in the wind farm's output by a redox flow battery is shown in **Fig. 8**[(2)].

In this figure, "Total Output" means the sum of the wind farm's power output and the battery's output, which is the output after stabilized by the redox flow battery. The target value for the total output is calculated by stabilizing the wind farm's power output by a first-order lag element with a time constant T. The output required to the redox flow battery is the difference between the target value of the total output and the wind farm's power output. However, since the battery's storage capacity is limited, battery loss may lower the battery's charge level to the lower limit or a strong wind may allow the battery to store more energy than its full capacity. To avoid such abnormal conditions, it is necessary to control the wind farm's power output and thus to continuously maintain the stored energy in the battery at a proper level by carrying out relevant auxiliary charge/discharge. The ideal SOC of the battery during the stabilizing output operation is considered as follows:

Let $G(s)$ denote the wind farm's power output, $X(s)$ the target total output, $Y(s)$ the battery's output, and $Z(s)$ the remaining energy in the battery. Then the target total output is the wind farm's power output after it is calculated by the first order lag element and is expressed by the following equation:

$$X(s) = \frac{1}{1+Ts}\,G(s) \quad \cdots\cdots\cdots\cdots\cdots (4)$$

If the losses in the battery system (battery loss, AC/DC converter loss, etc.) and auxiliary charge/discharge are not considered, the output required of the battery is determined as the difference between the target total output and wind farm's power output and is expressed as follows:

$$Y(s) = X(s) - G(s) = -TsX(s) \quad \cdots\cdots\cdots\cdots\cdots (5)$$

The remaining energy in the battery depends on its charge and discharge, and is therefore determined by the integral of the battery output power as follows:

$$Z(s) = \frac{-1}{s}\,Y(s) = TX(s) \quad \cdots\cdots\cdots\cdots\cdots (6)$$

It can be understood from **Equation (6)** that, in ideal conditions, the remaining energy in the battery is proportional to the target total output. In other words, continuous stable system operation can be ensured under appropriate SOC conditions by performing auxiliary charge or discharge so that the above proportional relationship is maintained. **Figure 9** shows the changes in each output and SOC when the output of a wind farm was stabilized according to the above al-

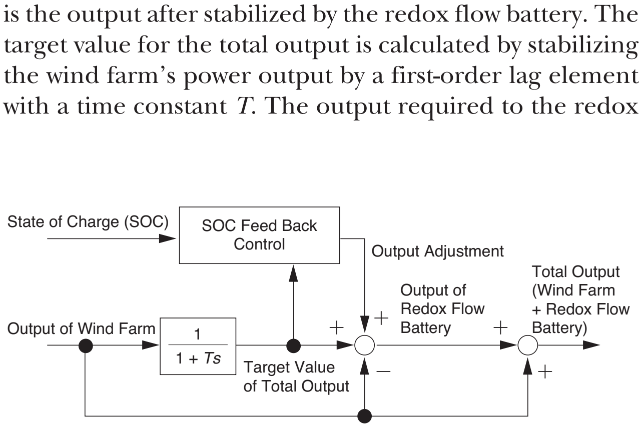

Fig. 8. Flowchart for stabilizing the fluctuations in output of a wind farm using a redox flow battery system

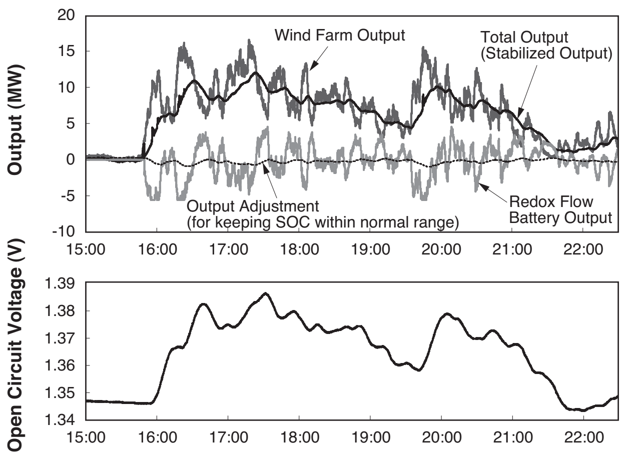

Fig. 9. Output waveform stabilized by a redox flow battery system

gorithm.

Monitoring the SOC of the battery is essential in making the above control scheme practicable. The redox flow battery system meets this requirement.

5. Application Example of a Redox Flow Battery for the Stable Supply of Renewable Energy

Demonstrations were carried out to check the effectiveness of a redox flow battery system used for the stable supply of renewable energy. Test results for (1) the stabilization of a wind farm's power output, (2) the stabilization of solar power generation output, and (3) supply/demand control for a micro grid system are described below.

5-1 Stabilization of a wind farm's power output

The demonstration test for stabilizing the short-period fluctuations of a wind farm's power output using a 6 MWh redox flow battery system was carried out over the period from January 2005 to February 2008 at the Tomamae Winvilla power plant (output power: 30,600 kW, wind turbines: 19 units) of Electric Power Development Co., Ltd. (J-Power). This demonstration is performed in the "Development of Technologies for Stabilization of Wind Power in Power Systems"[(2),(4),(5)] project promoted by New Energy and Industrial Technology Development Organization (NEDO). The major specifications and equipment configuration, equipment layout, and circuit configuration of the redox flow battery system are shown in **Table 1**, **Fig. 10**, and **Fig. 11**. The battery system comprised four banks. The number of battery banks to be operated was changed automatically in response to the wind farm's power output to minimize the power losses in the auxiliary equipment. The rated output of the redox flow batteries installed in each battery bank was 1,000 kW. On the other hand, for the power conditioner, a 1,500 kW AC/DC inverter was used for each battery bank since the above-described instantaneous high-output characteristics allowed the battery system to charge and discharge AC power of up to 1.5 times the rated output of the batteries.

Figure 12 shows an example of the wind farm's power output stabilizing at a time constant of 30 minutes. The bat-

Table 1. The specification and equipment configuration of a 6 MWh redox flow battery system

Connected Line	3p3w 6,600V±5%, 50Hz±1Hz
Maximum AC Output	Power Conditioner : 1,500kVA × 4 Banks Battery(Cell-stacks) : 1,000kW × 4 Banks
Discharge Capacity	6,000kWh

Equipment	Number	
Power Conditioner	4	1 / Bank
Cell-stack	96	24 / Bank
Heat Exchanger	16	4 / Bank
Electrolyte Tank	32	4 set / Bank
Electrolyte Pump	32	4 set / Bank
Battery Controller	4	1 / Bank
Bank Controller	1	1 / 4 Bank

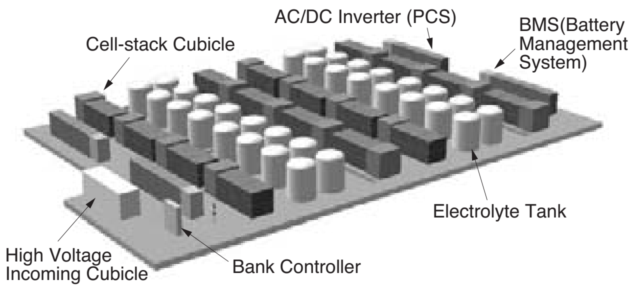

Fig. 10. The layout of 6 MWh redox flow battery system

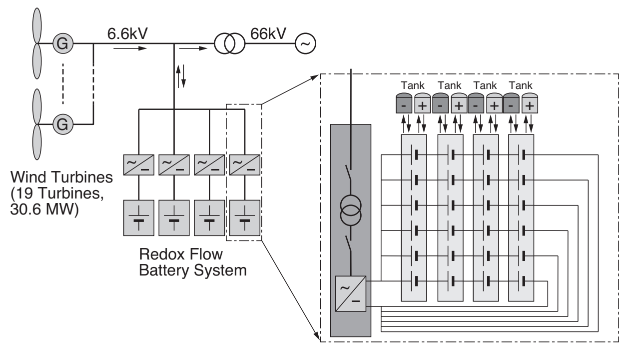

Fig. 11. The circuit configuration of a 6 MWh redox flow battery system

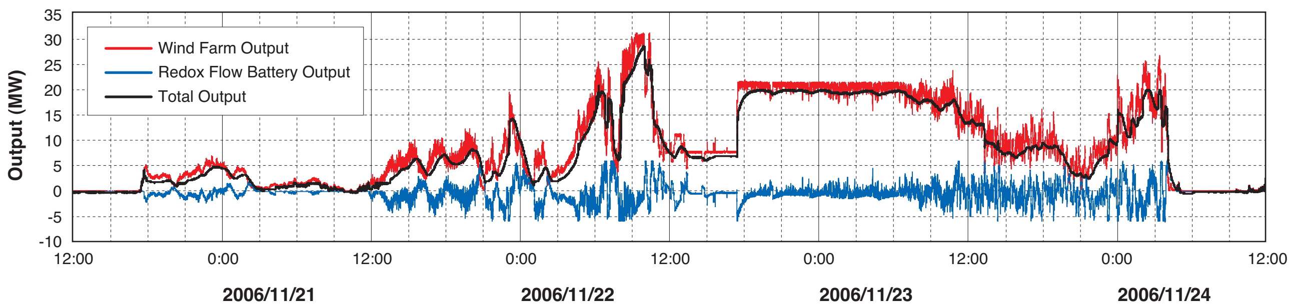

Fig. 12. Example of wind farm power output stabilization

tery system would not be able to follow drastic fluctuations in the wind farm's power generation output, since the maximum capacity of the storage batteries (6 MW) was smaller than the wind farm's rated power generation capacity. To cope with this situation, this system was controlled to reduce the stabilizing time constant temporarily when the wind farm's power output fluctuated intensively, and thus to limit the output required of the battery system. As **Fig. 12** shows, the redox flow battery system was confirmed to stabilize output stably without its storage capacity collapsing.

5-2 Use of redox flow batteries for solar power generation

With the aim of checking the effectiveness of various control schemes using redox flow batteries, as well as to check the long-term reliability of the power supply system, a demonstration system (a megawatt-class electric power generation/storage system[(6)]) was installed on the premises of Sumitomo Electric's Yokohama Works. This demonstration system consists of a 100 kW photovoltaic system and a 1 MW × 5 hour redox flow battery system. An external view of the system is shown in **Photo 1**. The main purpose of the demonstration is to confirm the effectiveness of redox flow batteries for output power stabilizing and the planned operation of the photovoltaic system. Another purpose is to test the factory energy management system (FEMS) by optimally combining the operations of the demonstration test system and the existing gas engine power plant. The redox flow battery system comprises three banks of batteries: 500 kW, 250 kW, and 250 kW units. For the photovoltaic system, the concentrator type system[(7)] developed by Sumitomo Electric is applied. The existing gas engine power plant consists of six generators, and their rated power output is 3.6 MW in total. The configuration of the demonstration system is shown schematically in **Fig. 13**. **Table 2** presents the equipment configuration of the redox flow battery system.

Photo 1. Outlook of a megawatt-class electric power generation/storage system

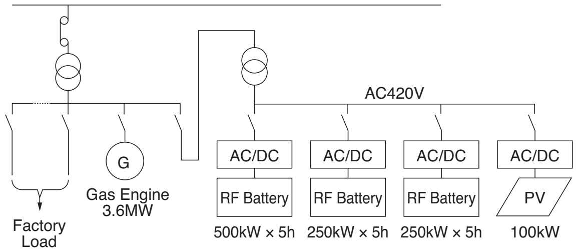

Fig. 13. The circuit configuration of a megawatt-class electric power generation/storage system

Table 2. The equipment configuration of the 1MW × 5H redox flow battery system

Equipment	Number	
Battery Cubicle	8	125kW × 8 (two pumps and a battery controller are inside)
Electrolyte Tank	16	$25m^3$ × 8set (a positive tank and a negative tank are connected to a battery cubicle)
Power Conditioner (AC/DC Inverter)	3	500kW × 1, 250kW × 2 (each power conditioner are connected by AC420V)

The redox flow battery system comprises a new type of cell stacks. An improved structural design and the use of newly-developed component materials have increased the charge/discharge power density and also extended their service life. **Photo 2** shows the new cell stack and the external appearance of the battery cubicle on which the cell stacks are mounted.

The demonstration system has been in the process of testing since July 2012. Some of the test results are given below.

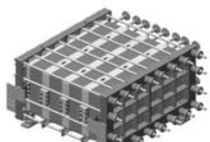

Photo 2. The new cell stacks and the battery cubicle

(1) Operation of stabilizing output of the photovoltaic system

Figure 14 shows an example of the output power waveform measured when the output fluctuations of the photovoltaic system were stabilized at a time constant of 60 minutes. As this figure shows, the redox flow battery system absorbed the short-period output fluctuations, abrupt increase (at around 9:00 a.m.), and abrupt decrease (at around 3:40 p.m.) of the output and thus smoothed the total output.

(2) Planned operation of the solar power output

In the planned operation, the system is operated to achieve the total power output according to a preliminarily established schedule. The difference between the planned and the momentary output of the photovoltaic system at each point in time is compensated by charging/discharging power of the redox flow battery system. The results of a planned operation test are shown in **Fig. 15**. For this test, the output was planned to 50 kW of between 7:00 and 10:00, 100 kW between 10:00 and 15:00, and 50 kW between 15:00 to 18:00. Since it was cloudy on the test day, the amount of solar radiation fluctuated wildly, making the output of photovoltaic system fluctuate dramatically. **Figure 15** confirms that the redox flow battery system can absorbs the fluctuations in the output and thus ensure the planned total output.

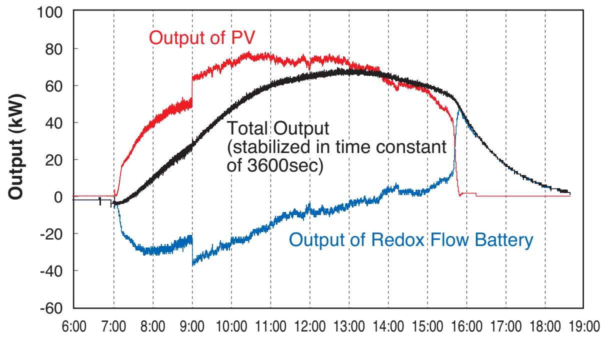

Fig. 14. Stabilizing solar power output operation

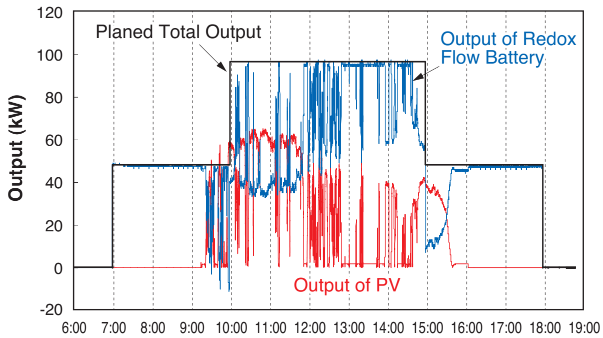

Fig. 15. Planned operation of the solar power output

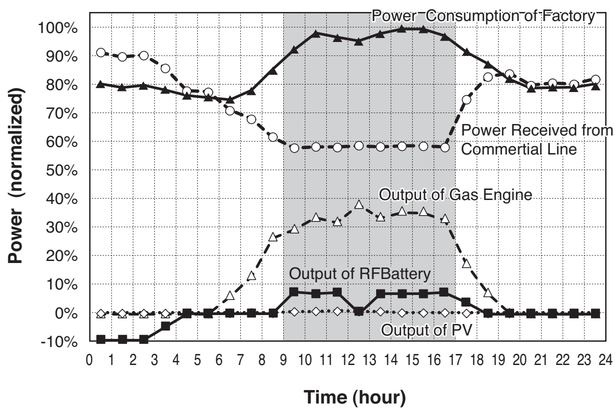

Fig. 16. Peak-cut operation

(3) Peak-cut operation

Separately from stabilizing the supply of renewable energy, the demonstration system was combined with the existing gas engine power plant to cut the peak demand for power from the commercial power grid. An example of the test results is shown in **Fig. 16**. Supplying power from the demonstration system during the peak power demand hours from 9:00 to 17:00 cut the Yokohama Works' peak demand for power supply from the commercial power grid by 40%.

5-3 Power demand/supply control for micro grid

Lastly, demonstrations of demand/supply control using a redox flow battery is described below. The configuration of the demonstration system is shown in **Fig. 17**[(8),(9)]. As shown in this figure, the demonstration system is a micro grid isolated from the commercial power line. The power source for the micro grid consists of only photovoltaic systems and a small wind turbine. The micro grid also contains a redox flow battery to realize the grid stability. Since the output of these renewable sources and of the redox flow battery are direct current (DC), all the electrical apparatus in the system is connected through a DC bus to minimize the DC/AC conversion loss. Generated DC power is transmitted on the DC bus to the receiving ends, converted to AC at the ends, and consumed by electrical loads (LCDs, LED lighting, compact refrigerators, etc.).

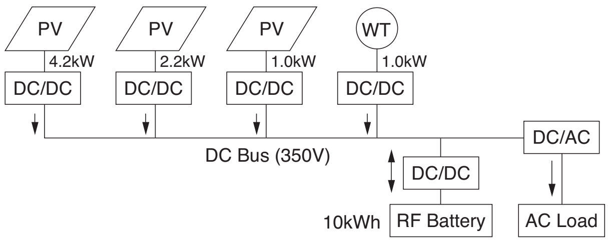

Fig. 17. The circuit configuration of the micro grid system

For the sake of stable operation of the power grids, it is necessary to maintain the electric power balance between demand and supply. All power sources in this micro grid are solar and wind power without any use of fossil fuels. The electric power generated by such renewables is dependent on the weather which is changing every moment, thereby making it difficult to plan the operation of supply-demand control. In this micro grid, the balance between supply and demand is maintained by compensating imbalanced electric power with charge and discharge of the redox flow battery. In such operation, energy storage components are required to be able to charge and discharge steeply and intricately. Furthermore, in order to avoid a shortage of capacity, it is necessary to manage the state of charge (SOC) with high precision. The redox flow battery system meets such requirements.

For this specific application, an "all-in-one" cubicle type of 10 kWh redox flow battery system was developed. This system features two 2 kW cell-stacks, pumps, tanks, a bidirectional DC-DC converter, and a battery management system. The outlook of the cell-stacks and "all-in-one" type 10 kWh redox flow battery system is shown in **Photo 3**.

The example output of the demand/supply control operation is shown in **Fig. 18**. If generated power is higher than power consumption, the voltage of DC bus raises. On the other hand, if generated power is lower than power consumption, the voltage of DC bus falls. In this system, demand/supply balance is maintained by feeding back the DC bus voltage and controlling the amount of electric charge of discharge from the battery system. As **Fig. 18** shows, according to the changes of generated electric power and consumption, the redox flow battery system carries out the complicated output, and DC bus voltage is maintained at 350 V (control target value). This small-scale demonstration system has already been operating continuously for more than one year. This fact suggests that scaling up this system will be effective in using redox flow batteries to control the demand/supply of commercial power line.

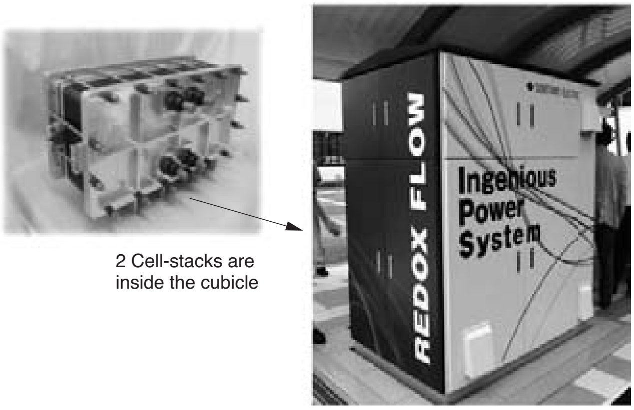

Photo 3. Outlook of 10 kWh redox flow battery

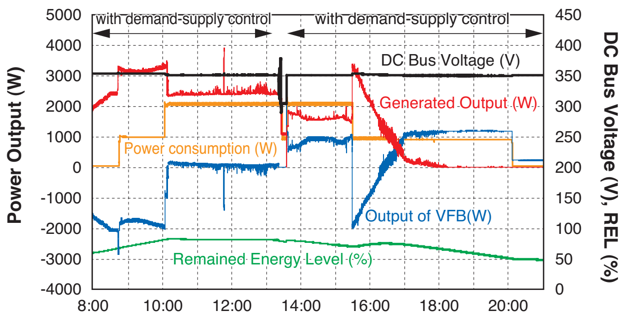

Fig. 18. Demand/supply control by 10 kW redox flow battery system

6. Conclusion

Further introduction of wind power generation and solar power generation is anticipated from the standpoints of resource preservation and energy self-sufficiency. However, since the output of renewables depends on the weather conditions, it is generally impossible to operate renewable energy generation facilities systematically. This paper outlined three demonstration tests using redox flow battery systems to allow the renewable energy to be used efficiently. Stabilizing the short-period fluctuations in the output power of wind farms and photovoltaic systems was anticipated to help increase the amount of renewable energy that can be supplied to commercial power grids. The use of storage batteries will enable planned renewable power plants, thereby making it possible to operate them systematically, like thermal power plants. Thus, redox flow batteries are expected to enhance the practical value of renewable energy and contribute to accelerating the introduction of renewable energy. Owing to its high responsiveness and short-term high output power characteristics, the redox flow battery is also expected to be an effective tool for controlling demand/supply of commercial power network. On the other hand, redox flow batteries and other storage batteries are expensive for commercial use. Reducing the cost of redox flow batteries is essential in making good use of their intrinsic advantages. The authors will continue to check the long-term reliability of redox flow batteries and develop marketable lower-cost batteries, thereby ensuring that they will contribute to the effective use of renewable energy.

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