Redox Flow Battery for Energy Storage

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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 system, which uses a large number of these distributed power generation sources, energy storage technologies will be indispensable. Among the energy storage technologies, battery energy storage technology is considered to be most viable. In particular, a redox flow battery, which is suitable for large scale energy storage, has currently been developed at various organizations around the world. This paper reviews the technical development of the redox flow battery.

Keywords: redox flow battery, energy storage, renewable energy, battery, vanadium

1. Introduction

To realize a low-carbon society, the introduction of renewable energies, such as solar or wind power, is increasingly being promoted these days worldwide. A major challenge presented by solar and wind power generators is their fluctuation in output. If they are introduced in large numbers to the power system, problems, such as voltage rises, frequency fluctuations and surplus of the generated power, are predicted to occur. As a solution to these problems, energy storage technologies are attracting attention, amongst which energy storage batteries are expected to become indispensable for use. Various energy storage batteries are being developed and many application verification projects using such batteries are currently being promoted. Thus, expectations are growing for their practical use to the power system in near future. The redox flow (RF) battery, a type of energy storage battery, has been enthusiastically developed in Japan and in other countries since its principle was publicized in the 1970s(1). Some such developments have been put into practical use. This paper reviews the history of the RF battery's development, along with the status quo of its use.

2. The Necessity of Energy Storage and Its Technologies in Practical Use(2)

As an energy storage technology that has long been used in the power system, pumped hydro energy storage is widely known. Occupying about 10% of the total power generation capacity, it functions as a load leveler; namely, it levels the power load by storing power during off-peak hours and discharging it during peak hours. Variable-speed pumped hydro energy storage, which can vary the rotating speed of a pump, is currently in practical use. Some pumped hydro systems have a sophisticated power system stabilization function of frequency regulation or others. As other energy storage technologies, energy storage batteries, superconducting magnetic energy storage (SMES), flywheels, compressed air energy storage (CAES), and electric double-layer capacitors (EDLC) are known. They are being developed for various applications to make effective use of their individual characteristics, and some of the developments have been put into practical use.

An advantage of SMES is that they are high in energy storage efficiency and can discharge a large amount of power instantaneously, since they store electric energy as it is. They are expected to be put into practical use in the near future, as electric power companies and national projects are conducting their verification tests. Chubu Electric Power Co., Inc. is field-testing a 5 MVA SMES at a liquid-crystal factory. This SMES, used for instantaneous voltage sag compensation, is among the world's largest. In other countries, such as the United States, SMES is already commercialized for the power system stabilization and for instantaneous voltage sag compensation. Regarding flywheel technologies, the Fusion Institute of the former Japan Atomic Energy Research Institute (currently the Japan Atomic Energy Agency) has a flywheel power generator with the world's largest energy storage capacity (8 GJ or 2,200 kWh). The generator is used as a magnetic field coil power supply. The Okinawa Electric Power Co., Inc, has a 23 MW flywheel for frequency regulation. The CAES is a technology that compresses air and stores it in an underground hollow space, and generates power in combination with a gas turbine generator where necessary. It is in practical use at some power stations in Germany and the United States. EDLC technology has a characteristic of instantaneous large output because, like capacitors, it charges and discharges electricity by absorbing and desorbing electric charge without any chemical reaction taking place. The technology is also advantageous in that it is maintenance-free. Recently, EDLC products with large capacities that can be used for electric-power facilities are commercially available, and are also being used in such applications as instantaneous voltage sag compensation, absorption of regeneration energy and voltage regulators for electric-railway, and natural-energy-generation output fluctuation stabilization.

Battery energy storage technology is superior in technical integrity to the above energy storage technologies and has excellent practicality because it can be installed and distributed in suburban areas. It is thus a highly promising technology.

3. Battery Energy Storage

Table 1 shows the varieties of energy storage batteries and their individual characteristics(3). Among them, lead acid batteries have the longest history and are extremely common for use in automobiles. In some overseas countries, such as the United States, Germany and Puerto Rico, lead acid batteries have been used as energy storage facilities as several aged application examples indicate. In Puerto Rico, 20 MW (40 minutes) lead acid batteries were introduced to regulate frequency and to provide spinning reserve. With the recent increase in demand for energy storage batteries, not only lead acid batteries but also various other types of batteries are being enthusiastically developed for practical applications worldwide, to make the best use of the characteristics of the individual batteries. Among them, sodium sulfur (NaS) batteries have excellent features, such as high energy density and superior charge/discharge efficiency, and have been used in many practical applications in Japan and in other countries. They are used not only for load leveling in power substations and industrial plants but also for use in combination with solar and wind power generation. At the Futamata Wind Power Station in Aomori Prefecture, Japan, 34 MW NaS batteries are installed along with 51 MW wind power generation facilities.

4. Redox Flow Battery for Energy Storage

The word redox is a combination of, and thus stands for, *reduction* and *oxidation*. A redox battery refers to an electrochemical system that generates oxidation and reduction between two active materials, forming a redox system, on the surface of inactive electrodes (the electrodes themselves do not change). A redox flow (RF) battery has the electrolyte including these active materials in external containers, such as tanks, and charges and discharges electricity by supplying the electrolyte to the flow type cell by pumps or other means.

4-1 Principle, configuration and characteristics of RF batteries

(1) Principle and configuration of an RF battery

As shown in **Fig. 1**, an RF battery consists mainly of a cell where the redox reaction occurs, positive and negative electrolyte tanks in which active material solution is stored, pumps and piping that circulate the electrolyte from the tanks to the cell. It is interconnected with the AC power system via an AC/DC converter.

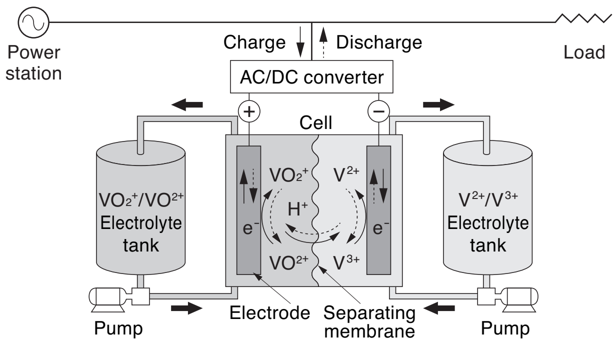

Fig. 1. Principle and Configuration of an RF Battery

Metal ions that change valence can be used in a redox system; however, in light of such factors as energy density and economy, the iron (Fe^{2+}/Fe^{3+})–chromium (Cr^{3+}/Cr^{2+}) system and the vanadium (V^{2+}/V^{3+}–VO^{2+}/VO_2^+) system are considered feasible redox systems. The V–V system is especially advantageous because it uses the same metal ions at both the positive and negative electrodes and the battery capacity does not decrease even when the positive and negative electrolytes are mixed each other through the membrane, while in the case of a system using two different metal ions, such as iron and chromium, the battery capacity decreases if the two electrolytes are mixed. The V–V system is thus currently widely developed around the world.

Table 1. Energy Storage Batteries

Battery variety	Redox flow	NaS	Lead acid	Lithium ions	Nickel hydride	Zinc bromide
Active material (positive/negative)	V ions/V ions	S/Na	Lead dioxide/Lead	Metal compound oxides containing Li ions/Carbon	Nickel oxyhydroxide/ Hydrogen-storing alloy	Br/Zn
Theoretical energy density (Wh/kg)	100	786	167	392~585	225	428
Open-circuit voltage/cell (V)	1.4	2.1	2.1	3.6~3.8	1.2	1.8
Operating temperature (°C)	Room temperature	About 300	Room temperature	Room temperature	Room temperature	Room temperature
Major accessory	Circulation pump	Heater	Not in particular	Not in particular	Not in particular	Circulation pump
Characteristics	• Independently designable output and capacity • Easily measurable state of charge • Reusable electrolyte	• Most common storage batteries • Useful under high temperatures	• Many records of use such as in cars and UPS	• Many records of use as small batteries	• Many records of use as small batteries	

The electrode reaction of the vanadium system can be expressed by the following formulae:

• Positive electrode

VO^{2+} (tetravalent) + $H_2O \leftrightarrows VO_2^{+}$ (pentavalent) + $2H^{+} + e^{-}$: $E^0 = 1.00$ V ·····························(1)

• Negative electrode

V^{3+} (trivalent) + $e^{-} \leftrightarrows V^{2+}$ (bivalent): $E^0 = -0.26$ V···(2)

In these formulae, the reaction from left to right represents the reaction during charging. At the positive electrode in the cell, tetravalent V ions (VO^{2+}) are oxidized to pentavalent V ions (VO_2^{+}) while at the negative electrode, trivalent V ions (V^{3+}) are reduced to bivalent V ions (V^{2+}). The hydrogen ions (H^{+}) generated at the positive electrode during charging move to the negative electrode through the membrane to maintain the electrical neutrality of the electrolyte. Supplied electric power is thus stored in the form of the transformation of V ions of differing valence. During discharging, the stored power is delivered by the reverse reaction. The RF battery's electromotive force is dependent on the redox system used. In the case of the vanadium redox system, the standard electromotive force calculated based on the standard oxidation reduction potential (E^0) is 1.26 V. However, when the electrolytes and cells are prepared practically, the electromotive force is about 1.4 V.

A structure of two or more cells stacked is called a *cell stack*. **Figure 2** shows a representative cell stack structure, and **Fig. 3**, the cross-section structure of such a cell stack. The voltage of a single cell is only 1.4 V at its highest, and to realize high voltage for practical use, many battery cells need to be connected in series. As to the connection method, the serial stacking method using bipolar plates, which resemble the method used in fuel cells, is employed. The role of the cells is to realize the efficient oxidation and reduction reaction of vanadium ions in the electrolyte. As in an electric circuit element, the cell should preferably have a low internal resistance. In addition, it is desirable that the oxidation and reduction in the cell do not involve side reactions. The cell components include the electrodes, a membrane, the bipolar plates, and a frame that houses these components to form a cell, as shown in the figure. Because an acidic solution is used as the electrolyte, the materials in contact with the electrolyte should be resistant to acid.

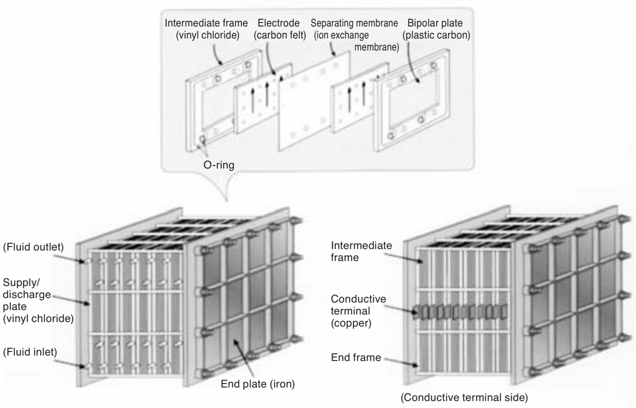

Fig. 2. Typical Cell Stack Structure (Sumitomo Electric)

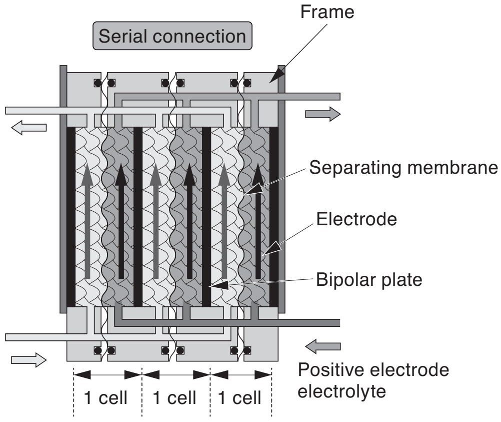

Fig. 3. Cross-Section Structure of Cell Stack (Sumitomo Electric)

(2) Characteristics of RF batteries

RF batteries have the following characteristics and can be used in various applications.

(1) The battery reaction principle is simply the change in valence of the metal ions in the electrolyte, realizing a long charge/discharge cycle service life.
(2) The output section (cells) and capacity section (tanks) are independent of each other and can be optimally designed according to application needs.
(3) Maintenance is easy mainly because the same electrolyte is supplied to individual cells and therefore the state of charge (SOC) in each cell does not need to be monitored, and because heat can be controlled easily based on the flowing electrolyte. Since the SOC can be easily monitored by measuring the potential of the electrolyte, the SOC can be monitored continually during operation.
(4) The electrolyte is stored in the positive and negative tanks separately, so that no self-discharge occurs during stand-by and stoppage, except in the cell section.
(5) RF batteries are useful to absorb irregular, short-cycle output fluctuations, such as in natural energy generation, because they have the characteristic of instantaneous response in an order of milliseconds and can charge and discharge at an output rate a few times larger than the designed rating for a short period of time[4].
(6) The electrolyte is friendly to the environment, because it scarcely changes during normal operation except for changes in ion valance, and it can be used virtually permanently and reused.

The disadvantages of RF batteries are as follows:

(7) Because an RF battery uses metal ions dissolved in a solution as its active material, solubility is limited, and hence the volume of the tank section is by necessity large, and the energy density is relatively small compared with other energy storage batteries.
(8) Pumping power is necessary to circulate electrolyte to the cells.
(9) Shunt-current losses may occur through electrolyte.

4-2 History of the development of RF batteries

Table 2 summarizes the history of the development of RF batteries. Full-scale development of the batteries started in the 1970s. The principle of the RF battery system was presented by L. H. Thaller of the National Aeronautics and Space Administration (NASA) of the United States in 1974[1]. NASA mainly conducted research on the Fe/Cr system, discontinuing it in 1984 with the publication of the Final Report[5]. At the same time in Japan, the Electrotechnical Lab. (ETL; currently the National Institute of Advanced Industrial Science and Technology) was conducting basic research, and the development of the Fe/Cr system made progress as a project of the New Energy and Industrial Technology Development Organization (NEDO). In about 1985, in Australia, the University of New South Wales (UNSW) proceeded to develop the V system.

Concerning the practical use of RF batteries, electric power companies and manufacturers in Japan jointly conducted research with enthusiasm, and in about 2001, the V system was partially put into practical use. The summary of the development of the Fe/Cr system and V system is explained below:

Table 2. History of RF Battery Development

1949	Kangro (German patent): Cr/Cr and other systems
1974	Battelle: Cr/Cr, Fe/Cr, V, Mo, Mn and other systems
1974	NASA released the principle of the RF battery—U.S. basic patent ('75) • Fe/Cr system 1 kW ('78), Final Report ('84) ETL started the research and development of RF Battery.
1980	NEDO (Moonlight Project) established the project "Advanced Battery Electric Power Storage System." • RF (ETL./Mitsui Engineering and Shipbuilding [MES]), NaS (Yuasa Battery), Zn/Br (Meidensha), and Zn/Cl_2 (Furukawa Electric) • ETL, Fe/Cr system, 1 kW ('82); MES, 60 kW ('84 to'87) NEDO (Sunshine Project) • RF battery for solar power generation (MES and Ebara)
1985	University of New South Wales (UNSW; Australia) released the V system RF battery and applied a basic patent ('86).
1989	ETL. and Kashima Kita Electric Power developed V system RF battery for the use of vanadium from the soot • V system, 1 kW (Ebara, '90); 10 kW (MES, '91); 200 kW (Kashima Kita, '97) KEPCO and Sumitomo Electric • Fe/Cr system, 60 kW ('89); V system (450 kW, '96)
1998	ETL. and Kashima Kita • 10 kW Redox Super Capacitor on-vehicle test
2001	Sumitomo Electric put V system RF battery into practical use (for load leveling, instantaneous voltage sag compensation and emergency use). NEDO verified the RF battery for stabilizing the wind power output fluctuation. Sumitomo Electric: 170 kW ('00), 6 MW ('05)
2011	The development of RF batteries is proceeding worldwide, including in the U.S., Europe and China.

(1) Iron–Chromium (Fe/Cr) system

Around 1980 in Japan, expectations grew regarding the development of large-capacity energy storage batteries that would complement pumped hydro energy storage to improve the load factor, which was getting lower at that time, by load leveling. In NEDO's Moonlight Project, the development of four advanced batteries, including RF, sodium/sulfur, zinc/bromine, and zinc/chlorine batteries, started. Among the batteries, research into RF batteries was conducted mainly by the ETL[12]. The laboratory conducted basic research on many possible redox pairs, and proceeded with practical research into the Fe/Cr system using hydrochloric acid solution[6]-[10].

Along with these elemental technology developments, Mitsui Engineering and Shipbuilding Co., Ltd. (MES) manufactured and tested 10 kW and 60 kW system prototypes as part of the NEDO project during 1984 to 1987[11]. Kansai Electric Power Co., Inc. (KEPCO) and Sumitomo Electric Industries, Ltd. (Sumitomo Electric) also started to develop RF batteries in 1985 on their own, and tested a 60 kW class Fe/Cr system RF battery in 1989[12], [13].

The Fe/Cr system has the following problems: the Cr ions' electrode reaction is slow; because the different metal ions are used in positive and negative reactions, each ion is mixed through the membrane and thus gradually decrease the battery capacity; the Cr ions' redox potential is close to the hydrogen gas generation potential and a small amount of hydrogen gas is generated from the negative electrode near the end of the charge, thereby reducing the battery capacity because of differences in the SOC between the positive and negative electrodes. KEPCO and Sumitomo Electric theoretically solved the problem of the mixture of redox ions between the positive and negative electrodes by using a single-fluid Fe/Cr system[14] in which Fe ions and Cr ions are mixed in both the positive and negative electrodes. To solve the problem of the generation of hydrogen gas, the electrode characteristics were improved, and various types of accessories known as *rebalancing systems*, which adjust the SOC for both the positive and negative electrodes in the long run, were proposed.

With the aim of improving the energy density of the Fe/Cr system, MES replaced Fe ions with Br ions for the positive electrode, and researched into Cr/Br systems[15]. Likewise, the ETL and Ebara Corp. jointly investigated the feasibility of the Cr/Cl system[16]. Furthermore, the V/O_2 system, in which air is used on the positive electrode, was studied[17].

(2) Vanadium system (V/V system)

In Australia, where vanadium resources are abundantly available, Prof. Maria Kazacos of the UNSW proposed V system RF batteries, which use V ions at both the positive and negative electrodes, around 1985[18]-[20], and applied for a basic patent in 1986[21]. In Japan, which has no natural vanadium resources, V system RF batteries were not researched into enthusiastically for economic reasons. However, Kashima Kita Electric Power Corp. (Kashima Kita) and the ETL. developed the technology of recovering vanadium included in petroleum and heavy fuels from the soot of the fuels burned at thermal power plants. Thus the economic value of V system RF batteries was reviewed and their development started in the country[22]. The electromotive force of the V system was approximately 1.4 V, which was 1.4 times as large as that of the Fe/Cr system, so that, provided that the cells and energy efficiency were the same, the output was double. Because the electrode reaction of V ions was comparatively fast in practical use, the output was found to be several times as large. The system used V ions at both the positive and negative electrodes; therefore, even if ions were mixed between the positive and negative electrodes through the membrane, the battery capacity did not decrease, in contrast to the Fe/Cr system.

The redox potential of V ions at the negative electrode was higher than that of Cr ions, so that hydrogen gas generation was extremely small, which did not need the rebalance system in practical use, this was also a great advantage. The development of V system RF batteries started in Japan in earnest in about 1989 because of these advantages and due to the applicability of the battery technology of the Fe/Cr system.

In 1997, Kashima Kita manufactured a 200 kW/800 kWh system on trial(23). KEPCO and Sumitomo Electric manufactured a 450 kW/900 kWh system in 1996(24). Thereafter, the development of small-capacity system for installation at consumers was proceeded(25), (26), and in 2000, a 100 kW/800 kWh system developed for buildings was actually installed in an office building and verification operations were conducted(27), (28). Sumitomo Electric developed practical products in 2001, and supplied products for various uses, such as for load leveling, instantaneous voltage sag compensation, and emergency power supply(29).

4-3 Application cases of an RF battery

The applications of an RF battery include not only load leveling, which was the initial aim of the development, but also instantaneous voltage sag compensation and emergency power supply at the sites of consumers; stabilization of output fluctuation for natural energy sources such as wind and solar power generation, which is recently becoming increasingly common; and frequency regulation in the power system for high-quality electric power supply. **Table 3** shows the test systems and practically used systems for which Sumitomo Electric supplied products, along with their application purposes. Following the table, the distinctive applications are explained.

(1) Load leveling system

At first when the development of RF batteries started, the purpose was to develop large-capacity energy storage batteries for installation at power substations, to level the load and improve the load factor; however, the first example of their practical use was a system installed at a consumer. Consumers can reduce the contract electric power and use inexpensive nighttime power by storing power during nighttime when the demand is low and discharging power from the battery during daytime peak hours to accommodate the peak power demand, thus reducing electric charge cost and, in some cases, reducing the size of power-receiving facilities. From the perspective of power suppliers, RF batteries enable power supply facilities to be used more efficiently as they level the electric power load, benefitting both the consumer and the supplier. **Photo 1 and 2** show a case of RF battery application at a university(30). **Photo 1** shows battery cubicles that house 12 battery cell stacks installed on the first floor of the storehouse. **Photo 2** shows the electrolyte tanks and pumps installed in the basement. Each electrolyte tank, made of rubber, is about 4 m in height and has a net capacity of 31 m^3, and each is installed in an iron frame. The system consists of three banks, one of which includes four cell stacks of AC 168 kW × 10 hours in capacity, and has an output of AC 500 kW and a capacity of 5,000 kWh.

(2) Case of instantaneous voltage sag compensation system

At semiconductor plants and other factories, an instantaneous voltage sag may damage products in process. Con-

Table 3. RF Battery Application Examples

Customer or owner	Application	Output capacity	Year of delivery
Electric power company	Research and development	450 kW × 2H	1996
Office building	Research and development (load leveling)	100 kW × 8H	2000
Electric power company	Research and development	200 kW × 8H	2000
NEDO	Wind power output fluctuation stabilizing verification (single unit)	170 kW × 6H	2000
Constructor	Research and development (combination with solar power)	30 kW × 8H	2001
Factory	Instantaneous voltage sag compensation, peak-cut control	3 MW × 1.5sec (1.5MW × 1H)	2001
Electric power company	Research and development	250kW × 2H	2001
University	Load leveling	500 kW × 10H	2001
Laboratory	Research and development	42 kW × 2H	2001
Electric power company	Research and development	100 kW × 1H	2003
Office building	Load leveling	120 kW × 8H	2003
University	Instantaneous voltage sag compensation, load leveling	55 kW × 5H	2003
Railway company	Research and development (load leveling, instantaneous voltage sag compensation)	30 kW × 3H	2003
Office building	Research and development	100 kW × 2H	2003
Data center	Instantaneous voltage sag compensation, emergency power supply	300 kW × 4H	2003
Laboratory	Load leveling	170 kW × 8H	2004
Office building	Load leveling, emergency power supply for fire-fighting equipment	100 kW × 8H	2004
University	Load leveling, emergency power supply for fire-fighting equipment	125 kW × 8H	2004
Electric power company	Research and development	152 kW × 2.6H	2005
Museum	Load leveling, emergency power supply for fire-fighting equipment	120 kW × 8H	2005
Electric power company	Research and development (combination with solar power)	100 kW × 4H	2005
NEDO	Wind power output fluctuation stabilizing verification (wind farm)	4 MW × 1.5H	2005

Photo 1. 500 kW System for Load Leveling (Battery Cubicles)

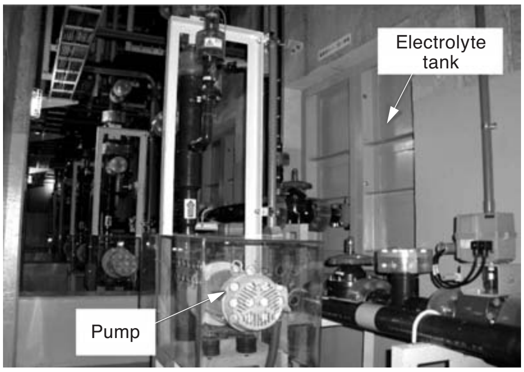

Photo 2. 500 kW System for Load Leveling (Electrolyte Tank)

sidering the loss of business opportunities resulting from a facility reset, the loss might be huge. When used in such an application, an RF battery system is required to quickly respond to instantaneous voltage sags and supply electric power to important loads during the moments of such sags. Because an RF battery system has an immediate high output characteristic and its tank capacity can be designed flexibly according to the required capacity, economical design is possible according to the requirements. The load leveling function and the peak-cut function can also be provided where necessary.

Photo 3 and 4 show an application at a liquid crystal factory(31). The major specifications of the RF battery system are shown in **Table 4**. The cell stacks are installed in the battery cubicle on the second floor of the building, and the electrolyte tanks, which are made of polyethylene (30 m^3 × 8 units), are installed on the first floor. Normally they perform peak-cut operation at 1,500 kW, and when a voltage

Table 4. Specifications of Instantaneous Voltage Sag Compensation System

Output capacity	During peak shift operation	1,500 kW × 1 h
	During instantaneous voltage sag compensation operation	3,000 kW × 1.5 s
Cell configuration	(100 cells × 4 stacks in series × 3 banks in parallel) × 3 systems	
Electrolyte	Sulfuric acid aqueous solution including vanadium at 1.7 mol/L	
Electrolyte tanks	Polyethylene tank 30 m^3 × 8 units	

Photo 3. Instantaneous Voltage Sag Compensation 3 MW System (Battery Cubicles)

Photo 4. Instantaneous Voltage Sag Compensation 3 MW System (Electrolyte Tanks)

sag occurs, they discharge 3,000 kW for 1.5 seconds.

(3) Application of RF batteries in combination with wind power generation

Energy storage batteries are expected to be a good solution when renewable energy, such as solar and wind power generation, is introduced in large amounts to the power system, and various verification projects are currently underway. Expectations are becoming higher for the introduction of energy storage batteries in near future.

Regarding RF batteries, NEDO performed verification tests by installing energy storage batteries to wind power generator facilities to see if their output fluctuations could be smoothed as expected. Generally speaking, wind power output fluctuations vary periodically, ranging from milliseconds to hours. RF batteries can be designed to either reduce or increase the battery capacity by adjusting the amount of electrolyte, thus satisfying the needs for large or small capacity. In particular for short-frequency fluctuation, RF batteries are expected to improve economic efficiency through design, taking advantage of their high-rate output characteristics. In the following, the summary of verification tests is explained.

(a) Application to single unit of wind power generation

In the fiscal 2000 NEDO project entitled "Investigation for Introducing Battery Energy Storage System to a Wind Power Generation(32)," three types of energy storage batteries (RF batteries, NaS batteries, and lead acid batteries) were installed along with wind generators for testing. Among the batteries, the RF batteries were tested by the Institute of Applied Energy (IAE), which was entrusted by NEDO. A system of 170 kW (maximum 275 kW) in output ratings and 1,020 kWh in capacity was installed in the Horikappu Power Station of the Hokkaido Electric Power Co., Inc.. This system enabled a test that used the immediate high-rate output characteristics of RF batteries by adjusting the AC/DC converter output to the rating of the wind power generator of 275 kW.

Figure 4 shows a conceptual configuration diagram of the system. The battery was installed at the wind power generation interconnection point, and smoothed the wind power output fluctuation by absorbing their fluctuations. As a smoothing method, the actual wind power output was passed through a low-pass filter characterized by a given time constant, and short-period components were thus removed. The obtained output value was set as the reference. An output equal to the difference between this reference and the actual wind power output was delivered from the battery. The output combining the battery output and the actual wind power output was sent to the power system.

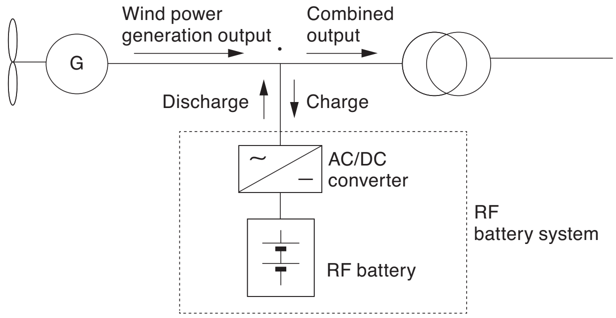

Fig. 4. Basic Configuration of RF Battery System Combined with Wind Power Generator

Figure 5 shows an example of data obtained when the smoothing time constant is one hour. While wind power output fluctuates little by little in the order of seconds, the combined output sent to the power system is favorably smoothed. **Figure 6** shows the output data of one day, which was obtained with the smoothing time constant set to one hour[33]. The changes in the remaining battery capacity during the period are also shown in the space at the bottom of the diagram. The larger the time constant, the better the smoothing level of the output fluctuation. However, the battery output needs to be larger when the time constant is greater, and thus a greater battery capacity is necessary. The remaining battery capacity shown in the diagram is calculated based on the data of the electrolyte potential monitor cell, obtained by using the advantage of the RF battery, which enables the online monitoring of the

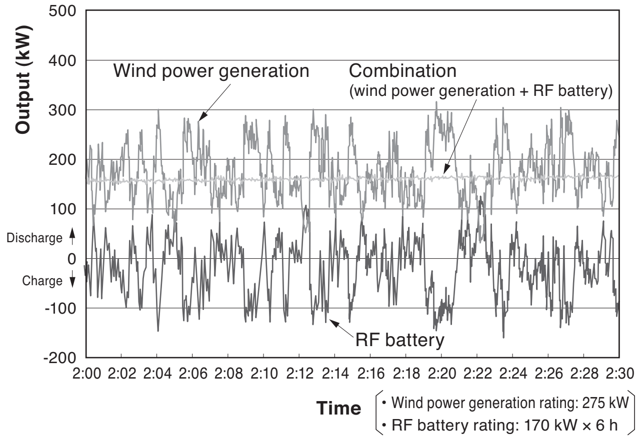

Fig. 5. Example of Wind Power Output Smoothing Characteristics (Time Constant: 1 h, May 22, 2001)

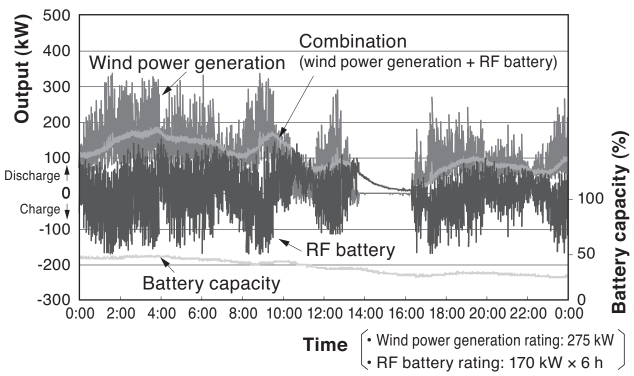

Fig. 6. Example of Wind Power Output Smoothing Characteristics (All Day) (Time Constant: 1 h, May 22, 2001)

remaining battery capacity.

(b) Application to wind farm power generation

As part of a NEDO project entitled the “Development of Technologies for Stabilization of Wind Power in Power Systems[34],” the Electric Power Development Co., Ltd. (J-Power) built an RF battery system (rated output: AC 4,000 kW/6,000 kWh, maximum output: 6,000 kW) as an annex to Hokkaido Tomamae Wind Villa Power Plant (output: 30,600 kW, wind power generators: 19 units, start of operation: December 2000) in fiscal 2003, to test and verify wind power output fluctuation smoothing[35]–[40].

Photo 5 and 6 show the battery cubicles, cell stacks, electrolyte tanks, and piping. This system consists of four banks, each of which comprising four modules. Each module includes electrolyte tanks (15 m^3 each for a positive and a negative electrolyte), six cell stacks, and one heat exchanger. Each cell stack in turn includes six sub stacks each consisting of 18 cells, totaling 108 cells. The rated DC output per cell stack is 45 kW. In each bank, cell stacks are connected with six in parallel and four in series, and the rated DC output per bank is 1,000 kW (maximum 1,500 kW).

This system aims at short-period output fluctuation smoothing (a few seconds to less than ten minutes). The smoothing method is basically the same as that for the single unit wind power generator described previously. The combined output is the sum of the wind farm output and

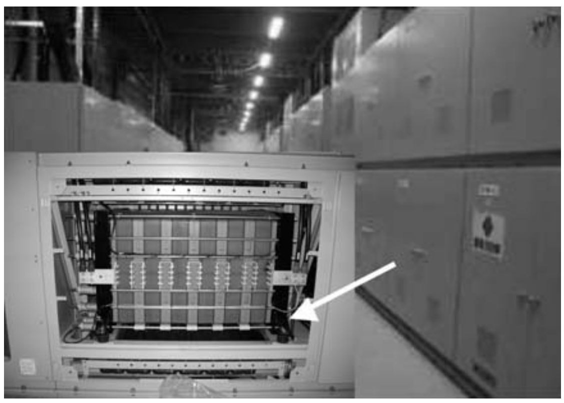

Photo 5. 6 MW RF Battery Annexed to Wind Farm (Battery Cubicle and Cell Stack)

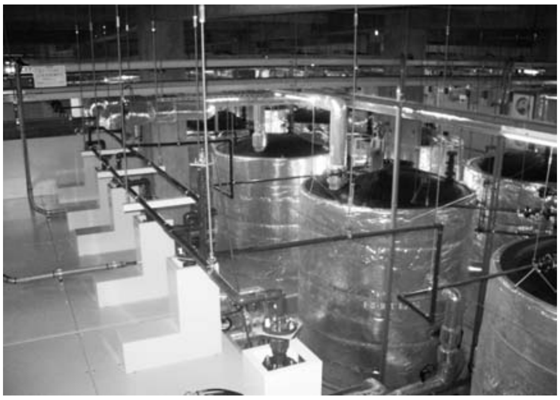

Photo 6. 6 MW RF Battery Annexed to the Wind Farm (Electrolyte Tanks)

the battery output, and the reference of the combined output is set to a value obtained by smoothing wind farm output using the first-order lag filter having a given time constant. Practically, the output required of the RF battery is the sum of (1) the difference between the combined output reference and the wind farm output, and (2) the correction amount required for the supplementary charge or discharge. This is because the battery capacity is limited, and if the SOC reaches the lowest limit by battery losses or if the charge amount exceeds the discharge amount due to wind conditions and the SOC can reach the upper limit, the SOC should be retained at an appropriate range to avoid these situations by supplementary charge or discharge with smoothing operation. This control is named SOC feedback control.

An example of results of the verification test is shown below. **Figure 7** is an example of verification test data using variable time-constant control. The basic time constant is set to 30 minutes, but in this test, it is variable depending on the conditions. When wind power output changes suddenly, the battery may not compensate for it because the battery capacity is limited. It is considered effective to provisionally reduce the time constant to decrease the load on

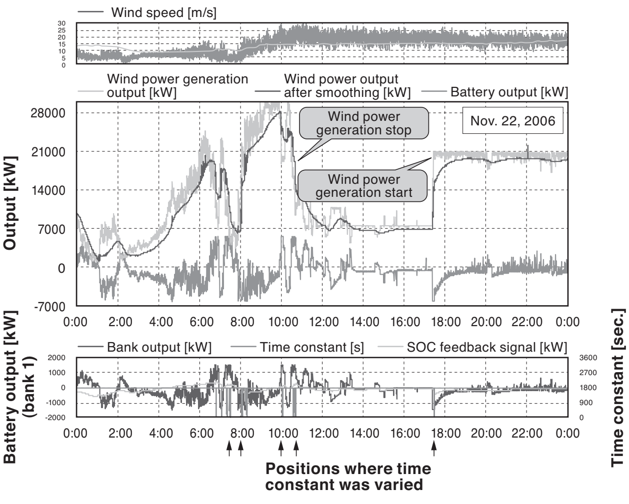

Fig. 7. Example of Test Results Using Variable Time Constant Control (Basic Time Constant: 30 minutes)

the battery and to perform smoothing operation as far as possible. The test data shows that optimal variable time-constant control and smoothing operation can be performed without overloading the battery, according to wind power output conditions.

Figure 8 shows an example of data of a test using bank control. The optimal number of banks is provided for control according to the required battery output, thus improving system efficiency. The test data indicates that the number of banks required for operation changes from four to three and from three to two, depending on the output required of the battery.

As explained so far, the RF battery system annexed to the wind farm is proven to perform the desired smoothing operation. It is also verified that the SOC feedback control and variable time-constant control for smoothing, both of which are designed not to exceed the battery capacity, operate effectively. Control technologies including bank control, which realize efficient operation at the optimal number of banks according to the output required of the battery, have also been verified to operate effectively. The system including these controls has thus been verified to operate stably and efficiently during the test period.

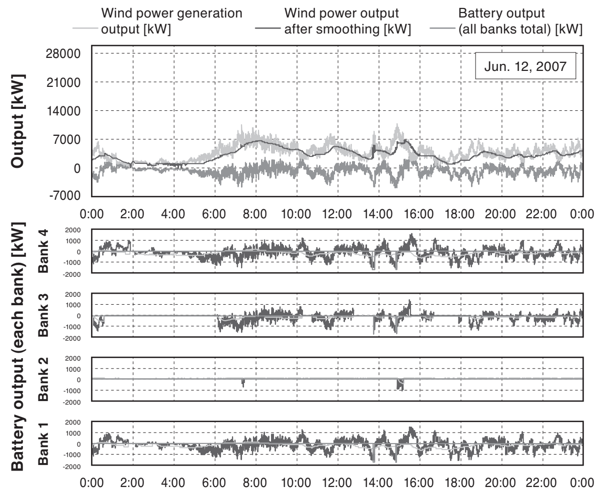

Fig. 8. Example of Test Results using Bank Control

(4) Expectations for applications to secondary control in the power system[(41)–(43)]

Large-scale battery systems are expected to be used for secondary control in the power system. Currently, frequency regulation is performed by adjusting those outputs while keeping the output of thermal power generation, pumped hydro energy storage, hydraulic power generation in good balance, based on load frequency control (LFC) signals from the power control center. When the LFC operation in such a current power generation is replaced with one using an RF battery system, the battery capacity required for the same LFC capacity is expected to be small, because the battery can vary charge/discharge output instantaneously (at high response speed), and because the battery have the characteristic of supplying high-rate output if it is only for a short duration. In such a case, economic benefit can be expected. For example, if an RF battery can produce output three times as large as the rating for a very short time, the RF battery's LFC capacity is 300% compared with the general thermal power generation's LFC capacity of 5%. This means that even a battery with a markedly small rating has the potential to be applied.

4-4 Overseas developments concerning RF batteries

The development of RF batteries initially started at the National Aeronautics and Space Administration (NASA) in the United States and the Electrotechnical Lab. in Japan. Since then, development for its practical use has been accelerated in Japan, exemplified by the research and development projects led by the Electrotechnical Lab. and NEDO and the joint development projects by electric power companies and manufactures. Recently, because smart-grid technologies are becoming increasingly common worldwide since the introduction of renewable energy in great amounts, energy storage batteries are expected to play a more important role, and hence the development of energy storage batteries is being promoted. RF batteries are no exception. They are attracting public attention anew as large-capacity storage batteries, and their development is being promoted worldwide. The main system of their development is the V system. The following is an update on their development overseas[(44)].

In Australia, Prof. M. Kazacos developed the V system jointly with V-Fuel Pty Ltd., and further developed the technology realizing the V/Br system, which is higher in energy density[(45)].

In the United States, Deeya Energy, applying NASA's technologies, developed a few kilowatt-order products using the Fe/Cr system for wireless base stations. Ashlawn Energy, LLC was entrusted by the U.S. Department of Energy (DoE) to perform a project, and released the plan of verifying the 1 MW/8 MWh class V system. Primus Power Corp. also received a budget from the DoE, and plans to develop a verification plant of the flow battery of 25 MW/75 MWh using Zn/Cl_2 system.

In Canada, VRB Power Inc. commercialized a few kilowatt class V system RF battery system for the use of combination with independent energy supply or renewable energy. The technology was purchased by Prudent Energy Corp. based in China, and its business is promoted to be expanded. Recently, in the United States and in China, the company plans to supply MW class RF battery facilities which will be used with solar power generation and wind power generation.

In Europe, an RF battery called Regenesys, which uses the Na/Br system (sodium polysulfide/sodium bromide), was developed on a large scale as a new redox system. However, the development has been discontinued. In Austria, Cellstrom GmbH developed a 10 kW/100 kWh V system RF battery, and has been working for the commercialization in combination with independent power supplies and solar power generation. In the United Kingdom, RE-Fuel technology Ltd. is developing a V system RF battery and has a concept that it is applicable to electric automobiles and their charge stations. In Germany, Fraunhofer-Gesellschaft is researching into non-aqueous electrolyte that is capable of realizing high energy density. In South Africa, CSIR is studying the Cr/Br system.

In Asia, Cellennium Company Ltd. is enthusiastically promoting the V system in Thailand. In South Korea, Samsung Electronics Co., Ltd. is developing the battery using non-aqueous electrolyte. Extremely enthusiastic development is observed in China: in 2009, the renewable energy introduction target was drastically raised (solar power 20 GW and wind generation 150 GW in 2020), and with this as an opportunity, the development of energy storage batteries is speeding up. As a major development, the State Grid Corporation of China (SGCC), a major power transmission company, plans a verification project, and battery manufacturers are competing in development. As for RF batteries, the previously mentioned Prudent Energy Corp, as well as research institutes, such as the Dalian Institute of Chemical Physics, the Chinese Academy of Sciences (DICP)[(46)], and Chengde Wanlitong Industrial Group, are promoting the development.

For zinc/bromine batteries, Australian ZBB Energy Corp. and RedFlow Ltd. and American Premium Power Corp. are committed to their development. Plurion Ltd., a British company, is developing Zn/Ce-system flow batteries to realize high energy density.

5. Conclusion

In Japan, most RF batteries that have been put into practice use at the sites of consumers comprise several hundreds of kilowatts class facilities. In other countries, on the other hand, relatively small systems of a few kilowatts to several tens of kilowatts have been commonly used for independent power supplies. The biggest facility among them is the 6 MW facility installed in the wind farm as NEDO's verification project. In the near future, such applications as smoothing of a larger scale wind power output fluctuations or secondary control in the power system are expected. In consideration of these applications, larger-capacity RF batteries will be necessary. Such facilities must be safe, reliable, durable and cost efficient at a level equivalent to conventional power systems. We expect that further development of the RF battery, including system up and improvement of cell materials, will be promoted along with various verification tests by end-users, and that the RF battery will play an important role in the power system in the near future.

References

(1) L. H. Thaller, "Electrically Rechargeable Redox Flow Cells," Proc. of the 9th IECEC, P.924 (1974)
(2) T. Ise, T. Tanaka, "Advanced Technologies for Electric Energy Storage Systems," CMC books (2006)
(3) JESC, "Battery for power storage system," JEAC 5006-2010
(4) T. Sasaki, T. Shigematsu, "Maintaining Electrical Power Quality using New Energy System -Evaluation for Applying Redox Flow Battery-," IEEJ Kansai Technical Meeting (2001)
(5) N. H. Hagedorn, "NASA Redox Storage System Development Project Final Report," DOE/NASA/12726-24, NASA TM-83677 (1984)

(6) H. Kaneko, K. Nozaki, T. Ozawa, "Characteristics of Redox Systems Used in Redox Flow Cells for Electric Energy Storage Criteria, Measuring Methods and Results of Chromium, Titanium, and Iron Systems," Bul. Electrotechnical Laboratory, vol.41, No.11, P.877 (1977)
(7) K. Nozaki, H. Kaneko, T. Ozawa, "Prospect of Electric Energy Storage by Secondary Batteries," Circulars of the Electrotechnical Laboratory, No.201, P.51 (1979)
(8) K. Nozaki, H. Kaneko, A. Negishi, K. Kanari, T. Ozawa, "Performance of ETL New 1kW Redox Flow Cell System," 19th IECEC P.844 (1984)
(9) K. Nozaki, I. Nagashima, H. Kaneko, T. Ozawa, "Relation between Cell Resistance and Electrolyte Composition of Redox Flow Battery," Denki Kagaku, vol.57, No.10 (1989)
(10) A. Negishi, K. Nozaki, H. Kaneko, Y. Sekita, "Electrode Materials for Redox Flow Cells in PV Power Generating Systems," Bul. Electrotechnical Laboratory, vol.54, No.11, P.1295 (1990)
(11) O. Hamamoto, M. Takabatake, M. Yoshitake, H. Misaki, "Research and Development of 10kW class Redox Flow Battery," 20th IECEC, No.2, P.98 (1985)
(12) T. Tanaka, T. Sakamoto, N. Mori, K. Mizunami, T. Shigematsu, "Development of a Redox Flow Battery," SEI Technical Review, vol.137, P.191 (1990)
(13) T. Shigematsu, T. Ito, T. Sakamoto, "New Energy Storage System with Redox Flow Battery," Electrical Review, vol.78, No.9 (1993)
(14) Randall F. Gahn, Norman H. Hagedorn, Jerri S. Ling, "Single Cell Performance Studies on the Fe/Cr Redox Energy Storage System Using Mixed Reactant Solutions at Elevated Temperature," NASA TM-83385 (1983)
(15) O. Hamamoto, M. Takabatake, M. Yoshitake, "Redox Battery Designing for the Practical Applications," Proc. of the 28th Battery Symposium in Japan, 3A19, P.183 (1987)
(16) K. Nozaki, Y. Wada, "Feasibility of Chromium-Chlorine Redox Flow Battery," Proceedings of the 28th Battery Symposium in Japan, 3A20, P.185 (1987)
(17) K. Nozaki, H. Kaneko, A. Negishi, K. Kurokawa, K. Sato, M. Nakajima, "Performance of All Vanadium Redox Flow Battery and Vanadium Air Battery," Proc. of the 59th Battery Symposium in Japan, 1J30 (1992)
(18) B. Sun, M. Skyllas-Kazacos, "A Study of the V(II)/V(III) Redox Couple for Redox Cell Application," J. of Power Sources,15, P.179 (1985)
(19) B. Sun, M. Rychik, M. Skyllas-Kazacos, "Investigation of the V(V)/V(IV) System for Use in the Positive Half-Cell of a Redox Battery," J. of Power Sources,16, P.85 (1985)
(20) M. Rychik, M. Skyllas-Kazacos, "Characteristics of a new all-vanadium redox flow battery," J. of Power Sources, 22, P.59 (1988)
(21) M. Skyllas-Kazacos, M. Rychik, R. Robins, "All Vanadium redox battery," JP2, 724, 817(1997)
(22) M. Nakajima, M. Sawahata, S. Yoshida, K. Sato, H. Kaneko, A. Negishi, K. Nozaki, "Vanadium redox flow battery with resources saving recycle ability I. Production of electrolytic solution for vanadium redox flow battery from boiler soot," J. of Electrochemistry, vol.66, No.6, P.600 (1998)
(23) "200kW Vanadium Redox Battery," J. of OHM, No.2, P.73 (1998)
(24) N. Tokuda, T. Kumamoto, T. Shigematsu, H. Deguchi, T. Ito, N. Yoshikawa, T. Hara, "Development of a Redox Flow Battery," SEI Technical Review, vol.151, P.95 (1997)
(25) T. Hara, T. Shigematsu, "Development of a Redox Flow Battery," J. of JABMEE, No.10, P.42 (1998)
(26) N. Tokuda, T. Kanno, T. Hara, T. Shigematsu, Y. Tutsui, A. Ikeuchi, T. Ito, T. Kumamoto, "Development of a Redox Flow Battery," SEI Technical Review, vol.156, P.73 (2000)
(27) N. Tokuda, K. Motoi, T. Hara, H. Sato, Y. Tsutsui, K. Emura, T. Shinzato, T. Kanno, "Development of a Redox Flow Battery for the office building," SEI Technical Review, vol.158, P.19 (2001)
(28) N. Tokuda, S. Kikuoka, M. Furuya, S. Kondou, T. Kanno, "Development of a Redox Flow Battery," Technical Meeting of IEEJ-B, (2001)
(29) T. Shigematsu, "Redox Flow Battery for Energy Storage Closing to Practical Use," MATERIAL STAGE vol.1, No.10, P.40 (2002)
(30) H. Morii, S. Miura, M. Minamiura, K. Motoi, "Application of Redox Flow Battery for Load Leveling," J.of JECA, No.10 (2001)
(31) T. Shinzato, K. Emura, T. Hara "Development of Vanadium Redox Battery for Voltage-sag Compensation," Technical Meeting of IEEJ-B, No.254 (2001)
(32) NEDO-NP-0004, "Investigation for Introducing Battery Energy Storage System to a Wind Power Generation," (2002)
(33) T. Shigemitsu, T. Kumamoto, H. Deguchi, T. Hara, "Application of a Vanadium Redox-flow Battery to Maintain Power Quality," IEEE T&D Conference, OR-25 (2002)
(34) NEDO Report, "Development of Technologies for Stabilization of Wind Power in Power Systems," (2008)
(35) K. Kobayashi, "Efforts of Electric Power Companies to Cope with Power Storage Problems 3) Wind Power Stabilization Technology Development Project," J. of Energy & Resources, vol.25, No.6, P.394 (2004)
(36) N. Tokuda, "Technology for Smoothing Fluctuations of Wind Farm Power Output," IEEJ Journal, vol.125, No.11 (2005)
(37) T. Shibata, "Application of Redox Flow Battery for Stabilization of Wind Power," J.IEIE Jpn, vol.25, No.10, P.800 (2005)
(38) K. Yoshimoto, T. Nanahara, G. Koshimizu, "Analysis of Data Obtained in Demonstration Test about Battery Energy Storage System to Mitigate Output Fluctuation of Wind Farm," IEEE PES CALGARY (2009)
(39) G. Koshimizu, T. Numata, K. Yoshimoto, H. Hasuike, T. Shibata, "Subaru Project Analysis of Field test results for Stabilization of 30.6 MW Wind Farm with Energy Storage," EESAT (2007)
(40) NEDO Report, "The Technical Development for Stabilization of Wind Power in Power Systems - Analytical study for the Aged Deterioration –," (2009)
(41) T. Kaizuka, T. Sasaki, "Evaluation of Control Maintaining Electrical Power Quality by use of Rechargeable Battery System," IEEE PES Winter Meeting Columbus (2001)
(42) K. Enomoto, T. Sasaki, T. Shigematsu, H. Deguchi, "Evaluation Study about Redox Flow Battery Response and its Modeling," T. IEEJ, vol.122-B, No.4 (2002)
(43) T. Sasaki, K. Enomoto, T. Shigematsu, H. Deguchi, "Evaluation Study about Redox Flow Battery Response and its Modeling," CEPSI Fukuoka (2002)
(44) http://www.flowbatteryforum.com/
(45) M. Skyllas-Kazacos, "Novel vanadium chloride / polyhalide redox flow battery," J. of Power Sources, 124, P.299 (2003)
(46) Ping Zhao, Huamin Zhang, Hantao Zhou, Jian Chen, Sujun Gao, Baolian Yi, "Characteristics and performance of 10kW class all-vanadium redox-flow battery stack," J. of power sources, 162, P.1416 (2006)

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