

Development of a Redox Flow Battery System

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1. Introduction

In recent years, with the spread of air conditioning devices, the annual load factor of electric power demand has shown a declining trend. Furthermore, due to the change of electric power to an open market system following recent deregulation and calls for CO₂ reduction in response to global environmental problems, the need for an increase in the electric load factor has heightened. In such circumstances, expectations toward electric power storage batteries designed for load leveling have increased.

Since 1985 Sumitomo Electric has been engaged in the development of redox flow batteries, which are a new type of secondary battery for electric power storage, in collaboration with Kansai Electric Power Co., Ltd. In the beginning, development was targeted at high-capacity systems to be used mainly for substations. In order to promote environmental conservation, and in response to a greater demand for low-capacity systems for building and other facilities, development efforts targeted at the commercialization of low-capacity systems for buildings are also proceeding concurrently with the development of high-capacity systems for substations.

This report describes firstly the principles and configuration of this battery system. Secondly, the status of testing of a 450-kW system that has been positioned as a basic unit for transformer substations and which was installed in 1996 in the Tatsumi Substation of the Kansai Electric Power Co., Ltd. is described. Thirdly, development of an underground tank-type 20-kW system designed for buildings is described, fourthly the development of a high-power 50-kW system and finally a 50-kW system for office buildings.

2. Necessity of Electric Power Storage Technology

In Japan, the annual load factor (annual average electric power/maximum three-day average electric power) has dropped to the 50%-60% range due to the acute peaking in electric power use in the summertime.

Redox flow batteries are charged late at night when electric power demand is less, and discharged during the day when demand is highest. This has made it possible to promote the leveling of the electric power load, which is a crucial issue in the electric power industry, and has helped promote the efficient operation of electric power facilities and improvements in power generation efficiency. This has been of great significance to

society by lowering electricity rates and reducing CO₂ output.

The pumped-hydro power stations are already playing this same role, but there are not many sites where pumped-hydro power stations can be constructed from an environmental point of view. For this reason, the early implementation of electric power storage cells is eagerly anticipated as a substitute.

The following are considered suitable applications of electric power storage batteries:

① Electric Power Companies (several MW to several hundred MW)

Used in the substations, etc., of electric power companies, electric power storage batteries can promote load leveling and replace functions performed by pumped-hydro power stations, such as frequency control.

② Electric power customers (several hundred KW to several MW)

When installed in factories and office buildings, etc., electric power storage batteries have features other than load leveling, such as a reduction in electric power charges and contract demand, an uninterrupted power supply, emergency power supplies, and an increased capacity for power supply facilities.

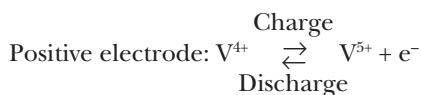
③ Combining with solar/wind power generation

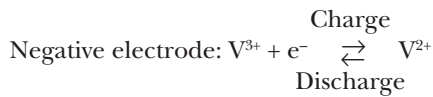
Because of global environmental problems, these natural energy technologies are expected to be implemented more frequently. At such a time, countermeasures are needed to assure system stability by preventing power output fluctuations, e.g., when there is no wind or at night. It is therefore important to use batteries in combination with solar and wind power generation.

3. Operating Principles and Features of Redox Flow Batteries

3-1 Operating Principles of Redox Flow Batteries

The configuration of a redox flow battery is shown in **Fig. 1**. A sulfuric acid solution containing vanadium ions is used as the positive and negative electrolytes, which are stored in respective tanks and circulated to the battery cell. The reactions that occur in the battery cell during charging and discharging can be expressed simply with the following equations:





3-2 Features

Redox flow batteries offer the following features, and are suitable for high-capacity systems that differ from conventional power storage batteries.

(1) Simple operating principle and long service life

The battery reaction only involves a change in the valence of vanadium ions in the electrolyte. There are none of the factors which reduce battery service life seen in other batteries that use a solid active substance, such as loss or electrodeposition of the active substance. Furthermore, operation at normal temperatures ensures less deterioration of the battery materials due to temperature.

Pumps and piping that are widely used in facilities such as chemical plants are usable as established technologies.

(2) Simple installation layout

The system configuration is such that battery output (cell section) and battery capacity (tank section) can be separated, therefore layout of sections can be altered according to the place of installation. For example, the tank can be placed underground. Design can be easily modified according to required output and capacity. For example, if the capacity is to be doubled while leaving output the same, then one has only to double the size of the tank.

(3) No standby loss and quick start-up

The charged electrolyte is stored in separate positive and negative tanks when the battery has been charged, therefore no self-discharge occurs during prolonged stoppage, nor is auxiliary power required during stoppage. Furthermore, start-up after prolonged stoppage requires only starting of the pump, thus making start-up possible in only a few minutes.

(4) Easy maintenance

The electrolyte (i.e., the active substance) is sent to each battery cell from the same tank, therefore the charging state of each battery cell is the same, eliminating the need for special operations such as uniform

charging. Furthermore, maintenance is also easy because the electrolyte is relatively safe and the operations are at normal temperature.

(5) Superior environmental safety

The electrolyte is relatively safe and assures superior environmental safety.

(6) Superior recyclability

Waste vanadium from power generating stations can be used. Furthermore, the vanadium in the electrolyte can be used semi-permanently.

4. Development Goal

The development goal for electric utility models is to achieve functionality and affordability equivalent or superior to that of pumped-hydro power stations. For power customer models, the goal is lower electricity charges for the installer, among other things.

The primary development goals are shown below:

- ① Efficiency: Total energy efficiency of at least 70% (including auxiliary devices and AC/DC conversion loss)
- ② Durability: At least 1,500 charge/discharge cycles (equivalent to 10 years' use)
- ③ Affordability: 20,000 to 30,000 yen/kWh

5. Component Technology of Redox Flow Batteries

The single cell battery, as shown in Fig. 2, is composed of a positive and a negative electrode, which are separated by a membrane. In order to obtain a high voltage, a bipolar plate is used to stack the components in a serial connection. This is called a battery cell stack.

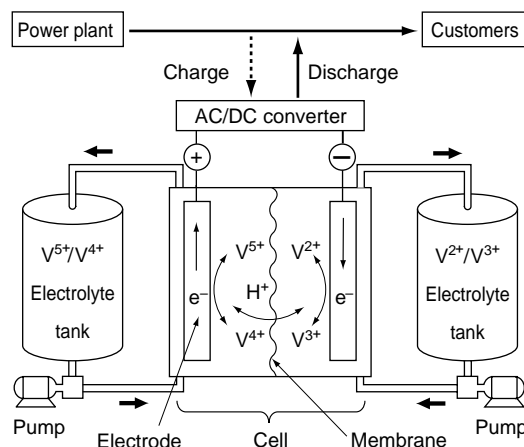


Fig. 1. Principles of a redox flow battery

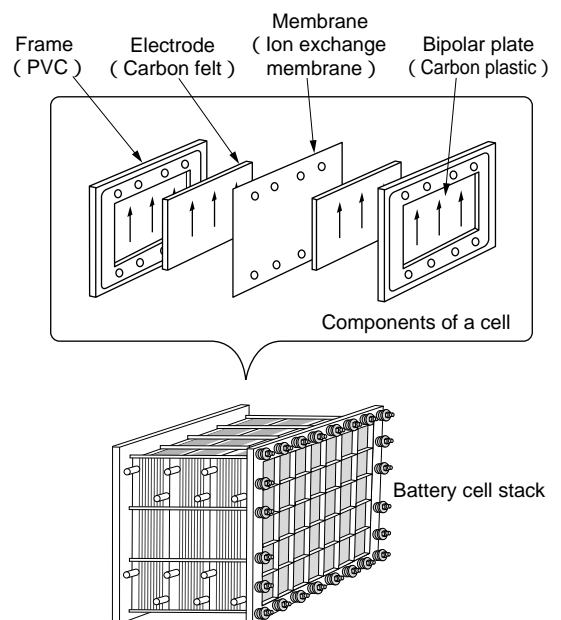


Fig. 2. Construction of a cell stack

The cell stack converts electrical energy to chemical energy, therefore its performance is an important determinant of the battery's basic performance, including its charging and discharging efficiency. In order to increase the efficiency of the battery cell stack, it is necessary to reduce internal resistance, which makes the development of materials like electrodes, membranes, and bipolar plates critical. The required specifications of each component are described below:

- (1) Electrodes: In consideration of resistance to acid, low pressure loss during electric flow and electric conductivity, carbon felt with an activated electrode surface is used.
- (2) Membrane: In consideration of electrical insulation, proton (H⁺ ion) conductivity, and vanadium ion insulation, a negative ion exchange membrane is used.
- (3) Bipolar plate: This component must allow only electricity to pass while keeping the electrolytic fluid inside. For this reason, a conductive plastic made by embedding carbon (which is electrically conductive) into plastic (which is fluid impermeable) is used.
- (4) Frame: In consideration of resistance to acid and cost, hard vinyl chloride is used.

Other battery cell stack requirements, besides lowered internal resistance, include the following:

- ① Pressure loss during pumping of the electrolyte should be minimal.
- ② Shunt current loss, which is self-discharge loss through the electrolyte supply pipe, should be minimal.

Keeping pressure loss during electrolyte pumping to a minimum helps raise system efficiency by reducing pumping power. Furthermore, although shunt current loss can be reduced using a narrower fluid route to raise electric resistance, this also increases pressure loss during fluid pumping and thereby increases the required pump power. Thus, it is important to achieve a design that minimizes the sum of pump power and shunt current loss.

6. Development of a 450-kW System

Charge/discharge testing of the 450-kW system, which is the basic unit for transformer substations, has been under way since December 1996, as part of the working system of Kansai Electric Power Co., Ltd. where its development and verification testing are described.

6-1 Development of a 20-kW Cell Stack

To verify the long-term stability of redox flow batteries, a long-term charge/discharge test of the battery cell stack, which is the smallest unit of the system, was implemented.

The cell stacks used in this testing contained a stack of 60 cells each with an electrode surface area of 5,000 cm². It produced a direct current output of approximately 20 kW (average voltage 80 V, electric cur-

rent 250 A). The specifications are shown in **Table 1**.

Using this battery cell stack, the charge/discharge test was implemented over a period of approximately two years. During this time, a shorted charge/discharge cycle time of approximately 30 minutes was used to assess the cycle life span on an accelerated basis. The results, summarized in **Fig. 3**, verified a consistently stable performance. Operational testing was continued for 12,000 charge/discharge cycles — far exceeding the development goal of 1,500 cycles.

6-2 Verification Testing of the 450-kW System

A 450-kW system was manufactured with 24 of the 20-kW battery cell stacks described above. The specifications are shown in **Table 2**, a block diagram in **Fig. 4**, and an exterior view in **Photo 1**.

The 450-kW system was constructed by serially connecting three battery modules in series, with each module comprising a 2 × 4 (serial × parallel) configuration of 20-kW cell stacks.

Electric equipment other than the batteries themselves consisted of an AC/DC converter, pump system, monitoring system, and protective relay system.

As an example of the test results, figures for the fixed current mode are shown in **Table 3**. These results

Table 1. 20-kW battery system specification

DC output	18.8 kW
Battery capacity	18.8 kW × 30 minutes (max.)
DC voltage	75.2 V
DC current	250 A
Area of electrode	5,000 cm ²
Cell stack	60 cells (series)
Electrolyte	Vanadium 1 mol/liter Sulfuric acid solution

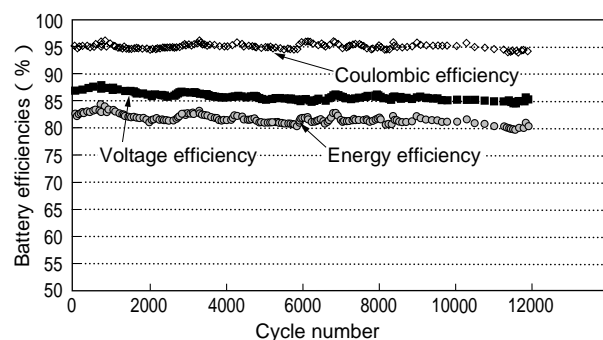


Fig. 3. 20-kW battery system cycle life test

Table 2. Result of 450-kW battery system Charge/Discharge test

Test items	Means of operation	Constant current
	Charge/Discharge current	1,000 A
	Coulombic efficiency	96.7%
Battery efficiency	Voltage efficiency	85.1%
	Energy efficiency	82.3%

show that the development goal of more than 70% was achieved for total energy efficiency, including the AC/DC converter and pump. (This was calculated on a trial basis assuming 95% efficiency for the AC/DC converter during charging and discharging.)

Changes in efficiency are shown in Fig. 5. Operation continues today, having achieved 530 cycles (as of September 1999), or approximately one third of the goal.

7. Towards Commercialization

7-1 Problems Facing Commercialization

The basic technology of the redox flow batteries was essentially validated in demonstration testing of the 450-kW system. To proceed toward commercialization, it is important to verify long-term reliability of the system,

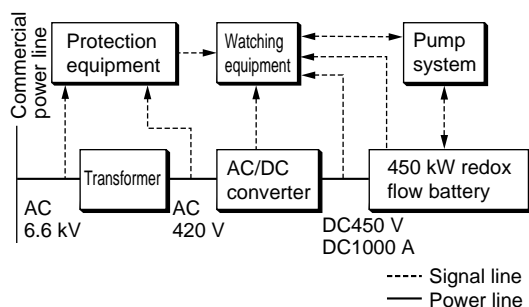


Fig. 4. 450-kW system concerned figure



Photo 1. 450-kW battery system in operation

Table 3. 450-kW battery system specification

DC output	450 kW
Battery capacity	900 kWh (450 kW × 2 hours)
DC voltage	450 V (av.)
DC current	1,000 A (av.)
Cell module	1 module: Cell stack 4P × 2S Series of 3 modules
Electrolyte	Vanadium 1 mol/liter Sulfuric acid solution
AC/DC converter	PWM control

reduce costs, and make the system more compact. Compactness is especially important for office buildings and similar locations because of restrictions on installation space. For these reasons, we are focusing on the following to improve the system:

- ① A reduction of manufacturing cost per kW by achieving high power output (high electric current density) in the battery
- ② Making the tank smaller by using a high-density electrolyte

To verify these technologies, the 20-kW system that uses high-concentration electrolytes, and the 50-kW system that uses high-power cell stacks were tested, and then the 50-kW system that uses both technologies for office building. The current status of this testing is described below.

7-2 Development of the 20-kW System with Underground Tank

In redox flow batteries, a large part of the battery's volume is occupied by electrolyte. As vanadium is used as the active substance in this electrolyte, increasing vanadium concentration in the electrolyte fluid is an important prerequisite for better compactness.

In the 450-kW system, vanadium ion concentration was one mole/liter. In subsequent development, the technology to dissolve vanadium to two moles/liter in a stable manner was developed and used to reduce tank capacity by half. Furthermore, because the redox flow batteries use a fluid as the active substance, they do not always provide a higher energy density than other batteries. However, the advantages of fluids were utilized to develop a rubber tank (Photo 2) with a flexible form and which effectively utilizes unused space in office buildings, such as underground cisterns.

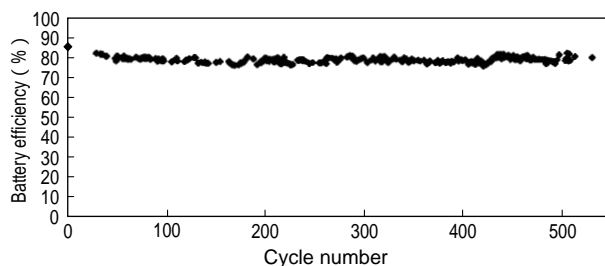


Fig. 5. 450-kW battery system cycle life test



Photo 2. Rubber tank

This rubber tank can be easily folded for insertion through the manholes of underground cisterns, and is durable enough to be placed on the ground. Furthermore, it is made of materials developed to assure a long life even during exposure to the electrolyte.

In order to verify these technologies, a 20-kW system with an underground tank that simulates a cistern in order to simulate installation in an office building (see conceptual diagram in Fig. 6) was installed at our Osaka Works, and is in the process of testing and assessment. Configuration is shown in Fig. 7 and specifications in Table 4.

The rubber tank was easily folded and inserted through the manhole without any trouble. Furthermore, it was confirmed that there were no problems with airtightness or electrical insulation.

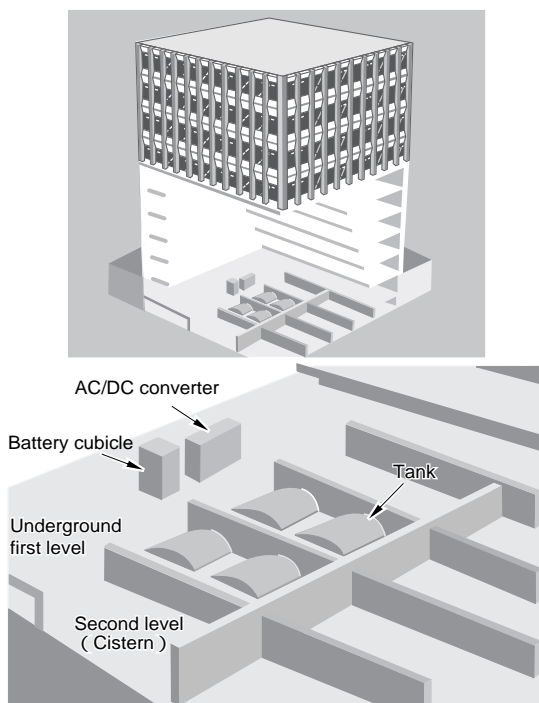


Fig. 6. Conceptual diagram of installation in an office building

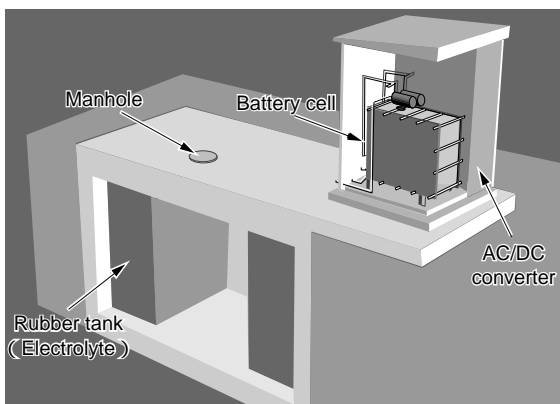


Fig. 7. Construction of 20-kW system with underground tank

7-3 Development of the High Power Output 50-kW System

In addition to high density technology, a high power output battery cell stack is also being developed. High power output in a battery cell stack requires reduction in internal resistance, and therefore we strove to reduce the internal resistance of materials such as the electrodes and membrane. For the electrodes, we examined different materials and densities, whereas for the membrane we examined film thickness and the ion-exchange group. Cell structure was also improved.

The electric current density and battery efficiency characteristics of the improved cell stack and the 20-kW cell stack that was used in the 450-kW system are shown in Fig. 8 (test data was achieved with a vanadium concentration of two moles/liter in both cases). The improved cell stack's reduced internal resistance made it possible to raise the electric current density from 50 mA/cm² to 80 mA/cm².

A high power output 50-kW system featuring the improvement cell stack was installed at the Osaka Works, and demonstration testing was begun in February 1999.

Specifications of the 50-kW system produced are shown in Table 4, and the exterior is shown in Photo 3.

The 50-kW system achieved an initial energy efficiency of 80% in 400-A constant current discharge. At present, a total of 108 cycles (as of September 1999) have been achieved, and operations have continued smoothly.

Table 4. Various battery system specifications

	20 kW (underground type)	50 kW (high power output type)	50 kW (office building type)
DC output	20 kW	50 kW	50 kW
Battery capacity	160 kWh (20 kW × 8 hours)	400 kWh (50 kW × 8 hours)	175 kWh (50 kW × 3.5 hours)
DC voltage (av.)	80 V	115 V	115 V
DC current (av.)	250 A	435 A	435 A
Cell stack	60 cells (series)	90 cells (series)	90 cells (series)
Electrolyte	Vanadium 2 moles/liter Sulfuric acid solution		
Electrolyte tank	Underground rubber tank (4 m ³ × 2)	Underground rubber tank (10 m ³ × 2)	Underground rubber tank (5 m ³ × 2)

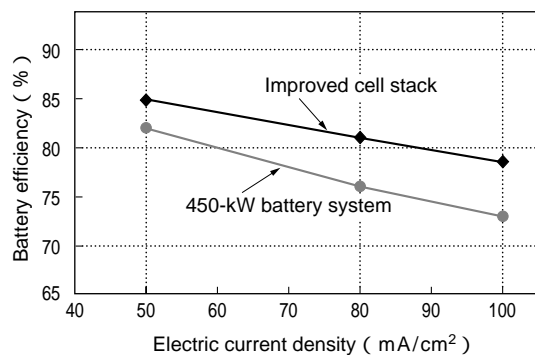


Fig. 8. Electric current density and battery efficiency characteristics

7-4 Development of a 50-kW System for Office Buildings

The improved cell stack and rubber tank were combined and installed at the Kansai Electric Power's Tatsumi Substation as a 50-kW model system for office buildings, and demonstration testing was implemented.

Also, for this system, the rubber tank was installed underground, in a small space simulating an office building's underground cistern, with battery cell stacks placed over the tank.

An exterior photograph is shown in **Photo 4** and specifications in **Table 4**.

Current plans are to use this system in the verification of long term reliability, in load pattern testing, in charging pattern optimization testing, and other forms of system assessment that simulate installation in an actual office building. We plan to reflect the data that are obtained in the designs of future office building systems.



Photo 3. High power output 50-kW system



Photo 4. 50-kW system for office buildings

8. Conclusion

With the verification testing of a 450-kW system that is regarded as the basic unit of a system for substations, the basic performance of redox flow batteries was essentially validated. With this technology, progress was made in achieving a high density electrolyte and a battery cell stack with a high power output, among other improvements. Furthermore, in response to the need for small capacity systems, such as buildings with low load factors, new technologies were examined with the goal of applying redox flow batteries to office buildings, culminating in the successful development of flexible rubber tanks capable of being installed in underground cisterns and other unused space in office buildings.

The performance of this new technology was confirmed through demonstration testing with a working system, and the redox flow batteries were demonstrated to have sufficient applicability in office buildings.

Current plans call for redox flow batteries to be installed in the underground of an actual office building in order to establish commercialization technology. Prototype 100-kW system was installed in an office building in Osaka city, and demonstration testing was begun in February 2000.

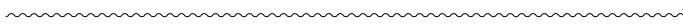
Technology development that focuses on lowering costs and verifying reliability will be continued to achieve commercialization soon.

References

- (1) N. Tokuda et al.: "Development of a Redox Flow Battery System", SEI Technical Review, No. 151 (1997).
- (2) N. Tokuda et al.: "Energy Storage Battery (Redox Flow Battery)", The Journal of the Institute of Electrical Installation Engineers of Japan, Vol. 19 (1999).
- (3) N. Tokuda et al.: "Development of a Redox Flow Battery System", Japan Society of Energy and Resources, The conference of energy system and economy and environment, 15th 6-5 (1998).



Photo 5. 100-kW system installed in an office building



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