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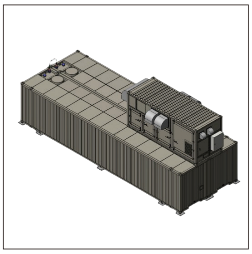

Performance Improvements and Latest Design of Vanadium Redox Flow Batteries

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Due to measures against global warming and the expansion of renewable energy introduction, the demand for energy storage systems to contribute to power system stability with a long lifespan has increased. This paper reports on the latest developments and designs aiming to improve the performance of vanadium redox flow batteries, which are gaining attention as effective energy storage technologies for stabilizing power quality. In particular, this paper focuses on enhancing cell stack output and increasing energy density to achieve energy storage systems that can meet diverse operational requirements. Additionally, this paper discusses the development of technologies to ensure high reliability for long-term operation over a 30-year period and contribute to reducing lifecycle costs. The outcomes of this development are intended to contribute to the efficient storage and long-term stable operation of renewable energy.

Keywords: vanadium redox flow battery, storage battery, Long-Duration Energy Storage (LDES), circular economy, long lifespan

1. Introduction

Growing climate concerns have spurred worldwide expansion of solar and wind power. The large-scale integration of these variable sources into the grid can degrade power quality (voltage and frequency fluctuations) and create surplus electricity. To address such concerns, grid-connected energy storage systems are being deployed.(1)

Vanadium Redox Flow batteries (VRFBs) use aqueous vanadium-ion solutions as both active material and electrolyte. Charging and discharging occur only through ion-valence changes, avoiding degradation and ensuring safety and longevity. The cell stack and electrolyte tank can be independently designed for flexible, application-specific configurations.(2) Development began in 1985, with deliveries totaling 52 MW and 190 MWh by September 2025.

However, the aqueous electrolyte limits solubility of the active material, giving a lower energy density and larger system sizes relative to other storage batteries. To address this, we have pursued higher energy density by improving cell stack performance and optimizing system operation.

Furthermore, we are developing VRFBs to achieve even longer lifespans, aiming to reduce the Life Cycle Cost (LCC). Extending the lifespan of each component and improving maintenance engineering will enable long-term operation of the storage batteries, significantly contributing to LCC reduction.

This paper reports on the development status and latest designs for achieving higher output, higher energy density, and longer life of VRFBs.

2. VRFB Operating Principle and Features

A VRFB consists of a cell stack of electrochemical cells that carry out the battery reaction, positive and negative tanks that store the electrolyte, and pumps that circulate the electrolyte from the tanks to the cells, piping, and heat exchanger (Fig. 1). Our VRFB uses aqueous vanadium sulfate solution as the electrolyte for both the positive and negative electrodes, and charging/discharging occurs via the following reaction Eqs. (1) and (2).

$$\text{(Positive Electrode)}\ 2VOSO_4 + 2H_2O \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} (VO_2)_2SO_4 + H_2SO_4 + 2e^- + 2H^+ \cdots (1)$$

$$\text{(Negative Electrode)}\ V_2(SO_4)_3 + 2e^- + 2H^+ \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} 2VSO_4 + H_2SO_4 \cdots\cdots\cdots\cdots (2)$$

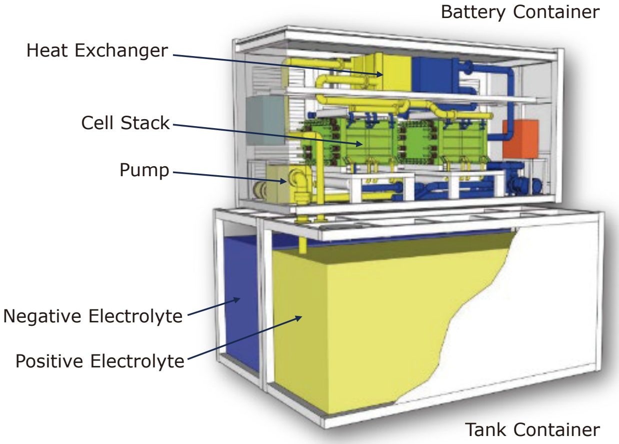

Fig. 1. VRFB configuration

During charging, when current flows through the battery, oxidation occurs at the positive electrode and reduction at the negative electrode, with protons (H^+) moving across the membrane. During discharge, the reverse reactions occur (Fig. 2).

The characteristics of VRFB include the following:

(1) High level of safety: The electrolyte in VRFBs is an aqueous, non-flammable solution. PVC piping and other cell-stack components are self-extinguishing, reducing fire risk. Under Japan's Fire Service Act, they

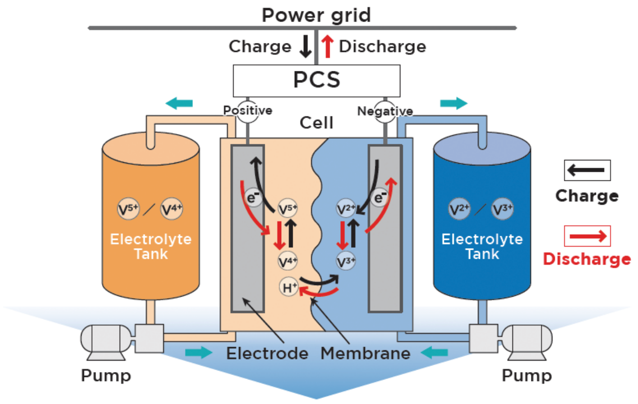

Fig. 2. Principle of VRFB

are not classified as hazardous materials. Therefore, licensed hazmat handlers are not required during installation or operation. Our VRFB cell stack is UL 1973 certified.

(2) Long Lifespan: The charge/discharge reaction involves only valence changes within the electrolyte, avoiding phase changes and minimizing degradation. Consequently, the electrolyte maintains performance over extended periods, with a feasible design life exceeding 20 years.

(3) Eco-Friendly: With no electrolyte degradation, the equipment can be reused after disposal. Furthermore, during removal, most components are reusable or recyclable, resulting in industrial waste generation of less than 1%. This means it excels in resource recyclability and contributes to building a sustainable society.(3)

(4) Life Cycle Cost Advantage: VRFBs allow independent design of the output section (cells) and the capacity section (tank). Increasing the electrolyte volume can extend lifespan, making them well suited for Long Duration Energy Storage (LDES)*1 applications. Their long lifespan and low degradation mean no need for large initial capacity boosts, cell-stack replacements, electrolyte exchanges, or expansions during operation, so the life-cycle cost advantage grows with longer operating years.

Other features include the ability to measure the State of Charge (SOC) in real time during charging and discharging by flowing electrolyte through dedicated cells with no current flowing, which can be measured from their open-circuit voltage. Furthermore, when the pump is stopped, the electrolyte in the tank is physically isolated from the cells, preventing the SOC of the tank electrolyte from decreasing due to self-discharge.

On the other hand, as mentioned above, its low energy density results in a larger system size, which is a weakness.

3. Development Goals for New VRFB Systems

To further expand the adoption of VRFBs, development is underway for a new VRFB system that offers higher performance and cost-effectiveness. The target values for this development are shown in Table 1.

Table 1. Target values for new VRFB system

Output	250 kW to 334 kW
Energy density	+15%
Operational period	20 years to 30 years
System efficiency	70% or more

While maintaining system efficiency,*2 including PCS conversion efficiency, to be 70% or higher, we aim to achieve an increase in cell stack output to 334 kW, a 15% improvement in energy density, and extension of operating life to 30 years.

The current model(4) features a configuration of 250 kW × 4 modules for a 1 MW system, whereas the new model employs a configuration of 334 kW × 3 modules (Fig. 3). This enables a 25% reduction in the equipment footprint while maintaining the same output.

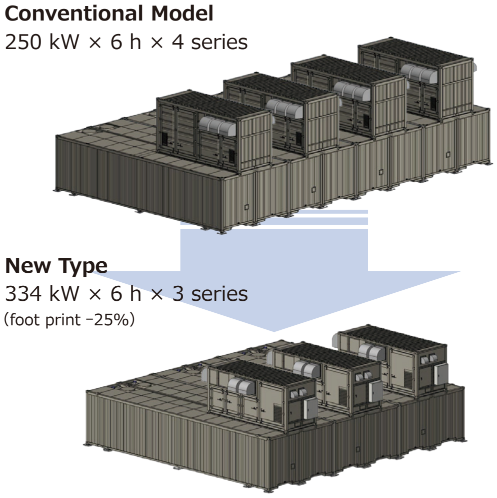

Fig. 3. Reduction in footprint for new VRFB system

Furthermore, the reduced number of modules also allows a corresponding reduction in the required equipment. This directly contributes to extending equipment lifespan and supports the circular economy.

However, achieving these goals requires addressing challenges such as reducing voltage loss associated with higher output, mitigating overcharge risks when improving electrolyte energy density, and enhancing the durability of the cell stack, a key system component.

4. Development of New VRFB Models

4-1 High-output cell stacks

The output (kW) of a cell stack is expressed as the product of voltage (V) and current (A). Therefore, achieving higher output requires both higher voltage and higher current.

But Joule losses increase proportionally to the square of the current density (A/cm^2) and the resistivity of the cell

(Ω·cm²), leading to reduced charge/discharge efficiency. To achieve high current density while minimizing efficiency loss, it is necessary to reduce cell resistivity.

The new cell stack employs highly conductive materials, reducing cell resistivity by 25%. Additionally, by increasing the number of cell layers by 10% and achieving higher voltages, a 34% increase in output power was achieved compared to conventional models (Fig. 4). Size was limited to a 5% increase in volume.

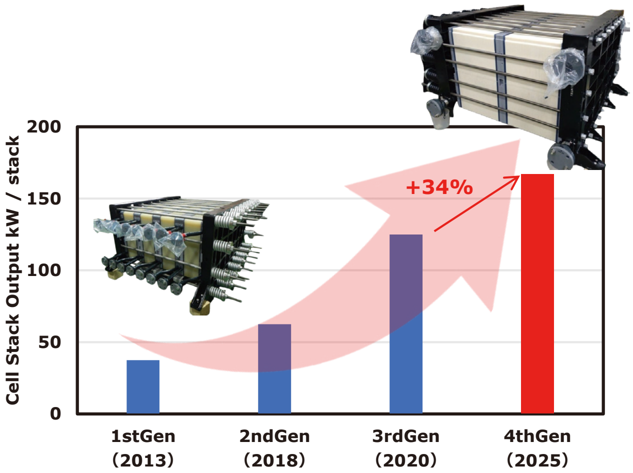

Fig. 4. High-power output of VRFB cell stack

4-2 Improvement in energy density

The energy density of the electrolyte (kWh/m³)*3 is determined by the theoretical energy density and the utilization rate of vanadium ions.

Theoretical energy density is determined solely by the concentration of vanadium ions in the electrolyte. Therefore, increasing the vanadium ion concentration could improve the theoretical energy density, but this is challenging due to solubility limitations. On the other hand, in conventional models, the vanadium ion utilization rate was around 60–75% due to the imbalance in vanadium ion concentration between the positive and negative electrolyte, as described later. As there remained scope for improvement in the utilization rate of vanadium ions, our development focused on enhancing this rate.

The electrochemical SOC*4 of a VRFB is expressed by Eqs. (3) and (4).

$$\text{Positive SOC} = \frac{[\mathrm{V(V)O_2}^{+}]}{[\mathrm{V(IV)O}^{2+}] + [\mathrm{V(V)O_2}^{+}]} \quad \cdots\cdots\cdots\cdots\cdots\cdots \ (3)$$

$$\text{Negative SOC} = \frac{[\mathrm{V(II)}^{2+}]}{[\mathrm{V(II)}^{2+}] + [\mathrm{V(III)}^{3+}]} \quad \cdots\cdots\cdots\cdots\cdots\cdots \ (4)$$

Therefore, under ideal conditions where the vanadium ion concentrations at the positive and negative electrolyte are equal, based on reaction Eqs. (1) and (2), the SOCs of the positive and negative electrolyte should be identical.

Here, the membrane, one of the cell components, prevents vanadium ion crossover within the cell. However, in practice, some vanadium ions migrate from the negative electrolyte to the positive electrolyte through the membrane during charging and discharging (Fig. 5). This causes an imbalance in the vanadium ion concentration between the positive and negative electrolyte.(5) Due to this imbalance, the SOC becomes lower at the positive electrolyte, where the vanadium ion concentration has increased compared to the ideal state, and higher at the negative electrolyte, where the vanadium ion concentration has decreased, resulting in an SOC imbalance (Fig. 6).

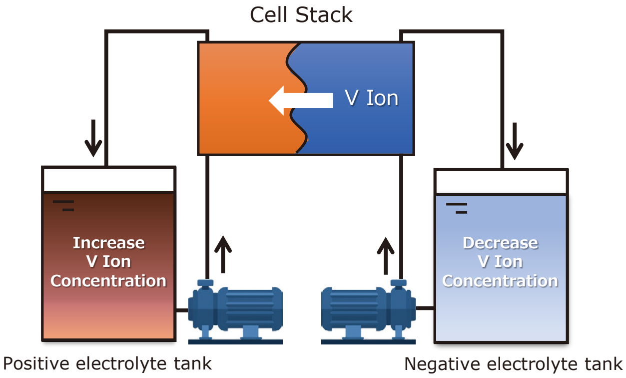

Fig. 5. Schematic of vanadium ion imbalance occurrence

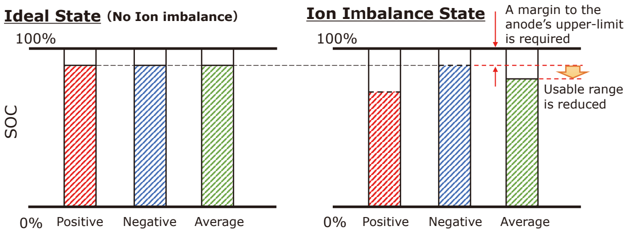

Fig. 6. Setting the SOC upper limit considering vanadium ion imbalance

To enhance the utilization rate of vanadium ions, we developed a membrane that reduces vanadium ion crossover and a control system capable of optimal control according to the SOC of both the positive and negative electrolytes.

Figure 7 shows the evaluation results for the newly developed membrane. While the conventional membrane exhibited a rapid decrease in negative electrolyte vanadium ion concentration during charge-discharge cycles, the developed membrane demonstrated an improvement in the rate of vanadium ion concentration decline, reducing it to approximately one-fifth. This indicates that the developed membrane reduces vanadium ion crossover to about one-fifth compared to the conventional membrane.

In the control system development, while only the average SOC of the positive and negative electrolyte could be measured previously, sensors capable of measuring the SOC of each electrolyte individually were introduced. This enabled the setting of appropriate upper limits for each electrolyte and implementation of control that charges only the positive or negative electrolyte to its set upper limit.(6)

The adoption of the newly developed membrane and control system has made it possible to raise the chargeable

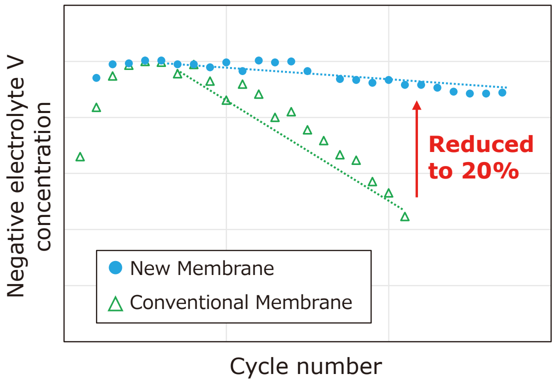

Fig. 7. Effect of suppressing vanadium ion concentration imbalance with the new membrane

SOC upper limit while preventing overcharging and improving the imbalance in vanadium ion concentration, as shown in Fig. 8.

Figure 9 shows the energy density of the conventional and improved VRFBs, calculated via simulation. It was confirmed that an improvement in energy density exceeding the target of 15% is achievable.

4-3 Addressing a 30-year operational period

Among the components constituting the VRFB, the cell stack in particular must withstand thermomechanical stresses due to electrochemical reactions and liquid pressure during operation, which is key to achieving a 30–year operational lifespan. Therefore, modifications were made to the cell stack, including changes to materials that have higher oxidation resistance and a revision of its structure. Subsequently, reliability tests were conducted to verify the validity of these design improvements.

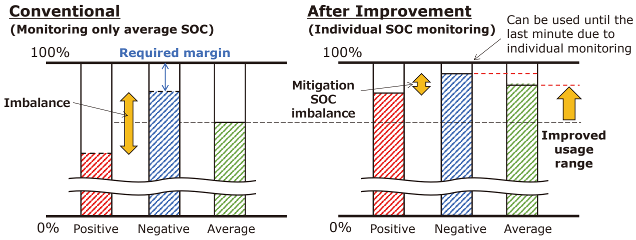

Fig. 8. Improvement in usable range through individual measurement of SOC for both electrodes

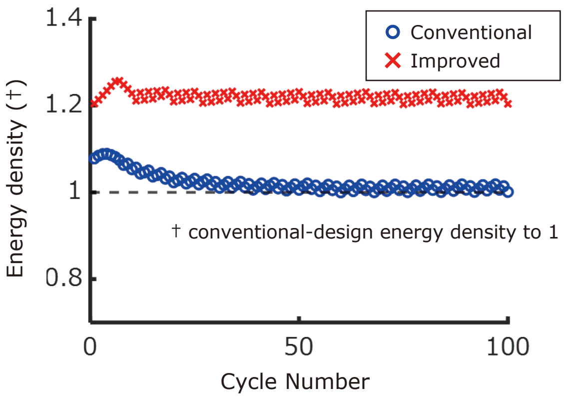

Fig. 9. Comparison of conventional and improved energy densities based on simulation

The cell stack reliability tests primarily consist of the following three test groups:(7)

1. Material life tests
2. Cell stack stress tests
3. System tests

This section describes the cell stack stress test, which most directly evaluates the long-term operational durability of the cell stack. This test simulates actual operating conditions under more severe conditions to evaluate performance changes under conditions that cause degradation or failure.

In addition to the stress tests, the cell stack safety tests (type tests)(8) of the cell stack specified in IEC 62932-2-2 Annex B were also conducted.

While the test items are diverse, Table 2 shows the major stress test items and conditions, and Table 3 shows the safety test items and conditions.

Table 2. Main cell stack stress tests conditions

Test name	Conditions
Heat cycle test	Test temperature: -30<->50°C Cycle number: 32
Pressure variation test	Test temperature: 50°C Test pressure: 70<->350 kPa Cycle number: 219,000
High temperature creep test	Test temperature: 50°C Test pressure: 480 kPa Test period: 240 days
Pump continuous operation shutdown test	Test temperature: 50°C Test pressure: 320 kPa Cycle number: 72,000
Low-temperature test	Ambient temperature: -20°C Test period: 3 days
Drop test	Drop impact: 15 G × 10 times

Table 3. Main cell stack safety test conditions

Test name	Conditions
Heat shock test	Test temperature: -10 <-> 50°C Test pressure: 320 kPa Temperature switching time: 1 hour Cycle number: 11
External short circuit test	SOC: 100% Ambient temperature: 20–25°C Resistance load: Up to 20 mΩ

As examples of test implementation, Photo 1 (a) shows a cell stack stored in a constant-temperature chamber at −20°C, and Photo 1 (b) shows the cell stack during a drop test from a height of 15 cm.

Before and after the stress tests, performance tests via charge-discharge cycles and pressure tests to confirm no leakage were conducted. This confirmed no performance changes before and after the stress tests, and the integrity of the cell stack was verified by disassembling it and finding no internal damage.

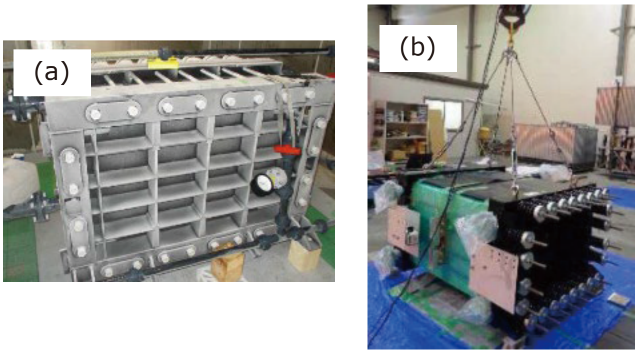

Photo 1. (a) Cell stack during low temperature test
(b) Cell stack during drop test

5. Demonstration of the New VRFB System

A prototype facility for the new VRFB system was installed at our in-house demonstration site (Photo 2), and field demonstration tests were conducted.

Photo 2. VRFB Prototype system

Figure 10 shows the results of cycle charge-discharge test conducted on this prototype equipment. The prototype equipment was confirmed to be capable of continuously discharging for over 6 hours at its rated output of AC 334 kW. This demonstrates that the target energy density of plus 15% has been achieved. System efficiency was also confirmed to be over 70%. Detailed results are shown in Table 4.

Additionally, the confirmed discharge time was able to maintain a duration of 6 hours even when accounting for degradation after 30 years of operation.

The prototype equipment is being operated continuously over the long term. We will continue to verify that performance degradation remains below expectations and that the reliability of all components, including the cell stack, can withstand a 30-year operational period.

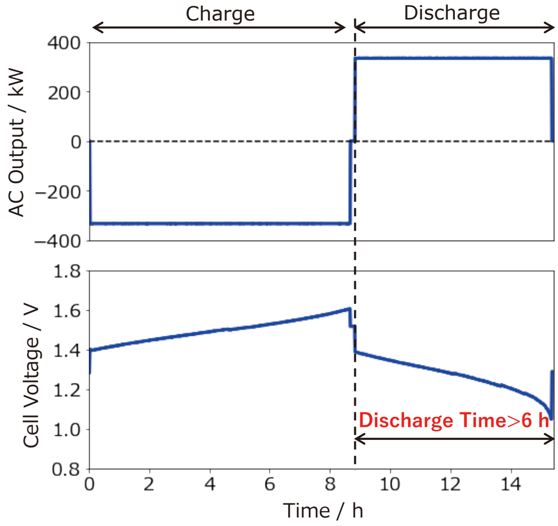

Fig. 10. Cycle charge/discharge test results on the VRFB prototype system

Table 4. Discharge time and system efficiency of the new VRFB system at the prototype facility

	Target value	Result
Discharge time	6 h or more	6 h 31 m 12 s
System efficiency	70% or more	70.7%

6. Conclusion

This paper reports on the development status and design of a new VRFB system focused on achieving higher output, higher energy density, and longer life.

In light of these technical achievements, the future outlook is to commercialize this new VRFB system as the V40 Series, with order acceptance scheduled to begin in January 2026. The first delivery project is expected to be completed by the end of 2026, contributing to the further expansion of renewable energy adoption and the maintenance of power grid quality.

Technical Terms

＊1 Long duration energy storage (LDES): A general term for systems that store energy for extended periods (typically 6 or 8 hours or more) and supply it as needed.

＊2 System efficiency: The ratio of the electrical energy input during charging to electrical energy that can be retrieved during discharge. This includes PCS conversion efficiency as well as losses due to auxiliary power equipment.

＊3 Theoretical energy density of electrolyte: The maximum amount of electrical energy that can be stored in 1 m3 of electrolyte under ideal conditions.

＊4 Electrochemical SOC: Electrochemical SOC is the theoretical state of charge based on the reaction rate of vanadium ions. However, for battery control purposes, it is expressed as the actual state of charge within the operational range, considering safety and lifespan.

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