Demonstration of Multiple-Use Applications with Redox Flow Battery

Riichi KITANO*, Toshio OOKA, Yoshiyuki NAGAOKA,
Kazuhiro FUJIKAWA, Toshikazu SHIBATA, and Takashi YANO

Sumitomo Electric Industries, Ltd. conducted a demonstration of its 2 MW/8 MWh redox flow (RF) battery system for multiple-use applications (MUA) in California, U.S.A. The system was operated within the distribution network to achieve peak shaving and voltage regulation. In the California Independent System Operator market, it simultaneously participated in the energy and ancillary service markets. In addition, the system successfully demonstrated microgrid operations for both black start and seamless transitions, providing MUA for normal and emergency operation to existing residential customers.

Keywords: energy storage, redox flow battery, multiple-use applications, wholesale market, microgrid

1. Introduction

In an effort to reduce greenhouse gas emissions, the introduction of renewable energy is expanding around the world. The state of California, U.S.A. passed state law SB 100[(1)] in September 2018 to promote the introduction of renewable energy. This law mandates that the whole in-state electricity demand must be fulfilled by 100% carbon-free energy sources by 2045.

The ability to adjust supply and demand is indispensable for the mass adoption of renewable energy, and energy storage is attracting attention as a key player in ensuring this ability. In California, state law AB 2514[(2)] and other laws are moving to require major electric utility companies in the state to integrate energy storage systems, and the California Public Utilities Commission (CPUC) has approved a plan to add a total of 15 GW of energy storage and demand response (DR) by 2032.[(3)] In addition, the California Energy Storage Alliance (CESA) has released a study showing that storing 45 to 55 GW of energy will be needed by 2045 to meet the requirements of SB 100.[(4)]

In California, institutional designs have been carried out to maximize the value of energy storage. One of these designs is multiple-use applications (MUA) that combine two or more uses. The CPUC, in its January 2018 decision, provided guidelines to electric utility companies on how to create sufficient economic value through multiple benefits and services that energy storage can provide.[(5)] In this decision, the services provided by energy storage are classified into "Reliability Services" and "Non-Reliability Services" for each of the five domains to which energy storage is connected (Table 1).

In addition, the CPUC has drawn up rules to manage the multi-use applications that combine these services. According to the rules, energy storage can provide services to either the domain to which it is connected or to one of its higher-level domains. For example, energy storage connected to a distribution network can provide services not only to the distribution network itself but also to the upper-ranked wholesale market.*1 The above rules give priority to Reliability Services over Non-Reliability Services, and prohibit competition between Reliability Services (prohibition of multiple service contracts in which

Table 1. Services provided by multiple-use applications of energy storage[(5)]
(CPUC Decision 18-01-003 in Rulemaking 15-03-011)

Domain	Reliability Services	Non-Reliability Services
Customer	None	TOU† bill management; Demand charge management; Increased self-consumption of on-site generation; Back-up power; Supporting customer participation in DR programs
Distribution	Distribution capacity deferral; Reliability (back-tie) services; Voltage support; Resiliency/microgrid/islanding	None
Transmission	Transmission deferral; Inertia*; Primary frequency response*; Voltage support*; Black start	None
Wholesale Market	Frequency regulation; Spinning reserves; Non-spinning reserves; Flexible ramping product	Energy
Resource Adequacy	Local capacity; Flexible capacity; System capacity	None

*Voltage support, inertia, and primary frequency response have traditionally been obtained as inherent characteristics of conventional generators, and are not today procured as distinct services. We include them here as placeholders for services that could be defined and procured in the future by the CAISO.

†TOU: Time of use

the fulfillment of one obligation prevents the fulfillment of other obligations).

Against the above background, Sumitomo Electric Industries, Ltd. installed an 8 MWh (= 2 MW × 4 h) redox flow (RF) battery system in California in order to demonstrate the multi-use applications of this battery system by participating in the distribution network and wholesale market under the state's regulations. This demonstration project was carried out with the support of the New Energy and Industrial Technology Development Organization (NEDO) and the California Governor's Office of Business and Economic Development (GO-Biz), and in cooperation with a major electric utility company in the state. This paper reports examples of multiple-use applications of the RF battery system.

2. Principles and Features of RF Batteries

An RF battery includes cell stacks (stacked electrolyte distribution cells) that perform battery reactions, positive and negative tanks that store an electrolyte, pumps that circulate the electrolyte from the tanks to the cells, pipes, and heat exchangers (Figs. 1 and 2). Sumitomo Electric's RF batteries use as the electrolyte the aqueous solution of vanadium sulfate (V) for both the positive and negative electrodes, and charge and discharge electricity according to the following reaction formulas.

(Positive electrode)

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

(Negative electrode)

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

Since the reactions associated with charge and discharge are only the changes in the valence of V-ion in the electrolyte and are not accompanied by phase change as shown in Fig. 1, the electrolyte does not degrade in principle and can be used semi-permanently, achieving a design life of 20 years or more. The electrolyte can be reused even after the battery is disposed of, contributing to cost and environmental impact reductions over a long period of time.

The reaction speed of RF batteries is extremely high because the battery reaction is only associated with the transfer of electrons to and from V-ions and is not accompanied by a phase change.

Since the electrolyte is non-flammable, there is no risk of fire even if the positive and negative electrodes are short-circuited in the cell or if the electrolytes from charged positive and negative electrodes are mixed. The components are also made of flame-retardant materials, minimizing the risk of ignition and maximizing safety.

Other features include: (1) The output section (cell) and capacity section (tank) are independent, allowing a high degree of design freedom; (2) By distributing the electrolyte to a special-purpose single cell that does not contribute to charge or discharge, the state of charge (SOC) can be measured on a real time basis from the open circuit voltage even during charge or discharge; and (3) When the pumps are stopped, the electrolytes in the tanks are physically separated from the cells and prevent the SOC of the electrolytes in the tanks from decreasing due to self-discharge.[6]

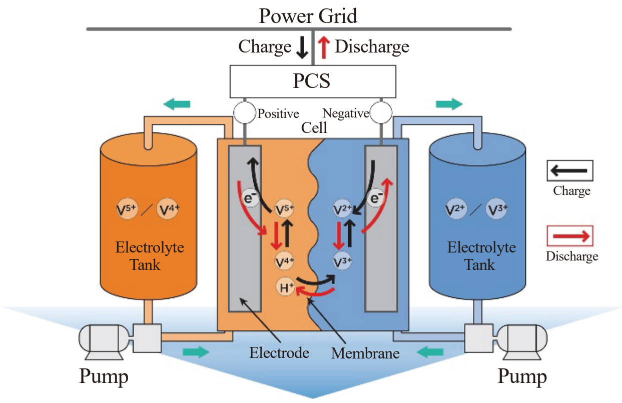


Fig. 1. Principle of RF batteries

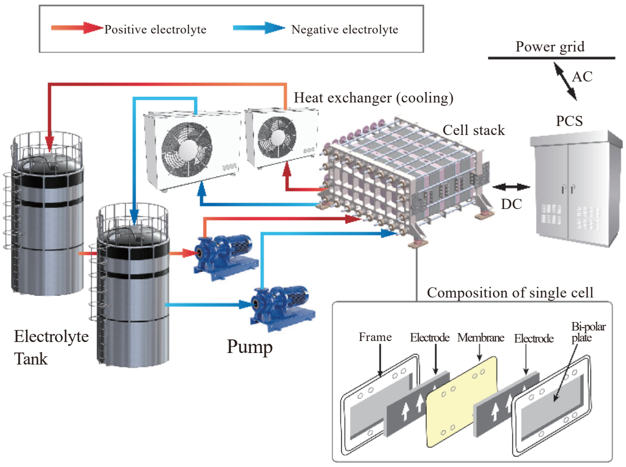
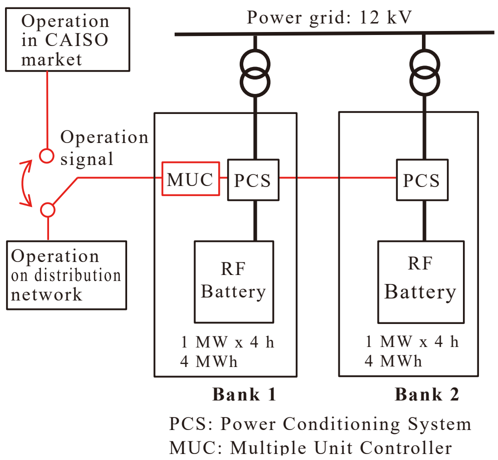


Fig. 2. System configuration of RF batteries

3. Examples of the Demonstration of an RF Battery for Multiple-Use Applications

The RF battery system used for the demonstration described in this paper was installed in 2017 in a key substation of the electric utility company in California with the cooperation of the company. The architecture and specifications of the RF battery system are shown in Fig. 3. As a result of discussions with the electric utility company in line with the CPUC guidelines described above, the battery system was connected to the distribution network for the demonstration of (1) multiple-use applications in the distribution network, (2) multiple-use applications in the wholesale market, and (3) multiple-use applications in the wholesale market and distribution network.



Output/capacity	Rated output: 2 MW, Rated capacity: 8 MWh
Appearance	

Fig. 3. Architecture and specifications of the RF battery system

3-1 Multiple-use applications in distribution network[7]

The RF battery system used for the demonstration had a variety of distribution network support functions, including frequency regulation using active power, peak-shaving/base-loading operation,*2 energy-shifting operation,*3 and voltage regulation using reactive power. The battery system enables multiple-use applications that combine these functions, in addition to the control mode that uses them independently.

The distribution network to which this RF battery system was connected had problems such as load and voltage fluctuations due to solar power output fluctuations, but the system contributed to the stabilization of the distribution network through the multiple-use applications of the above functions.

As an example, the multiple-use application of peak-shaving/base-loading operation (active power) and voltage regulation (reactive power) is discussed. These two functions correspond to distribution capacity deferral and voltage support, respectively, in the distribution network shown in Table 1. Although both are reliability services, they do not conflict since active and reactive power regulation can operate independently. Figure 4 shows an example of regulating the active power output from the RF battery system so that fluctuations in the output combined with that of the distribution network load (sum of power consumption and solar power output) stay within a certain range, while regulating the reactive power output so that the grid voltage stays within a certain range. The RF battery system could suppress the fluctuation of the distribution network load and voltage fluctuation.

Next, an example of a multiple-use operation between energy shifting and voltage regulation is discussed. The RF battery system was operated to mitigate the duck-curve phenomenon (a demand curve having rapid demand fluctuations in the morning and evening) by deliberately discharging during the morning and evening hours when customers' electricity consumption is heavy, and charging during late night to early morning and during daytime hours. However, since the predetermined charge/discharge power is generally larger than that used for the said peak-shaving/ base-loading operation, it was expected that the voltage would fluctuate widely when the energy-shifting operation was performed, due to the capacity of the distribution network to which the RF battery system was connected and other causes. As a means of dispelling the above concern, we carried out a multiple-use operation (between distribution capacity deferral and voltage support)

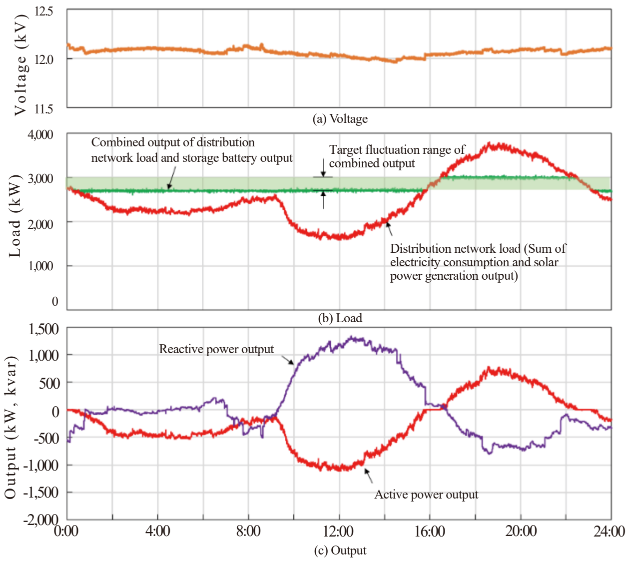


Fig. 4. Example of operation for peak shaving/base loading

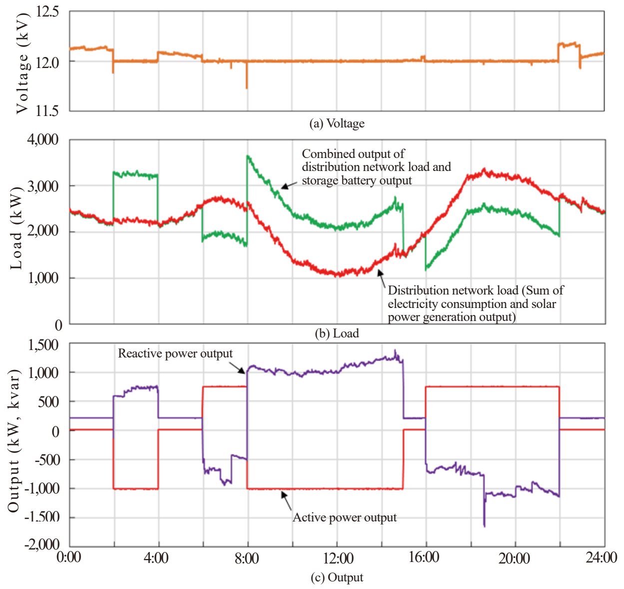


Fig. 5. Example of operation for peak-shifting

to adjust the voltage by supplying the excess apparent power of the power conditioning system (PCS) to the distribution network as reactive power. As shown in Fig. 5, we could achieve an energy-shifting operation by charging or discharging the electricity during the scheduled time period, and also keep the distribution line voltage within the allowable range by supplying reactive power.

3-2 Multiple-use applications in the wholesale market[(8)]

This RF battery system participated in California's wholesale energy market (CAISO*4 market) in December 2018. This service corresponds to the wholesale market shown in Table 1. This market includes an energy market and an ancillary services (AS)*5 market. The former supplies electricity, while the latter provides frequency regulation and so on.

An example of the RF battery system operation during one day in the energy market is shown in Fig. 6. In the two cycles per day (a short cycle at midnight and morning and a longer cycle during the daytime and nighttime), the SOC fluctuated widely between 0 and 100%. RF batteries are suitable for this operation since they are independent of the restrictions of the depth of discharge (DOD) or the number of cycles.

Figure 7 shows an example of the multiple-use operation of the RF battery system when it participated simultaneously in the energy market (non-reliability service) and AS market (frequency regulation). When the battery system received an output command, which was a short-period signal (period: four seconds) derived from the AS market trading result superimposed on a long-period signal derived from the energy market trading result, the output of the battery system followed the command signal with high accuracy. RF batteries are also suitable for simultaneous operation for both long-period (supply) and short-period (e.g., frequency regulation) applications since these batteries can continually repeat deep charge and discharge while following such short-period signals.

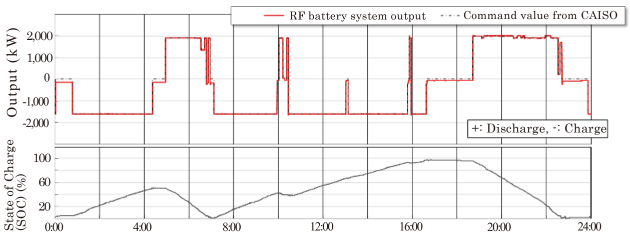


Fig. 6. Example of operation in CAISO market (energy market)

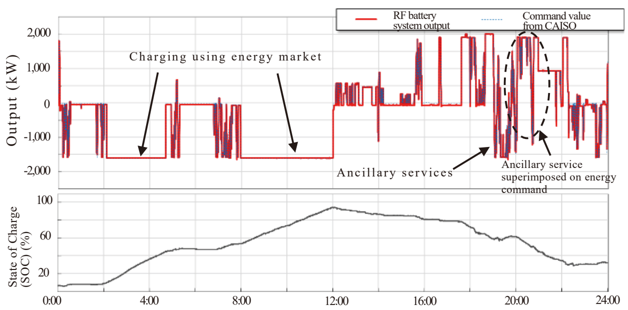


Fig. 7. Example of operation in CAISO market (energy and AS markets)

In the CAISO market operation, we continuously improved the bidding strategy to increase revenue. As a result, the following findings were obtained: (1) Since the AS market is more profitable than the energy market, the focus should be on generating revenue from the AS market, and (2) Charging while avoiding expensive electricity during evening peak hours is an effective way to increase revenue.

3-3 Multiple-use applications in the wholesale market and distribution network[(9)]

In California, Public Safety Power Shutoff (PSPS) was institutionalized (SB 901) in 2018 to help prevent wildfires and other disasters in the face of increasingly severe climate threats. On the other hand, there are growing expectations for microgrids*6 as a means of ensuring resilience – to keep supplying electricity to customers even during power outages.

Against this background, we demonstrated, with the cooperation of actual customers, the multiple-use applications of the RF battery system in a wholesale market and distribution network, while earning revenue by operating the battery system in the CAISO market during normal times and supplying power to the distribution network as a power source for the microgrid in times of emergency. This is an example where an RF battery system connected to the distribution network also serves a higher-level wholesale market shown in Table 1.

We carried out a demonstration of a microgrid by installing a re-closer at the demarcation point of a portion of the distribution network to which the RF battery system was connected (66 customers with a contracted capacity of 400 kW) (Fig. 8). For the transition from the interconnected state to the microgrid, we demonstrated two methods (black start and seamless transition).

In the black start configuration (Figs. 9 and 10), the electricity supplied to the subject customers was turned off. Then the battery system was connected to the distribution network and the microgrid was started. Although an inrush current was detected at the time of connection, the PCS responded appropriately to this current and maintained the voltage and frequency after the connection within the specified ranges (voltage: 12 ± 0.6 kV, frequency: 60 ± 0.3 Hz).

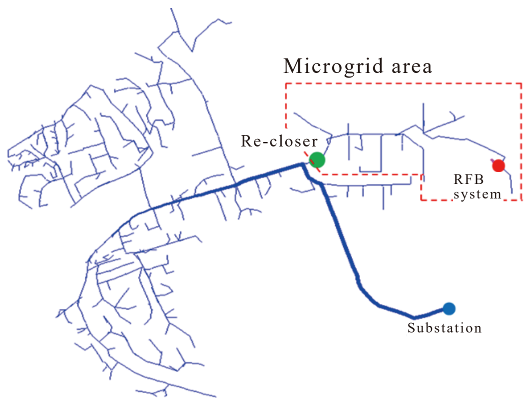


Fig. 8. Microgrid area

In the seamless transition (Figs. 11 and 12), uninterrupted transition to the microgrid was confirmed, and both voltage and frequency were maintained within the specified range during the microgrid operation. In Fig.12, the time when the RF battery output becomes negative (charge) was also confirmed. This is an example where the amount of

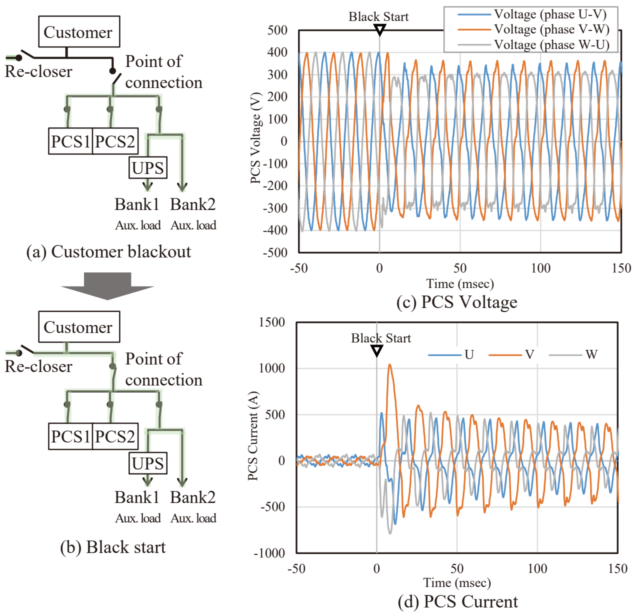


Fig. 9. Black start procedure and waveforms during start-up

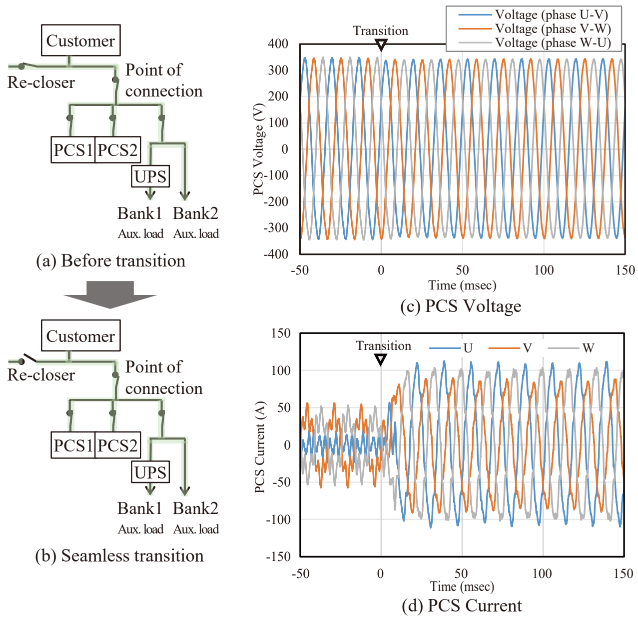


Fig. 11. Seamless transition procedure and waveforms during transition

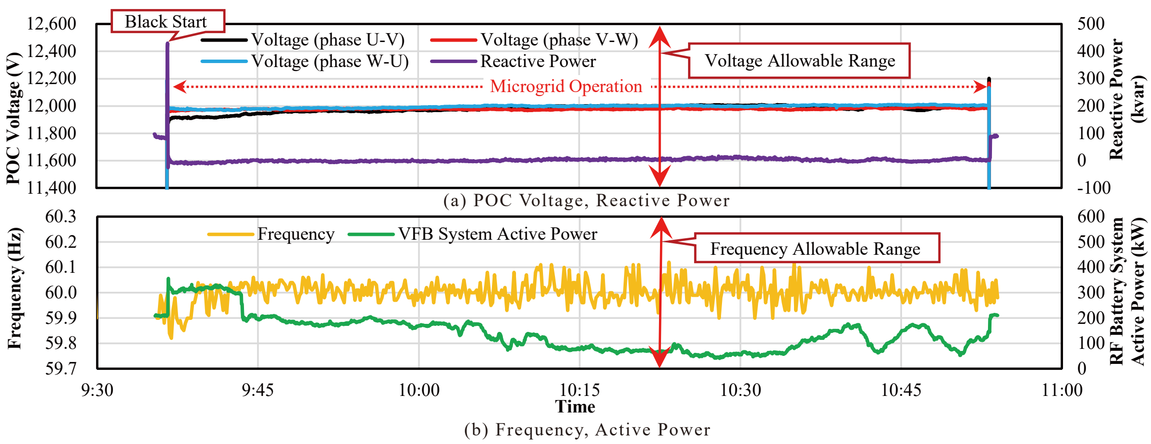


Fig. 10. Microgrid (black start) operation results

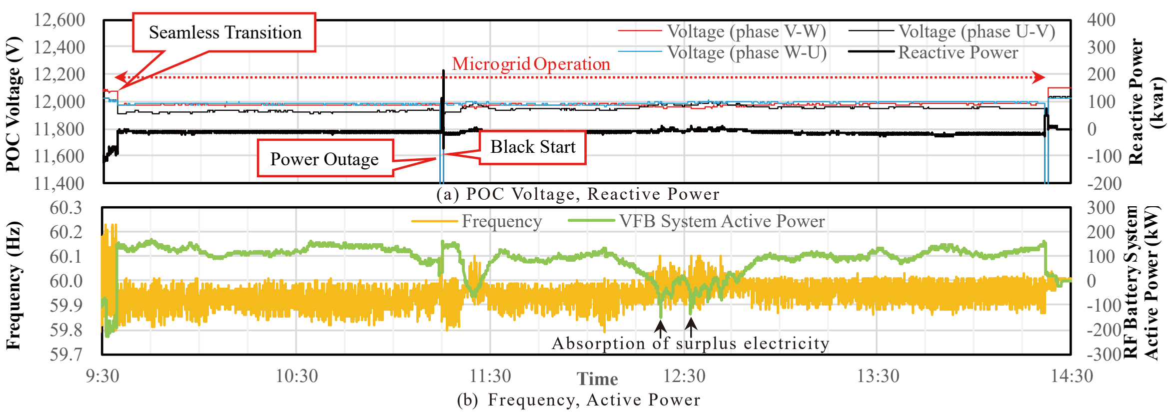


Fig. 12. Microgrid (seamless transition) operation results

solar power generation exceeded the electricity demand of the subject customers, and the surplus electricity generated was absorbed by the charge of the RF batteries. In the case of a microgrid using a generator as a voltage source, it is necessary to suppress the output of solar power generation when there is surplus power. In contrast, it was validated from the demonstration that using a storage battery as a voltage source is effective to use solar power output without wastage. During the microgrid operation, black starts were also conducted by temporarily stopping the electricity supply.

3-4 Evaluating the long-term performance of the RF battery system used for the demonstration

To evaluate the degradation level of the RF battery system after completion of its demonstration for multiple-use applications, the discharge capacity was measured during the demonstration period from 2017 to 2021. The results are shown in Fig. 13. Although the capacity decreased slightly with time, all measured values exceeded the rated capacity (4,000 kWh, 1,000 kW × 4 h), verifying that the battery system can maintain the rated capacity even after its design life of 20 years.

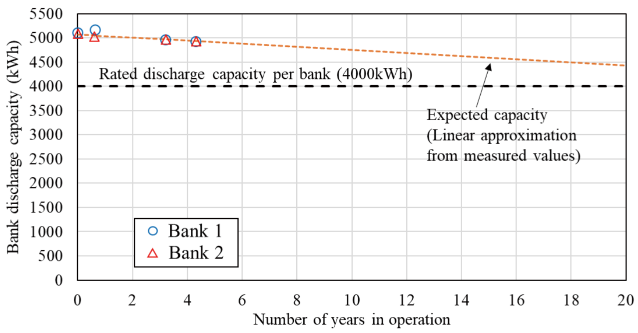


Fig. 13. Discharge capacity of RF battery system and estimated capacity after 20 years

In addition, the reliability of the RF battery system was evaluated with its availability ratio calculated from Eq. (3) (Fig. 14). The availability ratio of the system was determined to be 99% during two years (September 2019 – August 2021) of its participation in the CAISO market (energy market and AS market), validating that RF batteries can be stably used for multiple-use operations.

$$\text{Availability ratio (\%)} = \frac{\text{Time for evaluation - Planned outage time - Forced downtime}}{\text{Time for evaluation – Planned outage time}} \quad \cdots (3)$$

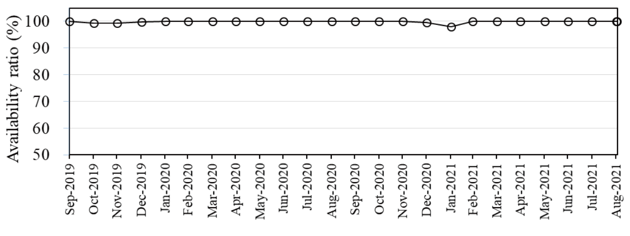


Fig. 14. Availability ratio of RF battery system

4. Conclusions

The authors have discussed in this paper a demonstration of an RF battery system for multiple-use applications in California, U.S.A., and verified that RF batteries are suitable for this type of applications due to their advantages of low operating constraints and low degradation rate. These batteries maintained the rated capacity and achieved an availability ratio of 99%, verifying their high performance over a long period of time. We will use the findings and expertise obtained from this demonstration to contribute to achieving greenhouse gas emission reduction targets in countries around the world.

The results of the demonstration discussed in this paper were obtained through the "Demonstration Project Testing Storage Battery Operation for Both Electricity Transmission and Distribution in California, USA" (JPNP93050), a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO). We would like to express our gratitude to all parties concerned.

Technical Terms

*1 Wholesale market: A place where businesses and retailers having resources (e.g., energy storage) participate in trading electricity. The objective of this market is to encourage free competition according to the market mechanism, thereby realizing low-cost, reliable, and clean power grids.

*2 Peak-shaving/base-loading operation: An operation for regulating distribution network load fluctuations so that they fall within a predetermined range. In particular, the upper and lower limits are set for the target distribution network load, and the load exceeding the upper limit is supplemented by discharging from the energy storage. When the load does not reach the lower limit, the surplus load is consumed to charge the energy storage.

*3 Energy-shifting operation: An operation for deliberately discharging the energy storage during the period of high customer load and charging the energy storage during the period of low customer load.

*4 CAISO: An abbreviation for California Independent System Operator, a non-for-profit corporation responsible for power grid stabilization, infrastructure planning, and market operation through the management of the transmission network.

*5 Ancillary services (AS): Frequency regulation and other functions that stabilize power quality by adjusting the instantaneous supply-demand balance.

*6 Microgrid: An operation for supplying electricity to outage/planned outage areas during emergencies such as disasters, and planned outages. To supply electricity, energy storage and other distributed power sources are used as stand-alone power sources.

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Contributors The lead author is indicated by an asterisk (*).

R. KITANO*
• Assistant Manager, Energy Systems Division

T. OOKA
• Senior Assistant Manager, Energy Systems Division

Y. NAGAOKA
• Group Manager, Energy Systems Division

K. FUJIKAWA
• Ph.D.
Group Manager, Energy Systems Division

T. SHIBATA
• Deputy General Manager, Energy Systems Division

T. YANO
• Sumitomo Electric U.S.A., Inc.