Technology for Estimating the Battery State and a Solution for the Efficient Operation of Battery Energy Storage Systems

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Expectations for a distributed energy system including renewable energy are increasing worldwide, and stationary battery energy storage systems are indispensable for securing peak-shifting of power demand and stable operation. For the efficient operation of these systems, it is crucial to identify battery conditions such as the state of charge and degradation and to make full use of battery pack capacity. This paper describes Yokogawa's solution for the efficient operation of battery energy storage systems. The technology for identifying the battery state is based on our original model of battery characteristics.

INTRODUCTION

From the viewpoint of stable power supply to the entire area and greenhouse gas reduction for global warming prevention, the need for distributed energy management incorporating peak shift control and renewable energy is increasing worldwide. Peak shift control charges a storage battery at night when the power demand is low and discharges the storage battery during peak hours when the power demand is high. This helps equalize power demand and enables reducing the energy cost by utilizing power when the energy cost is low. Furthermore, although renewable energy has the advantage of a low environmental load, it has the disadvantage that a storage battery is required to compensate for changes in the power output, because its power output dynamically changes depending on the weather conditions.

To keep up with such trends, the main focus of the energy business is shifting globally from conventional "power generation and transmission/distribution network infrastructure" to "operation and service from the viewpoint of users." The operation technology for a battery energy storage system is critical to provide efficient and stable operation and service to users.

In a business using storage batteries, it is important to understand the energy situation and policies, in addition to the battery technology trends and changes in energy prices. Recent rising oil prices and tightening greenhouse gas emissions regulations in each country are significantly expanding the electric vehicle (EV) market. Lithium-ion batteries with high energy density are mainly used in EVs. A rapid increase in their production volume lowered the cost to about half compared to three years ago. Furthermore, efforts to reuse the used lithium-ion batteries from EVs for battery energy storage systems have intensified.

Under these circumstances, we are partnering with a battery energy storage system manufacturer to carry out activities for the purpose of efficient operation of a battery energy storage system using lithium-ion batteries while sharing issues in order to help provide additional high value operation and service to energy users.

This paper first describes issues on efficient operation of a battery energy storage system shared with the partner, then describes our proposal for an efficient battery operation solution and our efforts to develop a battery state estimation technology, and finally describes the experimental verification results.

ISSUES ON OPERATION OF A BATTERY ENERGY STORAGE SYSTEM

A battery energy storage system uses a battery pack composed of many series and parallel connected cells. The voltage per cell is determined electrochemically depending on the electrode material used. Multiple cells are connected in series to ensure suitable voltage. Furthermore, the capacity per cell is about several tens of ampere-hours (Ah) mainly due to production technological constraints. Therefore, multiple cells are connected in parallel to ensure practical capacity. Accordingly, several thousand to several tens of thousands of cells are used in total in an MWh class battery energy storage system.

Overcharging and overdischarging a battery with a voltage larger or smaller than the nominal voltage not only significantly reduces the battery life but also causes an

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internal short-circuit and rupture. Therefore, conventional battery energy storage systems are operated by monitoring the voltage of each of the series connected cells to ensure that any cell does not deviate from the predefined voltage range. If there is even one cell that has reached the predefined voltage, the battery energy storage system does not discharge or charge anymore. If there is an imbalance in the state of charge between cells, the effective capacity of the battery pack decreases so that the charge/discharge capacity range narrows during operation, which decreases the operational efficiency.

Therefore, a battery pack needs a technology to accurately estimate the current state of charge of each of the series connected cells and a system to balance the state of charge by combining cell balancing techniques. A cell balancing technique corrects an imbalance of the state of charge between cells. There are two types of cell balancing technique. One is consuming electric charge stored in a cell that has a large amount of charge via a resistor (passive balancing). The other is transferring electric charge from a cell that has a larger amount of charge to another cell that has a smaller amount of charge (active balancing). These techniques enable the battery pack to maximize the effective capacity from which energy can be retrieved (Figure 1).

Furthermore, if cells in different states of degradation are connected in parallel, a difference arises in the current that flows to the cells due to a difference in internal resistance. As a result, a circulating current flows from a cell where charging is completed to other cells where charging is not completed. In addition to normal charging/discharging, such a local exchange of charge between parallel connected cells accelerates the degradation of cells and reduces the effective capacity of the battery pack.

For these reasons, it is desirable that a battery pack in a battery energy storage system in which many cells are connected in series and in parallel is composed of cells with less variation in the state of charge and degradation. However, a cell is a device using an electrochemical phenomenon. Therefore, variations in degradation are unavoidable even in a battery energy storage system composed of new cells, because the state of charge changes due to side reactions such as self-discharging, the effective active material decreases and the internal resistance increases. The variations in degradation are dependent on the operating conditions and temperature distribution inside the battery pack, so the imbalance of characteristics between cells gradually increases when it is used for a long period of time. As a result, a decrease in the effective capacity of the battery pack is unavoidable. Furthermore, when used cells are used, their characteristics differ depending on their usage history, so a decrease in the effective capacity of the battery pack from which energy can be retrieved is a real problem. The current solution is to give leeway to the capacity to make up for a predicted decrease in the effective capacity. Furthermore, the operation of a battery energy storage system is shut down periodically to perform maintenance for a long period of time to adjust the balance in the state of the battery and measure the effective capacity to improve the operational efficiency. Significantly deteriorated cells are replaced at the time of maintenance. However, giving a large leeway to the capacity increases the capital investment cost, including the installation space of the battery system, and spending considerable time on the maintenance causes loss due to downtime. Accordingly, important issues in actual battery energy storage systems are efficient operation that minimizes an increase in imbalance in the battery state and planned operation that accurately understands the current effective capacity.

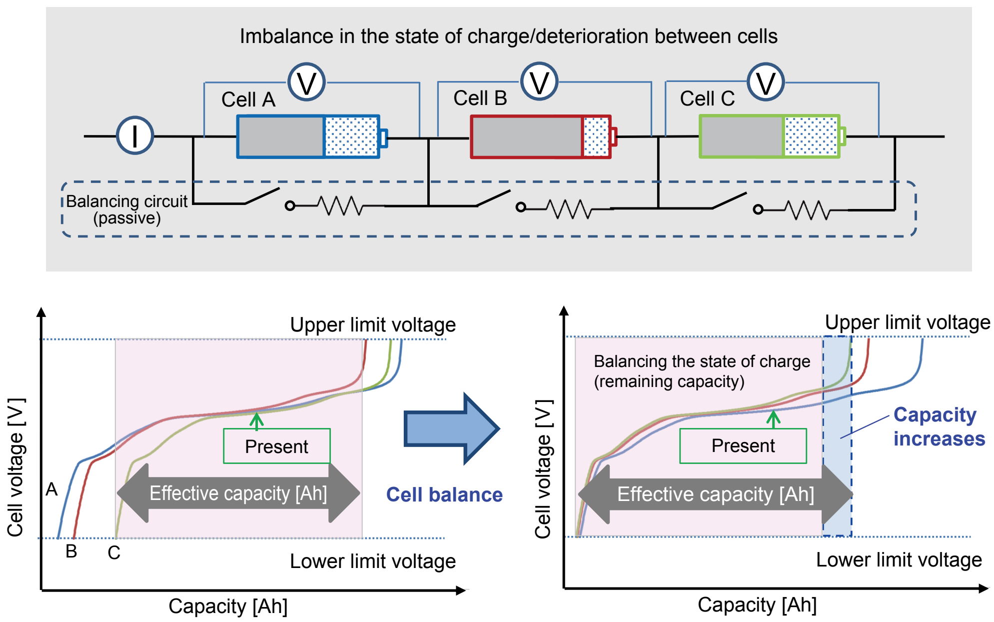


Figure 1 Cell balancing effect

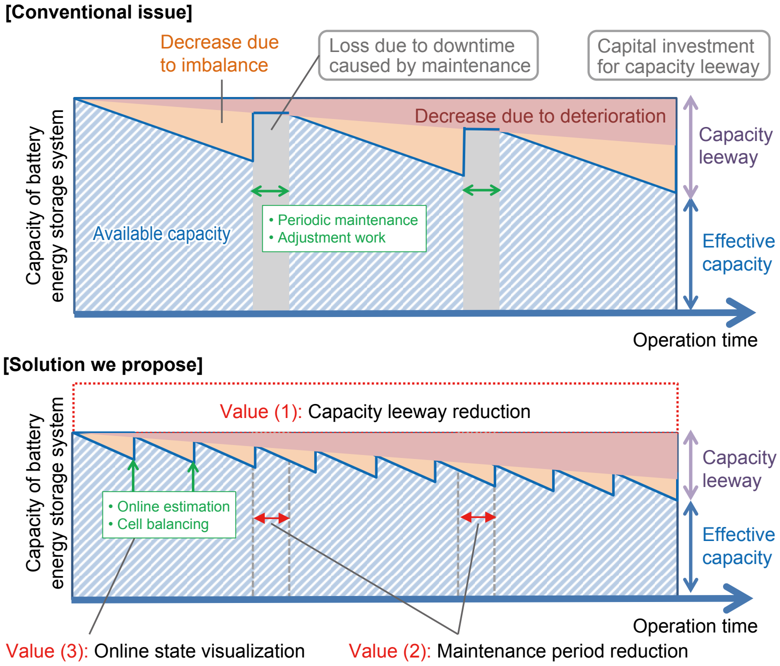


Figure 2 Providing value by online battery state estimation

SOLUTION FOR EFFICIENT OPERATION OF A BATTERY ENERGY STORAGE SYSTEM

To solve the issues described above, we are proposing a solution for efficient operation of a battery energy storage system based on an online battery state estimation technology. Decrease in the effective capacity caused by imbalance can be reduced by estimating the battery state online and balancing the state of charge by cell balancing. This technology creates additional value of a "decrease in capital investment" by reducing the capacity leeway and of a "reduction in loss due to downtime" by reducing the maintenance period (Figure 2).

To operate a battery energy storage system efficiently and as planned, it is very important to visualize the state of each of the series connected cells, in other words, the "remaining capacity" and "full charge capacity." Remaining capacity refers to the quantity of electricity that can be discharged and represents the current state of charge. The remaining capacity is used to determine the quantity of electric charge for balancing each of the cells and then balance the state of charge of all cells. Furthermore, full charge capacity refers to the capacity of electricity to fully charge a battery from a fully discharged state, in other words, the maximum capacity of electricity that can be stored in a battery. The full charge capacity decreases as a battery deteriorates.

The current effective capacity of a battery pack and the effect of an increase in the effective capacity when performing cell balancing can be estimated from the visualized information on the residual capacity and full charge capacity of each cell. This enables making an operational plan and maintenance plan such as determining when to replace the battery.

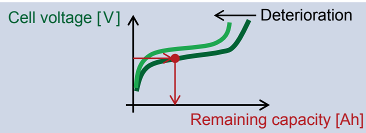
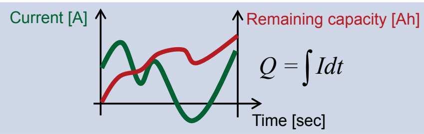
Remaining capacity estimation	Voltage measurement technique	Current integration technique
System outline		
Principle	Estimate from the measured voltage values using the relationship between the voltage and remaining capacity	Integrate the current (I) and control the remaining capacity (Q)
Issue	• Change in the relationship due to deterioration • Difficult with a cell with a small voltage gradient • Significant influence of IR change and noise	• Accumulation of measurement errors of the current sensor • Periodic reset to empty or full charge state • Reset is difficult in battery pack

Figure 3 Conventional remaining capacity estimation techniques and issues

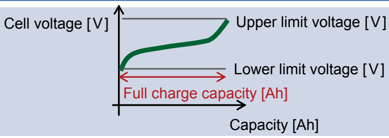
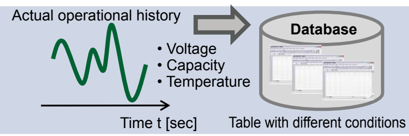
Full charge capacity estimation	Measurement by charging	Table look-up technique
System outline		
Principle	Measure by charging from the lower limit voltage to the upper limit voltage	Look up in a table that is based on actual operational history
Issue	• Full charging/discharging required • Measurement takes a few hours • Battery pack cannot be measured	• Database must be created • Preparation takes a lot of time and cost • Lot of memory resources are required

Figure 4 Conventional full charge capacity estimation techniques and issues

Conventional Battery State Estimation Techniques

There are two techniques for "remaining capacity estimation" for mobile PCs, etc. One is a technique to use the relationship between measured voltage and remaining capacity (voltage measurement technique) and the other is a technique to integrate the measured current (current integration technique) (Figure 3). These techniques are simple, but in the former technique the error becomes large when the relationship between the voltage and remaining capacity changes due to battery deterioration or when a change in the voltage is small when charging and recharging. Furthermore, in the latter technique, offset errors and linearity errors of the current sensor are gradually accumulated, so the integrated current value must be reset periodically by fully charging or discharging the battery. However, if the charge/discharge range is limited by imbalance between cells like a battery pack, the integrated current value cannot be reset so this technique cannot be used.

Meanwhile, there are two techniques for "full charge capacity estimation." One is a technique to charge an empty battery until it is fully charged. The other is a technique to create a database of characteristics measured under various conditions to enable looking up in a table that is based on the actual operational history information (table look-up technique) (Figure 4). However, in the former technique, the measurement takes a few hours and the charge/discharge range is limited for a battery pack, so the full charge capacity of each cell cannot be measured. Furthermore, in the latter technique, a database must be created beforehand, so the preparation takes a lot of time and is costly.

Thus, in a battery pack in which many cells are series connected, the charge/discharge capacity section becomes limited as the state between cells becomes imbalanced. Furthermore, the relationship between the voltage and residual capacity of each cell changes over time due to deterioration, so it is difficult to understand the battery state in an actual battery energy storage system.

Online State Estimation Algorithm by a Battery Characteristic Model

To solve the issues of the conventional techniques, we have developed an online state estimation algorithm based on an original battery characteristic model with a focus on the battery reaction principle [(1) (2)].

First, we describe the battery characteristic model. When a lithium-ion battery is charged or discharged, the crystal structure changes, because Li^+ ions move between the positive and negative electrode and Li^+ ions are inserted into the electrode active material (reduction) or separated from it (oxidization). This change of the crystal structure is called a "phase transition," which is a phenomenon that occurs near the electrochemically determined potential specific to an electrode active material. The "battery" characteristics are determined by a combination of this positive electrode characteristic and negative electrode characteristic. Based on this battery reaction principle, we have created a battery characteristic model with a focus on the characteristics of each of the positive and negative electrodes and the mutual relationship between the positive and negative electrodes.

Figure 5 shows an overview of the online state estimation algorithm. Suppose that input data is the voltage (V) and capacity (Q) when charged in a given section, which are converted to voltage differential characteristic (dQ(V)/dV) and capacity differential characteristic (dV(Q)/dQ). Next, determine whether data in the necessary range can be measured appropriately depending on the estimation target battery state ([1] remaining capacity and [2] full charge capacity) and determine whether the estimation can be performed. If it can, optimize the given variables of the model by performing a curve fit between the battery characteristic model and the measured data and output the estimated battery state.

Our algorithm has the following features.

■ Battery pack estimation available

The created battery characteristic model is based on the battery reaction principle and deterioration phenomena so it can accurately describe the battery characteristics. Therefore, even when the available charge/discharge section is limited like a battery pack in which there is imbalance between cells, highly accurate estimation (remaining capacity estimation error ±2% or less and full charge capacity estimation error ±5% or less) is implemented by performing a curve fit on the section in which the characteristic of state change is clearly observable.

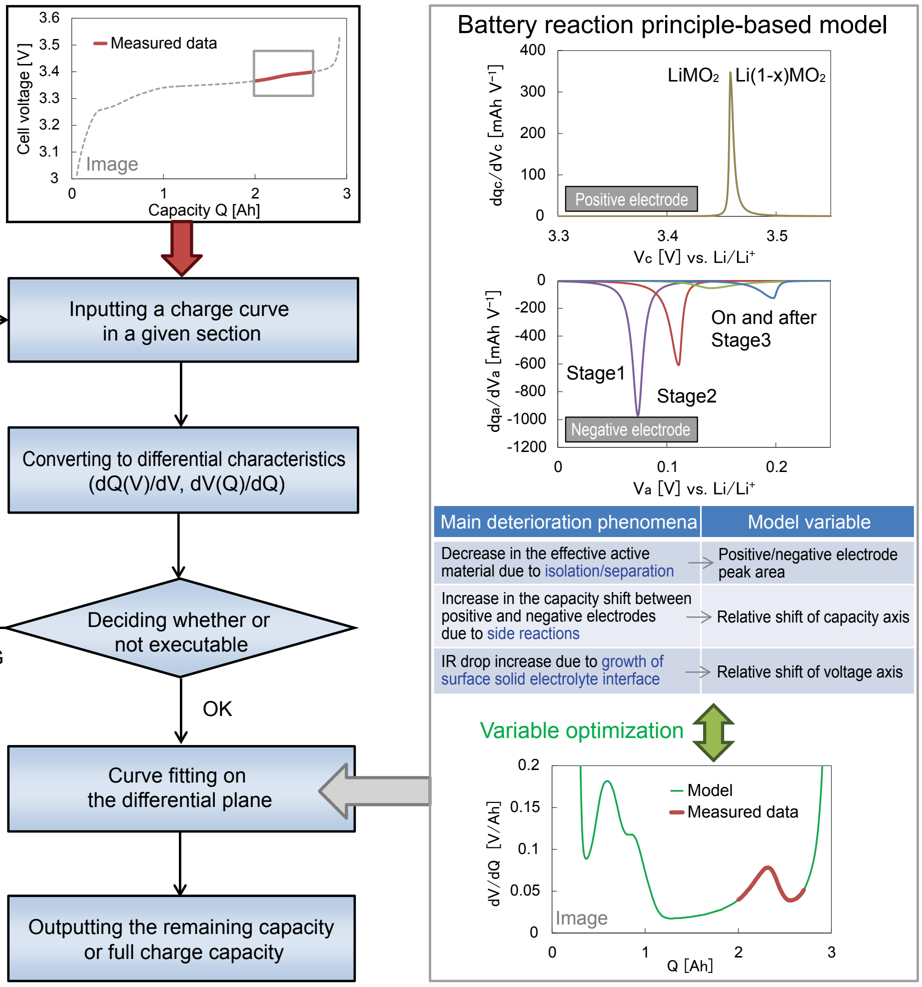


Figure 5 Overview of online state estimation algorithm

■ A cell with a small voltage change can be estimated

A lithium-ion cell has a characteristic that a voltage change is small when charged and discharged, so it is difficult to understand the state of change. Therefore, we focused on the differentiation of a charge curve, specifically the rate of change, and improved the sensitivity for the state of change by performing a curve fit on the differential planes (dQ(V)/dV and dV(Q)/dQ).

■ Low computational load

In general, differential equations are often used to describe physical phenomena, but the downside is that computational load is very large. However, we found out that the differential characteristic (dQ(V)/dV) for an electrode active material undergoing a phase transition can be approximated using several probability density functions. So we managed to simplify the model and reduce the computational load by describing the battery characteristics using probability density functions. This will enable us to implement computation using embedded equipment.

EXPERIMENTAL VERIFICATION

To visualize the battery state using the developed algorithm and verify the effect of the effective capacity improvement by cell balancing, we carried out an experiment using a measurement system that simulates the practical operation as shown in Figure 6. A battery pack module is composed of a few hundreds of series connected lithium iron phosphate-graphite cells. We charged the battery module at a constant current using a power conversion system (PCS). PCS has a variety of functions, such as a storage battery charge/discharge function, a DC-to-grid-AC and grid-AC-to-DC conversion function when charging/discharging the storage battery, and grid connection control such as voltage fluctuation suppression. We measured the voltage and temperature of each cell using a cell sensing unit (CSU) we developed and measured the charge current using a battery sensing controller (BSC) we developed. From these measured data, we estimated the remaining capacity and full charge capacity using a PC and visualized the state of each cell. Furthermore, we determined the quantity of electric charge to balance the state of charge using these results, performed a cell balancing operation using the passive method, and verified the effect.

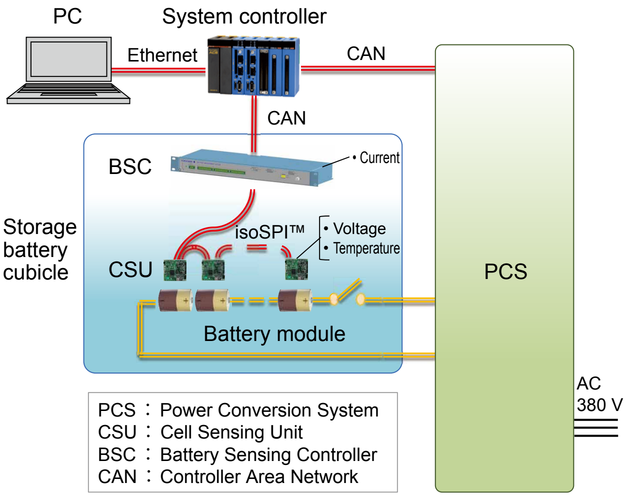


Figure 6 Measurement system

Figure 7 shows the state of cells before and after cell balancing. According to the estimation results before cell balancing, the remaining capacity and full charge capacity significantly differ between cells. Variations in the state of cells can be confirmed. However, cell balancing reduced the imbalance in the remaining capacity and improved the effective capacity of the battery energy storage system by 9%. The application of this algorithm is expected to expand the charge/discharge capacity range during operation, which will improve the operational efficiency.

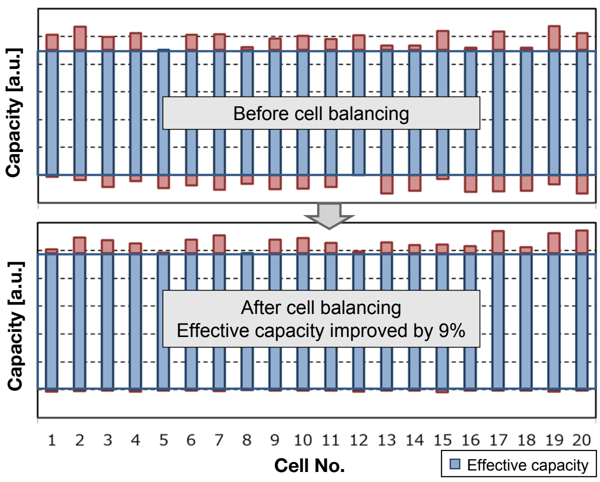


Figure 7 Cell state visualization and cell balancing effect

CONCLUSION

Energy systems are being transformed as distributed energy systems such as photovoltaic generation and battery energy storage systems are being widely used. As part of the activities of Yokogawa in the energy field, we are carrying out activities aimed at efficient operation of a battery energy storage system in cooperation with our partner company. This paper described the proposal on "capital investment reduction" and "downtime loss reduction" of battery energy storage systems with a focus on the online state estimation technology for lithium-ion batteries. We will further strengthen cooperation with the partner company to perform more detailed value verification.

REFERENCES

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