

Solutions for Manufacturing and Utilizing Lithium-ion Batteries

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In recent years, the development and diffusion of electric vehicles (EVs) has accelerated. California in the US, China, Europe and other countries have enacted regulations on gasoline vehicles to curb air pollution. Lithium-ion batteries are used as a clean power source for EVs, and contribute to the Sustainable Development Goals (SDGs). After serving as a power source of EVs, automotive lithium-ion batteries are expected to be reused as rechargeable batteries, thus helping to build a recycling-oriented society which Japan is aiming for. This paper introduces a solution for the production of lithium-ion batteries, for which it is considered to be difficult to provide high-performance specifications in terms of both manufacturing and utilization, and solutions to assist the reuse of rechargeable batteries.

INTRODUCTION

Environmental regulations for automobiles are becoming stricter. For example, the California Air Resources Board (CARB) issued the zero emission vehicles (ZEV) regulation, and an increasing number of other states in the U.S. have adopted regulations that are practically equivalent to the ZEV regulation. In China, passenger cars are subjected to the new energy vehicles (NEV) mandate policy. Companies with an annual production or import volume of at least 30,000 conventional cars must purchase credits according to the ratio of the NEV production volume to the production or import volume of gasoline vehicles, and the credit target will be raised year by year. These examples symbolize the trend of environmental regulations in the industrial world. Since

this trend is critically important, the automotive industry of Japan is rapidly changing direction toward electric vehicles (EVs). The trend is also closely related to the 17 sustainable development goals (SDGs) (United Nations Information Centre), especially to the five goals listed below.

- Goal 3: Good Health and Well-being
- Goal 7: Affordable and Clean Energy
- Goal 9: Industry, Innovation and Infrastructure
- Goal 12: Responsible Consumption and Production
- Goal 13: Climate Action

EVs are powered mainly by lithium-ion batteries because of their high energy density, and the production volume of lithium-ion batteries is rising sharply. Although EV manufacturers are claiming long driving distances, EVs still have the following technical issues. EVs are generally more expensive than gasoline vehicles, and so EV manufacturers strongly request lower battery costs. Laminated batteries enhance the freedom of EV design, but still need improvements in volumetric efficiency for more efficient use of space and in charging time. The popularization of charging infrastructure will depend on whether these technical issues are solved or not. As EVs become popular, the handling of used batteries also needs to be addressed. The recycling and reuse of batteries used for EVs must be considered in

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conjunction with developing social infrastructure. Especially, secondary use of lithium-ion batteries for battery energy storage systems is attracting attention.

Batteries are manufactured through long, elaborate processes. Reusing the batteries that have been returned from the market requires advanced technologies, which are still in the research stage. Figure 1 shows the concept of the life cycle of lithium-ion batteries from manufacture to reuse.

Yokogawa has assisted the growth and development of many industries by providing sensing, control, and information processing technologies and by helping customers solve problems in their manufacturing sites. To solve the issues of lithium-ion batteries described above, steady efforts are required in wide-ranging areas from development and manufacturing to application technologies. Yokogawa places great importance on evaluations in all processes of battery manufacturing, including solving problems in the upstream processes such as evaluating slurry kneading degree and coating precision. Coat weight measurement systems are used by many manufacturers for improving the coating precision. For details of coat weight measurement systems, see the paper, “WEBFREX3ES Dedicated Coat Weight Measurement System for Battery Electrode Sheets,” in this special issue.

This paper introduces the application of real-haptics technology to a quality control solution for physical properties that enables continuous manufacturing of products with stable performance and quality by acquiring data on physical properties during slurry agitation using a unique method.

The paper also introduces information technology for using the massive amounts of data acquired during manufacturing processes. When analyzing the data, development engineers often spend time searching for correlations among the collected data, which is not the primary role of engineers. The digital plant operation intelligence (DPI) system is a tool to quickly identify key performance indicators (KPIs) in the field, and can liberate engineers from such tasks. Various data on quality and equipment acquired during battery manufacturing must be effectively used and

centrally consolidated and stored to enable quick responses to feedback requests from the post-processes and the market. The traceability technology installed on Yokogawa’s manufacturing execution system (MES) is also introduced later.

Lithium-ion batteries are still useful for battery energy storage systems even after they have degraded and become inadequate for EVs, and their reuse is increasing in the field of battery energy storage systems. To achieve such systems with reused lithium-ion batteries, accurate identification of battery degradation state and appropriate handling based on the state are required. Accordingly, Yokogawa is developing an efficient operation solution for storage batteries, details of which are introduced later.

QUALITY CONTROL OF SLURRIES USING REAL-HAPTICS TECHNOLOGY

Problems in Slurry Coating

Battery electrodes are made by coating slurries on metal foils. Slurries are prepared by mixing and agitating powdery active materials, conductive auxiliary agent, and binder in organic solvents. The battery performance depends heavily on the coating qualities of the electrode slurry, such as thickness and uniformity. Slurry coating machines are designed to provide a uniform coating on metal foils at the prescribed slurry viscosity. Therefore, managing slurry viscosity is crucially important for maintaining coating quality. In the current slurry agitating process, the agitation state differs slightly due to differences in the raw materials, even though the machine keeps agitating at constant conditions. Therefore, slurry viscosity must be checked periodically by interrupting the agitator temporarily and sampling the slurry. It must be verified that the slurry viscosity is the prescribed value before moving on to the next process. Reliable operations by skilled operators and much time and effort are required for maintaining the coating quality. A technology to monitor slurry viscosity in situ, in an agitator during production, would improve slurry quality and productivity.

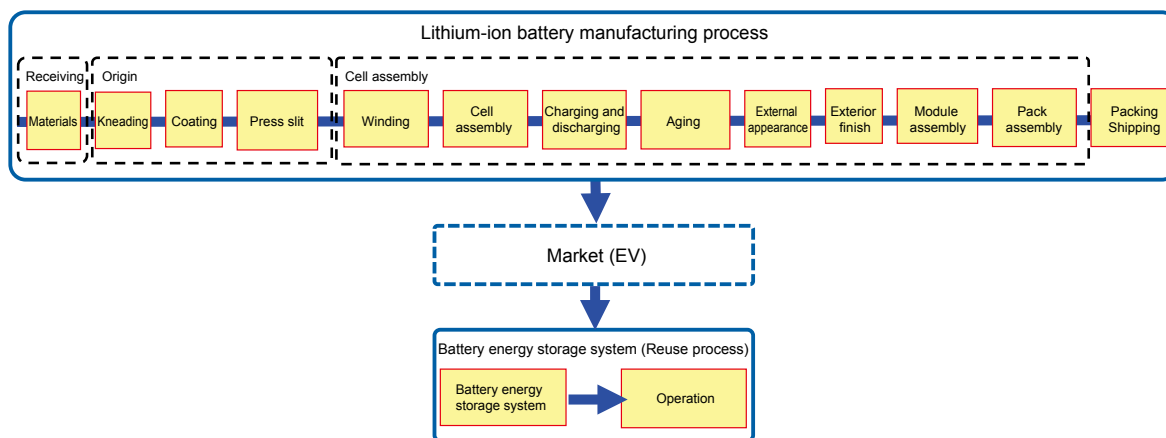


Figure 1 Life cycle of lithium-ion batteries

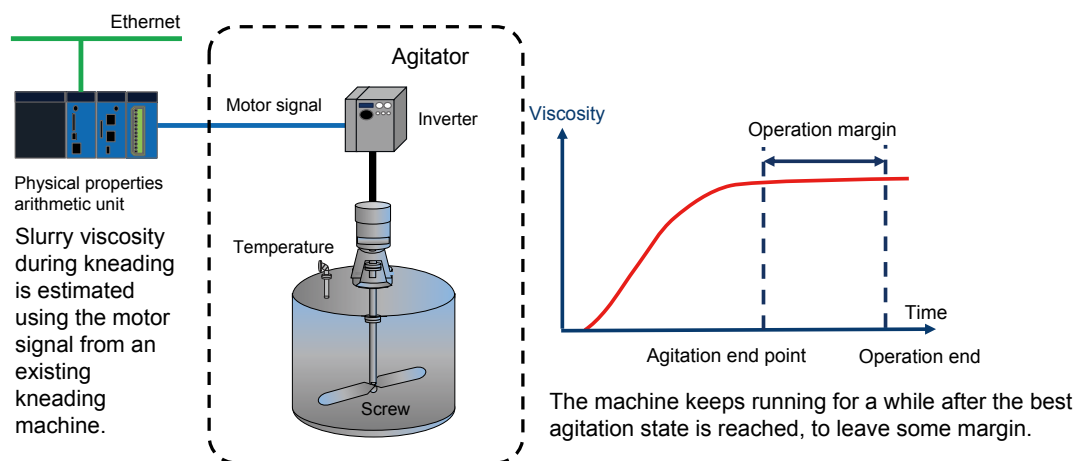


Figure 2 Diagram of agitator using real-haptics technology

Revolution in Kneading Process Using Real-haptics Technology

In collaboration with Keio University, Yokogawa has been working on the application of real-haptics technology to quantify the physical properties of products in production processes. Figure 2 shows the measurement of an agitator. By applying this technology to the stirrer motor of the agitator, viscosity values of the slurry under agitation can be measured in real time, enabling perfect monitoring of slurry stickiness in the production process. Automatic control of slurry viscosity enables quality control of battery electrodes.

Contribution to Stable Production

Yokogawa aims to establish a quality control solution for physical properties to help customers continue production of slurries with stable performance and quality, using the viscosity values obtained by real-haptics technology. This solution not only provides the measured physical property values, but also converts the measured values into indices that are necessary for actual operations. Then the solution controls the process to keep such control indices constant, and saves the values of various control indices during production. Finally, the solution links the control index values with each product to be shipped, for quality control of the shipped products. Thus, this is a total solution.

INFORMATION SYSTEM TECHNOLOGY

Approach to Stable Quality of Lithium-ion Batteries

Outline

Lithium-ion batteries are used in a wide range of fields from consumer products to vehicles and aerospace applications, owing to their various features including high energy density and output density, little degradation on repeated charging and discharging, and light weight. However, the cost of producing lithium-ion batteries is high because of their sophisticated internal structure and large number of raw materials and production processes. How to lower the cost of producing

lithium-ion batteries is a problem that needs to be solved.

The main components of lithium-ion batteries are positive and negative electrodes, separator, electrolytic solution, and case. Especially, the manufacturing processes of electrodes, melting, reaction, drying, mixing, agitation, dispersion, burning, and crushing, are the keys to stabilizing the product quality.

Yokogawa has been working on solving problems in manufacturing sites for the past 10 years, by identifying the causes and exploring the issues in factory management indices, productivity, quality, cost, delivery, and safety (PQCDS), after classifying them into the four components of manufacturing sites: material, machine, method, and man (4M). Through this experience, Yokogawa has found that the main cause of the issues in manufacturing sites is unexpected variations in 4M. Especially recently, PQCDS and 4M are related to each other in a complicated manner, making solutions difficult.

DPI process stabilization system

The digital plant operation intelligence (DPI) process stabilization system, released in October 2018, is introduced below.

This system aims to control the effect of variations in 4M on product quality by the operations within the process.

In the manufacturing sites of customers, quality requirements are becoming increasingly severe. However, their processes are not designed flexibly enough against the factors that destabilize 4M, such as variations in the quality of raw materials, aged facilities, and insufficient operator skills.

To address this problem, Yokogawa considers it is necessary to design processes that can tolerate variations in material, machine, and man (3M), focusing on process control and process management. For this purpose, visualization, countermeasures, and real-time action must be achieved. Figure 3 shows the tree structure of manufacturing sites.

Traditionally, PQCDS has been improved by partial, individual optimization of 4M elements. Recently, however, partial optimization alone is found to be insufficient because

■ Drawing up indices from the viewpoints of on-site 4M, being linked to PQCDs and executable in the sites

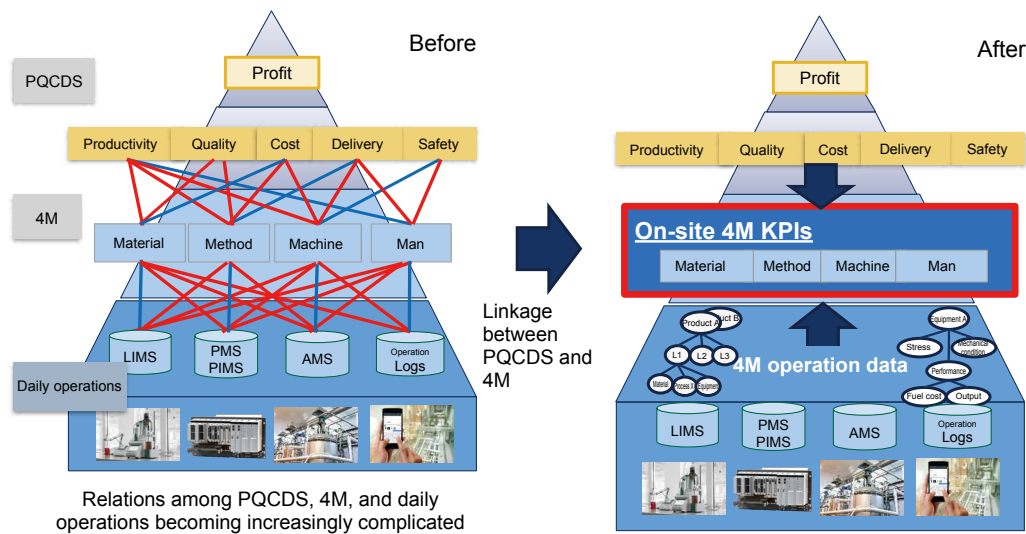


Figure 3 Tree structure of manufacturing sites

of unexpectedly large variations in 4M. Therefore, 4M must be visualized and KPIs must be drawn up while considering PQCDs total optimization and manufacturing sites linked to each other. The DPI system achieves stable quality through the following three steps.

(1) Drawing up KPIs (Data linking)

Critical management parameters, critical quality characteristics, and unique in-house priority parameters have been managed for each lot by using commercially available tools in manufacturing sites. However, this is not enough for achieving stable quality. In the DPI system, KPIs are derived by applying machine learning to these parameters as well as the data on temperature, flow rate, and pressure, which are routinely monitored by operators and are prone to fluctuation. In this way, the relations among PQCDs, 4M performances, and on-site operations can be clarified. Figure 4 shows an image of this relationship.

(2) Planning countermeasures

A variety of information is found in manufacturing sites and used for planning countermeasures to improve quality. For example, possible countermeasures for decreased production yield may be (a) raising the reaction temperature, (b) extending the reaction time, (c) decreasing the load, (d) using a different kind of catalyst, and (e) using a different method of cooling. In the DPI system, countermeasures are identified naturally as a result of deriving KPIs by carefully assessing the 4M states. Thus, this tool shows what actions should be taken in case of trouble, together with the logic that has led to the conclusion. Figure 5 shows the flow of deriving KPIs.

(3) Real-time actions

The DPI system enables operations that are tolerant to unexpected variations in 4M, by visualizing the flow from KPI to logic, countermeasure, and action. KPIs of

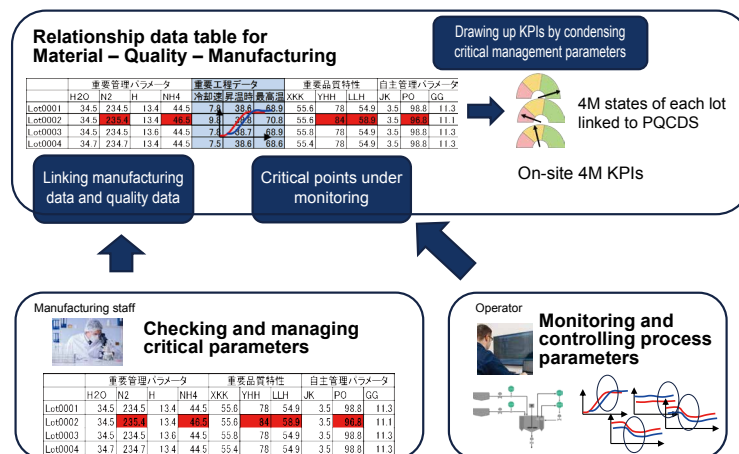


Figure 4 Image of relationship among PQCDs, 4M performances, and on-site operators

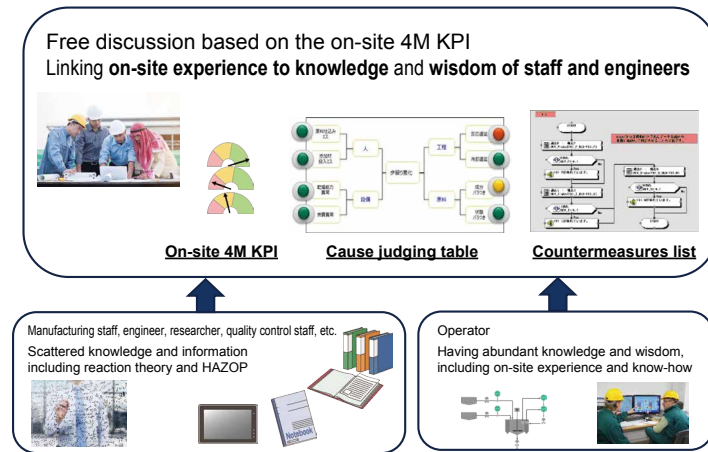


Figure 5 Flow of deriving KPIs

manufacturing processes are monitored in real time. When a KPI is deviating from its tolerance, manufacturing staff can immediately instruct on-site operators to take measures to avoid quality degradation.

Foresight of DPI

This system enables real-time visualization of the states of 4M that are linked to PQCDs during manufacturing, and helps customers' process engineers to achieve stable product quality using information, knowledge, and the wisdom of customers' research and development, manufacturing, quality control, and plant management departments in a cross-organizational manner.

Furthermore, this system aims to build an operation improvement platform (Figure 6) with which customers' process engineers can maintain and expand the factory's

capabilities continuously by following the PDCA cycle in manufacturing sites with the three viewpoints of maintaining operations, analyzing operations, and gathering operation information, together with the problem-solving program offered by consulting specialists from the Yokogawa Group.

Visualizing the Causal Relation between Product Quality and Manufacturing Process by Strengthening Traceability

Need for traceability

Yokogawa has been offering traceability systems to lithium-ion battery manufacturers since around 2010, when the production volume of lithium-ion batteries started to expand for EVs and mobile devices.

Especially for EVs and mobile devices, lithium-ion battery manufacturers are requested by manufacturers of cars

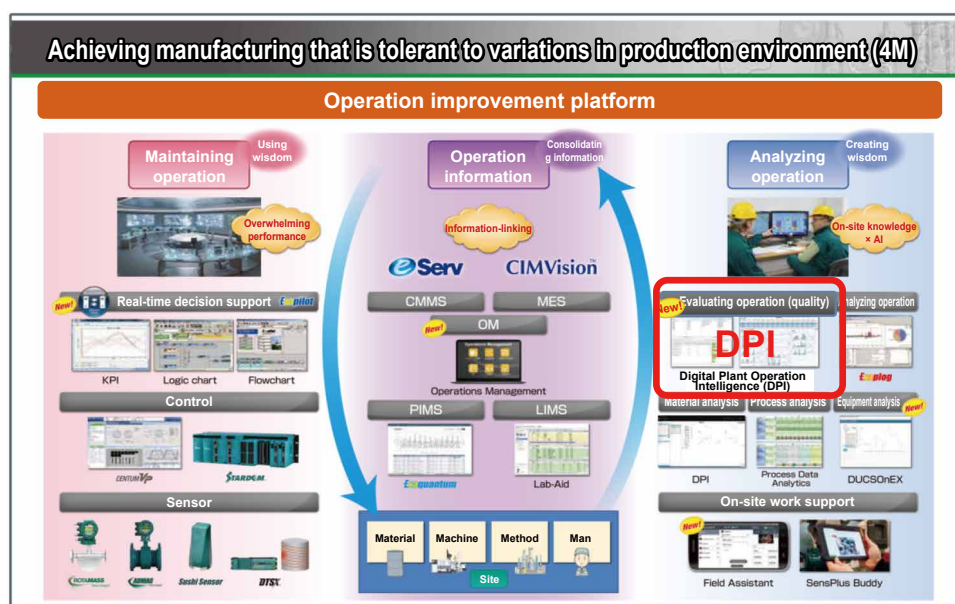


Figure 6 Image of operation improvement platform

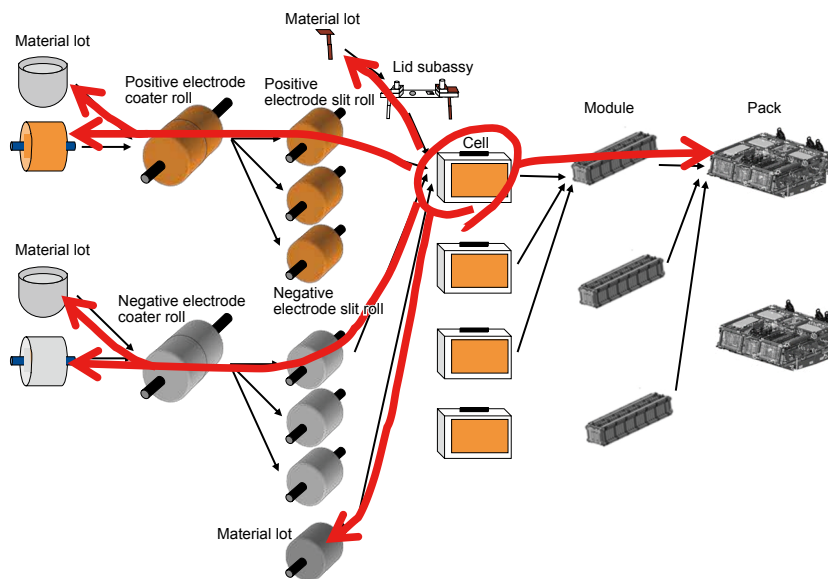


Figure 7 Image of tracing back and tracing forward

and mobile devices to submit data on production conditions, process records, and inspection results, for routine quality checks and for identifying the extent of impact in case of a recall. Therefore, battery manufacturers must save and manage the entire manufacturing data including the data on manufacturing equipment and the records of the processes run by operators. The collected data are attached to the product on delivery as quality data, and used for supplying information on the occurrence of defects.

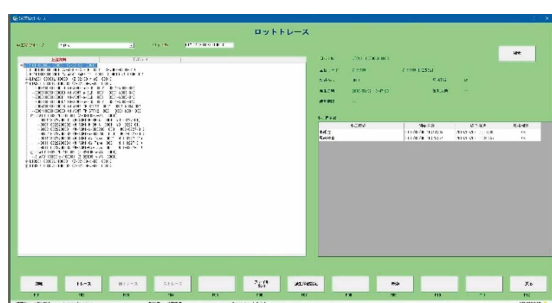
Yokogawa's traceability system

Yokogawa's traceability system is a data acquisition system covering all the processes of battery manufacturing: receiving of raw materials, electrode processes, cell assembly, and shipping. Each item is managed by the serial number attached to it, and can be traced back or traced forward by linking all the data from receiving to shipping. Figure 7 shows an image of tracing back and tracing forward. Information can be obtained instantly on, for example, which coating roll a particular cell came through or which lot of slurry material was used for a particular cell.

Quality improvement using traceability data

The traceability system not only saves the linked serial numbers but also saves the manufacturing conditions and processing and inspection records linked to each serial number. Most of the traceability systems delivered by Yokogawa have been working for several years and the data volume amounts to several terabytes, which can be used for statistical analyses of battery quality. In lithium-ion battery manufacturing, there are failures whose causes are unclear. This situation can be improved by factorial analyses over the entire processes using the data collected by the traceability system. Many battery manufacturers are working on such analyses to identify the causes of failures and feed the results back to the on-site manufacturing control.

Last year, Yokogawa released the CIMVisionAssembly, which is a manufacturing execution system (MES) with a built-in traceability function. Figure 8 shows examples of its screen. Yokogawa believes that the CIMVisionAssembly can help manage the manufacturing history of not only lithium-ion batteries but also all products used in critical, or fatal, scenes. Yokogawa will continue to support such activities to improve quality.



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Figure 8 Example of CIMVisionAssembly screen

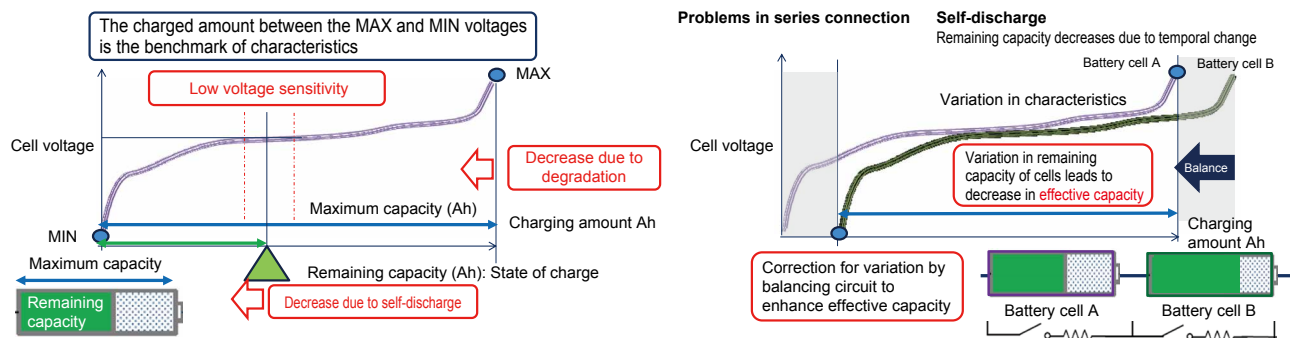


Figure 9 Characteristics of storage batteries

EFFICIENT OPERATION OF BATTERY ENERGY STORAGE SYSTEMS

Outline of Battery Energy Storage Systems and Characteristics of Battery Cells

Renewable energies and distributed power supplies are becoming increasingly popular. The balance between supply and demand is crucial for electricity systems, because the loss of this balance could lead to a large-scale power outage. Although thermal power generation has been used for adjusting the supply-demand balance, clean energy is now required for this adjusting function, from the viewpoint of environmental protection. The virtual power plant (VPP) framework is being developed in which distributed power supplies installed at users are used flexibly as virtual power plants. Accordingly, battery costs are expected to fall as EVs spread and the production volume of batteries increases, and lithium-ion batteries originally made and used for EVs are expected to find secondary use for battery energy storage systems to maintain the supply-demand balance.

The voltage of lithium-ion batteries varies as a result of repeated charging and discharging, while the batteries can only be used within a specified voltage range. Also, repeated charging and discharging of a lithium-ion battery to the specified voltage degrades the battery, and could lead to an explosion in the worst case. In actual battery energy storage systems, multiple battery cells are connected in series and a variation in cell characteristics induces a limitation on the voltage range of charging and discharging, reducing the effective capacity⁽¹⁾. To solve this problem, battery management systems (BMSs) are installed in battery energy storage systems to monitor the conditions of each battery cell. The BMS monitors the voltage of each cell, and operates the system so that the voltage does not deviate from the prespecified range. The BMS also has a balancing circuit to adjust the unbalance in the charge amount of each cell. Especially when degraded batteries are reused, the degree of degradation and characteristics of cells are not uniform, making it imperative to monitor the conditions of each cell and equalize them. Figure 9 shows the characteristics of storage batteries.

Difficulty in Estimating Battery Conditions and Problems of Battery Energy Storage Systems

The remaining capacity and the maximum capacity are critical indices of battery cells. The remaining capacity is the amount of available battery capacity, and changes with charging and discharging. Even if a battery is left unused, the remaining capacity decreases due to self-discharge. The maximum capacity indicates the amount that the battery can be charged, and decreases gradually as a result of degradation by repeated charging and discharging over a long period. The BMS has a function to estimate these indices.

In commonly used battery energy storage systems, the BMS estimates the remaining capacity by integrating the amounts of charging and discharging. However, the offset error and the linearity error of current measurement circuits accumulate to significant amounts. Therefore, the batteries must be completely discharged or completely charged periodically to reset the errors.

The maximum capacity can be obtained by charging a battery from the completely discharged state to the fully charged state. However, this method of charging and discharging is not applicable to actually operating battery systems. Therefore, the maximum capacity is estimated statistically based on the data from previous evaluations, the number of times the battery has been charged and discharged, and the operating time.

In contrast to the batteries for EVs and mobile devices, which can be fully charged periodically, battery energy storage systems have little chance of recharging, because their main purpose is to adjust the supply-demand balance. The chance of periodic recharging will be further reduced for the batteries used for VPP operation, in which both users and power aggregators use the battery systems in common.

Actual battery energy storage systems are connected to electric power systems via power conditioning systems (PCSs) for conversion between AC and DC powers. The efficiency of a PCS differs depending on the operation rate. Accordingly, the dischargeable capacity and the effective capacity, measured as the AC output of the system, vary depending on the operating conditions. It is hard to compare or manage these values from various systems based on a unified standard, because different

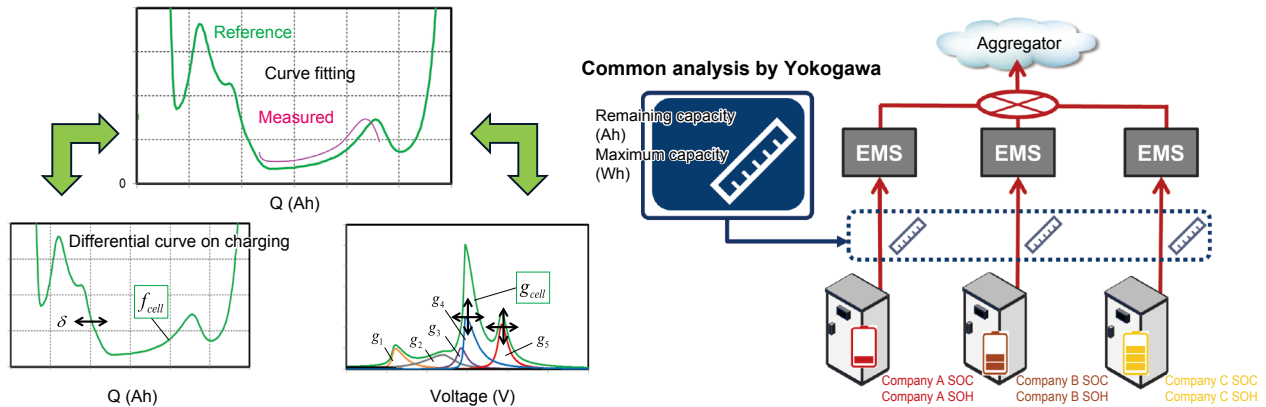


Figure 10 Outline and working example of algorithm for estimating battery conditions

system manufacturers use different standards to estimate these values from the remaining capacity and the maximum capacity obtained by BMS.

Proposal of Efficient Operation

To solve such problems, Yokogawa has developed an original differential curve analysis method for a state estimation algorithm that enables online estimation of the maximum and remaining capacities of batteries without fully charging or discharging them, using the voltage, current, and temperature data from the battery energy storage system. Figure 10 shows an outline of the algorithm.

Focusing on the differential curve on charging, the remaining capacity and the maximum capacity of a battery can be estimated without fully charging or discharging by fitting the theoretical charging characteristics curve to the observed curve. This method can be a great help for reducing the maintenance cost and boosting the use of a VPP. The method will also enable the provision of common guidelines for operation that do not depend on individual battery energy storage systems, by acquiring the voltage and current characteristics of each battery energy storage system during charging and discharging through communication, and estimating the maximum and remaining capacities by the algorithm installed in an external server. Furthermore, this algorithm will help battery manufacturers report to their clients the conditions of battery energy storage systems such as the dischargeable capacity, with an appropriate timing and format depending on the current operation conditions and the operation plans.

Currently, battery energy storage systems are entering full-scale operations. Yokogawa will continue to improve the system efficiency to help achieve a more efficient energy society.

CONCLUSION

This paper introduced two solutions, one for manufacturing and the other for using lithium-ion batteries. Both solutions have been developed through the mutual interaction of supporting customers' technological advancement and receiving support from customers' technologies. Yokogawa continues to address new problems in partnership with customers, under the corporate slogan, "Co-innovating tomorrow." Yokogawa will spread the concept of the corporate slogan and contribute to activities for the SDGs, aiming to make the next-generation technologies applicable today.

REFERENCES

- (1) Soichiro Torai and Masahiro Kazumi, "Technology for Estimating the Battery State and a Solution for the Efficient Operation of Battery Energy Storage Systems," Yokogawa Technical Report English Edition, Vol. 60, No. 1, 2017, pp. 25-30

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