Technologies for Using Batteries in Energy Management Systems

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Society increasingly requires better energy management systems (EMS). Home energy management systems (HEMS) are spreading, and building and community energy management systems (BEMS/CEMS) are now globally being evaluated for practical usage. As an electrical energy storage device for the EMS, lithium-ion batteries are attracting attention. Measuring battery conditions such as their state of charge (SOC) and state of health (SOH) is essential for their effective use. This paper describes the roles of these batteries in social systems, and the keys to effectively operating the batteries.

INTRODUCTION

Since the Great East Japan Earthquake in 2011, Japan has suffered remarkable shortages of electric power, while the dependency for electricity on nuclear power plants has been being reduced even more. Under such circumstances, the introduction of an energy management system (EMS) which promotes the use of renewable energy, and a power peak shift has intensified. Typical renewable energy sources include solar power and wind power, and the amount of power generated by such sources depends on weather, and thus changes dynamically. When the ratio of the power supply occupied by such renewable energy increases in a power grid system, the power supply in combination with power generation systems using renewable energy and electricity storage systems is required, to ensure a stable power supply. Meanwhile, the power peak shift can be achieved by charging batteries with electricity generated during the night, in which power supply can afford its consumption, and by discharging them during a period of daytime in which power consumption reaches its peak. Batteries are suitable for electricity storage systems due to their ease of use. Batteries used for electricity storage systems include lead batteries, NAS batteries, redox flow batteries, lithium-ion batteries, and so on. In particular, lithium-ion batteries, which have recently been attracting attention for use with an electric vehicle (EV), tend to be practical because of their compactness and simplicity. This paper explains applicable areas of batteries for social systems and features various types of batteries, describing the specific characteristics and keys for their effective use, focusing on lithium-ion batteries.

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APPLICATION OF BATTERIES TO SOCIAL SYSTEMS

Electrical energy is easy to use and is flexible for various applications, including energy conversion. Batteries are devices which can store and discharge energy, and are used in many areas. From among such uses, this section outlines three that are attracting attention in the areas of industry and infrastructure. These are: the power peak shift, which shifts the peak time at which the most electricity is consumed; business continuity planning (BCP), which is important after a disaster; and ancillary service, which aims at stabilizing power grid systems.

Power Peak Shift

Power peak shift aims to lower the peak of total power consumption by shifting a period of time in which each home, office, factory and the like consumes power most. Especially in the summer daytime, power consumption increases due to use of air conditioners and the like at home and in the office. Electricity power infrastructure requires facilities which are capable of providing enough electricity to meet peak time usage. Meanwhile, as power generators differ in power generation efficiency according to the load placed on them, changing electric power generation according to fluctuating demand leads to a deterioration in efficiency. Furthermore, it is not effective to prepare power grid systems so as to meet power needs at peak load. Because power suppliers can reduce costs of their infrastructure by leveling power consumption, suppliers in Japan are offering electricity rate structures where the basic charges are determined by contracted maximum amperage. Additionally, those power suppliers are now actively promoting the leveling of power consumption by offering another rate structure in which the night rate is set lower than the daytime one, in which demand is higher. Electricity consumers can reduce their expenses by shifting their power peak time.

Electricity cannot be intrinsically produced in advance.

Thus consumers can shift peak time in the following ways: by rearranging processes in production lines; seeking a better power consumption pattern by adopting a shift work system; and suppressing power supplied from the grid system by using in-house power generation at the daytime peak. As well, electricity can be stored at night in batteries or in the form of thermal energy for effective use during the daytime.

Business Continuity Planning (BCP)

BCP is an activity in an organization for preparation of plans or policies to recover important functions in a short time after a disaster and reactivate its businesses. When preparing the plans or policies, it is important to analyze the impact of a supposed disaster on its business, clarify the tasks to be resumed on a priority basis, along with the necessary facilities and systems, and to define the target time for recovery, and the recovery procedures.

In the case of the Great East Japan Earthquake in 2011, it became clear that even companies which had prepared their plans using BCP spent a lot of time in resuming their businesses, and their coordination with the outside did not work. In particular, suspension of infrastructure and information communications due to the decrease in power supply capability was a big problem. For example, mechanical power generation equipment such as diesel generators did not work because of the interlock by its safety mechanism against the vibrations caused by the earthquakes. In addition, some emergency power supply equipment did not work due to the interruption in fuel supplies. These examples indicated that the planned measures did not work as expected. The need for battery power backup therefore began to attract attention.

Ancillary Service

The frequency in a power grid becomes higher when its load is light, i.e. an amount of power consumption is small, and becomes lower when its load is heavy. However, because this frequency is used for the rotation control of electric motors at production facilities and others, its stability is extremely important. Meanwhile, power generation using renewable energies such as solar power and wind power, which depend on unstable nature phenomena, causes short-term power fluctuation. Thus, the more such renewable energies are used, the more significant fluctuations of the frequency and voltage of a power grid are generated, causing deterioration in quality of the power grid. Although pumped-storage hydroelectricity is effective for responding to long-term power demand fluctuation such as that caused by daytime and nighttime, it cannot respond to such short-term power fluctuation. Accordingly, electrical storage devices which can charge and discharge electricity in a short time are required. In other words, devices that can supply energy (discharge electricity) in the overload status while store energy (charge electricity) in the low load status are needed.

In the U.S. and some other countries, independent power producers (IPP) have a relatively large market share in the power supply industry, and ancillary service businesses for stabilizing power grids are popular. In Japan, the government has decided on a policy for electricity liberalization, and the ancillary service businesses are expected to pervade the power industry. For batteries for an ancillary service, rapid charge and discharge in a time span of several tens of minutes are required. Suppressing the storage capacity of the devices by using those capable of high-rate charge and discharge can minimize the introduction cost. Currently, lithium-ion batteries are often adopted for that purpose from the view point of performance.

TYPES AND CHARACTERISTICS OF RECHARGABLE BATTERIES

For electricity storage systems, batteries called 'secondary' or rechargeable batteries are usually used. These batteries can be used repeatedly by charging them, where electrical energy is converted into chemical energy and stored in them during charging, and then the stored chemical energy is converted into electrical energy during discharging. Table 1 shows types of batteries used for industry and summarizes their characteristics. Details of each type battery are explained below.

Lead Battery

The lead battery cell comprises a positive electrode of lead dioxide, a negative electrode of lead, and electrolytes of dilute sulfuric acid. Relatively high nominal voltage of two volts per cell is available, and the lead for electrode material is inexpensive, so that they are the most popular among secondary batteries. Furthermore, this battery shows a relatively stable performance during large current discharge in a short time as well as during gradual discharge over a long time. This battery has no memory effect causing apparent decrease in the maximum battery capacity, and it is desirable to keep it in a fully charged condition. Thus, this battery has been used as an automotive battery or a backup power source such as an uninterruptible power system (UPS). However, the lead battery is apt to deteriorate through repeated charge–discharge cycles and unsuitable for applications which require frequent charge and discharge. Meanwhile, lead batteries with improved cycling characteristics have recently been under development.

NAS Battery

The NAS battery cell comprises a positive electrode of sulfur, a negative electrode of liquid sodium, and electrolytes of β–alumina. This battery cell is compact with approximately one third the size and weight of a lead battery cell. The NAS battery is designed for large-scale electricity storage. For example, power suppliers can use these batteries to stabilize power output in combination with wind and solar power generation, whose output fluctuation is larger. Electricity consumers can use them for power peak shifts or emergency power sources in case of disasters. Meanwhile, this battery does not work at normal temperatures and its operating temperature, approximately 300°C, needs to be maintained by using heaters and its own heat generated during discharge. The NAS battery is more suitable for charge and discharge over a relatively long interval than over a short interval.

Redox Flow Battery

The redox flow battery is a rechargeable flow battery that performs charge and discharge through the reduction-oxidation (redox) reaction of ions accelerated by circulating liquid electrolytes using a pump. Its cycle life is expected to be over 10,000 cycles, and its service life over ten years. The structure is simple and suitable for large-scale storage. The redox flow battery has been already put to practical use as 1 MW-class electric power equipment. This battery is being used as electricity storage and its main usages are as follows: leveling the inter-day load fluctuation of power consumption; compensating instantaneous low voltage; and leveling the power generated by wind and solar power generation. Meanwhile, it is difficult to downsize this battery because of its low weight energy density.

Table 1 Secondary batteries and their characteristics

Type	Lead battery	NAS battery	Redox flow battery	Lithium-ion battery
Applications	Automobile starter, UPS	ESS*	ESS*	Mobile devices, EV, ESS*
Temperature	Normal	300 °C	Normal	Normal
Auxiliaries	None	Heater	Circulation pump	Balancing circuit
Operating loss factor	Reflesh	Heater loss	Pump loss	Balance loss
Energy density	Approx. 30 Wh/kg	Approx. 100 Wh/kg	Approx. 6 Wh/kg	Approx. 110 Wh/kg
Cycle life	4500	4500	10000	4500
Characteristics	Most practically used, Inexpensive	High energy density, Compact, High-temperature type	Easy to enlarge capacity	No auxiliaries, High energy density

* ESS: Energy Storage System

Lithium-ion Battery

The lithium-ion battery is a non-aqueous electrolyte secondary battery in which movement of lithium ions in electrolytes causes electric conduction. At present, the most popular lithium-ion battery cell uses lithium metallic oxide as the positive electrode and carbon material such as graphite as the negative electrode. For the positive electrode, various materials are used such as manganese-based, cobalt-based and iron phosphate-based compounds. Although the nominal voltage differs depending on the materials, lithium-ion batteries show a better performance in both energy density and output density than any other commercialized secondary batteries. Energy density indicates energy storing capability, and output density indicates energy output capability. The former is often quantified by the amount of energy stored per unit weight as shown in Table 1. The latter shows the amount of energy instantaneously available, which can be said to be “instantaneous power,” and is normally used conceptually. This performance determines the acceleration performance when used in EVs. In this respect, lithium-ion batteries are superior to lead batteries which have been commonly used for automobile starters requiring instantaneous power.

In addition, the lithium-ion battery features less memory effect and less self-discharge, and does not require temperature control, unlike NAS batteries. For these reasons, lithium-ion batteries have been practically used in consumer type areas ranging from personal devices such as mobile telephones and notebook computers to power sources for automobiles such as EVs, hybrid electric vehicles (HEV), and plug-in hybrid electric vehicles (PHEV). Meanwhile, because the energy density of this battery is so high, an incident caused by overcharging, or a defective product due to foreign matter contamination or other may often cause significant damage. To prevent such incidents, lithium-ion battery packs are used with safety monitoring by an electronic circuit and a built-in safety protective circuit.

As the lithium-ion battery has high energy density and output density, studies on improvement in performance and operational technologies have been most proactively carried out for it to be used as a secondary battery for industrial electricity storage systems.

CHARACTERISTICS OF LITHIUM-ION BATTERIES AND KEYS TO EFFECTIVELY OPERATE THEM

To effectively operate the lithium-ion battery, it is necessary to manage its self-discharge, battery capacity, and internal resistance. These three properties vary depending on temperature, discharge rate and use history. If evaluation of these properties under actual operating conditions in advance is not accurate, margins for such performance are required, leading to increases in the introduction cost or too much weight and volume. In contrast, from the view point of deterioration, operation with low depth of discharge (DOD) is recommended, counterweighing the issues concerning cost, weight and size.

Self-discharge and Balance between Cells

Self-discharge is a factor which may cause loss of the balance of the amount of energy charged in each cell in a battery module composing a set of multiple cells. Figure 1 shows the electricity availability of the module including two serially connected cells with the same capacity between which the balance is lost. Suppose that the module is operated while monitoring the state of charge (SOC) of each cell under the SOC control with a lower limit of 30% and an upper limit of 80% without considering the balance between them. As shown in Figure 1-(A), when the SOC of the upper cell becomes 80%, the charge stops, the SOC of the lower cell indicating 70%. When in use, the lower cell first reaches 30% and the discharge stops as shown in Figure 1-(B). Then, the charge starts again as shown in Figure 1-(C). This shows that the amount of actually available electricity is 40% of the full charge capacity. If the cells are balanced, 50% is available, that is the imbalance decreases the available electricity by 20% (10% to 50%). To make the best use of the storage capacity, it is necessary to continuously balance the cells with each other during their operation, from their installation to the end of their life. A battery cell balancing circuit is incorporated into a battery module, and a discharge type passive balancing method is usually used for it where a SOC of each cell is adjusted to match with that of the cell with the largest self-discharge. In recent years, an active balancing method has been also used, where each cell is additionally charged until it reaches the highest SOC among the cells.

During operation, an extreme increase in self-discharge of a cell due to its temporal deterioration requiring its replacement is rarely seen. For this reason, it is important to monitor the amount of self-discharge of each cell.

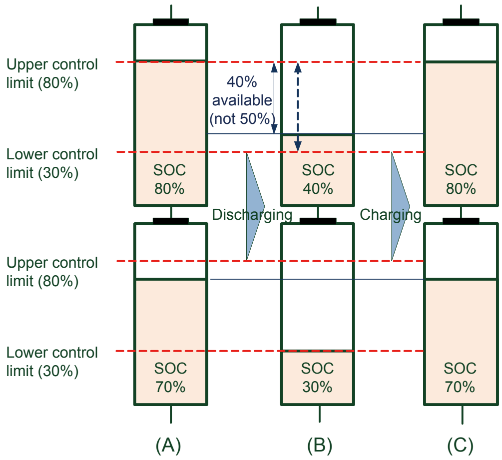

Figure 1 Decrease in available electricity of cells due to imbalance between cells

Battery Capacity and Internal Resistance

Japanese Industrial Standards (JIS) C8715-1:2012 describes the detailed definition and measurement method of performance, such as capacity, of various types of batteries. However, the performance is based on the pre-defined temperature and charge/discharge rates and is not always guaranteed during practical use. Figure 2 shows the discharge characteristics curves of a commercially available lithium-ion battery using lithium iron phosphate for its positive electrode. Three curves with the discharge rates of 0.2 C at 25 °C, 0.2 C at 0 °C, and 0.05 C at 0 °C are shown. Discharge rate is the ratio of an actual discharge current to the current when nominal capacity of a battery is discharged in an hour, and is expressed in units of C. The discharge lower limit voltage of this battery is 2.5 V. These curves show that the lower the discharge rate is and the higher the temperature is, the larger the capacity that can be secured. This is mainly due to the internal resistance of the battery. During low-rate discharge, the voltage drop caused by the internal resistance is small. At room temperature, the internal resistance is smaller than at a lower temperature. Thus, these conditions make the storage capacity larger.

The lithium-ion battery is well known for its deterioration in capacity by being repeatedly discharged and charged. For example, many mobile phone users feel that the operating time after the full charge becomes remarkably shorter around one year after the purchase. If the deterioration in the capacity of a lithium-ion battery is not accurately grasped, it may stop operation due to a sudden low voltage, showing the appearance of a sudden decrease in charged electricity.

Many studies on the method for accurately evaluating battery capacity have been reported. It is reported that the capacity decreases in proportion to approximately one-half the power of the elapsed time [(1)]. In recent years, methods for separately evaluating temporal deterioration and that caused by repeated charge–discharge cycles have been investigated [(2), (3)]. Both methods apply a deterioration model based on the same deterioration mode. In addition, another method is proposed which estimates deterioration in a battery from its internal impedance and determines the ratio of the remaining capacity to the original one [(4)].

Meanwhile, the internal resistance of a battery also deteriorates as time passes. Some studies propose an algorithm in which the deterioration in internal resistance and the capacity deterioration can be separately detected [(5), (6)]. The internal resistance deteriorates depending on operating time and the number of charge-discharge cycles, and it increases in both cases. Figure 3 shows example Nyquist diagrams of the impedance of a battery after storage at a high temperature of 60 °C. The sample battery is a 18650 type lithium-ion battery used for commercially available notebook computers and others, and the Nyquist diagrams are measured at low SOC, 3.2 volt output. Although the capacity ratio of the cell left after 28 days is 97% showing little deterioration, the internal resistance at 100 mHz is more than double that of the initial state.

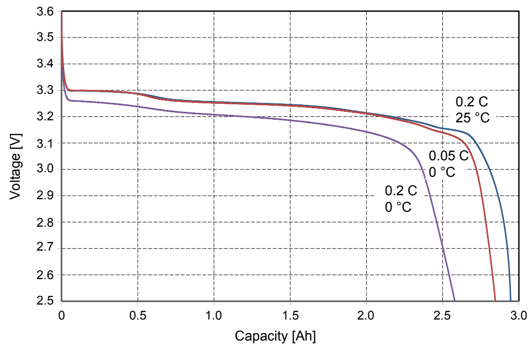

Figure 2 Discharge characteristics curve (depending on discharge rate and temperature)

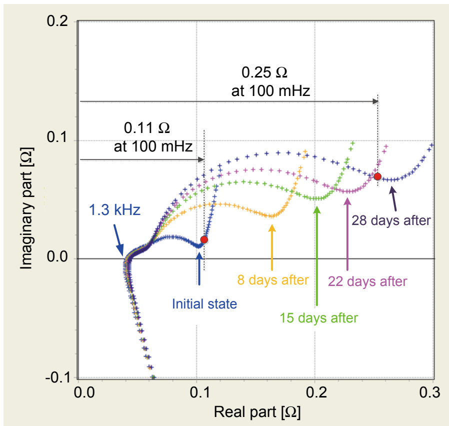

Figure 3 Nyquist diagrams showing temporal deterioration in internal impedance of a battery

Expectation of Measurement Technologies

Accurately measuring the capacity and internal resistance of a battery makes the simulation of battery behavior possible. For example, such battery measurement technology will play an important role in power supply systems or the EMSs which make use of the power based on the charge and discharge of batteries, which is to be used as part of the power for daily production in plants based on production plans. In particular, measuring functions which can accurately measure actual available capacity in a battery are indispensable in the future in the industries where batteries are used, and such functions must be incorporated into electricity storage devices.

CONCLUSION

As economic activities in developing nations become more vigorous, global energy consumption is expected to drastically increase. Although shale gas and other unconventional resources are attracting attention, the fact remains that fossil fuel reserves will be depleted in the near future. Batteries are expected to be key devices for building a society which does not depend excessively on fossil fuels. However, battery control technology to be used in industries is not yet established. Moreover, battery costs have not yet been reduced enough to ensure their economic rationality. We are expecting batteries to become energy devices which can be used in industry by establishing battery control technology through innovation of battery state monitoring technology, and by reducing the costs by innovation of production technology, mass production of batteries, and by deregulation of the installation of battery systems.

REFERENCE

(1) M. Brousselya, S. Herreyreb, P. Biensanb, et al., “Aging mechanism in Li ion cells and calendar life predictions,” Journal of Power Sources, Vol. 97-98, 2001, pp. 13-21

(2) M Abe, K Nishimura, K Kohno, et al., “Lifetime Prediction of Lithium-ion Batteries used Charge/Discharge Cycle Test”, Summary of Lectures, The 52nd Battery Symposium in Japan (3A22), 2011 in Japanese

(3) K. Kaji, K. Tanaka, K. Maeda, et al., “Evaluation model for used Lithium-Ion battery life,” PRiME 2012, #1068, 2012

(4) Y Tominaga, M Kawamura, K Takemasa, “Creation of a model of battery capacity degradation reflecting battery internal states,” Summary of Lectures, The 54th Battery Symposium in Japan (2B06), 2013 in Japanese

(5) A. Takuya Shimamoto, B. Ryuta Tanaka, C. Kenji Tanaka, “A study on evaluation method for the Lithium-ion battery life performance for stationary use,” 2013 International Conference on Clean Electrical Power (ICCEP), 2013, pp. 115-119

(6) Y Monden, H Sakurai, M Hoshino et al., “Development of State calculation algorithm of Lithium Ion Battery by Charging curve analysis method,” Summary of Lectures, The 53rd Battery Symposium in Japan (3A18), 2012 in Japanese

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