Development of UltraBattery

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ABSTRACT We have developed UltraBattery (hereinafter called UB) for valve regulated micro Hybrid Electric Vehicles (HEVs). The UltraBattery has a lead storage battery and an asymmetric capacitor in the same cell. The cycle life characteristics of the UB are about the double of the existing lead storage batteries. We have also developed a stationary UltraBattery for smart grid uses. It has high energy efficiencies, long cycle life characteristics and superior recovery characteristics when driving in partial charge states. This stationary UltraBattery is at the stage of demonstration test in the "Kitakyushu Smart Community Creation Project", which is a subsidized project of the Ministry of Economy, Trade and Industry.

1. INTRODUCTION

In recent years, there is an increasing need for reduction in CO_2 emission and for the use of renewable energy in automobiles as mitigations against global warming. Mileage regulations and CO_2 emission regulations for automobiles are becoming stricter year after year domestically and in the United States and Europe. Therefore, automobile makers around the world have been launching idling stop system (ISS) vehicles, micro HEVs and full HEVs which are contributing to improved fuel efficiencies. Also, the need for the use of renewable energy is increasing not only from the viewpoint of mitigation against global warming but also from a problem of tight power supply caused by the power condition in recent years and also from an efficient use of power by smart communities.

Given these factors, storage batteries have been the focus of the attention. The requirements for their applications have been expanding from the existing standby uses, such as for starting engines and for emergency power, to the cycle use which consists of repeated and frequent charge and discharge.

In this report, we describe the characteristics of two types of developed UBs for cycle uses, one is for a vehicle installation type and another is for a stationary type. In the last part, we describe the "Kitakyushu Smart Community Creation Project". This is one of the "Next-Generation Energy and Social System Demonstration Projects", which are subsidized by the Ministry of Economy, Trade and Industry.

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2. UltraBattery FOR AUTOMOBILE

ISS vehicles mean the automobiles with an idling stop system, and micro HEVs mean the automobiles with a charging function using breaking energy recovery in addition to an idling stop function. Full HEVs mean the automobiles with motors and generators[1)]. They can drive only with electricity at startup and at low speed drive[2)].

Hereafter, we describe the circumstances of automobiles and batteries in Europe. In 2012, the sales of micro HEVs accounted for about 40% of the automobile sales in the whole 27 countries in EU. The sales are expected to reach or exceed 60% in 2015[3)]. It indicates that the market of batteries for the micro HEVs will grow significantly in the future.

The load of installed lead storage batteries between micro HEVs and existing automobiles is significantly different. For example, in micro HEVs, power for electrically-driven devices such as lights and audio systems are all supplied from batteries and the discharge is deeper than in the existing automobiles. That is because power is not generated by alternators when micro HEVs stop idling. Also, as micro HEVs restart the engines each time they stop idling, the number of large-current discharges increases compared with existing systems. Moreover, as the charge by recovery brakes needs to be accepted efficiently, batteries are used in the partial state of charge (PSOC), which means that the batteries are used at about

90% state of charge (STOC). Therefore, lead storage batteries for micro HEVs require both a charge acceptance and a resistance in the PSOC[4].

Given these factors, we have developed the UB for valve regulated micro HEVs.

2.1 Development of UB for Valve Regulated Micro HEV

UltraBattery is a hybrid battery in which a lead storage battery and asymmetric capacitors are installed in the same cell. Figure 1 shows the shape and Figure 2 shows the construction[5]. The UB can be used under severe conditions in which the PSOC and large current pulse charge-discharge are combined, which was difficult to be achieved with lead storage batteries.[6)-9)].

In order to develop the UB suitable for micro HEVs, we adopted a part of high-performance technologies of 36 V valve regulated lead acid (VRLA) developed for mild HEVs and enhanced the performance further. The following shows the developed items.

Figure 1 Shape of valve regulated UltraBattery for micro HEV.

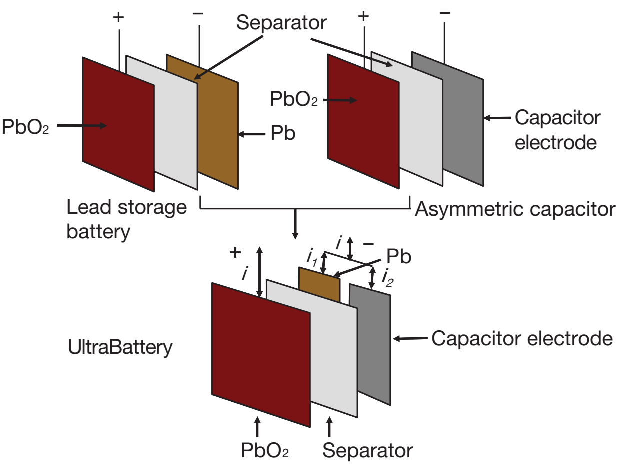

Figure 2 Construction of UltraBattery.

2.1.1 Positive plate

Positive and negative active materials repeat dissolution-precipitation at charge and discharge. Positive active materials lose the original solid backbone structure gradually by the dissolution-precipitation and it causes softening. We adopted active materials which are denser than the existing ones to enhance the resistance (softening resistance) of positive active materials. In addition, we adopted our company's "C-21 alloy" as a positive lattice alloy to keep a high corrosion resistance and the long-term stability of the mechanical characteristics in high temperature environments[11].

2.1.2 Positive and negative lattice

The optimization of the number of polar plates, the forms of lattices and the sizes of lattices are the available measures for enhancing the output characteristics[12]. We optimized the forms of lattices (addition of reinforced lattices, refinement of lattices) by computer simulation because it is desirable to have a uniform distribution of potentials to increase the rate of utilization of active materials. Figure 3 shows the results. The distribution of potentials improved after the optimization.

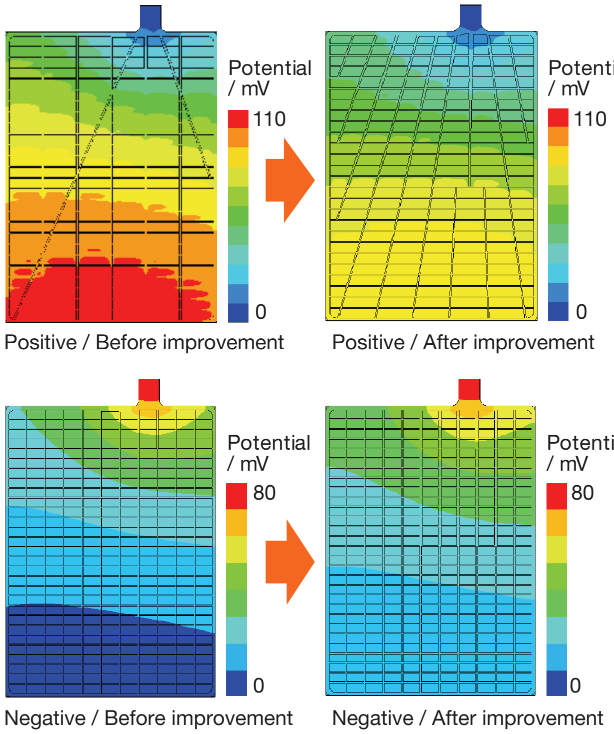

Figure 3 Analysis of distribution of potentials.

2.2 Life Test of UB for Micro HEV

2.2.1 Test condition

Batteries in micro HEVs are used at about SOC90% (PSOC) to accept the charge generated by recovery brakes efficiently. We tested under the condition of SOC70%, which is severer than that of 90%. In line, we tested under the conditions of SOC80% and 90% to investigate the effects of SOC on the lives of the batteries (Test condition ① SOC70%, ② SOC80%, ③ SOC90%). The test profile is a pulse charge-discharge pattern with the maximum discharge current of 4 CA.

2.2.2 Test result

Figure 4 shows the relationships between the SOC and the capacity turnovers. The test conditions are ①-③. The depth of discharge (DOD) is 5%. For comparison, we show the results of an existing storage battery tested under the conditions of same capacity and of SOC70%. A capacity turnover is obtained by dividing the sum of the electrical charge which is available before the battery's life ends by the battery's rated capacity. A comparison of life cycles becomes possible by comparing capacity turnovers.

The relation between the SOC and the Capacity turnovers shows that as the SOC increased from 70%, 80% to 90%, the capacity turnovers became higher. On the other hand, the UB battery had about 1.8 times as much capacity turnover as the existing one under the condition of SOC70%.

This result means the life of the UB is longer than that of the existing battery. After these tests, we disassembled the batteries. In the existing battery, the softening of the positive active materials and a significant sulfation of the negative active materials were observed. On the other hand, in the UB, although positive active materials were observed, noticeable sulfation of the negative active materials was scarce.

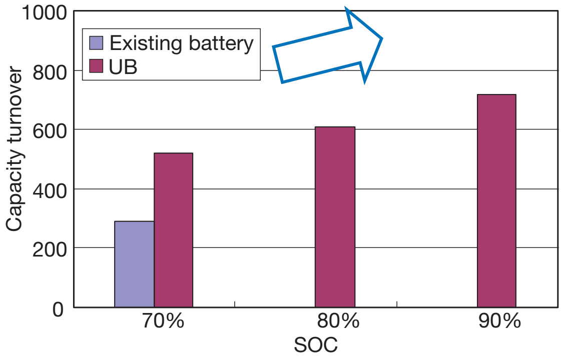

Figure 4 **Relationship between SOC and capacity turnover.**

3. STATIONARY UltraBattery

Stationary storage batteries have been considered as devices for power storage and output leveling. Therefore, they require a long-lived performance under the conditions of large-current charge-discharge and of PSOC. We have developed a stationary UB suitable for these purposes.

3.1 Characteristic Evaluation in PSOC

3.1.1 Wh efficiency test

We report the characteristics of the stationary UB in PSOC. When storage batteries are used in a stationary state, they need equal or exceed 10 years of life. Therefore, energy efficiency is an important point. We evaluated UB1000 (2 V-1000 Ah/10 h) under the conditions stated in Table 1 to calculate the Wh efficiency of the UB. SOC was adjusted by steps of 10%. We conducted 30 cycles of charge-discharge at the rates of 0.1C$_{10}$A-0.6C$_{10}$A, and conducted a recovery charge after that. The quantity of charge-discharge electricity is equivalent to 10% of the rated capacity. Given the sum of the discharged electrical quantity per operation day is 50% of the rated capacity, five cycles are equivalent to the charge-discharged electrical quantity a day. Therefore, 30 cycles are equivalent to the operation for six days. Testing conditions were set assuming that operations are conducted from the first to the sixth day and a recovery charge is conducted on the seventh day of a week. Figure 5 shows the Wh efficiencies during the cycle tests. As figure 5 shows, in the case of 0.1C$_{10}$A charge-discharge, the Wh efficiencies were high although they vary from 91% to 94.5% depending on the SOCs. When the cycle of discharge0.6C$_{10}$A-charge0.45C$_{10}$A was tested, the Wh efficiencies tended to decrease because the polarization of the voltage became larger. Nevertheless, the Wh efficiencies were 83%-87%, which were still high values.

Table 1 **Condition of Wh efficiency test.**

		Charge-discharge rate (C$_{10}$A)				SOC (%)	Remarks
①	Discharge	0.1				10-100% (Per 10%)	SOC adjustment
②	Break	–				–	10 min
③	Discharge	0.10	0.20	0.40	0.60	-10%	Repeat charge-discharge (③-④) for 30 times
④	Charge	0.10	0.20	0.40	0.45	10%	
⑤	Break	–				–	10 min
⑥	Charge	0.2				100%	Recovery charge

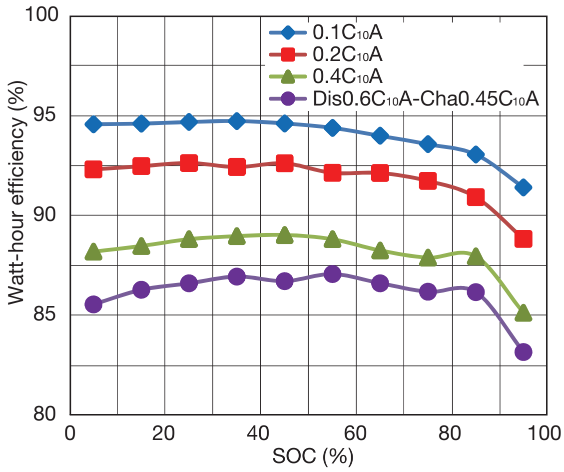

Figure 5 **Result of Wh efficiency test (cycle test only).**

3.1.2 Input-output characteristic test

Next, we report the results of input-output characteristic tests in PSOC. Figure 6 shows the profiles of the input-output tests at SOC50% (indicated by the red line). After SOC was adjusted to 50%, tests were conducted at the charge-discharge currents of 0.1C$_{10}$A, 0.2C$_{10}$A, 0.3C$_{10}$A, 0.4C10A, 0.6C10A, 0.8C10A, 1C10A, respectively (indicated by the blue lines). The ambient temperature was set at 25°C. Charge-discharge was conducted for 30 seconds at each rate and a break was given for 10 minutes after each charge-discharge. The operable range of the battery voltage was set at 1.8 V-2.35 V (indicated by the orange lines). This is because batteries' lives could be shortened by over discharge if the charge voltage is under the lower limit of 1.8 V, and because drawdown of the moisture in electrolyte is accelerated by electrolysis and the loss of the charged energy could occur if the charge voltage is over the upper limit of 2.35 V. As the figure shows, the discharge voltages did not fall below the lower limit of 1.8 V at any current values, but the charge voltages exceeded the upper limit of 2.35 V at 0.8C10A and 1C10A. That is, the maximum discharge current was 1C10A and the maximum charge current was 0.6C10A at SOC50%. These values were higher than those of the existing batteries (compared with our existing products).

repeated for three times a day, a recovery charge per 90 cycles was conducted to recover the SOC up to 100%, then the changes in 0.1C10A discharge capacities were confirmed. In general, when lead storage batteries repeat the cycle in such a PSOC operation, the recovery charge (full charges) is conducted per one week to remove the lead sulfate accumulated on the polar plates by oxidizing it on the positive electrodes and resolving it on the negative electrodes. This is for avoiding the decrease of the discharge capacities caused by the growth of lead sulfate's crystals. In this test, the recovery charge was not conducted for 1 month. Therefore, it was a severer test condition for PSOC evaluation. The existing cell and the UB were used for the test batteries.

Figure 7 shows the changes in the initial capacity ratios. The longitudinal axis shows the initial capacity ratios (%) of 0.1C10A capacity. The capacity ratio of the existing cell after 270 cycles was 93%, which was a moderate declining trend.

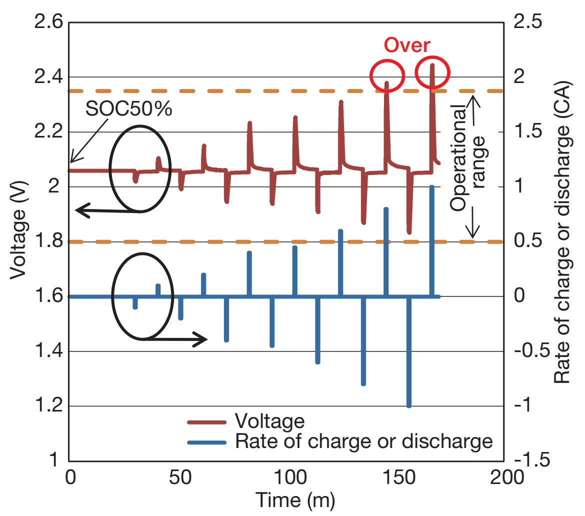

Figure 6 Profile of input-output characteristic tests.

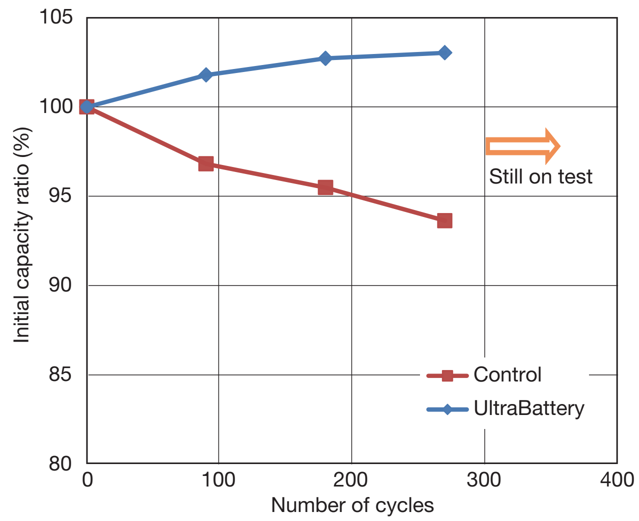

Figure 7 Changes in initial capacity ratio in PSOC cycle test.

3.2 Cycle Life Characteristics

3.2.1 PSOC cycle life test

We evaluated the cycle characteristics of the UB1000 (2 V-1000 Ah/10 hr) when it was operated in PSOC for a long period. The following (1)-(3) show the test conditions[9].

(1) Cycle condition (temperature: 25°C)
- · Start at SOC60%
- · Discharge : 0.1C10A × 3 h
- · Break : 1 h
- · Charge : 0.1C10A × 3 h
- · Break : 1 h

(2) Condition of recovery charge (temperature: 25°C)
- · Conducted per 90 cycles (1 month)
- · Charge: 0.1C10A, charge voltage 2.45 V × 20 h

(3) 10 hour rate capacity test after recovery charge (temperature: 25°C)
- · Discharge : 0.1C10A, final voltage 1.8 V

In this test, the cycle of SOC60%⇔SOC30% was

On the other hand, the UB kept equal or exceeding 103% after 270 cycles. That is, the cycle characteristics of the UB are superior under the PSOC condition. It also means that the recovery charge characteristics of the UB are superior.

Figure 8 shows the changes in the positive and the negative potentials during recovery charge after the cycle test for 180 times. Figure 9 shows the changes in the charge currents and the charge capacities during recovery charge after 180 cycles. In the figure 8, the negative potential of the existing cell is polarized to the negative side along with the beginning of the recovery charge. This is because the crystals of the lead sulfate grew and accumulated to be a resistance in the negative active materials during the PSOC cycle test. The UB restrained the accumulation of the lead sulfate during the PSOC test because no significant polarization was observed in the negative potential of the UB. Also, figure 9 shows that in the UB, the droop of the charge current is slower due to the smaller polarization in the negative potential. Along with that, the charge capacity of the UB is bigger than the existing cell. Also, the UB was confirmed to have a superior charge acceptance compared with the existing cell.

The UB has a possibility of extending the interval of the recovery charge significantly compared with the existing lead storage batteries. The reduction in the quantities of the recovery charge, the enhancement of the operational efficiencies and the Wh efficiencies can be made possible by extending the interval of the recovery charge.

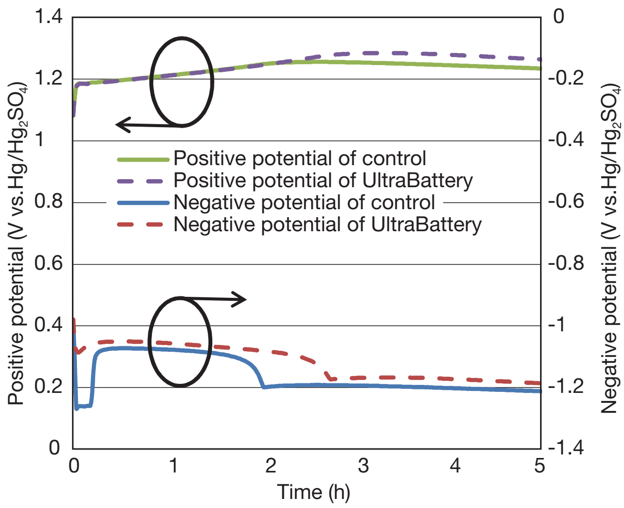

Figure 8 **Changes in positive and negative potentials during recovery charge after 180 cycles.**

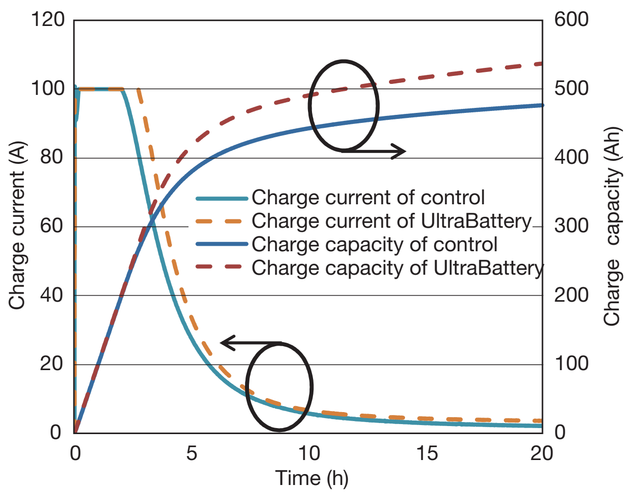

Figure 9 **Changes in charge current and charge capacity during recovery charge after 180 cycles.**

3.2.2 HR-PSOC cycle life test

Next, we conducted high rate partial state of charge (HR-PSOC) cycle test in which a cycle test is repeated at high-rate charge and discharge currents under the PSOC condition[13]. The UB500 (2 V-500 Ah/10 hr) was used for evaluation and the existing lead storage battery with the same capacity was used for comparison. The ambient temperature was set at 25°C. After adjusting the SOC to 50% at $1C_1A$ charge current, the cycle of a discharge $1C_1A$ for 6 minutes-a break for 5 minutes-a charge $1C_1A$ for 6 minutes-a break for 5 minutes was repeated for 1000 cycles. After that, we conducted a $1C_1A$ capacity test.

In addition, when the charge final voltage reached 2.45 V and the discharge final voltage reached 1.75 V during the cycle, we conducted the $1C_1A$ capacity test and continued the cycle test.

Figure 10 shows the changes in the discharge terminal voltages during the cycle test. Figure 11 shows the changes in charge terminal voltages. No significant gap was observed between the two batteries with respect to the changes in the discharge terminal voltages during the cycle test. However, with respect to the charge terminal voltages, the voltage of the UB scarcely reached the charge terminal voltage. On the other hand, the voltage of the existing storage battery frequently reached the charge terminal voltage. The fact indicates that the charge voltage of the UB is stable, thereby keeps a good charge acceptance.

Figure 12 shows the changes in $1C_1A$ initial capacity ratios. Compared at the point where the capacity ratios dropped to 80%, the life of the UB is twice as longer as that of the existing lead storage battery. The UB shows good cycle life characteristics at high rate charge-discharge currents under the condition of the PSOC.

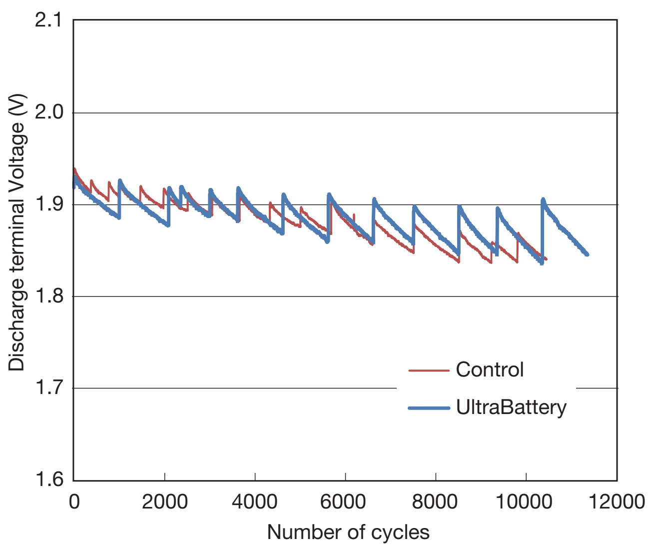

Figure 10 **Changes discharge terminal voltage during HR-PSOC cycle test.**

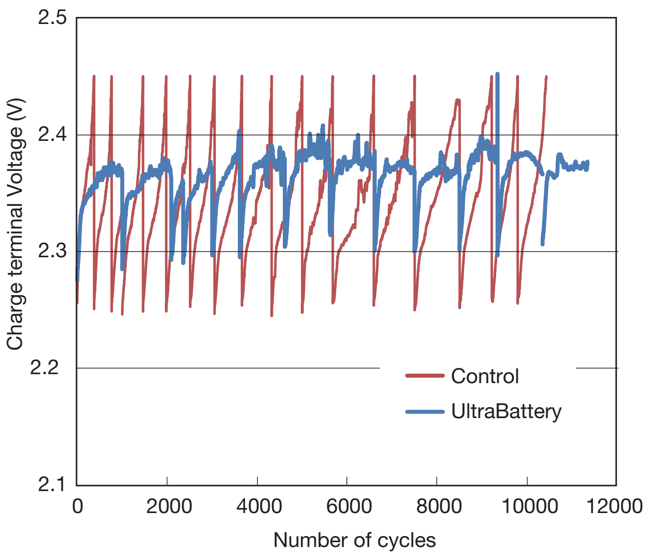

Figure 11 Changes in charge terminal voltage during HR-PSOC cycle test.

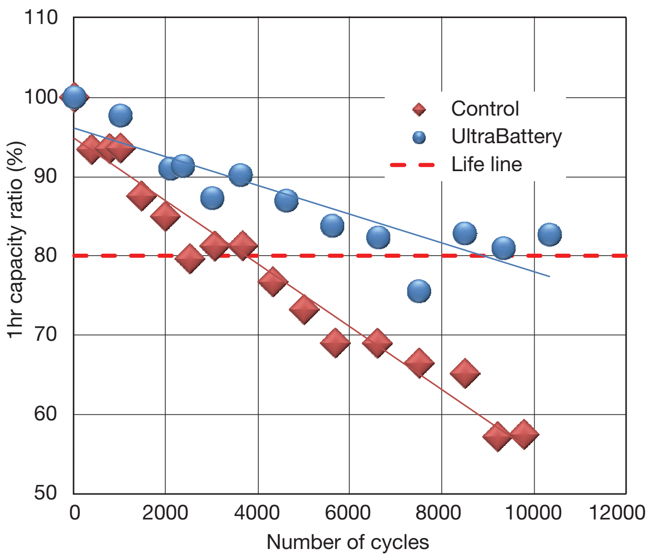

Figure 12 Changes in initial capacity ratio in HR-PSOC cycle test.

4. PARTICIPATION IN THE KITAKYUSHU SMART COMMUNITY CREATION PROJECT

Yahata Higashida-area, Kitakyush-city was selected as one of the four regions where the Ministry of Economy, Trade and Industry conducts the Next-Generation Energy and Social System Demonstration. The name of the project is the Smart Community Creation Project, which is aiming at reducing 50% of the CO_2 and at maintaining the electrical quality at the introduction of new energy[14].

In this project, our company has completed the installations of the UBs in cooperation with the community energy management system (CEMS) for the purpose of adjusting the supply-demand of energy and for supplying power at times of disaster and at the times of massive black out. We have installed 336 cells of the UB1000 (168 series x 2 parellel) in Maeda Area (Figure 13), 192 cells of the UB500 and 32 cells of the UB100-6 (6 V-100 Ah/10 hr) in the Kitakyushu Museum of Natural History and Human History (Figure 14), 32 cells of the UB 100-6 in the Human Media Creation Center／KYUSHU (Figure 15). The demonstration test has started in 2012. In the future, we will demonstrate the superiority of the UBs from the viewpoints of energy efficiencies, equalized charge intervals and elongation of the lives of storage batteries.

This project is being undertaken by the outcomes of the NEDO's collaborative research, "Technical development of the complex systemization of storage", and by the Ministry of Economy, Trade and Industry's subsidized project, "Next-Generation Energy and Social System Demonstration Project".

Figure 13 UB1000 × 336 cells, Maeda-Area.

Figure 14 UB500 × 192 cells, Kitakyushu Museum of Natural History and Human History.

Figure 15 UB100-6 × 32 cells, Kyushu Human Media Creation Center.

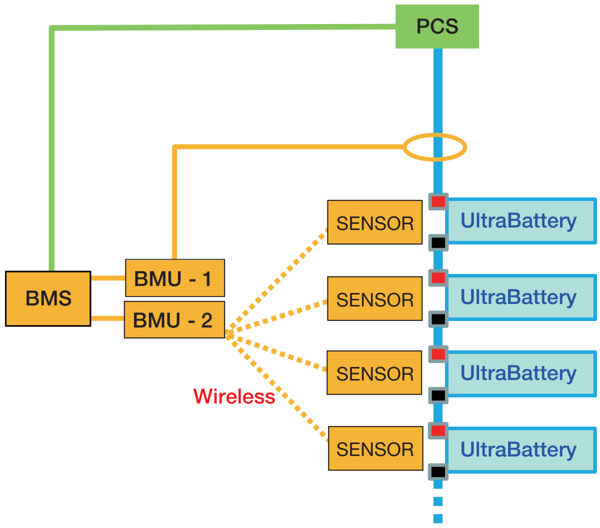

Figure 16 Battery Management System.

5. BATTERY MANAGEMENT SYSTEM

The battery management system (BMS) is the important system to protect storage batteries and to grasp the remaining capacities in storage systems, and to maintain high reliabilities of the systems. We have installed a BMS in the storage system of the Kitakyushu Smart Community Creation Project in joint development with Furukawa Electric Co., Ltd.

Figure 16 shows how the scheme of the BMS. Battery monitoring unit -1 (BMU-1) manages the currents, voltages and the temperatures of the whole assembled batteries. BMU-2 manages each battery's voltage, its inner impedance and the battery temperature which is transmitted from battery condition watcher (BCW) attached to each battery. The BMS aggregates and manages the data of the BMU-1 and -2, and transmits the information of SOC and state of health(SOH), etc. to PCS. The installation of the BMS enables the status determination of the storage batteries under the PSOC conditions, the lifetime determination by the inner diagnosis function in each cells and the transmission of the data of the storage battery statuses by connecting to a LAN. By installing the BMS in this demonstration, we received successive data of the storage battery status, we will be able to discover the behaviors of the storage batteries in operation, the improvement points and the problems. Their countermeasures and their improvements enable the optimization of the operation system.

6. CONCLUSION

We have developed the UB battery for micro HEVs whose battery life is 1.8 times longer than that of the existing batteries. We disassembled the batteries after the tests. As a result, the existing battery had softened positive active materials and significantly sulfated negative active materials. On the other hand, the UB had softened positive active materials, although it had scarce significantly sulfated negative active materials. This is one of the reasons why the UB obtained a good lifetime characteristics.

We obtained the following achievements in the development of the stationary UB.

(1) The stationary UB showed the Wh efficiencies of 91-94.5% in $0.1C_{10}A$ charge-discharge, and 83-87% in discharge $0.6C_{10}A$-charge$0.45C_{10}A$ in the range of SOC30-90%. That is, the UB had high Wh efficiencies not only in low charge-discharge currents but in high charge-discharge currents.

(2) The stationary UB had good capacity ratios of equal or exceeding 100% despite a recovery charge of once per 90 cycles in the PSOC test. It was also confirmed to have a superior recovery charge characteristics.

(3) The life performance of the stationary UB was about the double of the long-lived lead storage battery in the HR-PSOC test.

By the results above, we confirmed that the stationary UB has high energy efficiencies, superior lifetime characteristics and superior recovery charge characteristics under the PSOC condition.

We have been participating in the Kitakyushu Smart Community Creation Project, and as a member of this project, we have installed the developed stationary UBs and have started the demonstration in 2012.

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