Development of Grid-stabilization Power-storage Systems Using Lithium-ion Rechargeable Batteries

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Mitsubishi Heavy Industries, Ltd. (MHI) has been developing large-capacity lithium-ion rechargeable batteries for many years. In 2010, we started shipping 50-Ah-class batteries produced in our verification plant. We are also developing new products using lithium-ion rechargeable batteries such as stationary power-storage systems and auto-mobile power train systems for new and expanding markets. Large lithium-ion batteries must be handled very carefully because of their short-circuit current due to their low internal resistance. We have studied the module structure, control and monitoring circuits, power conditioners, and other components of large-capacity lithium-ion rechargeable batteries from the ground up to produce highly reliable systems.

1. Introduction

Renewable energy technologies such as photovoltaic (PV) power and wind power are being introduced countries other than Japan. President Obama has proposed the Federal Renewable Portfolio Standard to ensure that 25% of the total US energy production comes from renewable sources by 2025. The EU has announced a strategy to increase the renewable energy ratio to 20% by 2020. The March 2011 earthquake in Japan and the resulting disasters involving nuclear power plants are expected to favor the introduction of renewable energy sources.

Because achieving the renewable energy targets set by various countries will be difficult with current technologies, new innovations in energy production are required. In particular, new methods of efficiently controlling fluctuations in the output of renewable sources such as wind and solar will be necessary, and large rechargeable batteries appear to be a promising approach. Many countries, including Japan, have started testing grid-stabilization power-storage systems using various types of batteries. These include projects such as the “Grid-stabilization Power-storage System with Lithium-ion Rechargeable Batteries” initiative by the New Energy and Industrial Technology Development Organization (NEDO) that started in 2006, and systematic development of electric charging for complex systems that started in 2010. These play an important role in accelerating the development of large power-storage systems using lithium-ion rechargeable batteries.

In conjunction with Kyushu Electric Power Co., Inc. (KEPCO), we have been developing large-capacity lithium-ion rechargeable batteries for portable and stationary applications for many years. This review covers the technical development of grid-stabilization power-storage systems with rechargeable batteries and the results of the post-2006 NEDO effort to develop large electric power-storage systems.

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2. Cell Development

Grid-stabilization power-storage systems need large capacities, ranging from hundreds to tens of thousands of kWh, corresponding to their associated PV-power and wind-power facilities. They also require the following characteristics:

- High energy density, i.e., lightweight and having a small package size
- High charge/discharge rate in the range of 1–2C (C is the discharge rate of capacity/hour)
- Long operational life of 10 years or more, i.e., low operational cost
- Enlarged size for parts number reduction, i.e., low capital cost

Lithium-ion batteries can have a cylindrical, rectangular, or laminated structure. We selected the rectangular shape with a metallic container shown in **Figure 1** to ensure a compact size and adequate heat dissipation for cells in a grid-stabilization power-storage system requiring large battery capacity. **Table 1** shows the specification of cells developed for the NEDO project.

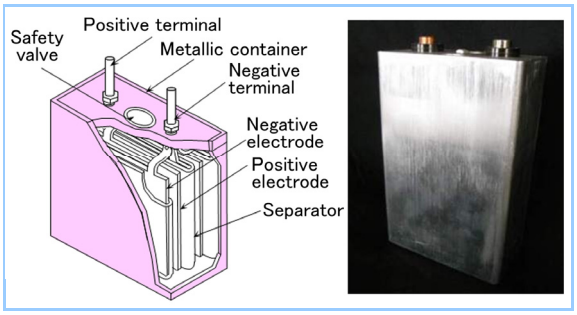

Figure 1 Rectangular laminated cell structure

Table 1 Specification of cells developed during the NEDO project

Item	Specification
Cell dimensions (mm)	116 W × 66.5 D × 175 H
Cell weight (kg)	2.7
Applicable voltage range (V)	3.1–4.15
Mean voltage (V)	3.8
Cell capacity (Ah)	91@1C

The cell must have a low internal resistance to be able to withstand high-current charge/discharge conditions. **Figure 2** shows the relationship between the current rate and discharge power capacity. The capacity at a discharge rate of 2C is only 8% less than the capacity at a rate of 0.2C, demonstrating that the cell is relatively robust under high electric current conditions.

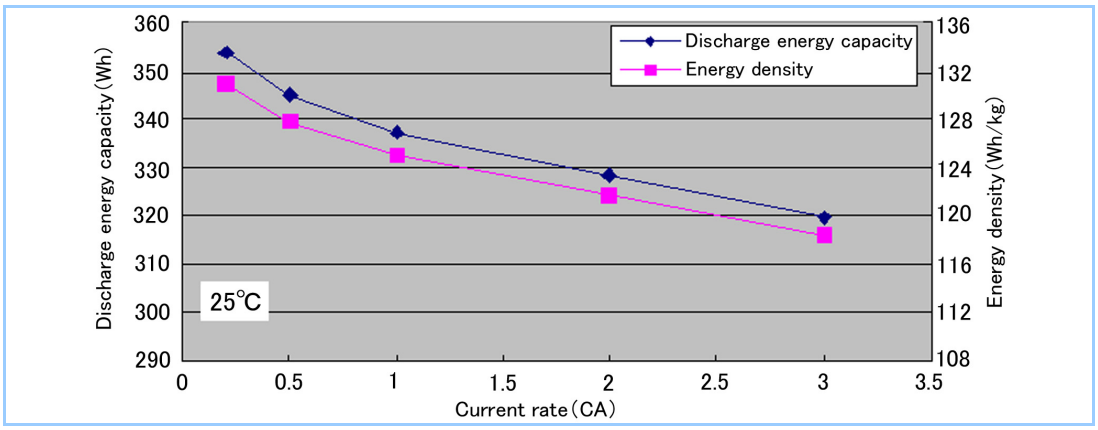

Figure 2 Discharge energy capacity as a function of current rate

A battery life test was performed in charging and discharging modes assuming a 30-minute time constant for smoothing based on the electric output of an existing wind power-generation system. **Figures 3**(a) and 3(b) show the charging and discharging test patterns, respectively. The test was conducted at 25ºC, 40ºC, and 50ºC using the following sequence.

(1) Check the initial capacity by discharging at a rate of 0.2C.
(2) Charge the battery from a 50% to 80% state of charge (SOC) using the charging pattern shown in Figure 3(a).
(3) Discharge the battery to a 20% SOC using the discharging pattern shown in Figure 3(b).
(4) Repeat steps (2) and (3) as one cycle.
(5) Check the capacity by discharging at a rate of 0.2C.

Figure 4 shows the results of a cyclic life test simulating the grid-stabilization of wind power generation.

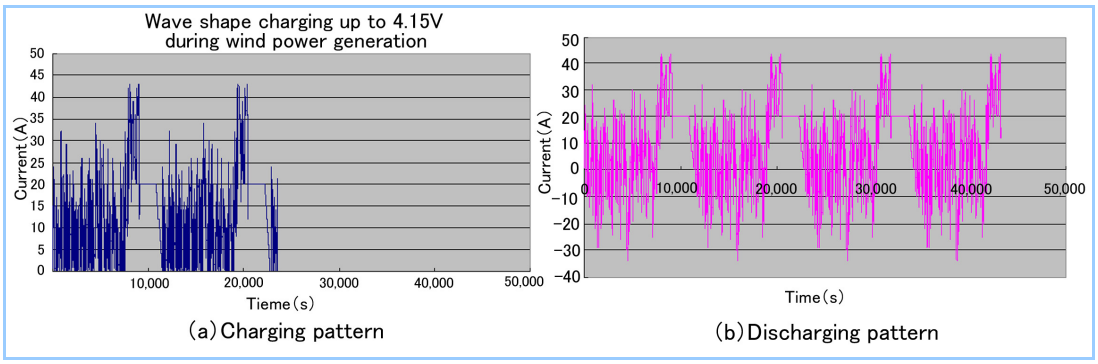

Figure 3 Charging and discharging patterns while simulating the stabilization of wind power generation

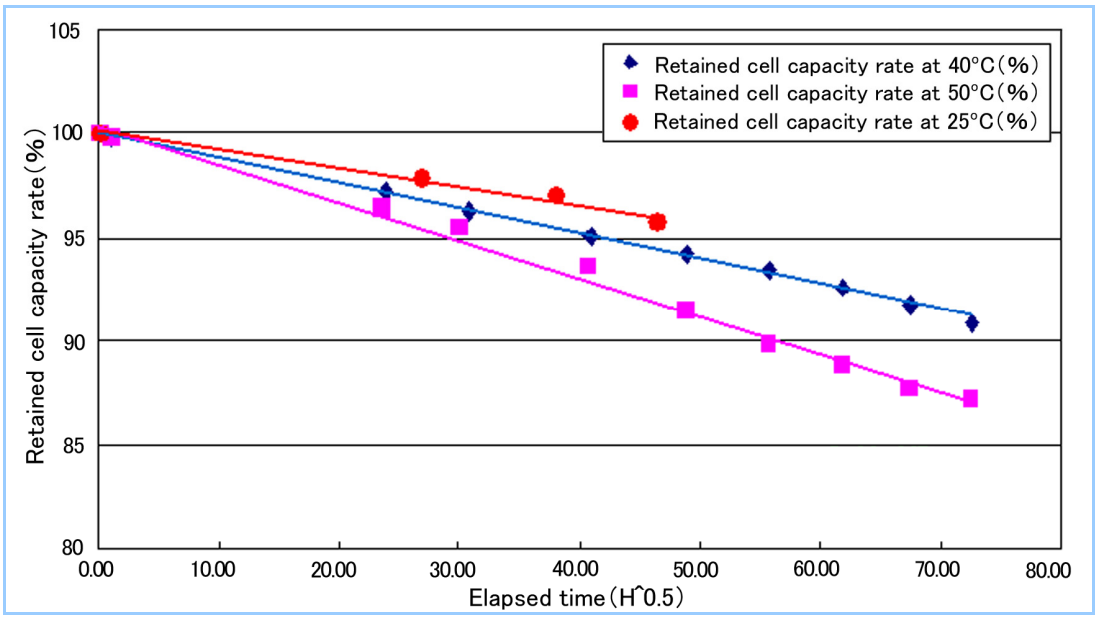

Figure 4 Cyclic life test while simulating the grid stabilization of wind power generation

The deterioration of cell capacity with age was verified to be a function of time, approximately linear to the one-half power. The capacity deterioration showed a temperature dependency that could be approximated with an Arrhenius plot. Based on this, the battery life was calculated to be approximately ten years by setting the end-of-life threshold to 70% of the initial capacity at room temperature. This ten-year lifespan seems reasonable compared to that of small lithium-ion batteries for consumer use, but is too short compared to the life of wind turbines and PV modules. One cause of deterioration is the temperature increase; the interior temperature rises approximately 8ºC at a 1C charge/discharge rate.

The design improvement objectives of a battery for the future are the following:

- Optimized size and structure considering the temperature and current distributions
- Selection of a stable electrode activation material
- Selection of an electrolyte and its additive considering the electrode surface reaction

Table 2 shows safety test results for this battery. It met the various testing criteria specified in the United Nations Recommendations on the Transport of Dangerous Goods under the conditions described therein.

Table 2 Safety test results using UN Recommendations for the Transport of Dangerous Goods

Test item	Test content	Test result			
		Blow out	Ignition	Voltage drop	Temp. rise
Altitude	20±5ºC, 11.6 kPa or less, left for 6 hr	No	No	>90%	-
Temperature	–40ºC to 75ºC oscillation	No	No	>90%	-
Vibration	Frequency: 7–200Hz, Acceleration: 8 G max	No	No	>90%	-
Impact	Acceleration: 50 G	No	No	>90%	-
External short circuit	Short-circuit resistance: 0.1Ω Cell temp: 55ºC	No	No	>90%	-
Impact	Drop 9.1-kg weight from 61-cm height	No	No	-	≤170ºC
Forced discharge	Discharge at the max current (2C)	No	No	-	-

3. System Development

A previous review introduced the experimental production of 100-kWh-class grid-stabilizing systems using large-capacity rechargeable batteries, and included preliminary evaluation results of cell balancing in grid-connected operations. The grid-stabilizing power-storage test system was connected to an actual renewable energy facility. Test operations have been underway since September 2010 with the system connected to PV modules installed at our Isahaya plant in Nagasaki Prefecture. This system is a small 120-kWh-class model connecting two 30-kWh-class battery unit boards in parallel through inverters with bidirectional choppers. Power-stabilizing operation tests were conducted at a 100-kWh PV power facility. **Figure 5** shows an overall schematic diagram, and **Figure 6** shows an external photograph of the system. **Table 3** lists various control parameters for the system.

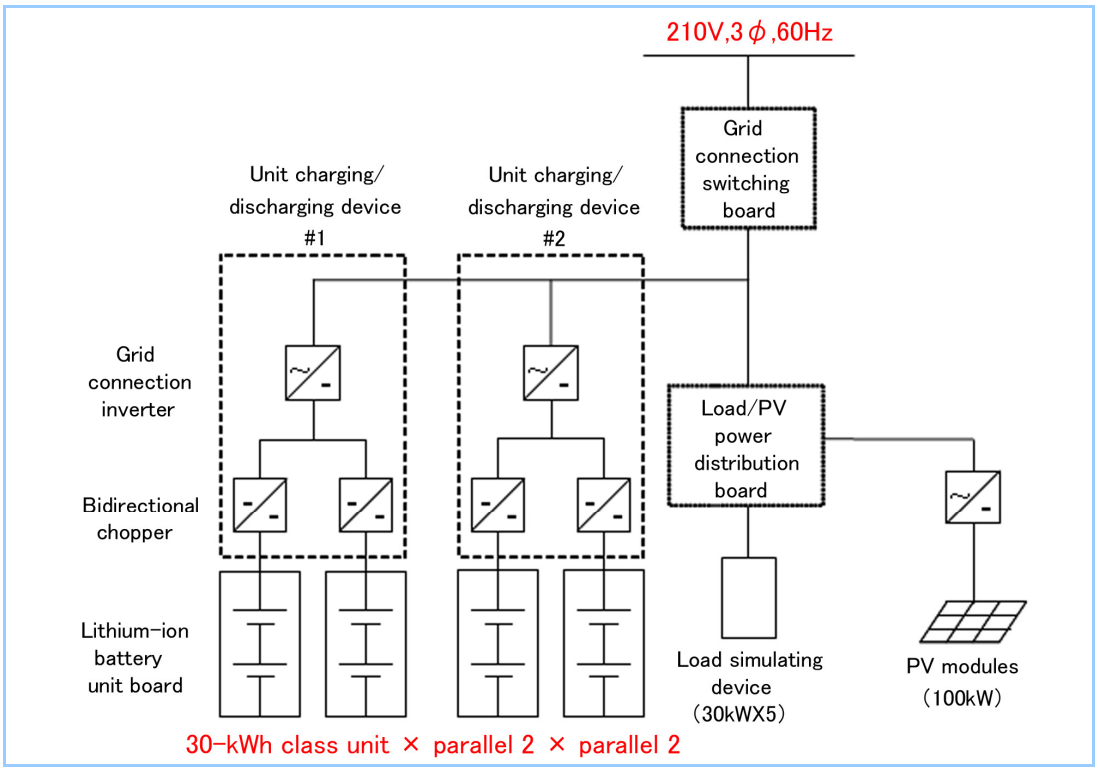

Figure 5 Schematic diagram of the grid-stabilization power-storage test system

Figure 6 External photograph of the grid-stabilization power-storage test system

Table 3 Stabilization control parameters for PV power generation

Hours of system operation	5 to 20 hours
Stabilization command	Transition mean value (average time, 20 minutes)
SOC maintain command	Control target: 50%
	Control gain: 800 W/kWh
SOC applicable range	20% to 80%

Figures 7(a) and 7(b) show the PV-module output and the final power output (PV modules plus lithium-ion batteries) after stabilization during continuous operation. These results confirm that the final power output was stable compared to the direct PV-module output. To evaluate the stabilizing effect, the degree of fluctuation suppression was measured in a fluctuating cycle lasting from several minutes to ten or more minutes, during which a load frequency control (LFC) unit was used as a stabilizing indicator, considering adverse effects to the LFC unit in distributed electric-power sources connected to the grid. In the electric-power spectrum distributions shown in **Figures 8**(a) and 8(b), the stabilization effect was high when the frequency value was small. In other words, the system countered the adverse effect to the LFC unit. The fluctuations at the affected frequency had a smaller final electrical power output than the original PV-module output due to the active power loss in the inverter, bidirectional chopper, and other components.

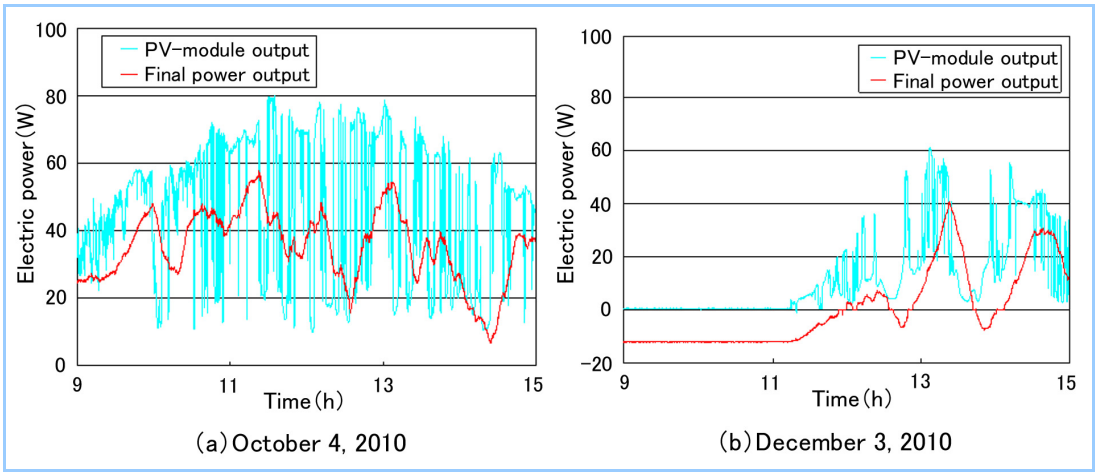

Figure 7 Examples showing transition of PV-module output and final power output after stabilization

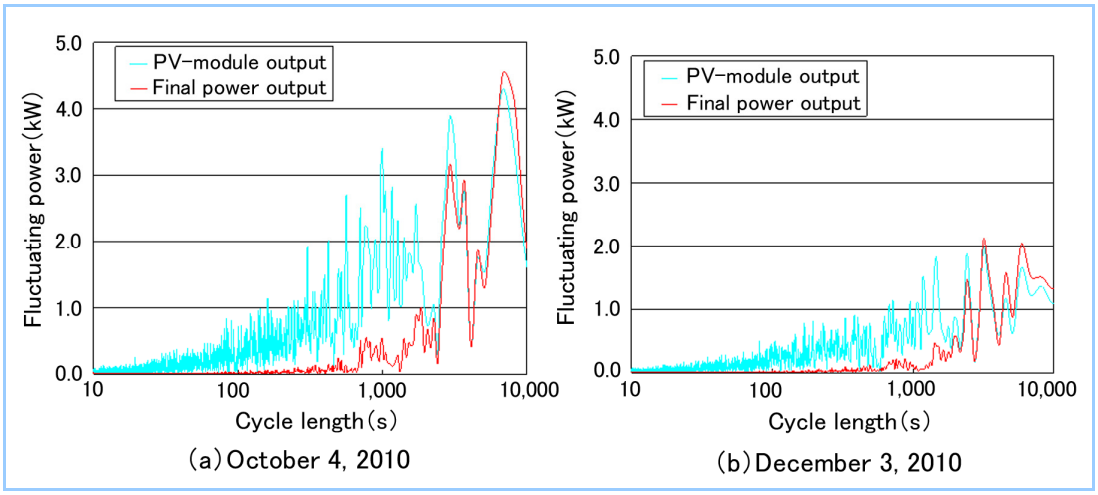

Figure 8 Examples showing electric-power spectrum distributions

Also for the solution in this control of degrading SOC with electric power conversion loss in converter and others, the maintenance of the SOC was also tested. **Figure 9** shows the SOC shift during a stabilizing test of a real PV system. **Figure 10** shows the daily range of the SOC during October. The SOC range was 40±10% at the start and end of the stabilizing operations, demonstrating that the control system facilitated long-term continuous operation. When the PV-module output changed suddenly, sufficient charging/discharging occurred to stabilize the system without causing any adverse effects. The SOC decreased to approximately 40% from the control target of approximately 50% at the start due to the electric-power conversion loss in the inverter and other components, as well as the auxiliary power loss. This value could be moved closer to the target position by adjusting the control gain. However, because of the adverse effect on the stability and the battery's wide availability over the SOC range in continuous operation, this unnecessary adjustment was not made.

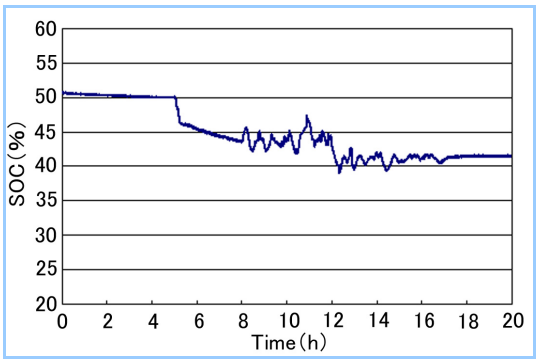

Figure 9 SOC shift while stabilizing during actual PV power generation (December 11)

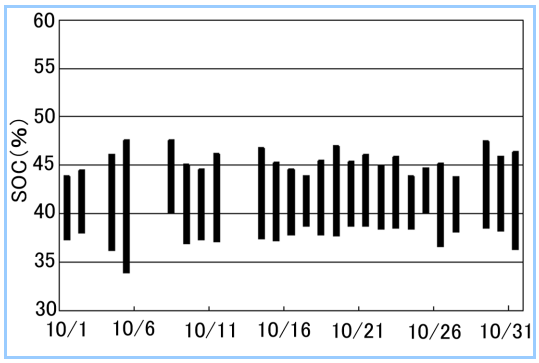

Figure 10 SOC range during continuous operation (October)

4. Practical Specifications

Based on the tests described above, various inverter and battery capacities were investigated to optimize the stabilization system for PV power generation.

(1) Investigation of inverter capacity

The cumulative distribution of the inverter output was calculated based on continuous-operation results from September 2010 to February 2011 to investigate the inverter working range and estimate the inverter capacity. **Figure 11** shows the cumulative distribution of the inverter output and the efficiency for the two 150-kVA inverters currently used. A comparison of the inverter efficiency and output distribution confirmed that the required inverter capacity was 80 kVA for a 100% response to the smoothing command in the 100-kW PV power facility used in this test.

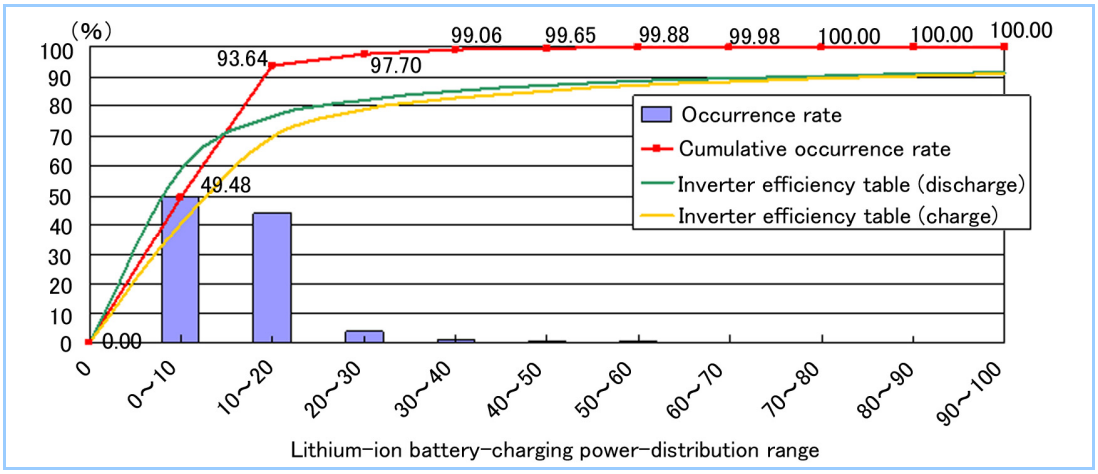

Figure 11 Cumulative distribution of inverter output and inverter efficiency

However, 99% of the inverter output was at 40 kW or less in the low-efficiency conversion zone. A 40-kVA inverter could satisfy 99% of the smoothing requirements and increase the operating frequency to the high-efficiency conversion range. The optimum inverter capacity for a grid-stabilization system with a rechargeable battery varies with the environment and with the power plant facility. In the PV power facility used in this test, an inverter with a capacity of approximately 40% of the generating capacity is appropriate considering the economic and system operating efficiencies.

(2) Investigation of the rechargeable battery capacity

A simulation was conducted to estimate the battery capacity using the data measured in this study. A 100-kW-class unit was used in the simulation, with one inline inverter and three parallel bidirectional choppers to match the PV-module-rated output. It had a rechargeable battery capacity of 25–100 kWh. The controlling gain was 400 W/kWh, and the target SOC was 50% in all simulation runs.

Figure 12 shows the simulation results. A large-capacity rechargeable battery allows operation close to the target SOC, and even in the case of 25-kWh capacity, 20% to 80% SOC operation was possible. Thus, a 25-kWh-class rechargeable battery capacity was sufficient for

operating with a 100-kW PV system. This is probably conservative because the SOC remained in the range of 50±20% for almost the entire simulation.

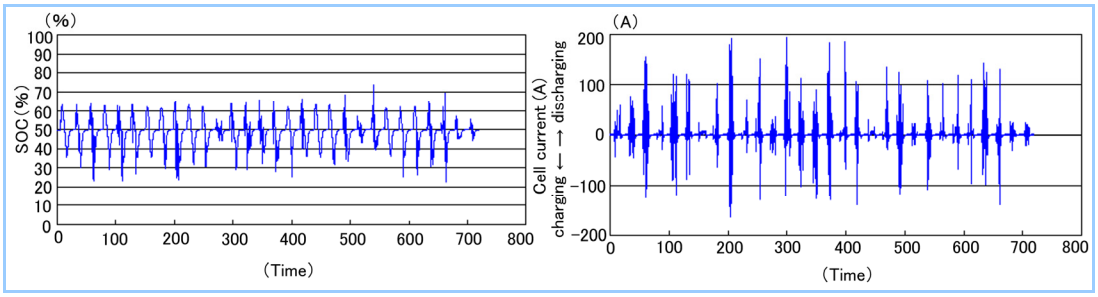

Figure 12 SOC operational range during continuous operation (October)

(3) Construction of a grid-stabilization power-storage system for a very large PV system

A grid-stabilization system with a rechargeable battery that connects units in parallel through a bidirectional chopper and inverter was considered and a simulation was conducted. A higher efficiency inverter without a bidirectional chopper was thought to be a promising approach to improving the system efficiency. A simulation of the system efficiency using real 100kW-class PV-module data with a 40-kVA inverter for showed that an operational efficiency of close to 90% was possible.

The results of the tests and calculations above indicate that a 2-MW inverter and a 1.25-MW-class rechargeable battery would be appropriate for a 5-MW PV system with battery grid-stabilization configured as shown in **Figure 13**. The 500-kW-class unit charging/discharging device would consist of ten lithium-ion battery boards stacked in parallel and connected to one inverter. The parallel connection of four sets would make a 2-MW system. The battery capacity of the minimum unit board would be 33 kWh, which is the same as the current system, and the capacity of a single charging/discharging device would be 330 kWh, or 1320 kWh in the system overall.

This system is but an example. The optimum inverter and rechargeable battery capacities will vary depending on the specific operational and grid conditions. This research provides the basis for designing grid-stabilizing systems with power-storage batteries tailored to various renewable energy generation facilities.

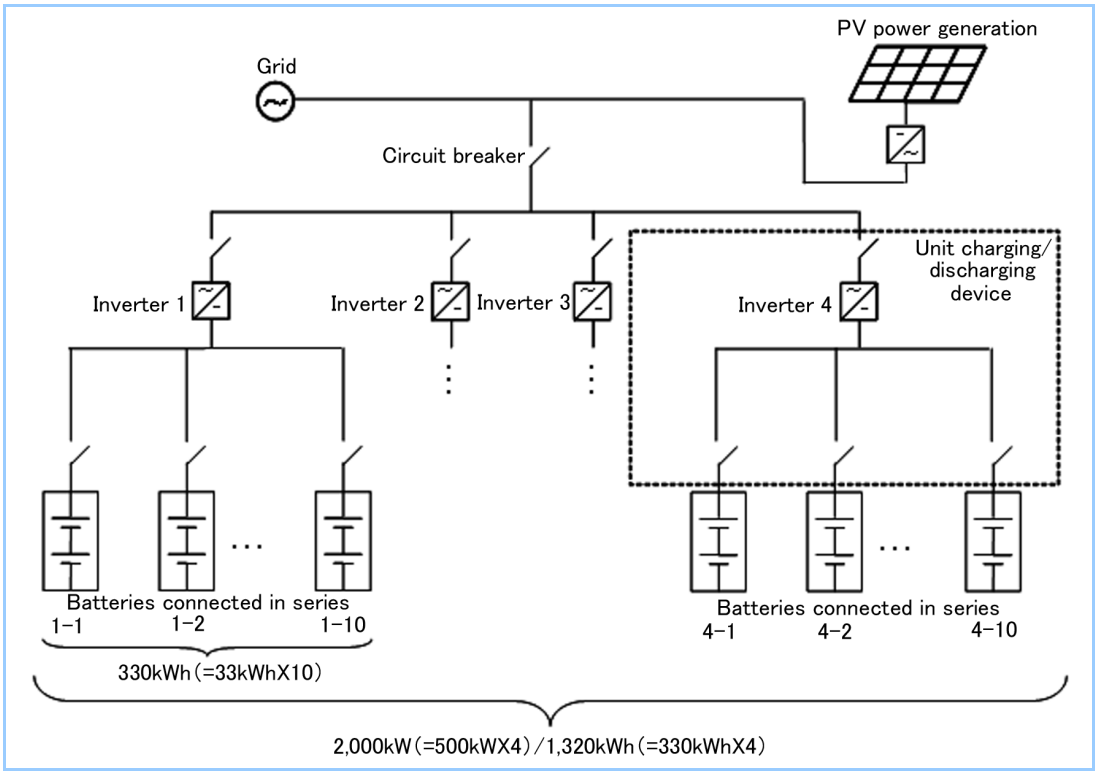

Figure 13 Suggested schematic for an optimized grid-stabilization system with a rechargeable battery for large-scale power generation

5. Conclusion

The US, EU, and Japan have announced plans to require that at least 20% of generated electrical energy come from renewable energy sources by the 2020s. PV-power and wind-power systems are prime sources of renewable but fluctuating energy. This will lead to an increasing requirement for grid-stabilization systems with rechargeable batteries. Such systems require high-performance, low-cost rechargeable batteries and appropriate control technology. Jointly with NEDO and KEPCO, MHI has developed a 120-kWh-class power-storage system consisting of large-capacity lithium-ion rechargeable batteries in series and parallel arrays. Issues related to the practical application of this system have been investigated during grid-stabilizing operations at the Isahaya PV power site. We will continue to work on increasing the performance and decreasing the cost of such systems even further, while developing a standard system that is larger in capacity and easier to transport. After testing in as many different types of renewable energy generation sites as possible, we intend to market this system commercially.

References

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