Contribution to the achievement of SDGs
by Furukawa Electric Group

Development of a Hierarchical Autonomous Decentralized Control Method in DC Microgrid

*Mitsuhiro Ito*1, Sumio Kachi*1, Junichi Kasahara*1,*
*Taihei Noro*2, Daisuke Watanabe*1, Tadataka Wakabishi*1*

ABSTRACT Aiming to accomplish the target of a carbon-neutral society in 2050, the large-scale introduction of renewable energies and the spread of electric vehicles are forecasted. It is a characteristic of these power sources to be input and output in direct current. The direct current power system, combined with direct current links, can reduce power losses that occur during the conversion from direct current to alternating current or vice versa. This results in economically superior operation compared to existing alternating current power systems.
In this research, we introduce our originally invented hierarchical autonomous decentralized control method which satisfies both the autonomous decentralized control to supply stable power robustly even against sharp fluctuations of the power demand and the total optimum operation to minimize the power rate. Additionally, we will describe the configuration of our small-scale model of the hierarchical autonomous decentralized control method constructed in our company, as well as the operation tests based on the demand and supply patterns during the summer, winter, and intermediate periods.

1. INTRODUCTION

Aiming to accomplish the target of carbon-neutral society in 2050, it is forecasted that renewable energies such as Photo Voltaic (PV) will be the main power source and that most of new vehicle sales will be replaced with Electric Vehicles (EVs)[1). However, we have problems to solve along with the large-scale introduction of renewable energies and EVs.

First, unstable power supply is mentioned as a problem because power sources with fluctuating output such as PV and wind power are considerably dependent on weather and seasons. Consequently, there are concerns that maintaining a balance between power demand and supply may become increasingly difficult, thereby elevating the risk of power failures.

Furthermore, electric power companies have been increasing their request to curtail the output along with the increase of the introduction of PV. When forecasting the demand and supply of power, an electric power company requests its power producers to stop the generation to avoid power failure when forecasting there will be an oversupply of power by PV generation, and the power producers have to follow the request. The amount of curtailed power output has been increasing year by year and it reached approximately 1,890 million kWh totally all over Japan in Fiscal Year 2023[2)]. If these conditions persist, renewable energy may be perceived as inefficient, potentially hindering its further adoption.

Further, the costs associated with electricity purchased from renewable energy producers, as well as the expenses related to the reinforced transmission and distribution infrastructure for renewable energy generation, will be passed on users' electricity bills.

Considering those mentioned above, it is desirable for the future power system required for a carbon-neutral society to be a self-consumption type of power system that promotes local energy production and consumption. This system alleviates the burden on existing grids while enhancing environmental sustainability and economic efficiency during normal operations, as well as resilience during disasters.

When consuming renewable energy self-consumption, power conversion loss is reduced by combining such devices as PV, EV and storage batteries in direct current links because these are direct current devices, and as a result the renewable energy can be used under a higher efficiency. Further, users in the area can continuously use electric power by effectively utilizing PV and storage batteries even during power failures of the grid.

Furthermore, when applying direct current, the control is simpler compared with that of alternating current because it is unnecessary to consider such as frequency

*1 Electronics Laboratory, Research & Development Division
*2 Laser Business Department, Global Marketing Sales Division

and phase. like alternating current, and the quality of electric power supplying to load devices is improved. Moreover, we can get such merit as to reduce such problems as harmonics and flickers caused by fluctuations of demand. The electric power system in which direct current devices are combined in direct current links is called Direct Current MicroGrid (DC-MG) and its demonstration examples are reported in Japan and overseas as well (Figure 1)[3), 4)].

On the other hand, until now, there has been insufficient progress in establishing standards related to direct current. Therefore, it is necessary to formulate safety standards and create conditions for interoperability among different vendors[5), 6)].

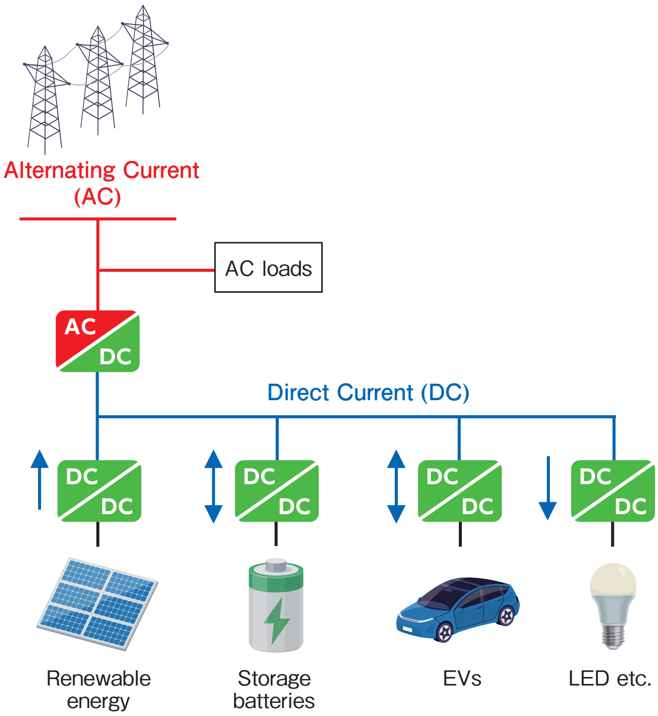

Figure 1 Schematic diagram of DC-MG.

2. CONTROL METHOD OF DC-MG

2.1 Central Control and Autonomous Decentralized Control

In general, the central control method is known as a DC-MG electric power control method (Figure 2). This method involves a single Energy Management System (EMS) that controls all devices and optimizes their overall operation. However, it requires high-speed communication between the EMS and the converters, which introduces a risk of all devices becoming inoperative due to communication failures during disasters or a single point of failure in the EMS. Additionally, when adding new devices, it is necessary to upgrade the EMS and establish a high-speed communication network, which results in low expandability of the system configuration. On the other hand, an autonomous decentralized control method (Figure 3) is such a method that controls each device according to the voltage at its own output/input terminals measured by each device itself. Although we have difficulty in optimizing its total operation, the communication cost can be reduced, because no high-speed communication is required between the EMS and converters[7)].

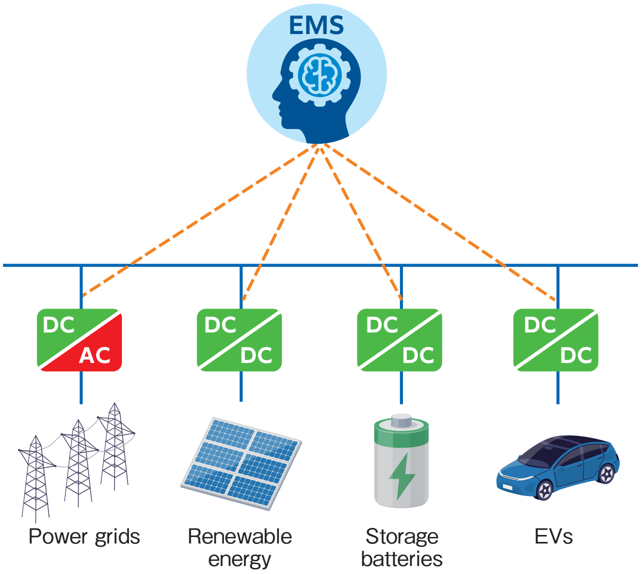

Figure 2 Schematic diagram of a central control.

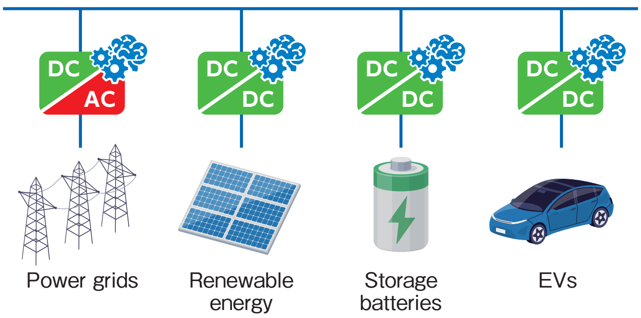

Figure 3 Schematic diagram of an autonomous decentralized control.

And we can construct a highly reliable system, which works even when communications are temporarily interrupted to avoid all the devices being stopped by a single failure. Observing these merits of the autonomous decentralized control method, we, authors, have been examining the DC-MG.

2.2 The Autonomous Decentralized Control Using the Voltage Margin Control Method[8), 9)]

The voltage margin control method as shown in Figure 4 is a combined method with a Constant Power (CP) control which keeps the power value constant and the Constant Voltage (CV) control which keeps the voltage value constant. Each device measures voltage at its own output/input terminals and determines its control mode and its target value according to the voltage. This voltage margin control method has an advantage to achieve an autonomous decentralized control with a comparatively easy structure of CP control and CV control. On the other hand, it has a disadvantage that only one CV control device can be set up in each voltage area, because the output sharing is not fixed, and the bus voltage becomes unstable when there are two or more CV control devices. Therefore, when charging and discharging more than two storage batteries or EVs, it is not possible to autonomously and flexibly control the ratio of charging and discharging amounts between the storage batteries or between the EVs. This leads to deviations in the State of Charge (SOC) of the batteries and unequal charging times among devices, as revealed by our examination. Moreover, to prevent interference among devices, it is necessary to establish a certain voltage difference in the set up voltage of the CV controller for each device, which results in a limitation on the number of devices that can be connected.

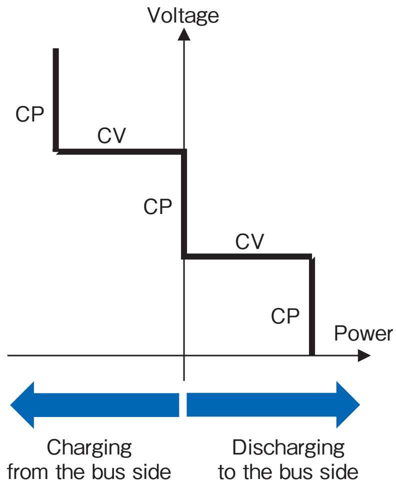

Figure 4 Voltage-margin control method.

2.3 The Autonomous Decentralized Control Using the Droop Control Method

We have examined the adoption of the Droop control method as an autonomous decentralized control to solve the problems mentioned above[10]. The Droop control is a method in which the relationship between electric power and voltage changes linearly, as shown in Figure 5. The linear function is called the Droop function. Giving a slope to the function in this a way, the voltage equilibrium point can be fixed to make the bus voltage stable even when the same function is set up on two or more devices. When making the slope of the Droop function steeper, not only the controllability becomes better but also enhances noise immunity, however, on the other hand, we have such trade-off relationships that wider voltage range is required. Setting the Droop function properly, the ratio of charging and discharging among either storage batteries or EVs can be freely controlled in an autonomously decentralized way. For example, using the same Droop function among two or more devices, equal charging and discharging can be realized with no occurrence of a deviated SOC of batteries or an unbalanced charging for EVs.

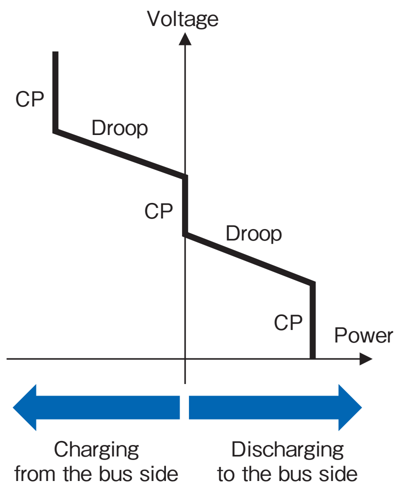

Figure 5 Droop control method.

3. HIERARCHICAL AUTONOMOUS DECENTRALIZED CONTROL

Although the Droop control can solve the problems of the existing voltage margin control method, the Droop control alone cannot optimize system operation because it is a sort of an autonomous decentralized control method. Therefore, we have combined total optimal control with autonomous decentralized control to develop a new hierarchical autonomous decentralized control system, which aims to achieve optimal control using the Droop control method.

3.1 An Outline of the Hierarchical Autonomous Decentralized Control

The hierarchical autonomous decentralized control is composed of the total optimum control and the autonomous decentralized control (Figure 6). In the total optimum control, the optimum energy operation plan is made based on a demand forecast and a PV generation fore-

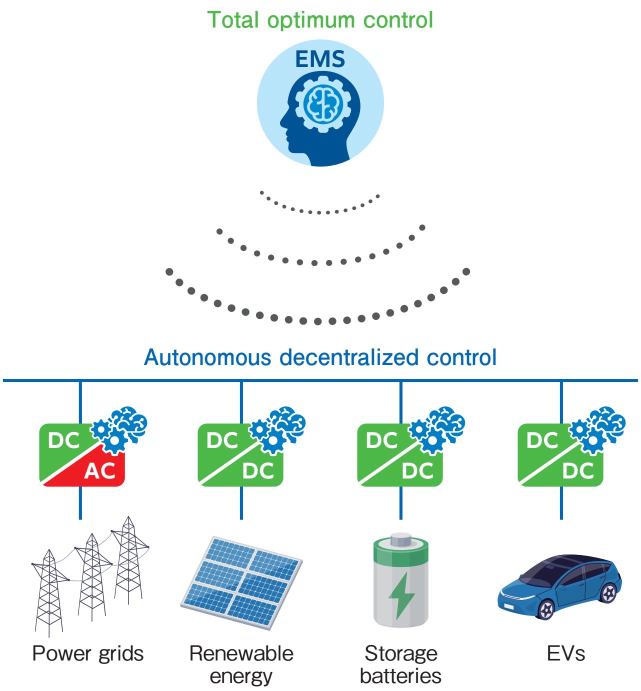

Figure 6 Schematic diagram of a hierarchical autonomous decentralized control.

cast, and the Droop function is designed. On the other hand, in the autonomous decentralized control, the Droop control is carried out based on its own output/input terminal voltage and the received Droop function to achieve a stable control of bus voltage in cooperation with two or more devices. For example, total optimal control is implemented in EMSs, while autonomous decentralized control is implemented in the power converters. This hierarchical autonomous decentralized control enables the economically rational and stable management of multiple devices connected to the DC-MG.

3.2 Total Optimum Control

In the total optimum control, an EMS carries out a mathematical optimized calculation based on an evaluation criteria (for example, minimization of power charge, etc.) and decides its operation plan. Furthermore, the EMS designs a Droop function not only to achieve the decided operation plan but also to maintain stable bus voltage and transmits the Droop function together with such information as a target SOC and contract power. A cycle of total optimum control is supposed to take from several ten minutes to one hour.

3.3 The Autonomous Decentralized Control

In the autonomous decentralized control, each control device observes its own output/input terminal voltage and carries out the Droop control following a received Droop function. A Droop function is set up for each device shown in Figure 7 and it is dynamically updated based on local information observed by each device (for example, SOC of storage batteries, accumulated power, power failure information, information of interrupted communications with EMS, etc.), (for example, the Droop function may be changed to prioritize charging when the present SOC is lower than the target SOC, or the Droop function may be changed to reduce purchasing power from the grid when its contract power may be exceeded, ... etc.).

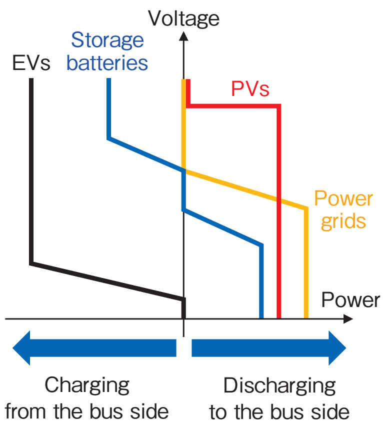

Figure 7 Example of Droop function for each device.

4. DEMONSTRATION

4.1 Demonstration Configuration

To demonstrate that a hierarchical autonomous decentralized control applied with the Droop control method can operate two or more storage batteries and EVs optimally and stably as well, we have constructed a small-scale model demonstration system applied with simulated devices. Figure 8 shows the schematic diagram of the constructed DC-MG small-scale model, and Table 1 shows specified rating of each device which makes the DC-MG.

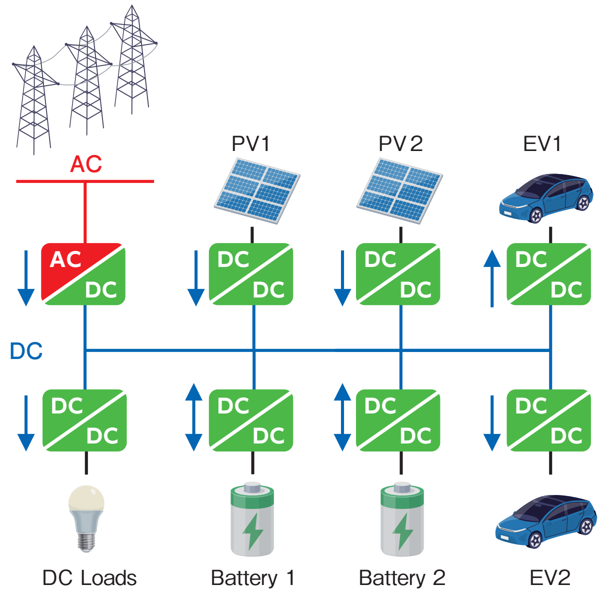

Figure 8 Schematic diagram of the demonstration system.

Table 1 Specified rating of each device.

Devices	Rating
DC/DC converter	300 W
Batteries	100 W / 700Wh (per a battery)
EV	200 W / 100Wh (per an EV)
PV	125 W (per a PV)
DC Loads	150 W

In addition, in this demonstration, batteries and alternating current power grids were substituted with bidirectional stabilized direct current power supplies, PVs were substituted with direct current supplies and circuit devices simulating PV output characteristics, and EVs were substituted with lead storage batteries. And AC/DC unit is substituted not with an inverter but with such a same type of DC/DC converter as those for other devices, and the demonstration was conducted.

In this demonstration, we have examined the following four items, (1) whether the bus voltage was operating within its normal range, (2) whether the SOC in two batteries did not deviate but settled within a normal range, (3) whether two EVs equally controlled the charging when the surplus charged power in the bus was insufficient during simultaneous charging of the two EVs, and (4) whether the purchasing power averaged in 30 minutes did not exceed the contract power.

4.2 Setup of Battery 1 and Battery 2

Setting up the normal operation range of SOC to be from 25% to 95%, we carried out the autonomous decentralized control to make the SOC closer to the target SOC determined by the total optimum control. For example, when a deviation occurs between the target SOC and the actual SOC caused by forecasting gaps and so on as shown in Figure 9, the control is executed to adjust the actual SOC towards the target SOC by changing the usual Droop function to the Droop function which gives priority on charging or discharging. In this demonstration, both Battery 1 and Battery 2 use the same three functions which are a usual Droop function set by EMS, a Droop function giving priority on charging and a Droop function giving priority on discharging, and then charging or discharging is achieved equally between two batteries.

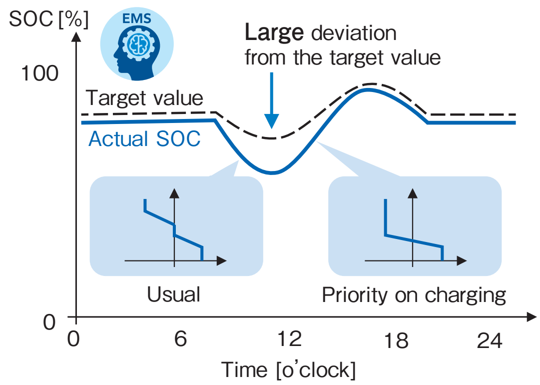

Figure 9 Schematic diagram of a SOC control.

4.3 Setup of EV 1 and EV 2

An EV is fully charged (SOC 100%) twice a day. It is set up that charging EVs starts at around 10 o'clock for two EVs and at around 17 o'clock for one. Further, it is not supposed to forecast when EV will start by the total optimum control. In this demonstration, EV 1 and EV 2 use the same Droop function for charging set up by EMS to achieve equal charging suppression between the two EVs.

4.4 Setup of Alternating Current Power Grids and AC/DC

The contract power is set at 130 W, and autonomous decentralized control is implemented to ensure that the purchasing power from the AC grid does not exceed this contract power. For example, if the actual purchasing power from the grid is high and is about to exceed the contract power, control will be implemented to reduce the purchasing power. Conversely, if the purchasing power is low, control will be implemented to increase the purchasing power within the allowable limits. In addition, in this demonstration, no alternating current loads are connected to the alternating current side of the AC/DC unit and input power at this side of the AC/DC unit is considered to be the purchasing power as it is.

4.5 Setup of PV1, PV2 and Direct Current Loads

As shown in Figure 10, we prepared a PV generation pattern peaked around noon and a direct-current demand pattern which became maximum from 9 o'clock to 12 o'clock. And we remotely controlled a direct-current supply and direct-current demand by a Personal Computer (PC) every 10 seconds to achieve each pattern. It was set up that approximately from 60% to 120% of forecast gap would occur for PV and approximately from 80% to 120% of forecast gap would occur for direct-current demand in the forecast data of the PV and demand used by the EMS.

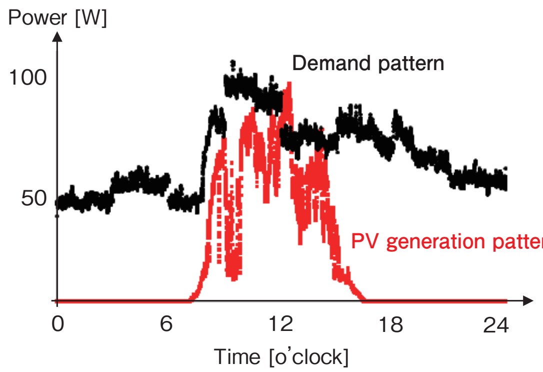

Figure 10 Patterns of demand and of a solar power generation.

5. RESULTS AND INVESTIGATION OF THE OPERATION TEST

The results of the operation test are shown in Figure 11. From the top, changes of bus side power of each device, bus voltage, SOC of Battery 1 and Battery 2, and moreover the purchasing power averaged in 30 minutes are shown along with respect to time. The purchasing power averaged in 30 minutes is the data on a 30-minute basis and all of the other data are measured at every 10 seconds. Observing the results of changes in the bus side power along with respect to time, we can find that the balancing of power demand and supply is controlled equally throughout the day.

5.1 Operation Result of Bus Voltage

From the results of changes in bus voltage along with respect to time shown in Figure11, we have confirmed that the bus voltage was operating within a normal range all day through. In the Droop control, because the bus voltage rises and falls along with the power balance of the bus, the bus voltage increases at a time period (around 12 o'clock) when PV generates a large amount of surplus power and on the contrary, the bus voltage decreases at a time period (around 10 o'clock and 17 o'clock) when the power falls short caused by charging EVs as a result. Furthermore, the bus voltage was separately measured at the DC/DC converter at a rate in the order of 10 ms in addition to the data at every 10 seconds to confirm that the operation was maintained within a normal range.

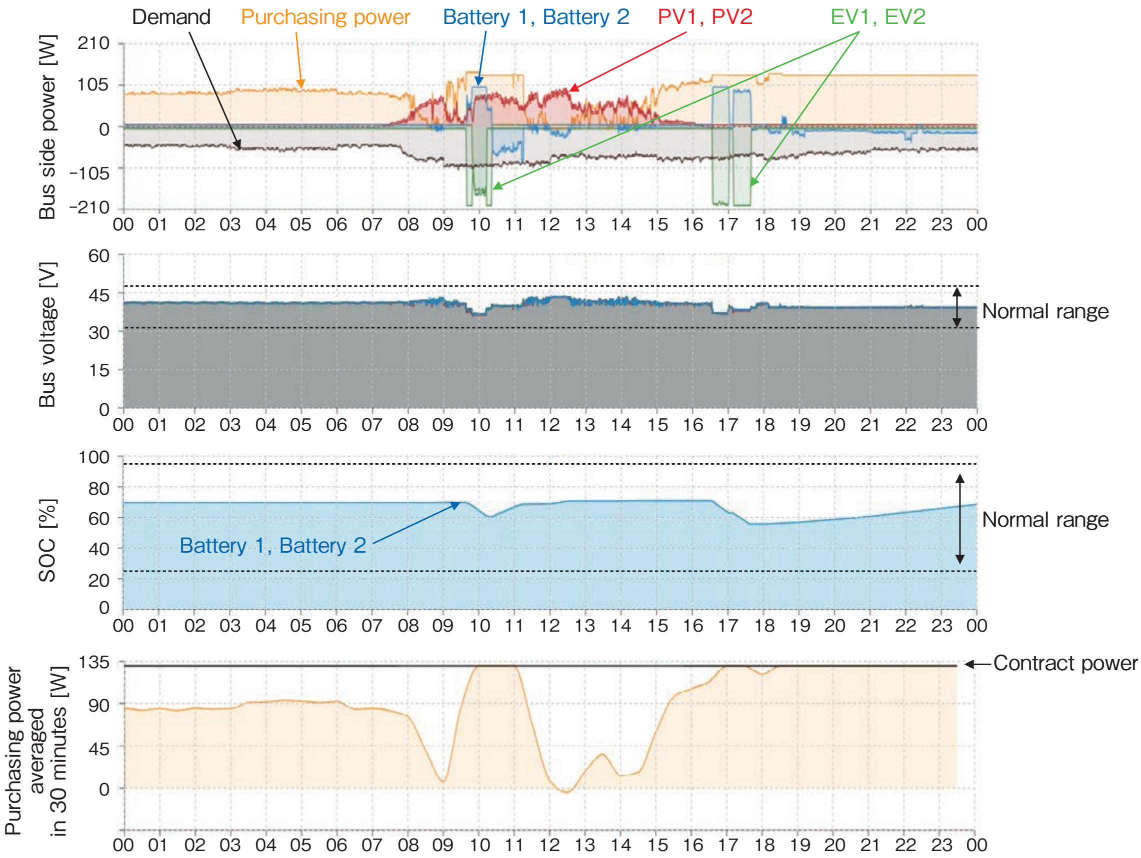

Figure 11 Results of the operation test.

5.2 Operation Result of Battery SOC

We have confirmed that the SOC of Battery 1 and Battery 2 did not deviate from each other (almost overlapped on a graph) and stayed within a normal range based on the result of changes in the SOC of the two batteries with respect to time as shown in Figure11. Figure 12 shows a comparison with the results of the same test applied with the voltage margin control method. In these test conditions in which the battery charging starts around half past 10 o'clock, an order of priority for the charging has to be fixed because no same function can be used for both Battery 1 and Battery 2 in the voltage margin control

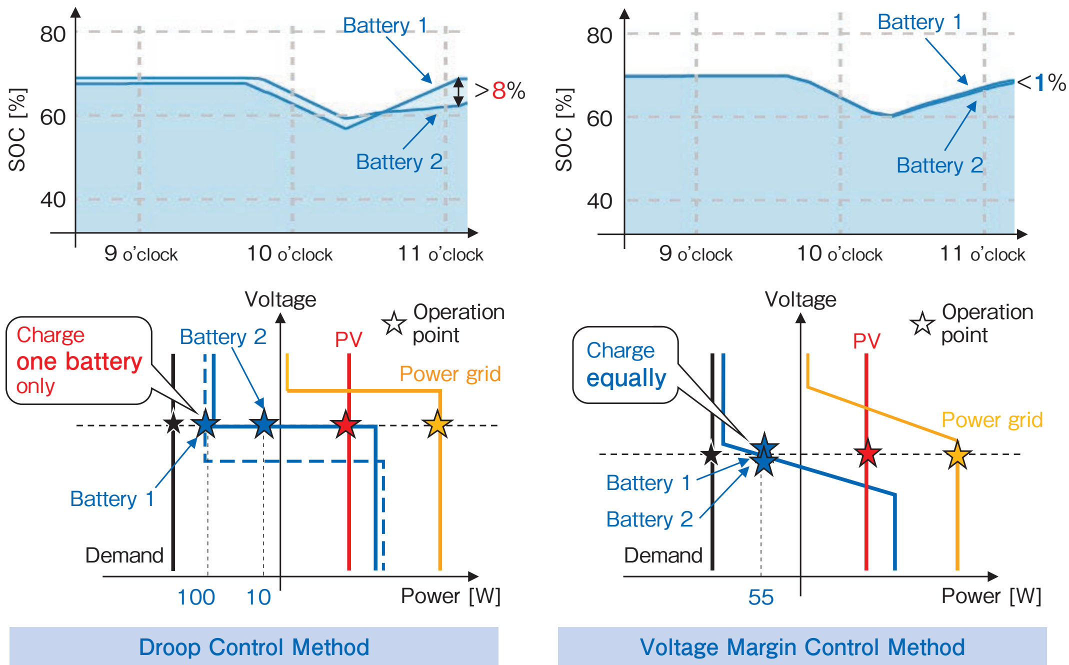

Figure 12 Comparison of the Droop Control Method and the Voltage Margin Control Method in battery charging.

method. In the function setup shown in Figure 12 (a blue solid line shows the voltage margin function for Battery 2, and a blue broken line shows that for Battery 1), Battery 1 is given priority to be charged. As a result, no less than 8% of SOC deviation has been generated. On the other hand, in the Droop method, the same function is applied to charge Battery 1 and Battery 2 equally and almost no deviation of SOC occurs. Therefore, we have confirmed that the Droop method can equally control charging and discharging of two or more batteries.

5.3 Operation Result of EV Charging

Simultaneous charging of EV 1 and EV 2 occurred around 10 o'clock as shown in the results of bus side power in Figure 11. In this time period, because there is not enough power to compensate for the charging amount (200 W × 2 = 400 W) from other devices (power grids, PVs, and storage batteries), a reduction in the charging amount occurs in the EV side. We have confirmed that both of two EVs equally carried out the suppression of charging at this time. A comparison with the test results applied with the voltage margin control method is shown in Figure 13. An order of priority for the charging has to be fixed because no same function can be used for both EV 1 and EV 2 in the voltage margin control method in the same way as the batteries. In the function setup shown in Figure 13 (a green solid line shows Voltage Margin Function for EV 2, and a green broken line shows that for EV 1), as EV 1 was given priority to be charged and only the charging of EV 2 was suppressed, so EV 2 had started its charging earlier but the inequitably resulted in both chargings completed at almost the same time. On the other hand, in the Droop Method, EV 1 and EV 2 were equally controlled to be suppressed, and we have confirmed that the Droop control method can equally control charging and discharging of two or more EVs.

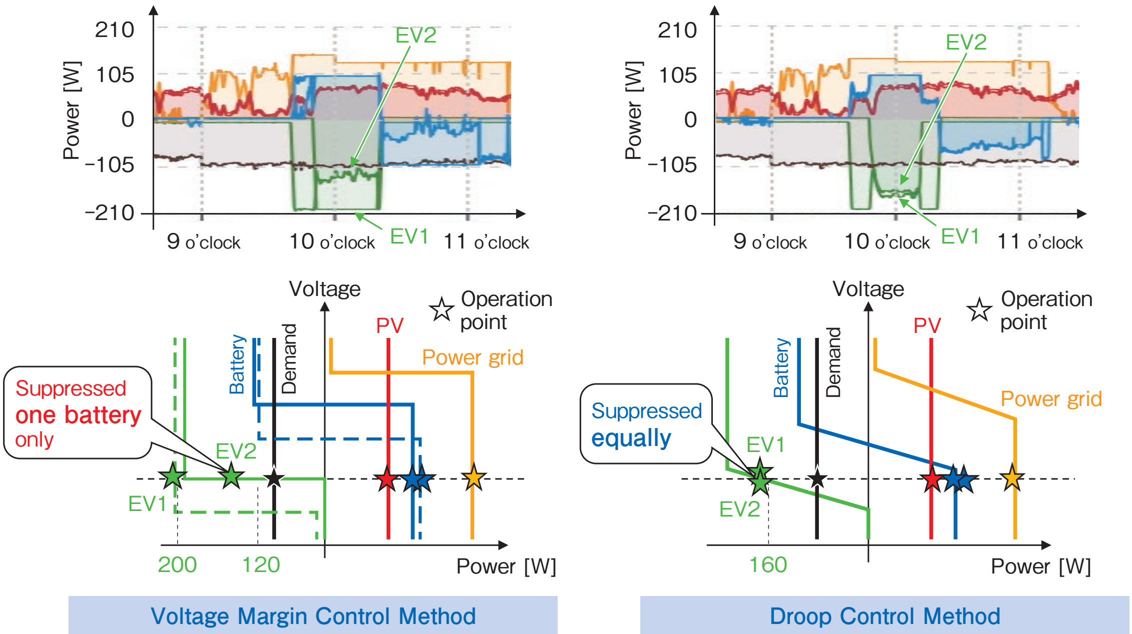

Figure 13 Comparison of Droop Control Method and Voltage Margin Control Method in EV charging control.

5.4 Operation Result of Power Grid Purchasing Power

From the results of changes in purchasing power averaged in 30 minutes shown in Figure11, we have confirmed that the purchasing power was carried out within a range of the contract power all day through. Especially around 10 o'clock and 17 o'clock EVs were charged along with the purchasing power at a maximum within the contract power. And after 18 o'clock batteries were charged in the same way along with the purchasing power at a maximum within the contract power to recover the SOC of batteries lowered by charging EVs.

5.5 Operation Result of Long-Term Test

Preparing both PV generation pattern and direct current demand pattern (for 28 days) during the summer period, the winter period and the intermediate periods, we conducted the same operation test duration of 28 days. As with the previous operational tests, evaluations were performed at four points, confirming that normal operations were maintained throughout the 28-day period.

6. CONCLUSION

We have confirmed that the hierarchical autonomous decentralized control method enables correct operation during the summer, winter, and intermediate periods, effectively eliminating the deviations in SOC and the inequalities in EV charging caused by fluctuations in power control among multiple storage batteries, as identified in conventional control methods.

In this study, we demonstrate control that allows for equal charging and discharging of both EVs and storage batteries. The ratio of charging and discharging is optionally controllable and therefore economically rational energy management can be achieved in compliance with the intention and behavior of users and the capacity of storage batteries.

In the future, we will proceed to a real-scale demonstration using the technology developed in this study, aiming for its social implementation of a direct current microgrid.

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