Development of DC Microgrid Control Method

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ABSTRACT Looking ahead on the future energy infrastructure such as the decarbonization and others that contributes to the Sustainable Development Goals (SDGs), Direct Current Microgrids (DC-MGs) have been attracting an interest as a mean to contribute to the expansion of renewable energies, storage batteries and Electric Vehicles (EVs). In order to implement the DC-MG in the society, it is important to establish an economical and stable power control technology. In this paper, we will introduce the hierarchical decentralized control, which is characterized by the introduction of Droop control and virtual inertia control to the primary control.

1. INTRODUCTION

In the process of realizing a carbon-neutral society (decarbonized society) by 2050, it is expected that renewable energies will become the main power sources and the spread and expansion of Electric Vehicles (EVs) will steadily progress. Since renewable energies, storage batteries, EVs and etc. are all Direct Current (DC) devices, it is thought that areas where the features of DC can be utilized will surely emerge in the existing Alternating Current (AC) power grid.

Since the widespread adoption of renewable energy sources with unstable power generation capacity and EVs as a new power load may induce the instability in the existing power grid, DC-MGs are attracting interest as a mean of realizing the future power and energy infrastructure.

An MG is a system that controls the energy supply and demand in a specific region by combining small-scale and a variety of decentralized power sources and it is a technology that supports the maintenance of power quality comparable to that of the power grid during an autonomous operation and the introduction and expansion of renewable energy sources such as Photo Voltaic (PV), wind power, etc[3].

In the power system applying the DC technology, the DC power can be used without converting to DC, so that the energy loss can be suppressed and the power can be converted by the simple voltage control without a frequency and phase control.

The DC-MG (Figure 1) is a fusion of this DC technology and the MG, and it is important to establish an economical and stable power control technology in order to implement the DC- MG in the society. This paper will introduce the hierarchical decentralized control, which features the introduction of Droop control and the virtual inertial control techniques for the primary control.

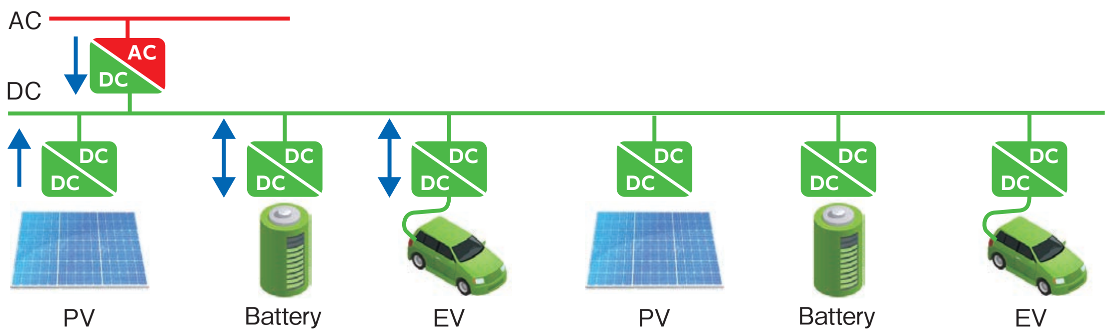

Figure 1 Figure 1 Outline diagram of DC-MG.

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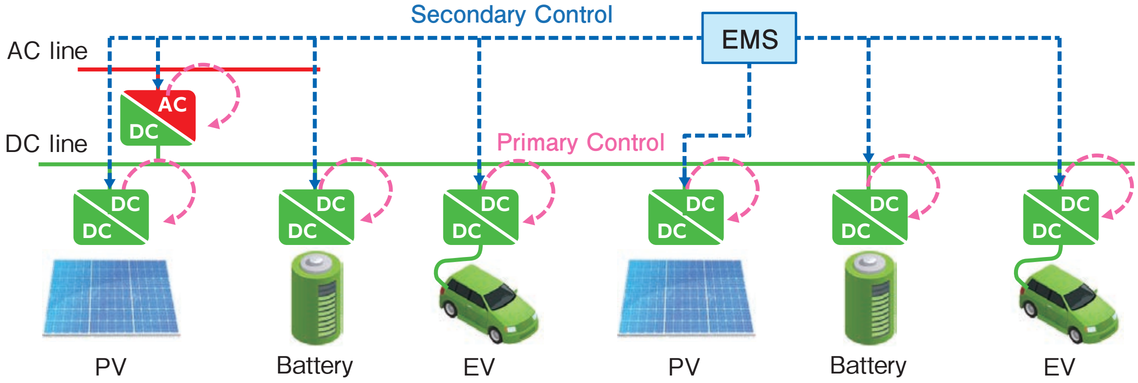

Figure 2 DC-MG hierarchical decentralized control.

2. FEATURES OF OUR CONTROL METHOD

2.1 Hierarchical Decentralized Control

Figure 2 shows the hierarchical decentralized control consisting of the primary control and the secondary control in a DC-MG where the power devices of grid power supply, PV, storage batteries and EV charger/discharger are connected to the DC line. The primary control is a decentralized control installed in the power converters within each device and the secondary control is a centralized control installed in the Energy Management System (EMS).

In the primary control, each power equipment plays a role in controlling the DC line voltage stabilization and the power conversion in a decentralized manner based on the EMS commands. When the EV rapid charger/discharger connected to the DC line operates, a sudden load fluctuation occurs so that the conventional centralized control method cannot follow the voltage control, resulting in unstable operation of DC-MG. On the other hand, in the decentralized control method, multiple power devices perform the voltage control in a decentralized manner, so that it can also follow sudden load changes.

In the secondary control, the EMS performs optimization calculations (derivation of target functions) based on the evaluation index (minimization of operating costs, etc.), and plays a role in sending communication commands (target functions) to each electric devices such as storage batteries and others. Target functions that reflect the evaluation index are used to achieve an efficient DC-MG operation.

The hierarchical decentralized control, which combines the primary control and the secondary control, can be applied to countermeasures against sudden changes in the power supply and demand, effective utilization of resources, etc., because it can achieve both the control stability and the control efficiency, which are the characteristics of each control.

2.2 Droop Control

The hierarchical decentralized control in this paper is built on the basis of Droop control. The Droop control can be classified into the Droop voltage control and the Droop current control according to the implementation details of the control.

The Droop voltage control is a voltage control in which the target voltage V_{out} varies linearly according to the observed current I_{obsv}. Let the proportionality coefficient be $-R$, the target function is determined by the following equation.

$$V_{out} = V_o - R * I_{obsv} \quad (1)$$

Controlling the power converter looks equivalent to a voltage source Vo + series resistance R, as shown in Figure 3.

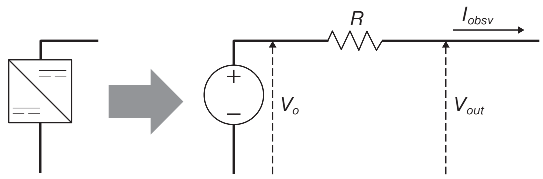

Figure 3 Droop voltage control.

In the Droop voltage control, by adjusting V_o and R, the voltage of DC line can be stabilized while the load sharing for the power conversion among devices is implemented according to the amount of power required for the DC line. In addition, if R is set to 0, Constant Voltage (CV) control is achieved, so that the Droop voltage control is an extension of so-called CV control.

Similarly, the Droop current control is the one in which the target current I_{out} varies linearly according to the observed voltage V_{obsv}. Let the proportionality coefficient be $-1/R$, the target function is determined by the following equation.

$$I_{out} = I_o - \frac{1}{R} * V_{obsv} \quad (2)$$

Controlling the power converter looks equivalent to a voltage source I_o + series resistance R, as shown in Figure 4.

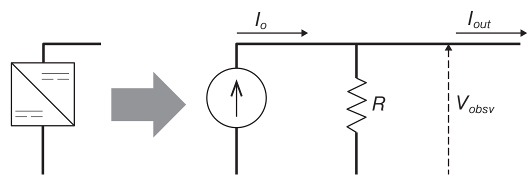

Figure 4 Droop current control.

In the Droop current control, by adjusting I_0 and R, the DC line voltage can be also stabilized while the load sharing for the power conversion among devices is implemented according to the amount of power required for the DC line. In addition, if R is set to ∞, constant current (CC) control is achieved, so that the Droop current control is an extension of so-called CC control.

3. THE DEVELOPMENT OF A HIERACHICAL DECENTRALIZED CONTROL

3.1 Algorithm Design

3.1.1 Primary control (Decentralized control)

As a primary control, we invented a target function tracking control that is an extension of the Droop control described above. The target function is defined as a combination of polygonal line in a two-dimensional space consisting of Voltage (V) and Power (P) as shown in Figure 5. For each power converter, a target function is set according to its equipment characteristics. Some target functions are defined statically, while others are defined dynamically so that they are updated according to the equipment information (e.g., SoC (state of charge) of storage battery observed locally by the power converter.

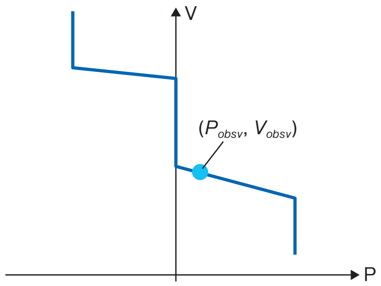

Figure 5 Target function.

Each power converter implements feedback control so that the operating points (P_{obsv}, V_{obsv}) can follow the target function. As a specific method, the Droop current control (Droop P control) and the Droop voltage control (Droop V control) shown in Figure 6 are applied according to the operating condition. This improves the robustness against observation and control errors and the control stability against power disturbances.

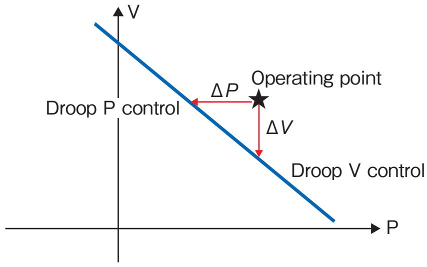

Figure 6 Target function tracking control; Droop P control and Droop V control.

3.1.2 Secondary control (centralized control)

As a secondary control, we designed an algorithm that calculates the target function to be set for each power converter by performing a mathematical optimization calculation based on an evaluation index (e.g., minimization of operating costs) while the EMS takes into account the power status of each device and the power supply and demand forecasts. In the mathematical optimization calculation, a constrained linear programming problem is solved as shown in the following equation.

The EMS executes the mathematical optimization calculation by triggering a periodic processing timer and an event such as an alarm, etc. The flow of EMS operation is shown in Figure 7.

$$\text{Minimize OPEX} = \sum_{\text{time}=0}^{n} \text{Usage power charge [¥/kWh]} * \text{Power consumption [kWh]} + \text{Basic power charge [¥/kW]} * \text{Contract power [kW]} \quad (3)$$

Subject to Inflow power [kW] = outflow power [kW] for each bus line at each time...< simultaneous same volume constraint >
Lower limit SoC [%] ≤ SoC ≤ upper limit SoC [kW] at each battery node at each time···< SoC constraint>
Output lower limit [kW] ≤ output [kW] ≤ output upper limit for each node at each time...< output constraint >
Reference SoC [%] ≤ Final SoC [%] for each battery node...< final SoC constraint >
Output [kW] ≤ contract power [kW] for utility node at each time...< contract power constraint >
Output [kW] ≤ predicted output value [kW] for each suppressionable node at each time···< output suppression constraint >
Output [kW] = predicted output power [kW] for each unsuppressionable node at each time···
< power supply and demand predicted value constraint >
Output [kW] = output plan value [kW] for each scheduled node at each time···< planned operation constraint >

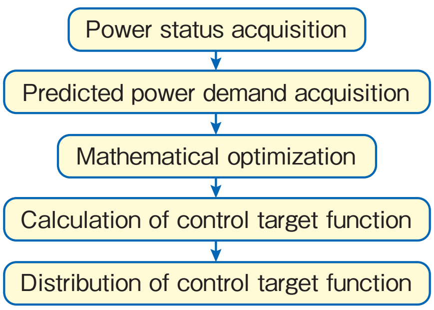

Figure 7 Flow diagram of a secondary control by the EMS.

The EMS defines a robust normal-time target function that allows each power converter to maintain the control stability against disturbances, while aiming to follow the control target value obtained from the mathematical optimization calculation. In addition, the target function at the time of communication interruption, which transitions when the power converter detects a communication interruption to the EMS, and the target function at the time of power failure, which transitions when the power converter detects a power failure, are simultaneously defined and distributed to the power converter as fail-safe target functions. Figure 8 to Figure 10 show examples of these target functions.

3.2 The Simulation Verification

In order to verify the effectiveness of the algorithm designed in Section 3.1, the primary control and the secondary control were developed as the MATLAB / Simulink simulator and the Python simulator, respectively.

As shown in Figure 11, we implemented a control block in the MATLAB / Simulink simulator where each power converter follows the target function in an autonomous and decentralized manner. In the Python simulator, a mathematical optimization module was developed as an optimization solver using Google OR-Tools. Also, a tool to evaluate the efficiency of hierarchical control was developed as a target function design / evaluation module. Figure 12 shows an example of the output. The power balance at every time section, and the effectiveness of the hierarchical decentralized control algorithm was confirmed in the simulation environment.

3.3 Actual Equipment Verification

A Dual Active Bridge (DAB) converter shown in Figure 13 was prototyped as a 300 W class bidirectional insulated DC / DC converter that supports the primary control of the hierarchical decentralized control, and a system assuming the actual grid operation was constructed and the operation verification was performed. Figure 14 shows a schematic view of DC grid.

Figure 15 shows the verification results of control traceability for the target function. It can be seen that the target function set from the EMS can be followed well. As a result, the effectiveness of the hierarchical decentralized control algorithm could be confirmed even in an actual equipment environment.

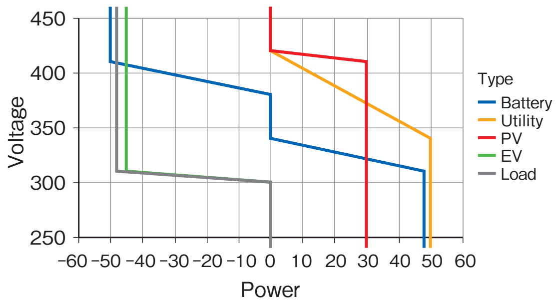

Figure 8 An example of the target function during normal time.

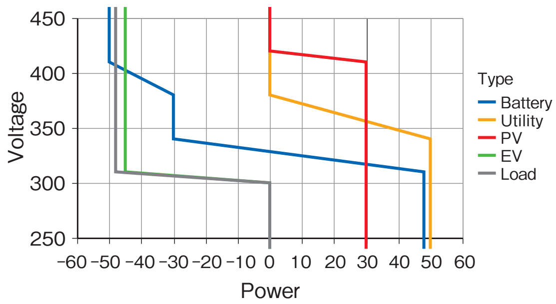

Figure 9 An example of the target function during communication interruption.

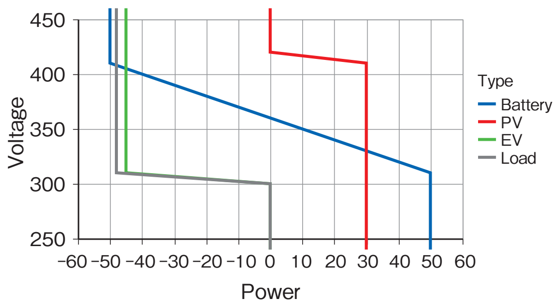

Figure 10 An example of the target function during power failure.

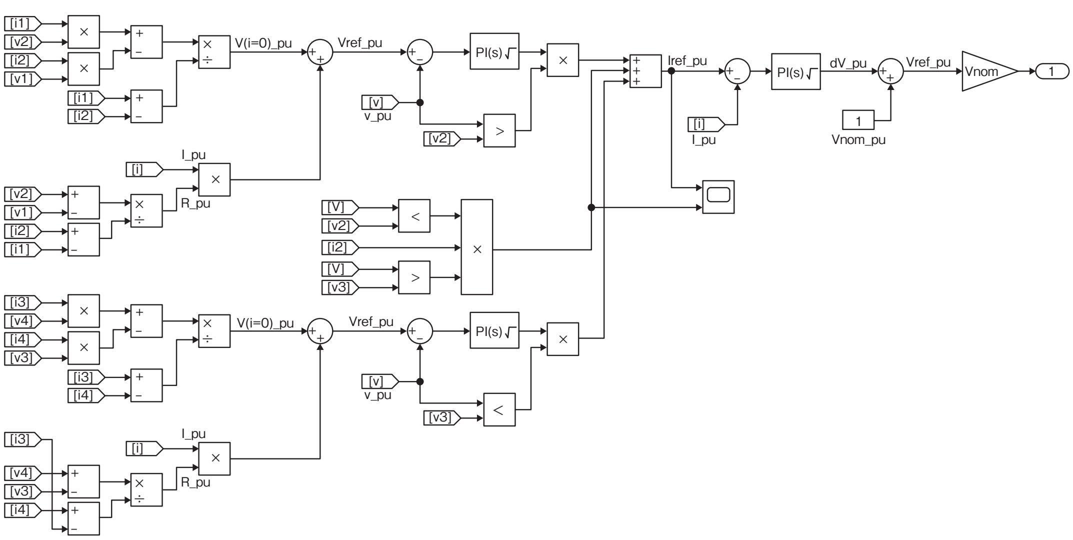

Figure 11 An example of the Droop control block implementation (MATLAB/Simulink).

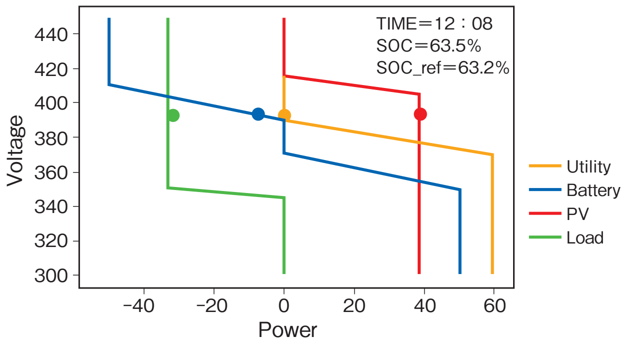

Figure 12 **An example output from the target function design and evaluation module (Python).**

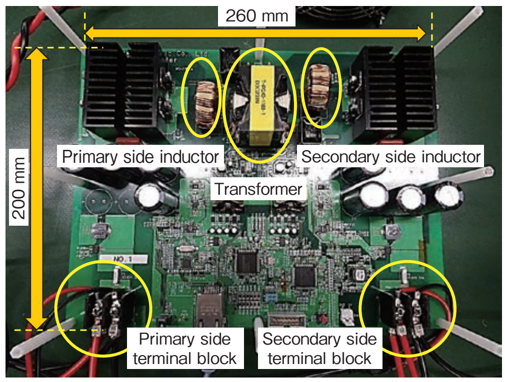

Figure 13 **DAB Converter.**

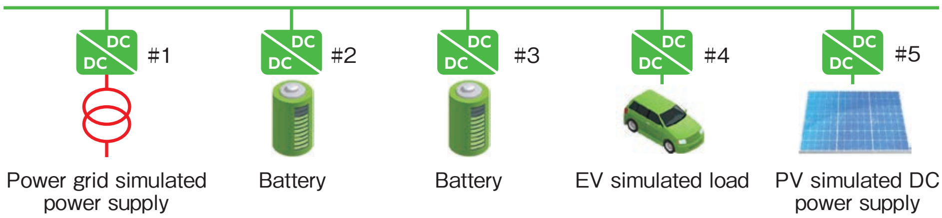

Figure 14 **DC grid configuration.**

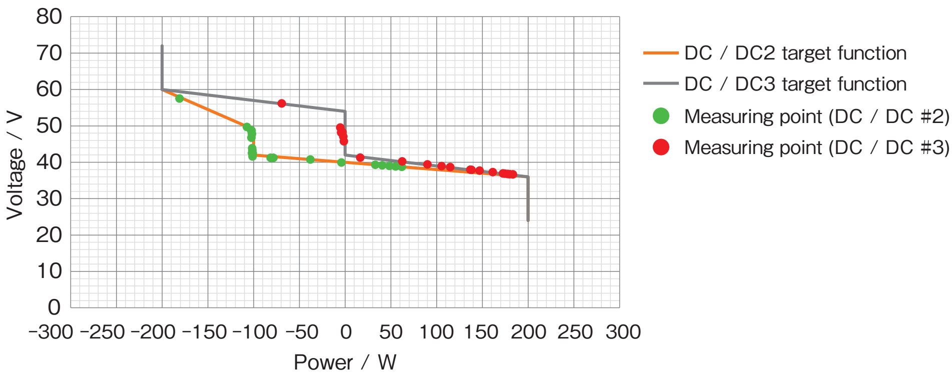

Figure 15 **An example of experimental result.**

4. EXTENSION OF THE HIERACHICAL DECENTRALIZED CONTROL: DC VIRTUAL INERTIA CONTROL

4.1 Algorithm Design

In order to further improve the control stability of the hierarchical decentralized control, we developed "DC virtual inertia control", designed by expanding the Droop control. The Droop control was realized by introducing a virtual resistance to the CV control and the CC control, but the DC virtual inertia control can be realized by introducing a virtual capacitor in addition to the virtual resistance[4)-9)]. The virtual capacitor generates an inertial force and suppresses fluctuations when sudden voltage changes occur. Because of this effect, the stability of DC-MG can be improved. Similar to the Droop control, the DC virtual inertia control can be roughly classified into the DC virtual inertia voltage (DC-VIV) control and the DC virtual inertia current (DC-VIC) control, depending on the details of control implementations.

Figure 16 shows the equation and the equivalent circuit of DC-VIV control, and Figure 17 shows that of DC-VIC control.

$$V_{out} = V_o - Z_{R||C} * I_{obsv} \quad (4)$$

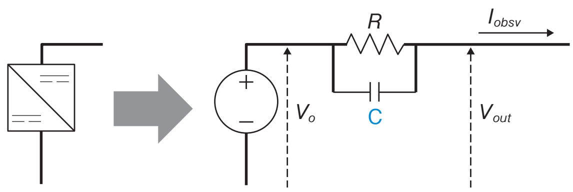

Figure 16 **DC-VIV control.**

$$I_{out} = I_o - Y_{R||C} * V_{obsv} = I_o - \left(\frac{1}{R} + sC\right) V_{obsv} \quad (5)$$

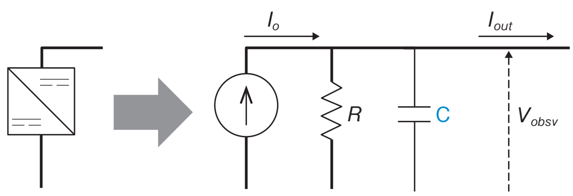

Figure 17 **DC-VIC control.**

To verify the operation of DC virtual inertial controls in the simulator and the actual equipment, we designed a digital control equation, by using bilinear transformation (Equation 6). For example, applying Equation 6 (bi-linear transformation) to Equation 5 (DC virtual inertia current control) gives the following digital control equation.

$$z = e^{sT_s} \approx \frac{1}{1 + sT_s} \tag{6}$$

The following digital control equation is obtained.

$$I_{out}[n] = I_o[n] - \left(\frac{1}{R} + \frac{C}{T_s}\right) V_{obsv}[n] + \frac{C}{T_s} V_{obsv}[n-1] \tag{7}$$

4.2 Simulation Results

The DC virtual inertial control was introduced by implementing Equation 7(digital control equation) in the Python simulator developed in Section 3.2. The evaluation results of the voltage stability against power disturbances are shown in Figure 18. Without DC virtual inertia control, the voltage drops from 390 V to around 365 V when a power disturbance occurs, but with DC virtual inertia control, the voltage does not drop below 370 V. The time until the convergence of the fluctuation is also shorter after the introduction of DC virtual inertia control.

4.3 Experimental Results

We improved the firmware of DAB converter developed in Section 3.3, implemented Equation 7 (digital control equation). Then we verified the operation. Figure 19 shows the state of the voltage fluctuation when a step-like power disturbance is applied. Table 1 shows the results of comparing the values around 20 seconds, where the voltage fluctuation is particularly large in Figure 19.

From Figure 19 and Table 1, it was confirmed that the DC virtual inertia control suppressed the voltage fluctuation during the transient.

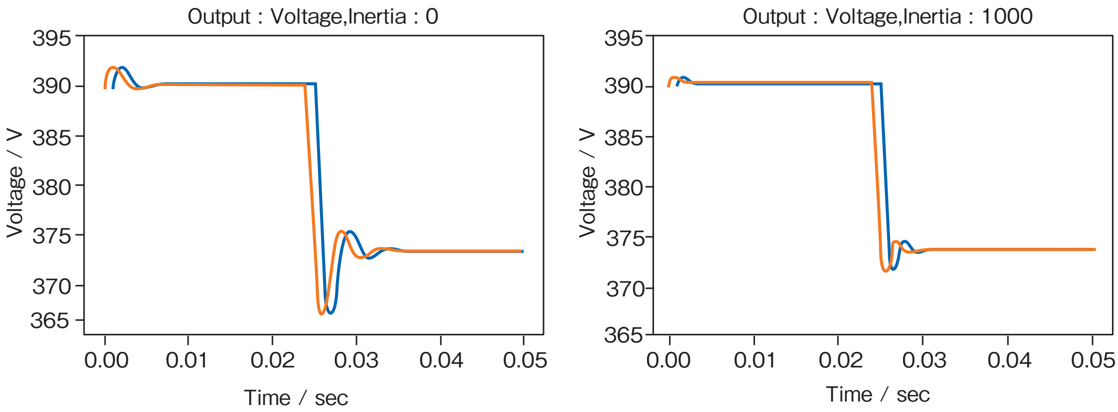

Figure 18 Voltage fluctuation during power disturbances for Droop control (left) and DC virtual inertia control (right) (simulation results).

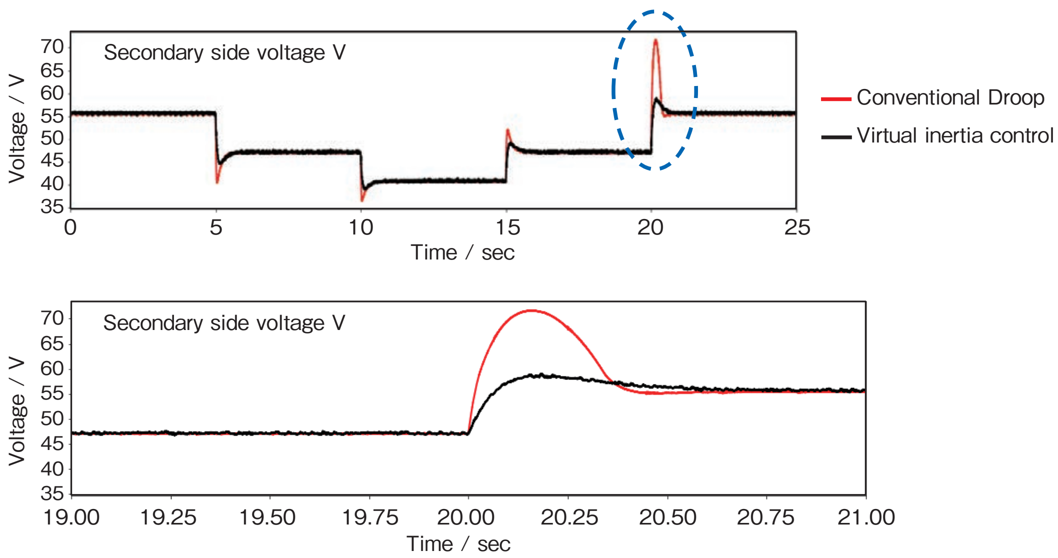

Figure 19 Voltage fluctuation when a step-like power disturbance is applied (evaluation of actual equipment).

Table 1 Experimental results.

	Overshoot quantity	Overshoot rate
Droop control	71.6 – 55.5 = 16.1 V	16.1 / 55.5 = 0.29
DC virtual inertia control	59.0 – 55.5 = 3.5 V	3.5 / 55.5 = 0.063

5. CONCLUSION

In this paper, as a part of the development of DC-MG control method, the Droop control and the virtual inertia control are introduced to the decentralized control of primary control, and the results of algorithm design, simulation verification, and actual verification of the hierarchical decentralized control combined with the centralized control of the secondary control are introduced.

These efforts are expected to lead to the social implementation of a DC-MG that can contribute to the realization of a carbon-neutral society and future urban development. We will continue to build a highly reliable system, to conduct the system demonstration assuming an operational environment, and to take on the challenge of solving social issues.

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