# Examination of Autonomous Distributed Control Method by Predictive Optimization in DC Microgrid

**Yoshito Nishita†, Yoshio Izui*, Masahito Honda*, Makoto Mizuochi*, Daisuke Natsuume*, Hirokazu Tabata***

**Abstract** – In recent years, blackouts due to large-scale natural disasters have frequently occurred. Therefore, Interest in energy resilience is deepening, and the number of households that generate their own power using renewable energy such as photovoltaic power generation systems is increasing. On the other hand, direct current (DC) has the advantage of having a high affinity with renewable energy and storage batteries. Due to its affinity, the number of cases where DC systems are adopted as microgrids is increasing. Based on these backgrounds, we are constructing a DC power supply and distribution system. We are also studying a charge / discharge control method for storage batteries using DC voltage in order to maintain autonomous operation for a long period of time in a DC microgrid system that is separated from commercial power. In this paper, we propose a method to control the charge and discharge of the storage battery using the DC bus voltage target value determined by the predictive optimum control in the control by the multi-time cross section. Then, the effectiveness of the proposed method was confirmed using the equipment configuration and experimental data.

**Keywords**: Renewable Energy Resources, Microgrid, Autonomous Decentralized Control, Independent Operation, DC

## 1. Introduction

For the purpose of low carbonization and decarbonization, the introduction of renewable energy such as photovoltaic power generation systems (PV) in the electric power and energy fields and electric vehicles in the transportation field is expanding. Also, in recent years, blackouts due to large scale natural disasters have frequently occurred. For example, the blackout occurred in the Hokkaido region in 2018 and the power outage due to the influence of the typhoon occurred in Chiba in 2019. Therefore, in Japan, interest in energy resilience is deepening and some households generate their own power using PV etc. On the other hand, direct current (DC) has the advantages of high resilience (relatively easy control) and low AC/DC conversion loss in the case of private power generation, and has a strong relationship with renewable energy, electric vehicles and storage batteries. Due to its affinity, the number of cases where DC systems are adopted as microgrids is increasing.

Based on these backgrounds, we constructed a DC power supply and distribution system using the "Community model demonstration experiment of renewable energy best mix" [1] at Kanazawa Institute of Technology (KIT). We are conducting demonstration experiments and data acquisition. In addition, in the previous research [2], [3], We investigated a control method that maintains the longest operation of the entire DC microgrid system in an independent operation state away from the grid and proposed a method that controls the charge / discharge amount using a DC voltage [4]. In order to confirm the effectiveness of the previous method, a simulation evaluation was carried out using the data of the demonstration experiment device [5], [6]. As a result of the evaluation, it was possible to operate independently for a long time on the DC microgrid system of the previous method. However, the previous method has the problem that PV power generation suppression occurs frequently. Therefore, in this paper, we propose an autonomous distributed control method in a multi-time cross section on a DC microgrid in order to further extend the self-sustaining operation time.

† Corresponding Author : Kanazawa Institute of Technology, Japan (nishita@neptune.kanazawa-it.ac.jp)
* Kanazawa Institute of Technology, Japan

## 2. Autonomous Distributed Control Method

In this chapter, we describe the previous method of the previous research.

### 2.1 Autonomous Distributed Control by DC Voltage

The purpose of the autonomous distributed control by DC voltage in this paper is to maximize the independent operation time of the system when power outage. That is, the aim is to maximize the self-sustaining operating time of the entire DC microgrid system by allowing each consumer to control the charging / discharging of the storage battery in an autonomous and decentralized manner. As a control method for autonomous decentralized control, droop control is generally used on a DC grid. The formula for droop control is shown below.

$$\Delta V_i = \alpha_i \Delta P_i \qquad (1)$$

$\Delta V_i$ is the amount of change in the bus voltage, $\alpha_i$ is the proportional coefficient, and $\Delta P_i$ is the amount of change in the charge / discharge. As shown by the equation (1), In droop control, each consumer controls the charging / discharging of the storage battery in proportion to the voltage deviation ($\alpha$). However, it is difficult to determine the appropriate α. In the previous research [5], [6], in order to maximize the independent operation time of the entire microgrid system, the following optimization function should be maximized.

$$\sum_i T_i(t) \rightarrow max \qquad (2)$$

$$subject\ to \quad \sum_i P_i(t) = \sum_i D_i(t) \qquad (3)$$

$T_i(t)$ is estimated remaining storage battery time and $D_i(t)$ is power consumption at time t. Equation (2), (3) can be solved using Lagrange's undetermined multiplier method, and the following equation is obtained.

$$\lambda = \frac{\partial T_i(t)}{\partial P_i(t)} = \frac{\partial\left(\frac{B_i(t)}{D_i(t)}\right)}{\partial P_i(t)} \qquad (4)$$

Here, $D_i(t)$ is independent of $P_i(t)$, and assuming that the approximate expression of $\frac{\partial(B_i(t))}{\partial P_i(t)} \approx \frac{B_i(t)}{P_i(t)}$ holds, it becomes $\lambda = \frac{1}{D_i(t)} \frac{B_i(t)}{P_i(t)}$. Here, if it is rewritten as $\lambda = \frac{1}{V_i(t)}$, $V_i(t) = \left(\frac{D_i(t)}{B_i(t)}\right) P_i(t)$ is obtained. Furthermore, if you rewrite it as $V_i(t) \rightarrow \Delta V_i(t)$ and $P_i(t) \rightarrow \Delta P_i(t)$ and set it as $\alpha_i(t) = \left(\frac{D_i(t)}{B_i(t)}\right)$, it will be as follows.

$$\Delta V_i(t) = \alpha_i(t) \Delta P_i(t) \qquad (5)$$

$B_i(t)$ is the remaining storage battery capacity at time t. In the previous research, the simulation evaluation showed that previous research had a longer independent operation time than the droop control, confirming the effectiveness of previous research (Fig.1 and Fig.2).

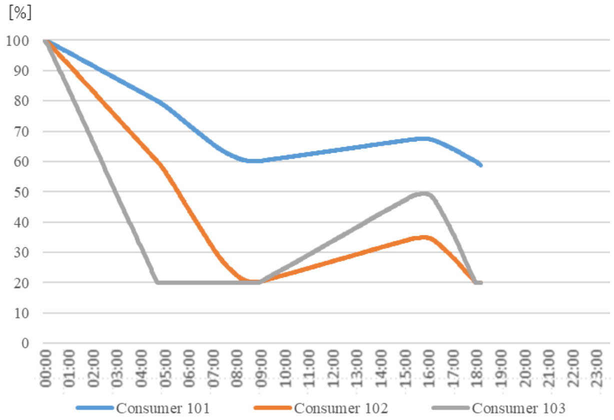


**Fig. 1.** Results of general droop control

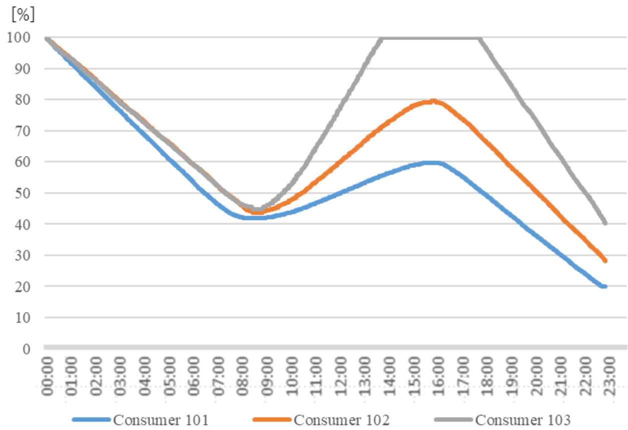


**Fig. 2.** Results of droop control by previous research

## 3. Autonomous Distributed Control in Multi-time Cross Section

The method described in the previous chapter controlled the amount of charge and discharge by performing calculations using a single unit at a specific time. In this paper, we propose a control method with a multi-time cross section that predicts the future DC voltage target value by using it multiple times and controls charging and discharging.

### 3.1 Problems with Single-time Cross Sections

In the DC microgrid, the voltage of the DC feeder is maintained properly by autonomously and decentralized charge / discharge control of the storage battery. However, depending on the weather conditions such as continuous sunny weather or rain, the storage capacity of the storage battery and the amount of power generated by PV power generation may be biased. In this case, as shown in Fig.3, there may be problems such as suppression of the output of photovoltaic power generation and limitation of the storage capacity of the stora

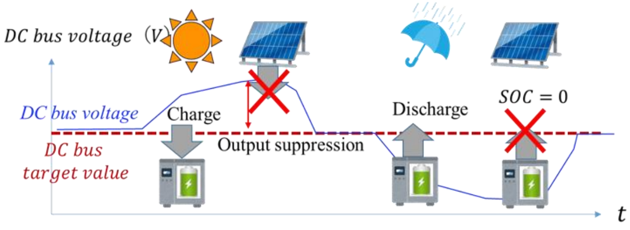


**Fig. 3.** Image of droop control by single time cross section

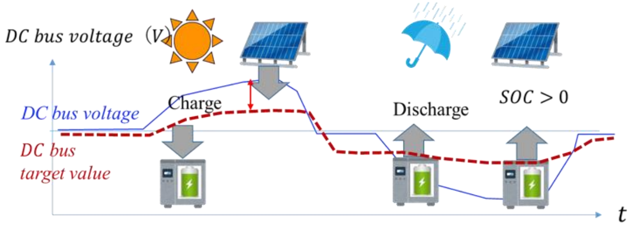


**Fig. 4.** Image of droop control by multi-time cross section

ge battery to the upper limit or the lower limit.

### 3.2 Examination of Droop Control in Multi-time Cr oss Section

The demonstration system used in the previous chapter has the problem that PV power generation suppression occurs frequently. This is because the capacity of the storage battery is fully charged and the power generated by the PV cannot be charged to the storage battery, so that the power generation of the PV is suppressed. Therefore, as shown in Fig.4, the DC bus voltage target value is controlled in a predictive and adaptive manner. The proposed droop control is applied to this DC bus voltage target value. Fig.5 shows an image of droop control centered on the DC bus voltage target value. In the proposed method, droop control is performed in a short cycle of about 1 hour around the DC target voltage value, and charge / discharge control of the storage battery is performed. The purpose of this is to suppress PV output and avoid excessive discharge due to full charge, and to enable longer-term autonomous operation. In the proposed method of predictive control in a multi-time cross section, the state of each element at each time is expressed by a vector. As an example of predictive control, the procedure of predictive control by droop control is shown below.

The power generation vector ($G$) is given by another software. The power generation vector ($G$) is shown below.

$$G_i(t) = (g(t), g(t+1), g(t+2) \cdots\cdots g(t+N)) \quad (6)$$

Demand vector ($D$) is shown below.

$$D_i(t) = (d(t), d(t+1), d(t+2) \cdots\cdots d(t+N)) \quad (7)$$

The target voltage vector ($V_o$) is shown below.

$$V_{i,o}(t) = (V_o(t), V_o(t+1), V_o(t+2) \cdots\cdots V_o(t+N)) \quad (8)$$

At this time, $V_o(t)$ is as follow.

$$V_o(t) = \alpha\big(g(t) - d(t)\big) + V_n) \quad (9)$$

$\alpha$ is a system constant and is given by actual measurement, and $V_n$ is the DC reference voltage, which is 360 [V] here. The actual voltage vector ($V_a$) is shown below.

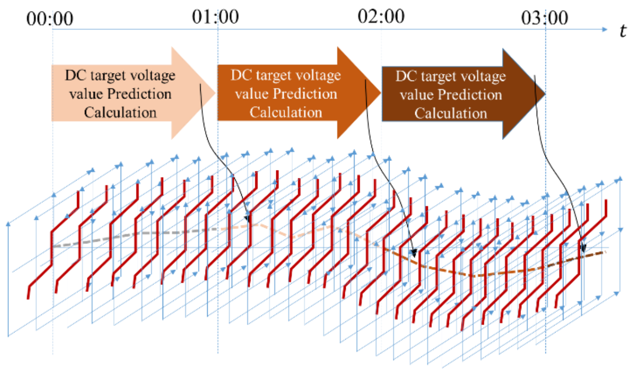


**Fig. 5** Image of DC voltage control in proposed method

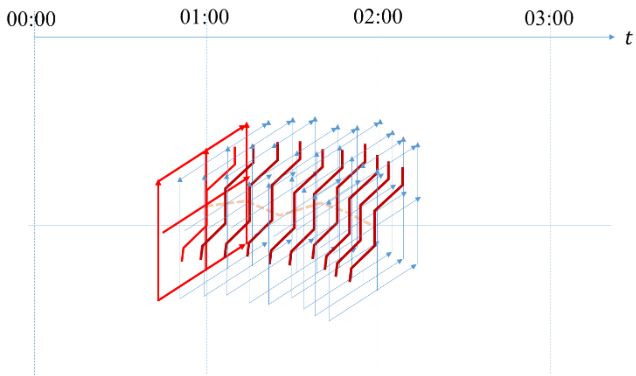


**Fig. 6** Image of DC voltage control by droop control in proposed method

$$V_{a,o}(t) = (V_a(t), V_a(t+1), V_a(t+2) \cdots\cdots V_{a_n}(t+N)) \quad (10)$$

The storage battery remaining amount prediction can be calculated when the charge / discharge amount is determined.

$$S_i(t) = (s(t), s(t+1), s(t+2) \cdots\cdots s(t+N)) \quad (11)$$

To calculate the charge / discharge vector ($\beta(t)$), it is necessary to calculate the droop slope vector, and the droop slope vector is shown below.

$$\beta_i(t) = (\beta(t), \beta(t+1), \beta(t+2) \cdots\cdots \beta(t+N)) \quad (12)$$

At this time, $\beta(t)$ is shown below.

$$\beta(t) = k_i \frac{s(t)}{d(t) - g(t)} \quad (13)$$

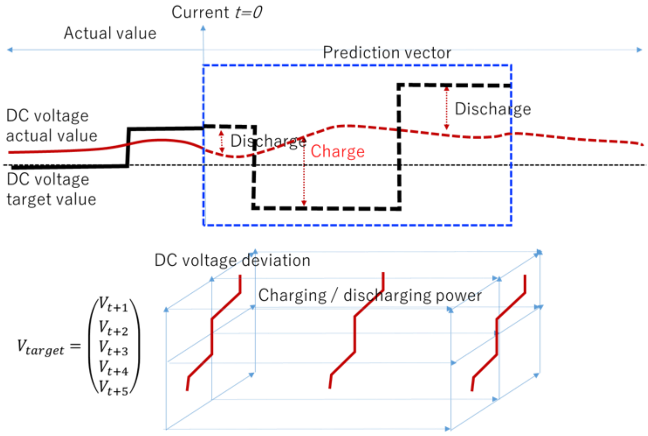

**Fig. 7.** Vector droop control in proposed method

The value of $k_i$ is determined for each consumer. The charge / discharge amount vector is determined by this droop slope, and the charge / discharge amount vector is determined.

$$B_i(t) = (B(t), B(t+1), B(t+2) \cdots\cdots B(t+N)) \quad (14)$$

At this time, $B(t)$ is as follow.

$$B(t) = \beta(t)(V_0(t) - V_\alpha(t)) \quad (15)$$

If the remaining battery level approaches 0 or 100 on the way, fine-tune B (t) and redo the calculation. Fig.6 shows an image of DC voltage control by droop control. The droop control itself is also a predictive control, and the droop control is performed from the current time to a little ahead with a certain control surface as the current time. If a constraint violation occurs in this prediction, the charge amount at the current time is corrected and the prediction control is performed again.

In order to maximize the autonomous driving time using the formula explained above, It is sufficient to calculate the optimum values of $\alpha$ in the equation for calculating the voltage deviation and $k_i$ in the equation for calculating the droop slope. $\alpha$ is the proportional coefficient and is determined for each consumer. The image of vector droop control is shown in Fig. 7.

### 3.3 Predictive Optimal Control of DC Bus Voltage Target Value

There are 6 constraints on this optimization problem: supply-demand balance constraint, storage battery state change constraint, storage battery upper / lower limit constraint, charge / discharge amount upper / lower limit constraint, power receiving point power upper / lower limit constraint, and bus voltage. It is an upper and lower limit constraint. Supply and demand balance constraint is shown below.

$$E(t) = Load(t) - Pv_{plan}(t) + Bat_{ch}(t) - Bat_{dis}(t) \quad (16)$$

$E$ is planned value of receiving point power, $Pv_{plan}$ is PV power generation planned value, $Bat_{st}$ is planned charging power for storage batteries, and $Bat_{dis}$ is planned discharge power of storage battery. The constraint on the state change of the storage battery is shown below.

$$Bat_{st}(t) = Bat_{st}(t-1) + Eff \cdot Bat_{ch}(t) - \frac{1.0}{Eff} Bat_{dis}(t) \quad (17)$$

$$Bat_{charge}(t) \cdot Bat_{discharge}(t) = 0 \quad (18)$$

$Bat_{st}$ is planned storage capacity of storage batteries and $Eff$ is charge / discharge efficiency. The upper and lower limit of the amount of electricity stored is shown below.

$$Bat_{st_{min}} \leq Bat_{st}(t) \leq Bat_{st_{max}} \quad (19)$$

$Bat_{st_{min}}$ is maximum value of storage capacity of storage battery and $Bat_{st_{max}}$ is minimum value of storage capacity of storage battery. The upper and lower limit constraints of the receiving point power are shown below.

$$0 \leq E(t) \leq E_{max} \quad (20)$$

$E_{max}$ is upper limit of planned grid power. The upper and lower limit constraints of the bus voltage are shown below.

$$V_{min} \leq V(t) \leq V_{max} \quad (21)$$

$V$ is bus voltage, $V_{max}$ is upper limit of bus voltage, a nd $V_{min}$ is lower limit of bus voltage.

## 4. Evaluation Experiment

In this chapter, in order to confirm the effectiveness of the proposed method, simulation verification using evaluation data and actual data will be performed. In the simulation verification, the results of the control method proposed in the previous research and the method proposed in this research are compared and evaluated.

### 4.1 Experiment using Evaluation Data

**(1) Experimental Conditions**

Fig.8 shows the configuration of the evaluation equipment assumed in this verification. Table 1 shows the capacity of the storage battery used in this verification. The graph of the power demand used for the verification is shown in Fig.9 a nd the graph of PV power generation is shown in Fig.10.

**(2) Experimental Results**

The experimental results are shown in Fig.11 and 12. The method in previous research causes power generation suppression due to the full charge of the storage battery, and the remaining storage amount falls below the lower limit. On the other hand, the proposed method can control the power generation suppression and the storage amount without exhaustion. From the above, we were able to confirm the effectiveness of predictive optimal control.

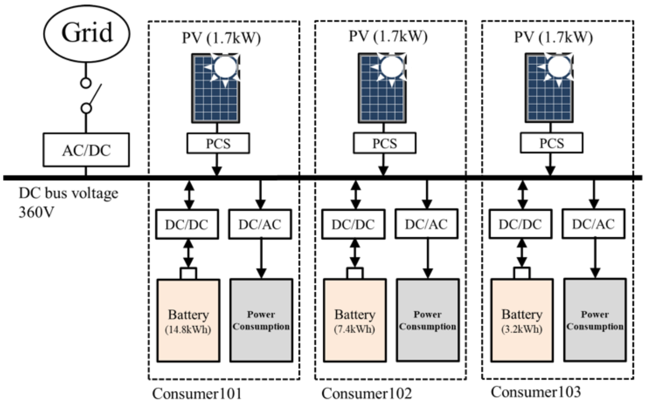


**Fig. 8.** Configuration of evaluation equipment

**Table 1.** Capacity of storage battery for evaluation

| Customer name | Battery capacity | Rated power output |
|---|---|---|
| Consumer101 | 14.8 kWh | 1.7 kW |
| Consumer102 | 7.4 kWh | 1.7 kW |
| Consumer103 | 3.2 kWh | 1.7 kW |

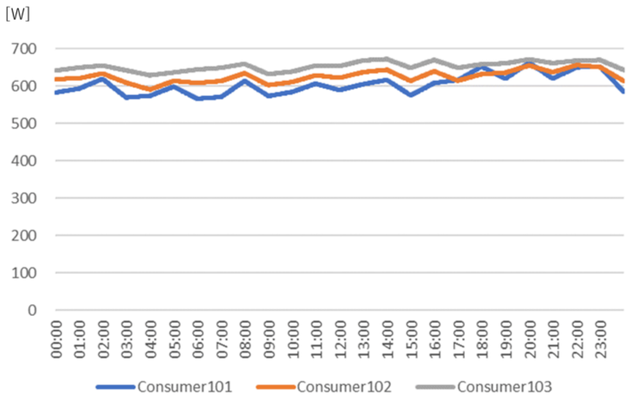


**Fig. 9.** Electricity demand for each consumer

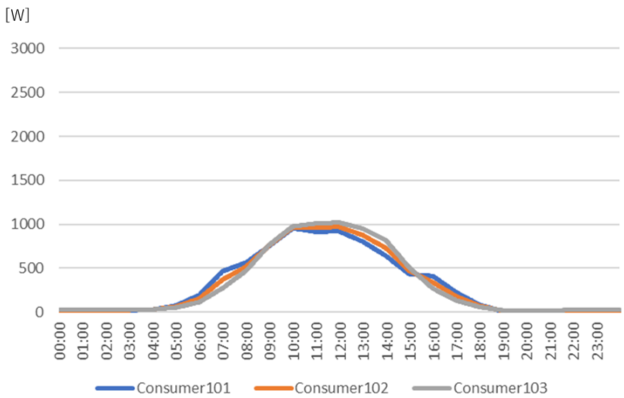


**Fig. 10.** PV power generation of each consumer

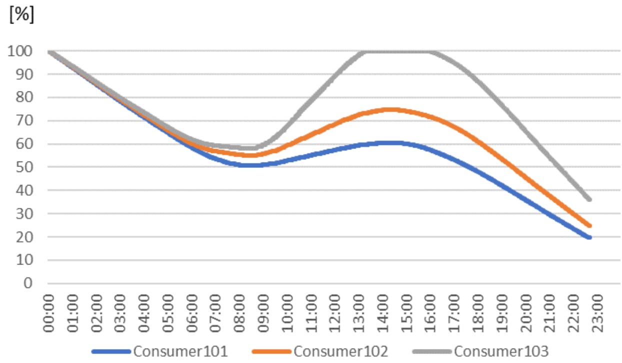


**Fig. 11.** Result of the previous research

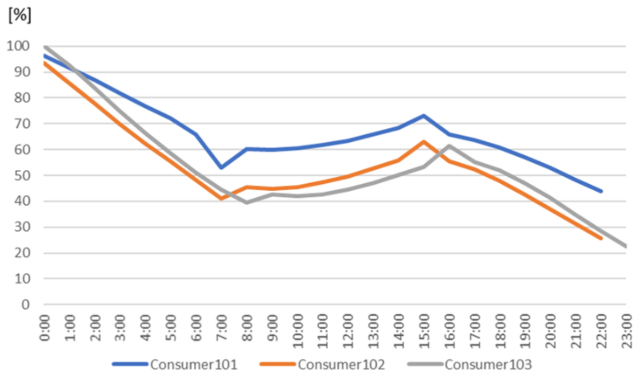


**Fig. 12.** Result of the proposed method

### 4.2 Experiment using Data from Demonstration Experiment

**(1) Experimental Conditions**

In this verification using actual data, the data obtained at Hakusan-roku Campus in KIT is used. Fig.13 shows the equipment configuration. In this demonstration experiment, the equipment shown in Fig. 14 was evaluated with the configuration shown in Fig.13. Table 2 shows the storage battery capacity of each consumer.

Since there is no power demand data for each consumer, the same power demand data will be used for all consumers on the same day. The data of PV power generation will be the data of each consumer on the same day. In order to confirm the effectiveness of predictive optimal control, the data used were prepared for cloudy days and sunny days. The graph of power demand used for verification is shown in Fig. 15 and 16, and the graph of PV power generation is shown in Fig.17 and 18.

**(2) Experimental Results**

As Experimental results, the changes in the amount of electricity stored in the storage battery of each consumer over time are shown in Fig.19 and 20. As shown in the Fig.19, the method of previous research caused a power outage in 21 hours and 40 minutes. On the other hand, the proposed method (the predictive optimal control) was able to supply power all day without a power outage. In addition, as experimental results on another day, changes in the

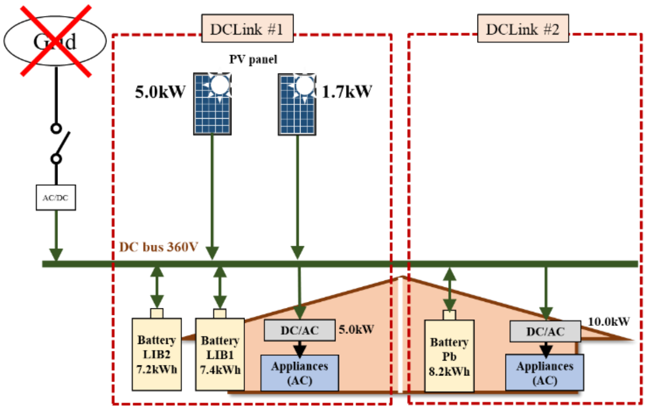


**Fig. 13.** Equipment configuration of Hakusan-roku campus

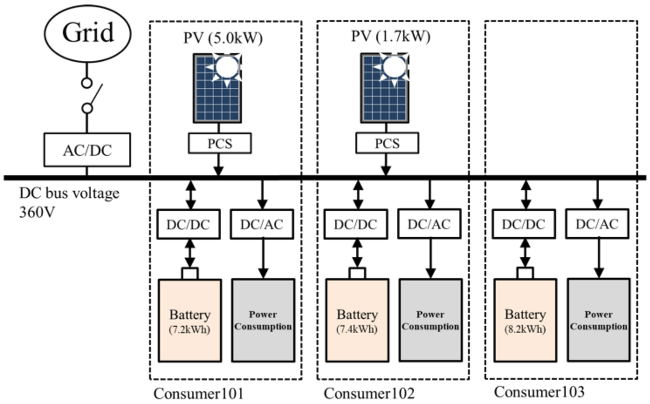


**Fig. 14.** Simulation conditions

**Table 2.** Storage battery capacity of each consumer

| Consumer name | Battery capacity | Rated power output |
|---|---|---|
| Consumer101 | 7.2 kWh | 5.0 kW |
| Consumer102 | 7.4 kWh | 1.7 kW |
| Consumer103 | 8.2 kWh | - |

amount of electricity stored in the storage battery of each consumer over time are shown in Fig.21 and 22 In the method of previous research, the PV output was suppressed when the remaining storage capacity reached 100%, but in the proposed method (the predictive optimal control), no output suppression occurred.

## 5. Conclusion

In this paper, for the purpose of prolonging the autonomous operation time in the DC microgrid system, we proposed a method for predicting and optimizing the DC bus voltage target value in order to prevent PV output suppression, which is a problem in previous research. Then, we compared and evaluated previous research, which is the previously proposed method, and the predictive optimal control proposed this time. Then, it was confirmed that the predictive optimum control can prevent full charge and at the same time maintain the electric power for a long period of time on both cloudy and sunny days. Since the verification was conducted by simulation verification this time, a demonstration system will be constructed at the

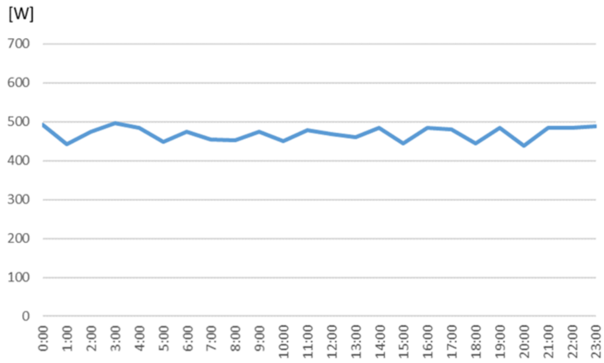


**Fig. 15.** Electricity demand for each consumer (cloudy)

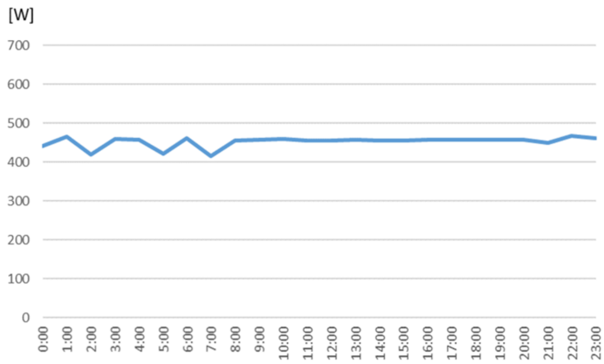


**Fig. 16.** Electricity demand for each consumer (sunny)

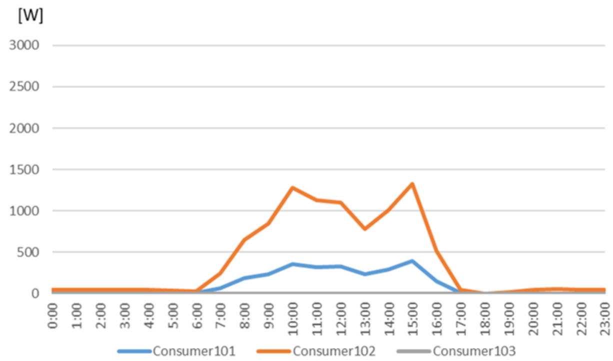


**Fig. 17.** PV power generation of each consumer (cloudy)

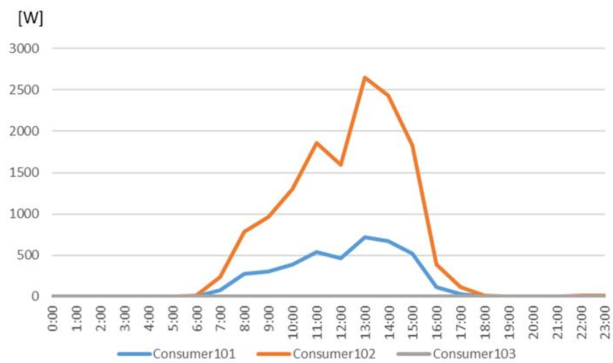


**Fig. 18.** PV power generation of each consumer (sunny)

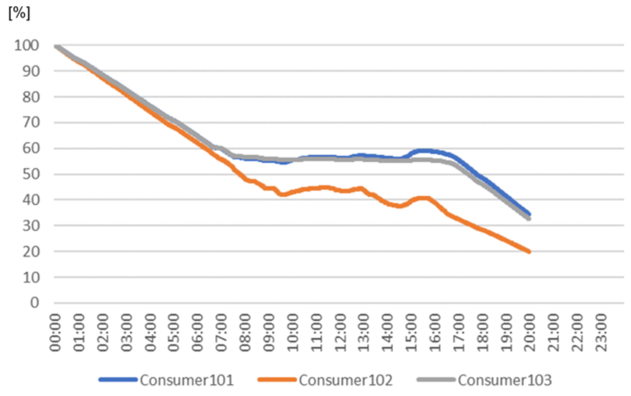


**Fig. 19.** Result of the Previous research (cloudy)

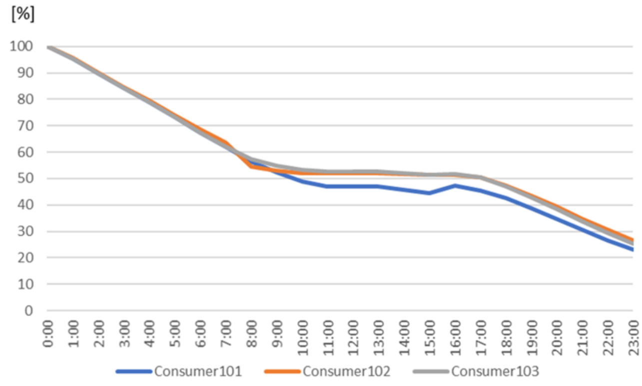


**Fig. 20.** Result of the proposed method (cloudy)

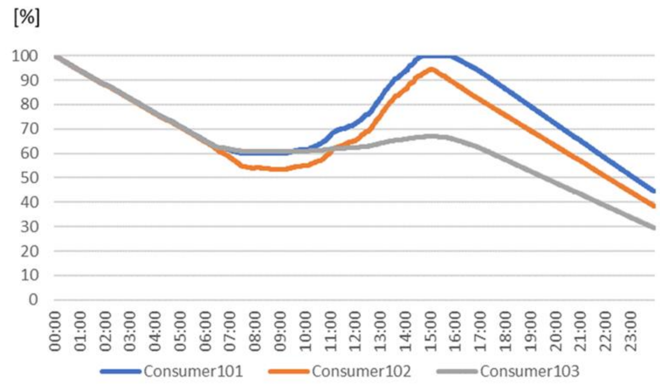


**Fig. 21.** Result of the Previous research (sunny)

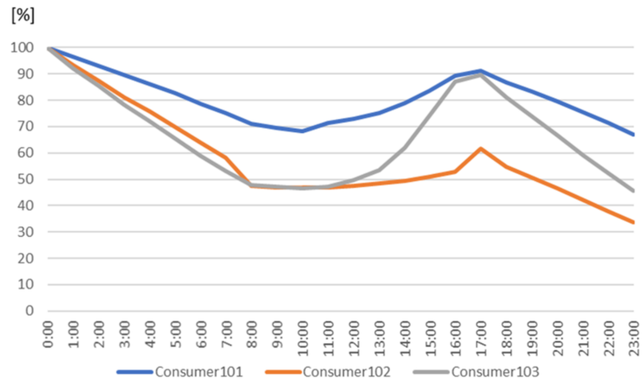


**Fig. 22.** Result of the proposed method (sunny)

Hakusan-roku Campus and a demonstration experiment will be conducted to actually evaluate the effectiveness.

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**Yoshito Nishita**
He received Ph.D degree in informatics from Kansai University. His research interests are Energy management, machine learning, optimal control and image processing.

**Yoshio Izui**
He received Ph.D degree in electrical engineering from the University of Tokyo. His research interest is Demonstration experiment research of energy management system for de-carbonization, local production for local consumption and energy resilience.

**Masahito Honda**
He received B.S in Electrical and Electronic Engineering from Kanazawa Institute of Technology. His research interest is Autonomous distributed control method by predictive optimization in DC microgrid.

**Makoto Mizuochi**
He received B.S in Electrical and Electronic Engineering from Kanazawa Institute of Technology. His research interest is Autonomous distributed control method by predictive optimization in DC microgrid.

**Daisuke Natsuume**
He received M.S degree in Electrical engineering and electronics from Kanazawa Institute of Technology. His research interests are Industrial automation system, energy system development design including DC microgrid system.

**Hirokazu Tabata**
He received M.S degree in Business architecture from Kanazawa Institute of Technology. His research interest is Research on DC microgrids for the realization of local production for local consumption of energy.