Development of Control Technologies of Battery for Large-Scale Photovoltaic Power Plants

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In recent years, in order to stably supply electric power and improve energy self-sufficiency in Japan, it has been proposed to utilize renewable energies. In particular, the construction of large-scale photovoltaic power plants (mega-solars) and system interconnections are actively performed. However, the amount of photovoltaic generated power largely varies due to some causes such as the effect of obscuring the sun, and therefore an adverse effect on the voltage and frequency of a system associated with the large-scale introduction of mega-solars is a concern. This paper describes a battery control technique for stably supplying power from a power plant to a system, which we are developing in response to such a concern, and future development.

1. Introduction

In recent years, in order to improve energy self-sufficiency and keep stably supplying electric power in Japan, it has been proposed to actively utilize renewable energies. In particular, thanks to assistance from legislative systems such as the renewable energy feed-in tariff [1], the construction of large-scale photovoltaic power plants (mega-solars) and system interconnections are actively performed[2]. However, photovoltaic power generation is an unstable power source because the amount of generated power may largely vary within a short period of time due to the effect of weather conditions. As a result, an adverse effect on the voltage and frequency of a system associated with the large-scale introduction of mega-solars is a concern. In order to solve such a concern, there are proposed many operating methods adapted to reduce (smooth) a variation in system supply power by installing an energy storage unit such as a battery in a power plant and performing charging/discharging in response to a variation in photovoltaic generated power[3]-[6]. When constructing a photovoltaic power plant, since the installation of a battery is not negligible in terms of cost and therefore largely affects the profitability of photovoltaic power generation business, it is desirable that the battery to be introduced has sufficient performance with respect to required smoothing and the introduction cost of it is kept as low as possible.

IHI has been focusing on technical development for effectively utilizing and widely spreading renewable energies[7], [8], in which in order to meet the above requirement, we are proceeding with

(1) the development of a battery control technique for smoothing mega-solar system supply power, and
(2) the development of an evaluation method for the capacity and maximum charging/discharging power of a battery (hereinafter referred to as required battery performance) required to smooth the mega-solar system supply power using the control technique to accomplish the primary technical object of smoothing the system supply power.

In addition, in terms of control, we are also aiming to examine the specifications of the battery to be introduced for the object.

This paper explains the above-described battery control technique and required battery performance evaluation method, as well as describing an example of required battery performance evaluation results based on actual power generation data acquired in a photovoltaic power generation system.

This paper is constituted as follows. First, in **Chapter 2**, a system model for a mega-solar including a battery, and the battery control model for smoothing system supply power will be described. In **Chapter 3**, the evaluation method based on the battery control model described in **Chapter 2** and for battery performance required to smooth the system supply power will be described. In **Chapter 4**, as an example of the required battery performance evaluation, the required battery performance evaluation results based on the actual power generation data acquired in the photovoltaic power generation system under multiple assumed constraint smoothing conditions will be described. Finally, in **Chapter 5**, challenges and future prospects will be described.

2. System model for mega-solar and battery control model for smoothing system supply power[9]

2.1 System configuration of mega-solar

In a typical mega-solar not having a battery, DC power generated using solar panels is converted to AC power by a power conditioner, and the AC power is directly supplied to a commercial system. Accordingly, when the generated power of the solar panels varies due to some causes such as obscuring the sun, the system supply power also varies correspondingly. For this reason, in this paper, a method for achieving the system supply power smoothing by installing a battery in a power plant and performing the charging/discharging control of the battery will be examined.

Figure 1 illustrates the system model for the mega-solar installed with the battery, which is assumed throughout this paper. In this model, without making supply power to a system dependent on the generated power of solar panels, the control target value of the supply power is successively determined, and the excess or deficiency of photovoltaic generated power with respect to the control target value is balanced by charging or discharging the battery to make the system supply power follow the control target value. In doing so, even when an abrupt variation occurs in the generated power of the solar panels, a variation in the system supply power can be reduced by charging or discharging the battery. Note that in order to obtain such a system, it is necessary to use a high-speed chargeable/dischargeable battery such as a lithium ion battery.

In **Fig. 1**, two sub-systems, i.e., a battery system and a power smoothing system play major roles in this system model.

The battery system receives the system supply power control target value from the below-described power smoothing system, and charges/discharges the battery so as to make the system supply power of the mega-solar follow the given control target value. A controller in the battery system feedback controls the battery so as to match a power value at a system interconnection point B measured by a power meter B with the control target value.

The power smoothing system determines the above-described control target value on the basis of the most recent trend of variation in photovoltaic generated power measured by a power meter A and the remaining amount of the battery received from the battery system. The power smoothing system ① acquires the photovoltaic generated power and the value of the battery remaining amount, ② calculates the control target value, and ③ updates the control target value of the battery system at regular intervals ΔT. Note that in the following, the times when the power smoothing system runs are represented by times $k = 0, 1, 2, \ldots$.

2.2 Battery control model

Figure 2 illustrates a calculation model (hereinafter referred to as the battery control model) for the system supply power control target value used for the batter charging/discharging control in the power smoothing system. As a smoothing process illustrated in the diagram, various method are conceivable. This paper describes a smoothing process using a moving average method[3], [4], [6], which is relatively easily implementable and widely used.

Smoothing using the moving average method is based on the idea that as the control target value of the system supply power, an average value of photovoltaic generated power during a certain period before the current time is used. In this paper, the battery control model is constructed on the basis of the control target value calculation based on moving average, as well as in consideration of the following two practically important points:

a. The assumed constraint conditions on mega-solar operation can be surely observed.
b. Energy loss associated with charging/discharging the battery is minimized.

In this paper, two constraints are assumed for a., i.e., ① the rate of change in the system supply power is limited, and ② the battery is charged only from the photovoltaic generated power, and system power is not allowed to charge the battery. The constraint ① is one intended to reduce an adverse effect on the voltage and frequency of the system due to an abrupt variation in the system supply power. Also,

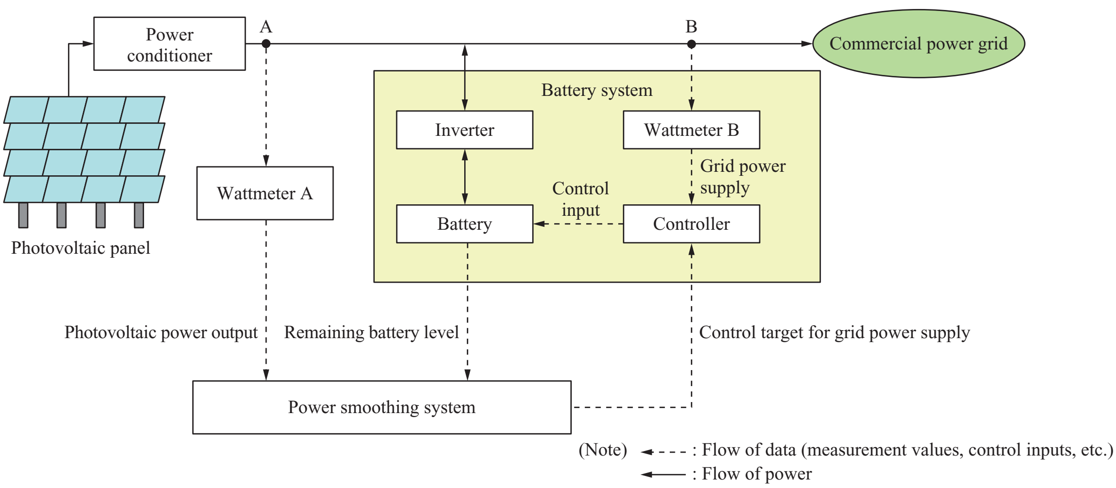
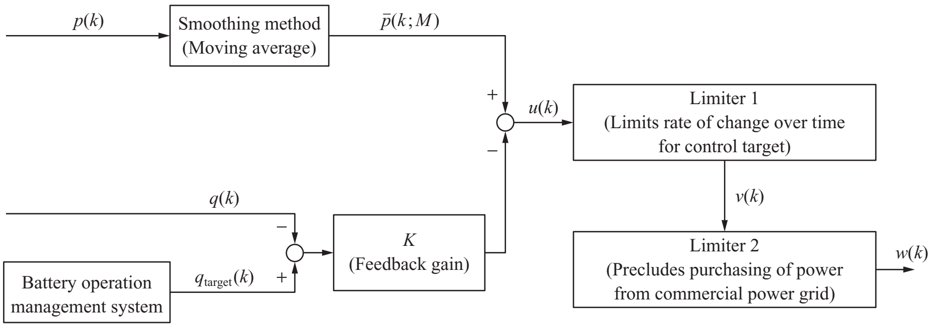


Fig. 1 System configuration of a mega-solar with a battery



(Note) $p(k)$: Photovoltaic power output before smoothing
$\bar{p}(k;M)$: Photovoltaic power output after smoothing
$q(k)$: Current remaining battery level
$q_{target}(k)$: Target remaining battery level
$u(k)$: Control target before consideration of constraints
$v(k)$: Control target after passing Limiter 1
$w(k)$: Control target after passing Limiter 2
(Final control target for grid power supply)

Fig. 2 Calculation model of the control target supplying power to the commercial power grid

the constraint ② is one taking account of preventing power purchased from the system and power generated by the solar panels from being mixed inside the battery, which is intended to properly operate the renewable energy feed-in tariff because the selling price of power supplied from the mega-solar to the system is favorably treated on the basis of the feed-in tariff.

As for b., in the battery, energy loss occurs due to, for example, AC/DC and DC/AC conversions by an inverter in the process of charging/discharging, and the total amount of the loss is proportional to an operation period. Accordingly, when taking account of the long-term operation of the mega-solar, the control model should be designed to minimize the energy loss.

A specific procedure for calculating the control target value of the system supply power will be described below. First, the moving average value $\bar{p}(k;M)$ of generated power from the current time to the most recent M point is obtained by

$$\bar{p}(k;M)=\frac{1}{M}\sum_{m=0}^{M-1}p(k-m), \quad \cdots\cdots(1)$$

where $p(k)$ represents the photovoltaic generated power at the current time k, and the control target value $u(k)$ before taking account of the constraint conditions is calculated in accordance with

$$u(k)=\bar{p}(k;M)-K\left(q_{\text{target}}(k)-q(k)\right). \quad \cdots\cdots(2)$$

The second term of the right-hand side of Equation (2) is a feedback term provided in order to minimize the energy loss associated with the charging/discharging, where $q_{\text{target}}(k)$ the target value of the battery remaining amount, $q(k)$ the current value of the battery remaining amount, and K a feedback gain. The target value $q_{\text{target}}(k)$ may be time-dependently determined in accordance with an appropriate algorithm, but is set as a constant in simulation in **Chapter 4** of this paper.

Then, limiters respectively corresponding to the above-described two constraint conditions are made to act on $u(k)$ calculated using Equation (2) in the order of $\mathcal{L}_1$ and $\mathcal{L}_2$ below:

(1) $\mathcal{L}_1$: a limiter for limiting the rate of change in the system supply power

$$v(k)=\mathcal{L}_1\left(u(k),u(k-1);\Delta T,\gamma,P_{\max}\right)
=\begin{cases} u(k-1)+\Delta T\gamma P_{\max}, & u(k)>u(k-1)+\Delta T\gamma P_{\max} \\ u(k-1)-\Delta T\gamma P_{\max}, & u(k)<u(k-1)-\Delta T\gamma P_{\max} \\ u(k) & \text{otherwise} \end{cases} \quad \cdots\cdots(3)$$

(2) $\mathcal{L}_2$: a limiter for prohibiting the purchase of power from the system

$$w(k)=\mathcal{L}_2\left(v(k)\right)=\max\left(0,v(k)\right). \quad \cdots\cdots(4)$$

In Equation (3), $v(k)$ represents a control target value after passing the limiter for the rate of change in the system supply power, γ represents the limit value of the rate of change in the system supply power, which determines the constraint smoothing conditions, and $P_{\max}$ represents the rated generated power of the solar panels. Also, in Equation (4), $w(k)$ represents the final control target value of the system supply power.

In this system, in order to achieve the control target value of the system supply power obtained using Equation (4), the battery is charged/discharged in response to a variation in the photovoltaic generated power. The battery remaining amount $q(k)$ at the time k can be approximately calculated by Equation (5) below on the assumption that the calculation period ΔT is sufficiently short as compared with a variation period of the generated power;

$$q(k)=\sum_{k=0}^{k-1}e'(k)\Delta T+q(0), \quad \cdots\cdots(5)$$

where

$$e'(k)=\begin{cases} \beta e(k), & e(k)>0 \\ \frac{1}{\beta}e(k), & \text{otherwise} \end{cases} \quad \cdots\cdots(6)$$

and

$$e(k)=p(k)-w(k). \quad \cdots\cdots(7)$$

Here, $e(k)$ represents battery charging/discharging power (positive corresponds to charging, and negative corresponds to discharging), $e'(k)$ represents charging/discharging power taking account of the loss as viewed from the battery side, and $0 < \beta < 1$ represents charging/discharging efficiency including inverter efficiency. When executing the battery charging/discharging control simulation using this system, the system supply power is obtained using Equations (1) to (4), and the remaining amount and charging/discharging power of the battery are obtained using Equations (5) to (7) with respect to the photovoltaic generated power $p(k)$ ($k = 0, 1, 2, \ldots$).

In the following discussion, $q(0)$ is assumed to be zero, i.e., $q(0) = 0$, and correspond to a 50% SOC (state of charge) of the battery. Therefore, note that when the remaining amount takes a lower value than that at the initial time $k = 0$, $q(k)$ takes a negative value.

3. Evaluation method for battery performance required to smooth system supply power of mega-solar

In order to achieve the smoothing of the system supply power of the mega-solar using the control model described in **Chapter 2**, a certain level of battery capacity or more (indicating how much energy the battery can store, unit: kW·h) and a certain level of maximum charging/discharging power or more (indicating how much power the battery can instantaneously charge/discharge, unit: kW) are required. As has been described in Introduction, when constructing a photovoltaic power plant, the installation cost of a battery is not negligible, and the cost is largely affected by the capacity and maximum charging/discharging power of the battery. For this reason, in this paper, these two (capacity and maximum charging/discharging power) are collectively defined as battery performance, and in this chapter, the method for evaluating the battery performance required to smooth the supply power of the mega-solar by means of the simulation based on the control model described in **Chapter 2** will be described.

The capacity and maximum charging/discharging power of the battery required to smooth the system supply power are represented by Q_{max} and E_{max}. The control model described in **Chapter 2** automatically satisfies the constraint smoothing conditions thanks to the effect of the limiters as long as the capacity and maximum charging/discharging power of the battery are sufficient. That is, the capacity and maximum charging/discharging power of the battery required for the smoothing can be obtained from the possible upper and lower limits of the remaining amount and charging/discharging power of the battery. Accordingly, as a conservative required performance evaluation method, it is conceivable that battery charging/discharging control simulation assuming that the capacity and maximum charging/discharging power of the battery are infinitely large is first executed, and from changes in the resulting remaining amount and charging/discharging power of the battery, the required capacity Q_{max} and maximum charging/discharging power E_{max} of the battery are respectively obtained from

$$Q_{max} = 2 \times \max\left(\max_k q(k), -\min_k q(k)\right) \quad \cdots\cdots\cdots\cdots (8)$$

$$E_{max} = \max\left(\max_k e(k), -\min_k e(k)\right), \quad \cdots\cdots\cdots\cdots (9)$$

where $\max_k q(k)$ and $\min_k q(k)$ represent the maximum and minimum values of the battery remaining amount throughout a simulation period, respectively, and $\max_k e(k)$ and $\min_k e(k)$ represent the maximum value (maximum charging power) and minimum value (maximum discharging power) of the battery throughout the simulation period. In addition, the part "2x" on the right side of Equation (8) is one taking account of the assumption described in **Chapter 2** that $q(k) = 0$ corresponds to 50% SOC.

The required battery performance evaluation using Equations (8) and (9) are relatively intuitive and conservative evaluation, and therefore suitable for approximately calculating the required performance and battery installation cost. However, this required battery performance evaluation has the following issues:

(1) not taking account of "a smoothing effect[10]" resulting from combining with other mega-solars, thus resulting in excessively conservative performance evaluation, and

(2) leading to evaluation results only depending on a power generation pattern acquired on a specified date when the required capacity and maximum charging/discharging power are maximized, thus resulting in failing to evaluate how much battery performance is required for regular operation,

and therefore may not be necessarily useful for actual mega-solar designing taking account of the scale of a plant and system situations. Therefore, this paper describes a method that without treating the constraint smoothing conditions as strict ones, evaluates "how much battery performance allows the constraint smoothing conditions to be observed and how often in terms of days they can be observed" in keeping with not only the photovoltaic power generation pattern contributing to the required performance and acquired on a small number of specified days but the trend of variation in power generation throughout the year. Specifically, by evaluating a constraint smoothing conditions observance day ratio R (hereinafter referred to as an observance day ratio) defined by

$$R(Q_{max}, E_{max}) = 100 \times \frac{S(Q_{max}, E_{max})}{D} \ (\%) \quad \cdots\cdots (10)$$

for various capacities Q_{max} and maximum charging/discharging powers E_{max} of the battery, the relationship between the battery performance and the observance day ratio is clarified, where D represents the total number of simulation target days, and S represents, among the total number of simulation target days, the number of days when the constraint smoothing conditions were able to be observed in the whole daytime. The number of observance days S and the observance day ratio R depend on the capacity Q_{max} and maximum charging/discharging power E_{max} of the battery, and therefore in Equation (10), respectively represented by

$S(Q_{max}, E_{max})$ and $R(Q_{max}, E_{max})$.

From the changes in the remaining amount and charging/discharging power of the battery obtained by the battery charging/discharging simulation assuming that the capacity and maximum charging/discharging power of the battery are infinitely large, the number of observance days $S(Q_{max}, E_{max})$ is obtained in accordance with

$$S(Q_{max}, E_{max}) = \left\| \left\{ d \,\middle|\, \begin{array}{l} 2\times\max\left(q^d_{max}, -q^d_{min}\right) < Q_{max} \\ \cap \max\left(e^d_{max}, -e^d_{min}\right) < E_{max}, \\ d = 1,\dots,D \end{array} \right\} \right\|, \quad \cdots\cdots\cdots\cdots(11)$$

where q^d_{max} and q^d_{min} respectively represent the maximum and minimum values of the battery remaining amount on the dth day ($d = 1, \dots, D$), and e^d_{max} and e^d_{min} respectively represent the maximum value (maximum charging power) and minimum value (maximum discharging power) of the charging/discharging power on the dth day. Also, the symbol $\|\cdot\|$ represents the number of elements of a set. **Figure 3** illustrates a conceptual diagram of Equation (11). **Figure 3** is partial results of the simulation to be described in **Chapter 4** (for conditions, see **Chapter 4**), and illustrates the changes in the maximum and minimum values of the remaining amount (**Fig. 3-(a)**) and the maximum charging and discharging powers (**Fig. 3-(b)**) of the battery throughout the year on a day basis obtained from the results of the battery charging/discharging control simulation based on the control model in **Chapter 2** and using the actual power generation data acquired in the photovoltaic power generation system. The green frames represent the given capacity (**Fig. 3-(a)**) and maximum charging/discharging power (**Fig. 3-(b)**) of the battery, and in **Fig. 3**, are set to be Q_{max} = 0.4 (pu·h) (**Fig. 3-(a)**) and E_{max} = 0.6 pu (**Fig. 3-(b)**), respectively. Note that pu (per unit) represents a ratio of power to a solar panel rated output of 1, and pu·h represents electrical energy corresponding to 1-hour charging/discharging at 1 pu. In the respective diagrams, days where both of the minimum (maximum) remaining amount and the maximum charging (discharging) power fall inside the green frames are constraint observance days.

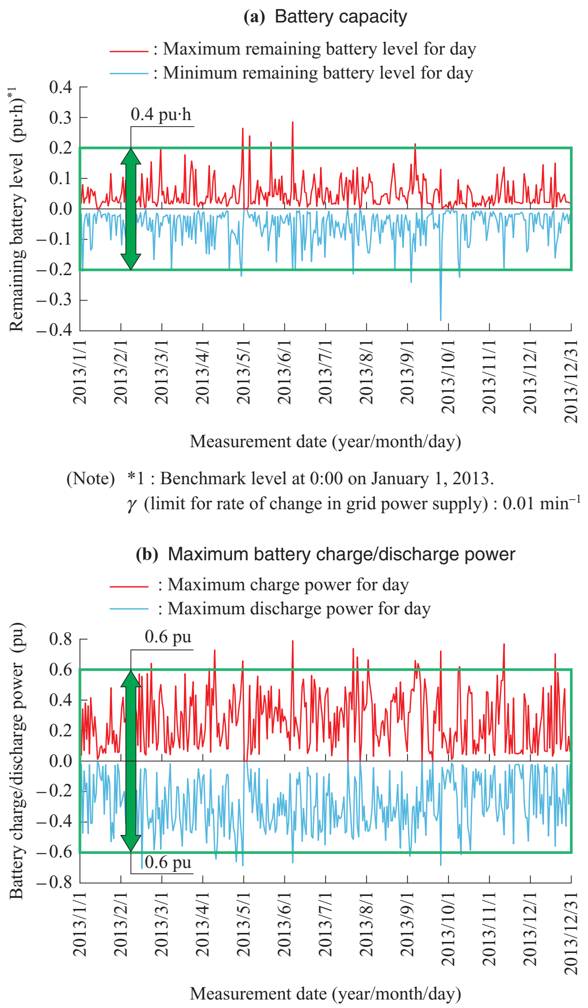


Fig. 3 Explanatory chart for the calculation of the number of days satisfying the smoothing constraint

The flow of the required battery performance evaluation based on the above concept will be described below.

Step 1 Execution of battery charging/discharging control simulation

By means of the successive battery charging/discharging control simulation based on the system model and control model described in **Chapter 2** and using the long-term (e.g., 1 year) photovoltaic power generation data, the battery remaining amount $q(k)$ and battery charging/discharging power $e(k)$ at each time k in the simulation are obtained. Note that the term "successive" means that the final remaining amount of the battery on the first day of any successive two days and the initial remaining amount of the battery on the second day are the same. Further, $q(k)$ and $e(k)$ in the simulation are not particularly limited.

Step 2 Calculation of minimum and maximum values of remaining amount and charging/discharging power on each day

The maximum value q^d_{max} and minimum value q^d_{min} of the remaining amount and the maximum value e^d_{max} and minimum value e^d_{min} of the charging/discharging power of the battery on the dth day ($d = 1, \dots, D$) during the simulation period are obtained.

Step 3 Calculation of observance day ratio with respect to battery performance

On the basis of q^d_{max}, q^d_{min}, e^d_{max}, and e^d_{min} ($d = 1, \dots, D$) obtained in Step 2, the number of observance days $S(Q_{max}, E_{max})$ and the observance day ratio $R(Q_{max}, E_{max})$ are obtained for various capacities Q_{max} and maximum charging/discharging powers E_{max} of the battery using Equations (10) and (11).

Step 4 Summary of relationship of observance day ratio with respect to battery performance

The relationship of $R(Q_{max}, E_{max})$ with Q_{max} and E_{max} is summarized.

By using the above-described evaluation method, wide and useful evaluation results can be obtained for consideration at the time of actual mega-solars designing, such as

(1) when assuming that a release from the constraints is allowed to a certain extent at the prospect of the smoothing effect, how much performance is obtained,

and

(2) how the battery operates throughout the year.

Also, even when using this method, the required performance corresponding to Equations (8) and (9) and for observing the constraint smoothing conditions throughout the simulation target days can also be evaluated.

Generally, the battery performance required to smooth the system supply power of the mega-solar depends, not only on the constraint smoothing conditions and the photovoltaic power generation pattern, but also on the control model and its parameters. In this paper, the simplified control model is used as an example. However, additionally note that when aiming to rationalize the battery performance, sophisticating the control model and optimizing its parameters become important challenges.

4. Example of required performance evaluation based on actual power generation data in photovoltaic power generation system

4.1 Evaluation conditions

This chapter describes an example of the evaluation results of the battery performance required for the system supply power smoothing. **Tables 1** and **2** respectively list photovoltaic power generation data and parameter settings[9] of the battery control model used for the evaluation. Also, **Fig. 4** illustrates the appearance of the photovoltaic power generation system in IHI Yokohama Office, from which the photovoltaic power generation data was acquired. In the evaluation, for the convenience of comparison of examination results, the value of generated power is normalized so as to make the rated output equal to 1 pu. In addition, during the simulation period (1 year: 365 days), there are totally 7 days when data was not acquired. As for this, in the simulation, photovoltaic generated power on each of the 7 days was assumed to be zero throughout that day, and the denominator D of the observance day ratio calculation Equation (10) was set to be $D = 365-7 = 358$ instead.

Table 1 Photovoltaic power generation data

Location		Isogo-ku, Yokohama-shi, Kanagawa (at IHI's Yokohama Office)
Panel azimuth	(°)	151.820
Panel inclination angle	(°)	10.0
Rated output	(kW)	10
Data period	(year/month/day)	2013/1/1 – 2013/12/31
Days with no data	(month/day)	5/3, 5/4, 5/5, 7/19, 7/28, 9/12, 9/20 (7 days)
Data interval	(s)	60 (data with 1-second interval is interpolated)

Table 2 Parameter settings of the battery control model [9]

Name	Parameter	Unit	Value
Calculation cycle	ΔT	s	1.0
No. of samples used for moving average	M	—	1 201 (20 min)
Limit for rate of change in grid power supply	γ	min^{-1}	0.01, 0.02, 0.03, 0.05, 0.10
Feedback gain	K	h^{-1}	1.0
Photovoltaic panel rated output	$P_{\max}$	pu	1.0
Target for remaining battery level	$q_{\mathrm{target}}(k)$	pu·h	0.0 (constant)
Battery charge/discharge efficiency	β	—	0.95

Fig. 4 IHI Corporation Yokohama office photovoltaic generation system

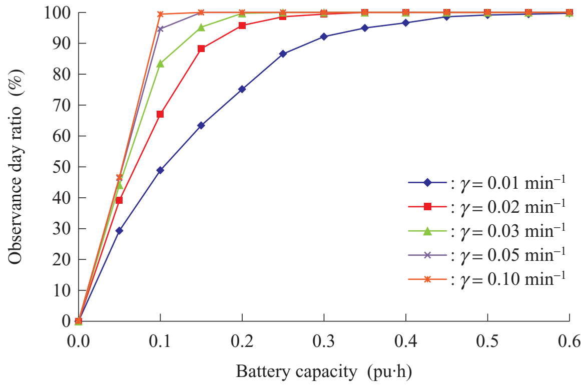
The photovoltaic power generation data used this time is acquired from the photovoltaic power generation system smaller in scale than a mega-solar. Variations in the generated power associated with weather variations depend on the scale of a system, and the smaller the scale of a system, the larger the variations in generated power with respect to the rated output. Accordingly, the following evaluation results are thought to be conservative in terms of considering the smoothing of the mega-solar system supply power.

4.2 Relationship between battery performance and observance day ratio (Individual evaluation of capacity and maximum charging/discharging power)

First, in order to understand how much each of the magnitudes of the capacity and maximum charging/discharging power of the battery contributes to improving the smoothing performance, ① the relationship between the capacity and the observance day ratio and ② the relationship between the maximum charging/discharging power and the observance day ratio were individually evaluated. Specifically, the observance day ratio was obtained on the assumption that for ①, the maximum charging/discharging power was infinitely large, and for ②, the capacity was infinitely large.

Figures 5 and **6** respectively illustrate the relationship between the battery capacity and the observance day ratio and the relationship between the battery maximum charging/discharging power and the observance day ratio obtained from the battery control simulation results on the basis of the idea of the individual evaluation.

As for the battery capacity, it turns out from **Fig. 5** that by preparing a larger capacity battery, the observance day ratio can be increased. It also turns out that as the limit value γ of the rate of change in the system supply power is increased, i.e., as the constraints become looser, the observance day



(Note) γ : Limit value for rate of change in grid power supply

Fig. 5 Relationship between battery capacity and the observance day ratio

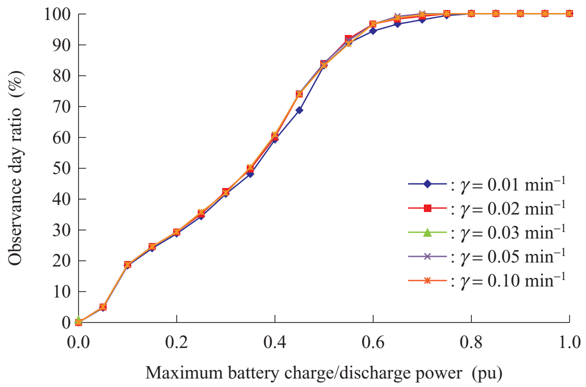
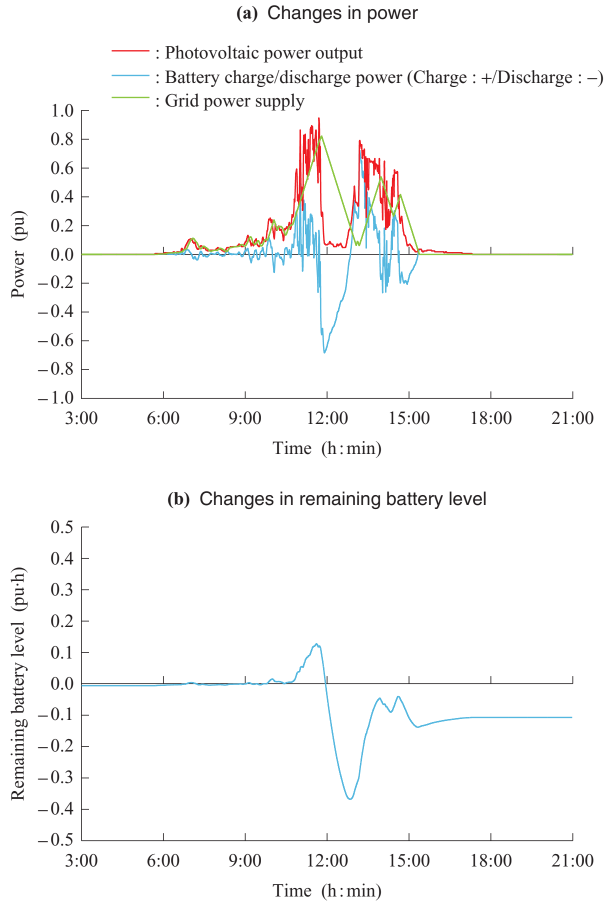


Fig. 6 Relationship between the battery maximum charge/discharge power and the observance day ratio



(Note) Conditions
- Simulation date : September 26, 2013
- γ (Limit for rate of change in grid power supply) : 0.01 min^{-1}

Fig. 7 Transition of the battery charge and discharge power and charged energy

ratio also increases. According to this simulation, in order to observe the constraint smoothing conditions throughout the simulation period, for $\gamma = 0.01\ min^{-1}$, a capacity of approximately 0.5 pu·h is required and for $\gamma = 0.10\ min^{-1}$, a capacity of approximately 0.1 pu·h is required.

Further, it turns out from **Fig. 5** that as the battery capacity is increased, an increase in the observance day ratio with respect to an increase in the capacity decreases. This means that a day when a photovoltaic power generation pattern requiring a large battery capacity appears does not frequently exist. **Figure 7** illustrates changes in various types of powers and the remaining amount on a day when a variation in the battery remaining amount was maximum. In **Fig. 7-(a)**, the photovoltaic generated power keeps low up to approximately am 10.00, then after that abruptly rises, and around noon, starts to abruptly fall. During this period, the battery is charged/discharged to observe the constraint smoothing conditions, and as a result, the battery remaining amount largely varies (**Fig. 7-(b)**). Since a variation in the battery remaining amount is given by the integral of the difference between the photovoltaic generated power and the system supply power, even when a large variation in the generated power occurs, as long as it is a short-period variation due to some causes such as temporarily obscuring the sun, a contribution to the variation in the remaining amount is small. However, as in the case of **Fig. 7**, in the case where a large variation in the generated power due to a sudden change in weather such as a change from sunny to cloudy (or from cloudy to sunny) occurs, and a generated power level after the variation continues for a long period of time, a variation in the remaining amount increases, and consequently, a large battery capacity is required for the smoothing.

Note that as described above, a day when a large variation in the generated power as illustrated in **Fig. 7** occurs does not frequently exist throughout the year, and when the observance day ratio can be set to 95% at the prospect of the smoothing effect, it turns out from **Fig. 5** that for $\gamma = 0.01\ min^{-1}$, the required battery capacity can be reduced to approximately 0.35 pu·h (as compared with 100% observance, –0.15 pu·h). Even in that case, a capacity of approximately 0.1 pu·h is sufficient on days corresponding to approximately half the year.

Next, as for the battery maximum charging/discharging power, it turns out from **Fig. 6** that by preparing a battery having a large maximum charging/discharging power, the observance day ratio can be increased as in the case of the capacity. However, the relationship between the maximum charging/discharging power and the observance day ratio is slightly different in tendency from the relationship between the capacity and the observance day ratio, and it turns out that the observance day ratio increases approximately in proportion to the maximum charging/discharging power until the observance day ratio reaches approximately 100%. This is considered because the power generation pattern causing the large variation in the battery remaining amount as illustrated in **Fig. 7** does not frequently appear, whereas a temporary abrupt change in the generated power frequently occurs throughout the year.

Also, it turns out from **Fig. 6** that the limit value γ of the rate of change in the system supply power hardly affects the observing day ratio. In the battery control model in this paper, the charging/discharging power of the battery at the time of a variation in the photovoltaic generated power is given by the different between the control target value of the system supply power and the photovoltaic generated power, and within a parameter range of $0.01 \text{ min}^{-1} \leq \gamma \leq 0.10 \text{ min}^{-1}$ used this time, a variation in the control target value of the system supply power is small as compared with the variation in the photovoltaic generated power. Accordingly, when γ is small, the required maximum charging/discharging power of the battery hardly depends on γ, and substantially corresponds to a possible variation width of the photovoltaic generated power. According to this simulation, in order to observe the constraint smoothing conditions throughout the simulation period, a maximum charging/discharging power of approximately 0.8 pu is required regardless of the value of γ.

4.3 Simultaneous evaluation of required capacity and maximum charging/discharging power of battery

In **Section 4.2**, the capacity and the maximum charging/discharging power are individually evaluated in terms of required performance. However, in this section, in order to evaluate more practical required performance of the battery, the relationship between the battery performance and the observance day ratio is evaluated while taking account of the capacity and the maximum charging/discharging power simultaneously when obtaining the observance day ratio using Equation (10). Here, for each combination of the values of the capacity and maximum charging/discharging power of the battery, the observance day ratio is evaluated. In this paper, as the ratio between the capacity and maximum charging/discharging power of the battery, C is defined by

$$C = \frac{E_{\max}}{Q_{\max}} \quad \cdots\cdots (12)$$

(C is also referred to as a C rate), and using C, the relationship between the capacity and the maximum charging/discharging power is summarized. A unit of C is the reciprocal of any time dimension, and in this paper, the unit of C is set to h^{-1} and represents what ratio of the battery capacity can be charged/discharged per hour.

Figure 8 illustrates the results of evaluating the relationship between the battery capacity and the observance day ratio for multiple maximum charging/discharging power-capacity ratios C. In each diagram, a $\gamma = 0.01 \text{ min}^{-1}$ ($C = \infty$) series is also plotted together. This is equivalent to a result of the individual evaluation taking account of only the capacity and performed in **Section 4.2**. It turns out from **Fig. 8** that when taking account of the capacity and the maximum charging/discharging power simultaneously, as compared with when taking account of only the capacity, the observance day ratio at the same battery capacity is small, and in particular, in the case of a small C value, such a tendency is prominent. Also, it turns out that there is almost no difference in the observance day ratio among different limit values γ of the rate of change in the system supply power. This is considered because the maximum charging/discharging power dominantly determines the observance day ratio, and is largely affected by the maximum charging/discharging power and the observance day ratio discussed in **Section 4.2**.

According to this simulation, in order to observe the constraint smoothing conditions throughout the simulation period, in the case of $\gamma = 0.01 \text{ min}^{-1}$, capacities of approximately 0.5 pu·h, 0.6 pu·h, and 0.8 pu·h are required for $C = 2.0 \text{ h}^{-1}$, 1.5 h^{-1}, and 1.0 h^{-1}, respectively.

These evaluation results can also be utilize for the approximate design of battery performance for an actual mega-solar. In that case, it is only necessary to multiply the above-described evaluation results by the rated output of a target mega-solar. For example, when applying one of the above-described results, i.e., 0.5 pu·h for $C = 2.0 \text{ h}^{-1}$ to a 4 MW mega-solar, the required capacity is 2 MW·h. Note that as referred to in **Section 4.1**, the evaluation results in this paper are based on the small-scale photovoltaic power generation system as compared with an actually envisaged mega-solar, and also conservative. Further, a power generation pattern of a mega-solar also depends on weather conditions in an installation area, and for example, the fact that in a cold area in winter, a power generation amount is reduced due to the effect of snow on solar panels is known. However, how much such a factor contributes to the required performance is not known at the moment, and therefore it is necessary to make examination through verification tests in the future.

5. Conclusion

In this paper, the battery control technique for smoothing mega-solar system supply power and the evaluation method for battery performance required to put the technique into practice have been described. In addition, as an example of the performance evaluation results, the required battery performance under the multiple assumed constraint smoothing conditions has been obtained by the simulation based on the actual power generation pattern acquired in the photovoltaic power generation system, and the results have been described.

Future challenges include demonstrating the system supply power smoothing system described in this paper using a practical plant. In addition, we are considering improving the battery control model for rationalizing the specifications of a battery required for the smoothing.

In the future as well, we will contribute to more widely spreading renewable energies including photovoltaic power generation by sophisticating the battery control technique.

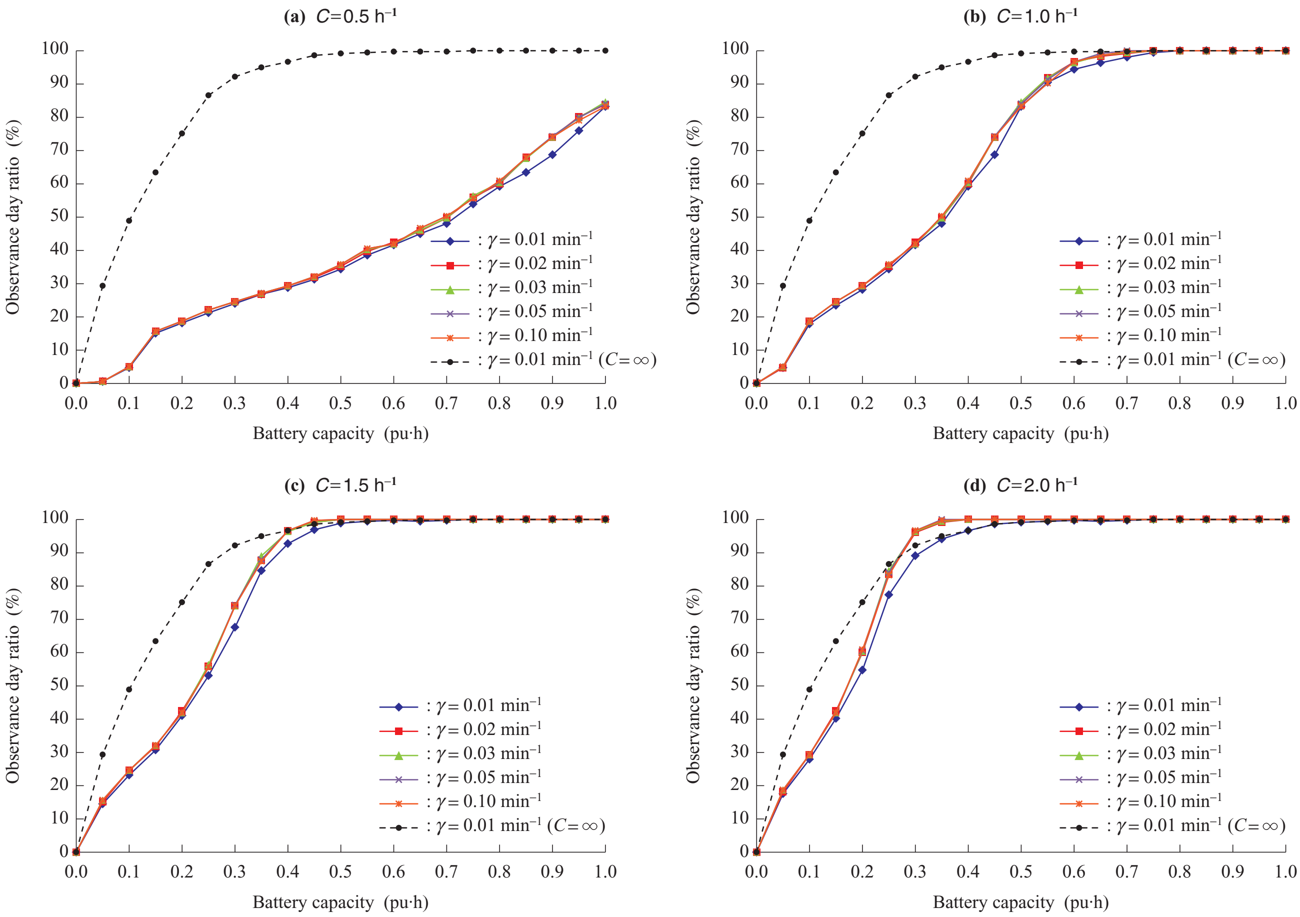


Fig. 8 Relationship between the battery capacity and the observance day ratio simultaneously considering the battery maximum charge and discharge power

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