IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received August 8, 2021, accepted September 1, 2021, date of publication September 7, 2021, date of current version September 16, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3110950

A Planned Power Generation for Battery-Assisted Photovoltaic System Using Short-Term Forecast

RYU ANDO[1], (Student Member, IEEE), HIDEO ISHII[2], (Member, IEEE), YASUHIRO HAYASHI[1], (Member, IEEE), AND GUIPING ZHU[3], (Member, IEEE)

[1]Department of Advanced Science and Engineering, Waseda University, Tokyo 169-8555, Japan
[2]Advanced Collaborative Research Organization for Smart Society, Waseda University, Tokyo 169-8555, Japan
[3]Department of Electrical Engineering, Tsinghua University, Beijing 100084, China

Corresponding author: Ryu Ando (ryu-anto@akane.waseda.jp)

This work was supported by the Graduate Program for Power Energy Professionals, Waseda University, through the MEXT WISE Program.

ABSTRACT The introduction of variable renewable energies, such as photovoltaic systems (PV), into electric power systems will increase the amount of resources necessary to balance supply and demand in terms of both quality and quantity. Thus, a planned power generation that matches the planned values submitted in advance with the actual values of PV power generation is required by installing battery energy storage systems (BESS). Currently, since the cost of BESS is still high, eliminating the imbalance which equals to the difference between planned and actual values of PV power generation by BESS is not economically feasible, and appropriate cooperation is required to share the role of balancing with regulating generators. However, variable renewable energies can cause steep imbalances which cannot be compensated by regulating generators due to their relatively slow response times. To address this problem, this paper proposes a planned power generation method that can reduce the burden on regulating generators by introducing a strategy to mitigate the changing rate of imbalance, (hereinafter called "imbalance leveling") by determining the optimal scheduling of BESS using the short-term forecast of PV power generation. Numerical simulations were conducted using a model based on Japanese frequency control to compare the proposed method with the conventional method without imbalance leveling. The results confirmed that the proposed method can improve the capacity value per unit of BESS in supply and demand adjustment owing to the effect of leveling the imbalance. Additionally, it can improve the performance of supply and demand adjustment with the same capacity.

INDEX TERMS Battery energy storage system, frequency control, photovoltaic system, planned power generation, short-term forecast.

I. INTRODUCTION

To realize a sustainable society, the introduction of variable renewable energy (VRE) sources, such as photovoltaic systems (PV), into the electric power systems is increasing in many parts of the world. According to an IRENA report [1], the global installed capacity of VRE reached 1,206 GW in 2019, and it is assumed that this deployment will continue. However, there are concerns that once the amount of installed VRE exceeds a certain level, fluctuations of power output of VRE will make it difficult to ensure stable operation of electric power systems [2]. As a measure to stabilize the grid under these circumstances, the provision of regulating power through the introduction of battery energy storage system (BESS) is an important approach because BESS can respond much faster than conventional regulating generators as well as provide high flexibility covering a wide range of time domains. Since the primary drawback of introducing BESS is its high initial cost, it is crucial that the required BESS capacity should be as small as possible in any kinds of countermeasures.

In general, prediction is important in compensating for VRE fluctuations, especially predicting the occurrence of the ramp-event is crucial; this happens when the output of VRE rises and falls significantly due to major changes in weather conditions, and up to 6 hours in advance, because it may be necessary to start-up generators that are stopped [3]. In addition, under a rule of balancing in a deregulated market,

The associate editor coordinating the review of this manuscript and approving it for publication was Shravana Musunuri.

which generally requires the balance between supply and demand to market participants, predicting the output of VRE for 30 min to several hours ahead is crucial to minimize the imbalance penalty while helping transmission system operators to reduce adjustment capacity for compensation of the imbalance after the gate is closed. The expansion in the introduction of VRE will increase the amplitude of such short-period fluctuations and make it difficult to maintain the frequency solely by conventional regulating generators. Thus, an economical method to keep the frequency fluctuations within an acceptable range by sharing and cooperating with the regulating generators while utilizing BESS becomes important. In recent years, it has been reported that the accuracy of short-term prediction of PV power generation has been improved by image analysis using all-sky cameras and machine learning [4]. Further, creating a method that contributes to supply and demand adjustment over a wide time range by utilizing predictions for controlling BESS is considered important.

Thus far, a large number of studies have been conducted on the method of combining PV with BESS to contribute to supply and demand adjustment. The cases will be reviewed separately for BESS owners, keeping in mind the relationship between the system and market rules. The BESS owners can be considered to be (1) grid operators, (2) aggregators (who bundle general consumers), and (3) power generation companies. If the BESS owner is the grid operator, the BESS may be integrated into the automatic generation control (AGC) system, which generally consists of thermal and pumped-storage power generation, and it is controlled by distributing area control error signals through filters. Ghafouri [5] and Tapabrata [6] proposed a control method that integrates stationary batteries into the conventional AGC control; Xie [7] proposed an AGC control method that integrates a group of electric vehicles connected to a swap charging station instead of stationary batteries. Xie *et al.* [8] demonstrated the integration of MW-class batteries into AGC control, which is mainly composed of coal-fired power generation, and they reported the excellent cost-effectiveness of battery installation. Yu *et al.* [9] used the finite-time consensus approach to balance the state of charge (SOC) of each BESS within a finite time period while integrating multiple small stationary storage batteries into the AGC control. In general, one of the advantages of the grid operator, which owns BESS and integrates them into the AGC control, is that the required capacity of the BESS is relatively small and economical compared to the case where BESS are attached to each renewable power source; this happens because it is possible to consider the leveling effect of the renewable power sources in the jurisdictional area. In the case where BESS are owned by an aggregator, the virtual power plant – a system that uses information and communication technology to bundle multiple small-scale distributed resources, such as stationary battery energy storages, electric vehicles, and controllable loads owned by consumers, such as households and office buildings, into a single giant power plant – can be utilized in the ancillary market. Diwei [10] and Jin *et al.* [11] proposed an optimal operation method to provide frequency ancillary services through the frequency ancillary market for multiple groups of BESS. Jonas *et al.* [12] proposed an optimal operation method for providing both frequency ancillary services and improving self-consumption for a single BESS. Qiwei *et al.* [13] proposed an optimal operation method for lithium-ion batteries when they, simultaneously, entered the wholesale electricity market (spot market) and the frequency ancillary market. In the case where the BESS owner is a power generation company, which is also the subject of this study, it is conceivable to attach the BESS to large-scale solar or wind power generation owned by the company, so that planned power generation has the same amount of actual and planned values submitted in advance through the wholesale power market and provide frequency ancillary services. Mostefa [14] and Sercan [15] proposed a rule-based control method that combines a BESS and renewable energy sources. Chunhua *et al.* [16] proposed a planned power generation method that combines solar, wind, pumped storage, and thermal power generation using a robust optimization framework. Francesco *et al.* [17] proposed a two-stage planning method for power generation (i.e., day-ahead planning, and real-time operation). Yun *et al.* [18] proposed a battery control method that introduces a new SOC adjustment method using short-term prediction and Monte Carlo simulations. Trudie *et al.* [19] proposed a battery control method based on the framework of Model Predictive Control. Moreover, Shuli *et al.* [20] proposed an AGC control method based on ultra-short-term prediction, while Xiaomeng *et al.* [21] and Mojtaba *et al.* [22] proposed a BESS control method that combines short-term predictions obtained from total sky images captured by a camera.

From previous studies, it has been confirmed that the amount of imbalance (in kWh) can be reduced from the charge and discharge control of the BESS attached to the PV according to the scale of the rated output and rated capacity of the installed BESS. From the perspective of adjusting supply and demand, it is desirable to completely eliminate the imbalance, which is the difference between the planned and actual values. However, although the cost of installing BESS has been reduced due to widespread use of electric vehicles, it is still currently high; and it is not economical to install large-capacity BESS that can completely eliminate the imbalance. In addition, since the control pattern of BESS for eliminating the imbalance is uniquely determined, it may be difficult to further reduce the amount of imbalance per capacity unit of BESS through the improvement of the control method. Therefore, the prediction of VRE fluctuations must be made as accurately as possible, and appropriate sharing with existing regulating generators must be pursued. Nevertheless, if the speed of change in the imbalance is steep, it will be difficult for slow response regulating generators, such as thermal power generations, to cope and the required capacity of the BESS will increase accordingly.

This study proposes a BESS control method to minimize the amount of imbalance at each time slot, and at the same time, to equalize the necessary adjustment power (in ΔkW) for supply and demand adjustment as much as possible. If the imbalance can be leveled out over time with decreasing the amount of imbalance (in kWh), the required tracking speed for the regulating generators can be reduced, thus the imbalance compensation by existing power supplies can be decreased. This is expected to lead to the minimization of the required capacity of the BESS. Using the proposed method and through leveling out the imbalance in a situation where a large amount of VRE is introduced, the required capacity of the BESS for planned power generation in coordination with existing regulating generators can be minimized. Further, the performance of supply and demand adjustment can be improved even with the same capacity of BESS. The following two points are novel in this study:

1. Proposal of a new planned power generation method using BESS that considers the leveling out of imbalance based on the short-term forecasting of PV power generation. The proposed method is expected to improve the performance of supply and demand adjustment, even with the same capacity, while avoiding the additional installation cost associated with the expansion of the BESS.
2. The effectiveness of the proposed method is evaluated from the viewpoint of system frequency through using a model based on Japanese frequency control; it simulates the dynamic characteristics of the regulating generators and corresponds to the current operation in Japan, as well as the unit commitment on the previous day and AGC control on the current day.

The remainder of this paper is organized as follows. Section II describes the model used in this study and the proposed method, and Section III presents the numerical simulation. Finally, Section IV summarizes the conclusion of the study.

II. PLANNED POWER GENERATION

A. MODEL

This section introduces the model used in this study, which is based on the case of a single PV owner and a single grid operator, as shown in Figure 1. We assume that the PV owner has one PV system and one BESS, while the grid operator owns 27 thermal power plants as regulating generators for frequency control (AGC control) and seven nuclear power generations as base load power sources. It is assumed that the PV owner will be able to sell electricity through the day-ahead market in the electricity wholesale market when the total amount of electricity generated by the PV and BESS is fully contracted. In addition, the output curtailment and other controls should not be performed on PV power generation, but only on the BESS.

B. IMBALANCE RULE

In Japan, the "30-min coincidental amount" is currently applied as an imbalance settlement rule [23]. This is for settling the monetary penalty corresponding to the amount of kWh shortage imbalance in the balance of payments within a 30-min time window. At this point in time, there is no incentive for power generation companies to enter the electricity wholesale market to perform the imbalance leveling (Δ kW) proposed in this paper. Actually, imbalance is compensated by the grid operator with resources procured from the frequency ancillary market. In this study, we will proceed assuming that the effect of imbalance leveling on reducing the required power of ancillary resources will lead to some kind of incentive in the future.

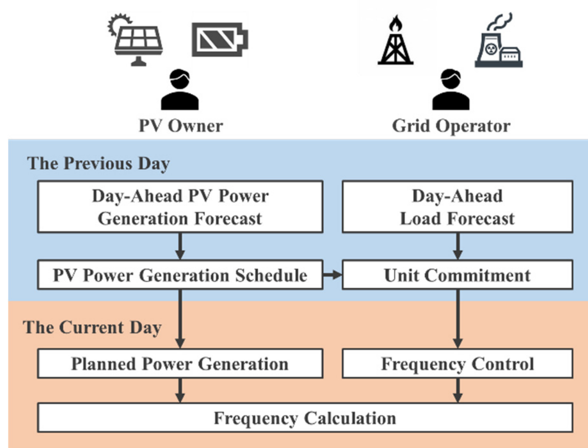

FIGURE 1. Model used in this study.

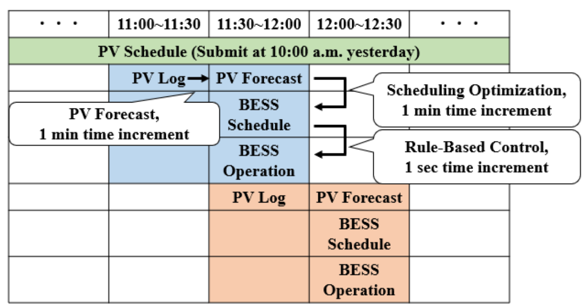

FIGURE 2. Operation flow.

C. OPERATION FLOW

The overall operation flow of the planned power generation proposed in this paper is shown in Figure 2. Initially, the PV power generation forecast for the day ahead is made at 10 am on the previous day, which is the deadline for the day-ahead market; the obtained forecast values in 30 min time increments and 48-time frames per day were submitted to the grid operator as the power generation plan. Next, on the current day, the PV power generation forecast for the next 1–30 min is made in 30 min cycles with 30 min time windows. Based on the short-term predicted values and the plans submitted in advance, the planned values in 1 min time increment for charge and discharge of the BESS are determined, taking imbalance leveling into consideration. Then, the final charge and discharge command values in 1 s time increment for the BESS were determined in real time based on rule-based control.

D. PV POWER GENERATION FORECAST

This paper deals with two types of PV power generation forecasts with different forecast lead time. One is the next-day forecast (14–38 hour ahead) for submitting planned values to the market, and the other is the short-term forecast (1–30 min ahead) for utilizing BESS control. The next-day forecast (14–38 hour ahead) was simulated by adding the forecast error to the correct values. The forecast error was determined based on a normal random number with mean parameter $\mu = 0$ and standard deviation parameter $\sigma = 0.05$ to the correct values [24]. In general, the planning value to be submitted is a step-like profile of the 30 min value. However, since we have confirmed in prior verifications that a steep change in the planning value before and after the 30 min time window has an adverse effect on the frequency control, we modify the planning value here to keep it within a certain maximum rate of change. The maximum change rate is determined based on that of the load frequency control (LFC) equipment owned by the grid operator, which is 5 %MW/min in this study. Long short-term memory (LSTM) is a type of Recurrent Neural Network with a forgetting mechanism, and it is suitable for time series analysis. In [25], [26], a forecasting method based on LSTM was implemented for 1-hour and 1-day forecasting; its prediction accuracy was reported to be superior to that of conventional forecasting methods based on classical machine learning techniques such as random forest and support vector machine. Therefore, in this study, LSTM is also adopted for short time prediction (1–30 min ahead); Only past actual values were used as input values. To further improve the accuracy of the model, we added a normalization process based on the theoretical values of total solar irradiance. The evaluation of the accuracy of the implemented forecasting model is discussed in Section III.

E. BATTERY OPTIMAL SCHEDULING

For each time window of the day (in this case, every 30 min), the planned values of charge and discharge of the BESS (in 1 min time increment) are determined in the framework of an optimization problem. It is obtained by solving the mixed integer linear programming (MILP) problem, which is formulated as follows using the modeling tool YALMIP with the commercial solver CPLEX. As shown in (1) – (3), 48 frames per 30 min of planned charge and discharge of the BESS, which minimize the objective function integrated with the weighted average for the amount of imbalance (kWh) and the rate of change of imbalance (ΔkW), are obtained by optimization calculation. In doing so, the short-term prediction of PV power generation (1–30 min ahead, in 1 min time increment) was used as an input value. In this study, the first term for the amount of imbalance is taken as an absolute value to reduce the imbalance in each frame instead of the same amount for 30 min simultaneously. The weight factors α and β are important parameters that greatly affect the control results of the planned power generation, which were set to 10 (YEN/kWh) and 2 (YEN/kW/hour), based on the Japanese wholesale electricity market and German frequency ancillary market prices, respectively. The equations are expressed as follows:

$$\begin{aligned} min\, F = \alpha \sum_{t=1}^{T} \Delta t \left| P_t^{PCC,SCHE} - P_t^{PV,SCHE} \right| \\ + \beta \sum_{t=1}^{T} \left| P_{t+1}^{PCC,SCHE} - P_t^{PCC,SCHE} \right| \end{aligned} \quad (1)$$

$$P_t^{PCC,SCHE} = \hat{P}_t^{PV} - P_t^{BAT,REF\_sche} \quad (2)$$

$$P_t^{BAT,REF\_sche} = P_t^{BAT,CHA\_sche} + P_t^{BAT,DIS\_sche} \quad (3)$$

where t, T is the time and its maximum value (T is equal to 30 min), Δt is the time increment (equal to 1 min), $P_t^{PCC,SCHE}$ is the total output of the PV and BESS at time t at scheduling stage, $P_t^{PV,SCHE}$ is the PV scheduled value at time t submitted to the market at previous day, $\hat{P}_t^{PV}$ is the forecasted PV generation power output value at time t, P_t^{BAT,REF_sche}, P_t^{BAT,CHA_sche}, P_t^{BAT,DIS_sche} are the planned values of the total charge and discharge power output and their respective charge and discharge power output of the BESS at time t at scheduling stage; α, β are the weight factors (positive values).

The constraints are expressed in (4) – (9). Equation (4) is a constraint on the upper and lower limits of the binary variables for the charge and discharge of the BESS. Equation (5) represents the upper and lower limit constraints on the charge output of the BESS. Equation (6) represents the upper and lower limit constraints for the discharge output of the BESS. Equation (7) is an equation for the SOC of the BESS. Equation (8) represents the upper and lower limit constraints for the SOC of the BESS. Equation (9) represents the upper and lower limit constraints for the total output of the PV and BESS, respectively. Here, by setting the lower limit of the total output of the PV and BESS to 0, the BESS is restricted from charging from the grid, and it is only charged with electricity derived from the PV power generation. The equations are expressed as follows:

$$0 \le \delta_t^{BAT,CHA\_sche} + \delta_t^{BAT,DIS\_sche} \le 1 \quad (4)$$

$$0 \le P_t^{BAT,CHA\_sche} \le \overline{P}^{BAT,CHA} \cdot \delta_t^{BAT,CHA\_sche} \quad (5)$$

$$\underline{P}^{BAT,DIS} \cdot \delta_t^{BAT,DIS\_sche} \le P_t^{BAT,DIS\_sche} \le 0 \quad (6)$$

$$\begin{aligned} SOC_t^{sche} = SOC_{t-1}^{sche} + 100 \\ \cdot \Delta t \frac{\gamma \cdot P_t^{BAT,CHA\_sche} + \gamma^{-1} \cdot P_t^{BAT,DIS\_sche}}{E^{BAT}} \end{aligned} \quad (7)$$

$$\underline{SOC} \le SOC_t^{sche} \le \overline{SOC} \quad (8)$$

$$0 \le P_t^{PCC} \le \overline{P}^{PCC} \quad (9)$$

where δ_t^{BAT,CHA_sche}, δ_t^{BAT,DIS_sche} are the binary variables for the charge and discharge power output of the BESS at time t at scheduling stage, respectively. $\overline{P}^{BAT,CHA}$ is the maximum charge output of the BESS (positive value). $\underline{P}^{BAT,DIS}$ is the maximum discharge output of the BESS (negative value). SOC_t^{sche} is the SOC of the BESS at time t at scheduling stage; $\underline{SOC}$, $\overline{SOC}$ are the upper and lower limits for the SOC of the BESS. γ is the one-way charge/discharge efficiency of the BESS; E^{BAT} is the rated capacity of the BESS, and $\overline{P}^{PCC}$ is the maximum output of the PV and BESS.

■ $P_t^{BAT,REF\_ctrl} = P_t^{PV} - P_t^{PCC,SCHE}$

■ $If\ P_t^{BAT,REF\_ctrl} \geq 0 \rightarrow positive\ means\ charge\ battery$

  □ $SOC_t^{ctrl} = SOC_{t-1}^{ctrl} + 100 \cdot \Delta t \frac{\gamma \cdot P_t^{BAT,REF\_ctrl}}{E^{BAT}}$

■ $Else \rightarrow negative\ means\ discharge\ battery$

  □ $SOC_t^{ctrl} = SOC_{t-1}^{ctrl} + 100 \cdot \Delta t \frac{\gamma^{-1} \cdot P_t^{BAT,REF\_ctrl}}{E^{BAT}}$

■ $If\ \underline{SOC} \leq SOC_t^{ctrl} \leq \overline{SOC}$

  □ $P_t^{BAT} = P_t^{BAT,REF\_ctrl}$

■ $Elseif\ SOC_t^{ctrl} < \underline{SOC}$

  □ $If\ P_t^{BAT,REF\_ctrl} \geq 0$

    ➢ $P_t^{BAT} = P_t^{BAT,REF\_ctrl}$

  □ Else

    ➢ $P_t^{BAT} = 0$

■ $Else$

  □ $If\ P_t^{BAT,REF\_ctrl} < 0$

    ➢ $P_t^{BAT} = P_t^{BAT,REF\_ctrl}$

  □ Else

    ➢ $P_t^{BAT} = 0$

FIGURE 3. BESS rule-based control.

F. BATTERY RULE-BASED CONTROL

In real time, the submitted PV planned values and the planned values of the total output of the PV and BESS (1 s time increment) are created using linear interpolation based on the corresponding values (1 min time increment) obtained in Section II. E. Subsequently, the final command values for charging and discharging the BESS (in 1 s increment) are determined from the rule-based control [27] shown in Figure 3. where P_t^{BAT,REF_ctrl} is the planned values of BESS charge and discharge at time t at control stage, SOC_t^{ctrl} is the SOC of the BESS at time t at control stage, P_t^{BAT} is the final command values of BESS charge and discharge at time t. The proposed method described above can be summarized as follows. Section II.D predicts the short-term ahead (1–30 min ahead) for PV power generation; Section II.E determines the planned BESS values for 1 min time increment. At this time, based on the PV power generation planned values submitted in advance and the obtained short-term predictions, the planned values (in 1 min time increment) for charge and discharge BESS that minimize the objective function, which integrates the amount of imbalance (kWh) and the rate of change of total output of PV and BESS (ΔkW) with certain weight coefficients, are determined to equalize the imbalance. Based on the rule-based control in Section II.F, the final command value for 1 s time increment is determined through making corrections based on actual values of PV power generation while adjusting the SOC of the BESS.

III. NUMERICAL SIMULATION

A. CONDITIONS

This section describes the procedure of the numerical simulation conducted to verify the effectiveness of the proposed method.

(1) The PV owner submits to the grid operator a PV power generation plan in 30 min time increments that is determined based on the day-ahead forecast.

(2) The grid operator makes a forecast of the area load for the next day, solves the unit commitment problem to minimize the operation cost of regulating generators based on this load forecast and the PV power generation plan submitted by the PV owner, and makes a generation plan in 30 min time increments for the regulating generators for the next day.

(3) While the PV owner plans to conduct planned power generation of PV with BESS, the grid operator adjusts the supply and demand, and controls the system frequency (AGC control) from the regulating generators to maintain the system frequency within an appropriate range.

The IEEJ AGC30 model [28], developed by the Institute of Electrical Engineers of Japan, was adopted as the analytical model for the frequency control simulation. The unit commitment problem to determine the day-ahead generation plan for regulating generators was solved based on our preliminary study [29]. In addition, economic dispatch control has not been implemented and will be considered in future work. In this paper, ±0.2 Hz was considered as the proper range of the system frequency. For the load data, we used the daily data, which peak value is 18,000 MW, for weekdays in summer distributed by the IEEJ as standard data while the installed generation capacity of regulating generators is 20,100MW; for the PV power generation data, we used the measured values of global horizontal irradiance in 1 s time increment measured by an irradiator installed at the Research and Development Center of Waseda University in Tokyo, Japan, which were finally converted to PV power generation data. A typical day when the PV occurs a ramp-up event was adopted. The PV installation capacity rate was set to 30% (5,400 MW in this case) based on the peak load value to consider the current actual situation in Japan [30], [31]. The load forecast for the next day were simulated by adding forecast errors which is determined by multiplying a normal random number with mean parameter $\mu = 0$ and standard deviation parameter $\sigma = 0.01$ to the correct values [32]. To verify the effectiveness of the proposed method, the following five cases were compared as planned power generation methods using BESS. Case 1 is the case where only PV and BESS are not considered; case 2 is the case with PV and BESS (conventional method without imbalance leveling); case 3 is the case with PV and BESS (proposed method with imbalance leveling and LSTM-based prediction), case 4 is the case with PV and BESS (proposed method with imbalance leveling and no prediction error), and case 5 is the reference case with PV and BESS (reference value, and no imbalance). For cases from 2 to 4, the attached BESS is assumed that its rated output is 5,400 MW which is the same size with the installed PV rated output, with a rated capacity of 1,080 MWh and a one-way charge and discharge efficiency of 90%. The upper and lower limits of the BESS SOC were set to 90% and 10%, respectively, and the initial SOC was set to 50%. Based on the low-pass filter, the smoothing effect of short-term fluctuations of PV power output of less than several tens of minutes [33] was considered (concentric circles of a 5 km radius in this case).

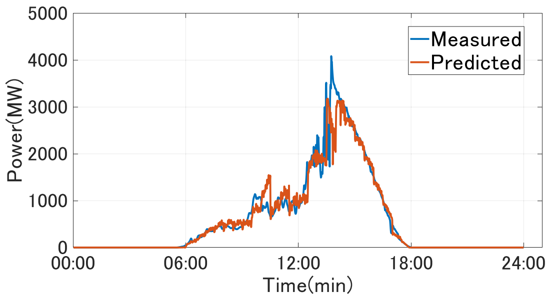

FIGURE 4. Short-term forecast of PV power generation.

TABLE 1. LSTM-based forecast accuracy (1–30 min ahead).

RMSE (kW)	MAE (kW)	MAPE (%)
0.05	0.03	17.54

B. RESULTS

Figure 4 shows the time variation of the PV short-term ahead forecast in a day; Table 1 shows the forecast error (1–30 min ahead) of the 1kW unit of PV short-term forecast. For the time period of 6:00 to 18:00, the forecast error was 0.05 for root mean square error (RMSE), 0.03 for mean absolute error (MAE), and 17.54% for mean absolute percent error (MAPE).

Figure 5 shows the time variation of the scheduled value of PV and planned power generation of PV and BESS for each method in a day. As shown in the figure, by using the attached BESS to perform charge and discharge control to compensate for the imbalance, which is the difference between the PV planning values submitted at the previous day and the actual values of PV and BESS on the day, it can be confirmed that the three cases including the conventional method and proposed methods are generally in agreement with the scheduled value of PV unless the BESS deviates from the rated output and SOC constraints. Figure 6 shows a closer look at the time variation of the planned power generation of the PV and BESS during the 12:00–13:00 time period. Because the conventional method does not perform imbalance leveling,

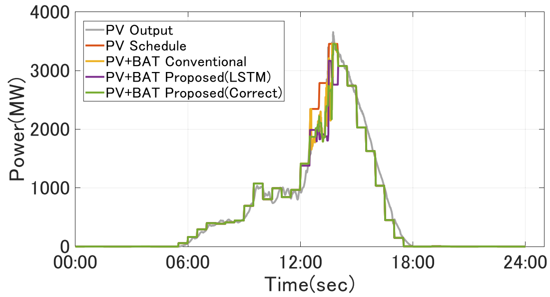

FIGURE 5. Planned power generation with PV and BESS (00:00–24:00).

when the SOC of the BESS reaches the lower limit, it is no longer possible to continue discharging; this results in spikes of imbalance. In contrast, it can be confirmed that the proposed methods avoid the occurrence of spiky imbalance by leveling the imbalance and reducing the rate of change of imbalance. This will reduce the burden of the maximum change rate of the regulating generators and contribute to maintaining the system frequency within the proper range during the relevant time period.

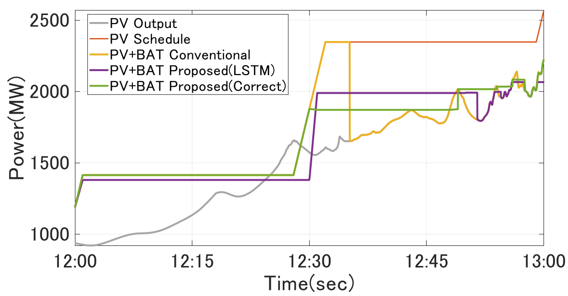

FIGURE 6. Planned power generation with PV and BESS (12:00–13:00).

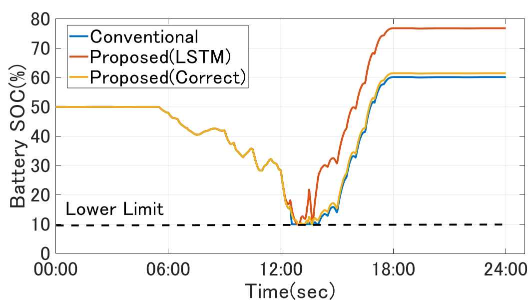

FIGURE 7. Battery SOC (00:00–24:00).

Figure 7 shows the time variation of the SOC of the BESS in a day; and Figure 8 shows a closer look at the time variation of the SOC of the BESS during the 12:00–13:00 time period. As shown in the figures, the conventional method reaches the lower limit of the SOC of the BESS during the 12:30–13:00 time period and can no longer continue discharging, while the proposed methods delay reaching the lower limit of the SOC of the BESS by leveling the imbalance.

Figure 9 shows the time variation of the imbalance in a day, and it can be confirmed that there occurs significant imbalance due to the lack of the SOC to keep discharging for

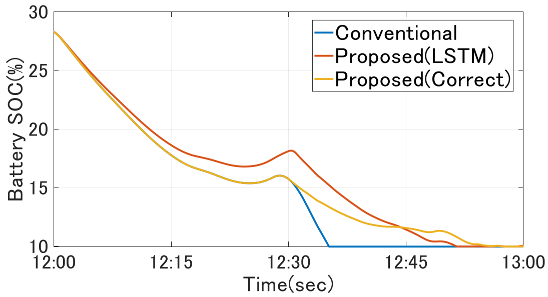

FIGURE 8. Battery SOC (12:00–13:00).

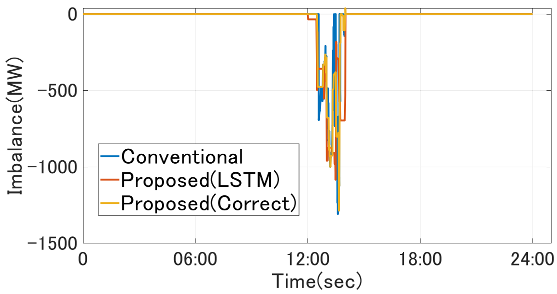

FIGURE 9. Imbalance (00:00–24:00).

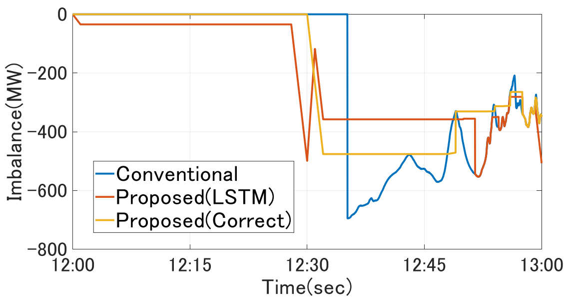

FIGURE 10. Imbalance (12:00–13:00).

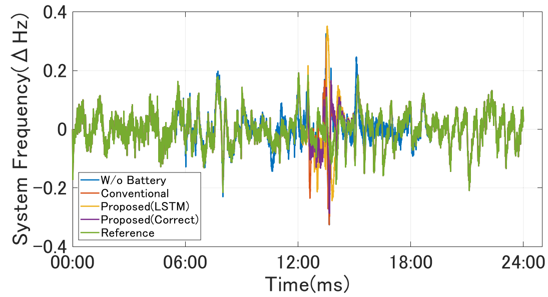

FIGURE 11. System frequency (00:00–24:00).

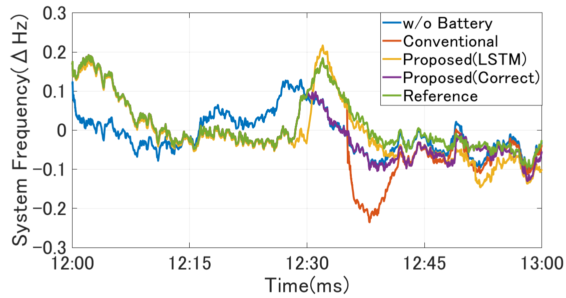

FIGURE 12. System frequency (12:00–13:00).

TABLE 2. Imbalance results.

Cases	Average of imbalance change [ΔMW/s]	Maximum of imbalance change [ΔMW/s]	Amount of imbalance [MWh]
W/o Battery	0.89	79	2,007
Conventional	0.49	848	711
Proposed (LSTM)	0.11	188	938
Proposed (Correct)	0.12	566	738
Reference	0	0	0

three cases. Figure 10 shows a closer look at the time variation of the imbalance during the period of 12:00–13:00. It can be confirmed that the proposed methods reduce the speed of imbalance change and the maximum amplitude of imbalance compared with the conventional method owing to the effect of imbalance leveling.

Figure 11 shows the time variation of the system frequency in a day. From the figure, we can see that in the morning and evening hours when no PV power was generated, the system frequency was kept within the appropriate range. Figure 12 shows a closer look at the time variation of the system frequency during the period of 12:00–13:00. It can be confirmed that the proposed method with no prediction error, which is corresponded to the proposed (correct) described in the graph, can maintain the system frequency within the proper range compared to the conventional method by performing imbalance leveling.

Table 2 describes the numerical results of the imbalance for each case. From the table, we can see that the average of imbalance change and the amount of imbalance for the conventional method is smaller, but the maximum of imbalance change is larger compared with the case of only PV but not BESS considered. This is because, in the conventional method, the BESS can compensate the imbalance with the attached BESS, but it could also occur the spikes of the imbalance due to the lack of the SOC. On the other hand, the average and the maximum of the imbalance change for the proposed method with no prediction error is smaller, but the amount of the imbalance is larger compared to the conventional method. This is because the proposed method can reduce the speed of change of the imbalance by conducting the imbalance leveling but in contrast it could prefer the imbalance leveling to the imbalance compensation based on the weight factors α and β considered here. And the amount of the imbalance for the proposed method with LSTM-based forecast is larger compared with the conventional method due to the forecast error.

TABLE 3. System frequency results.

Cases	Max [ΔHz]	Min [ΔHz]	Deviation Amount [ΔHz]	Deviation Rate [%]
W/o Battery	+0.32	-0.32	259.46	0.64
Conventional	+0.31	-0.32	215.35	0.59
Proposed (LSTM)	+0.35	-0.24	587.75	1.03
Proposed (Correct)	+0.19	-0.28	75.08	0.18
Reference	+0.19	-0.21	1.53	0.02

Table 3 describes the numerical results of the system frequency for each case. For the evaluation indices, the system frequency deviation rate is defined as the ratio of the time when the system frequency deviates from the proper range (in this case, ±0.2 Hz) to the entire day. And the system frequency deviation amount is defined as the total amount of the system frequency which deviates from the proper range for the entire day. From the table, we can see that the conventional method outperformed the case only with PV and BESS not being considered by compensating the imbalance with the attached BESS. In addition to that, the proposed method with no prediction error outperformed the conventional method for all evaluation indices by conducting the imbalance leveling; thus, it reduces the rate of change of the imbalance and leads to the reduction of the burden on the maximum rate of change of the regulating generators. It is confirmed that the maximum, minimum, deviation amount and deviation rate of the system frequency in the proposed method with no prediction error improved by 38%, 12%, 65%, and 69% respectively, compared to the conventional method. And also, the reference case outperformed the proposed method with no prediction error by eliminating the imbalance with the attached large enough capacity of the BESS. In the reference case, when the required rated capacity of the BESS to achieve no imbalance on the relevant day was calculated using the difference between the maximum and minimum SOC values of the BESS on the relevant day, it was estimated to be about 10% larger than the rated capacity of the BESS used in the conventional method and the proposed methods. Note that, the proposed method with LSTM-based forecast underperformed the conventional method because the forecast error makes it difficult for the BESS to conduct the proper imbalance leveling under the circumstance of the actual PV power generation. Because of the PV short time forecast accuracy having a significant impact on the performance of the BESS control method proposed in this paper, the improvement of the forecast accuracy will continue to be an important issue for further study. These results suggest that the proposed method can contribute to improve the performance of supply and demand adjustment even with the same capacity while avoiding the additional installation costs associated with increasing the capacity of BESS.

IV. CONCLUSION

This paper proposes a novel planned power generation method using BESS based on a short-term forecast of PV power generation to contribute to the adjustment of supply and demand in electric power systems. As the initial cost of BESS remains high at present, PV owners, which aim to pursue profit maximization, find it difficult to eliminate the imbalance because the capacity of the BESS attached to the PV is limited to match the planned and actual values simultaneously. If the rate of change of the imbalance that occurs is steep, there is concern that the response of the regulating generators will be slow and unable to follow it completely; this adversely affects the adjustment of supply and demand. On the other hand, the proposed method can contribute to the improvement of the performance of supply and demand adjustment by leveling out the speed of change of imbalance (ΔkW) from the charge and discharge control of the BESS using the short-term forecast of PV power generation. Based on the numerical simulation results, it is confirmed that the proposed method in the case of no prediction error can reduce the system frequency deviation rate by approximately 69% compared to the conventional method which doesn't conduct the imbalance leveling. Therefore, it was suggested that the proposed method could contribute to improving the performance of supply and demand adjustment.

REFERENCES

[1] *Renewable Energy Statistics 2020 The International Renewable Energy Agency*, IRENA, Abu Dhabi, United Arab Emirates, 2020.

[2] H. Holttinen and R. Hirvonen, "Power system requirements for wind power," *Wind Power Syst.*, vol. 8, pp. 143–167, Apr. 2005.

[3] M. Ito, Y. Fujimoto, M. Mitsuoka, H. Ishii, and Y. Hayashi, "Power and hour capacity requirement for an energy storage from grid codes," in *Proc. IEEE PES Asia–Pacific Power Energy Eng. Conf. (APPEEC)*, Brisbane, QLD, Australia, Nov. 2015, pp. 1–5, doi: 10.1109/APPEEC.2015.7381022.

[4] A. Ryu, H. Ishii, and Y. Hayashi, "Battery smoothing control for photovoltaic system using short-term forecast with total sky images," *Electr. Power Syst. Res.*, vol. 190, Jan. 2021, Art. no. 106645, doi: 10.1016/j.epsr.2020.106645.

[5] A. Ghafouri, J. Milimonfared, and G. B. Gharehpetian, "Coordinated control of distributed energy resources and conventional power plants for frequency control of power systems," *IEEE Trans. Smart Grid*, vol. 6, no. 1, pp. 104–114, Jan. 2015.

[6] T. Chakraborty, D. Watson, and M. Rodgers, "Automatic generation control using an energy storage system in a wind park," *IEEE Trans. Power Syst.*, vol. 33, no. 1, pp. 198–205, Jan. 2018.

[7] P. Xie, Y. Li, L. Zhu, D. Shi, and X. Duan, "Supplementary automatic generation control using controllable energy storage in electric vehicle battery swapping stations," *IET Gener., Transmiss. Distrib.*, vol. 10, no. 4, pp. 1107–1116, Oct. 2016.

[8] X. Xie, Y. Guo, B. Wang, Y. Dong, L. Mou, and F. Xue, "Improving AGC performance of coal-fueled thermal generators using multi-MW scale BESS: A practical application," *IEEE Trans. Smart Grid*, vol. 9, no. 3, pp. 1769–1777, May 2018.

[9] Y. Wang, Y. Xu, Y. Tang, K. Liao, M. H. Syed, E. Guillo-Sansano, and G. M. Burt, "Aggregated energy storage for power system frequency control: A finite-time consensus approach," *IEEE Trans. Smart Grid*, vol. 10, no. 4, pp. 3675–3686, Jul. 2019.

[10] D. Zhu and Y.-J.-A. Zhang, "Optimal coordinated control of multiple battery energy storage systems for primary frequency regulation," *IEEE Trans. Power Syst.*, vol. 34, no. 1, pp. 555–565, Jan. 2019.

[11] J. Tan and Y. Zhang, "Coordinated control strategy of a battery energy storage system to support a wind power plant providing multi-timescale frequency ancillary services," *IEEE Trans. Sustain. Energy*, vol. 8, no. 3, pp. 1140–1153, Jul. 2017.
[12] J. Engels, B. Claessens, and G. Deconinck, "Combined stochastic optimization of frequency control and self-consumption with a battery," *IEEE Trans. Smart Grid*, vol. 10, no. 2, pp. 1971–1981, Mar. 2019.
[13] Q. W. Zhai, K. Meng, Z. Y. Dong, and J. Ma, "Modeling and analysis of lithium battery operations in spot and frequency regulation service markets in Australia electricity market," *IEEE Trans. Ind. Informat.*, vol. 13, no. 5, pp. 2576–2586, Oct. 2017.
[14] M. Kermadi, Z. Salam, and E. M. Berkouk, "A rule-based power management controller using stateflow for grid-connected PV-battery energy system supplying household load," in *Proc. 9th IEEE Int. Symp. Power Electron. Distrib. Gener. Syst. (PEDG)*, Jun. 2018, pp. 1–6.
[15] S. Teleke, M. E. Baran, S. Bhattacharya, and A. Q. Huang, "Rule-based control of battery energy storage for dispatching intermittent renewable sources," *IEEE Trans. Sustain. Energy*, vol. 1, no. 3, pp. 117–124, Oct. 2010.
[16] C. Peng, P. Xie, L. Pan, and R. Yu, "Flexible robust optimization dispatch for hybrid wind/photovoltaic/hydro/thermal power system," *IEEE Trans. Smart Grid*, vol. 7, no. 2, pp. 751–762, Mar. 2016.
[17] F. Conte, S. Massucco, G.-P. Schiapparelli, and F. Silvestro, "Day-ahead and intra-day planning of integrated BESS-PV systems providing frequency regulation," *IEEE Trans. Sustain. Energy*, vol. 11, no. 3, pp. 1797–1806, Jul. 2020.
[18] Y. Zhou, Z. Yan, and N. Li, "A novel state of charge feedback strategy in wind power smoothing based on short-term forecast and scenario analysis," *IEEE Trans. Sustain. Energy*, vol. 8, no. 2, pp. 870–879, Apr. 2017.
[19] T. Wang, H. Kamath, and S. Willard, "Control and optimization of grid-tied photovoltaic storage systems using model predictive control," *IEEE Trans. Smart Grid*, vol. 5, no. 2, pp. 1010–1017, Mar. 2014.
[20] S. Wen, Y. Wang, Y. Tang, Y. Xu, and P. Li, "Proactive frequency control based on ultra-short-term power fluctuation forecasting for high renewables penetrated power systems," *IET Renew. Power Gener.*, vol. 13, no. 12, pp. 2166–2173, Sep. 2019.
[21] X. Ai, J. Li, J. Fang, W. Yao, H. Xie, R. Cai, and J. Wen, "Multi-time-scale coordinated ramp-rate control for photovoltaic plants and battery energy storage," *IET Renew. Power Gener.*, vol. 12, no. 12, pp. 1390–1397, Sep. 2018.
[22] M. Saleh, L. Meek, M. A. S. Masoum, and M. Abshar, "Battery-less short-term smoothing of photovoltaic generation using sky camera," *IEEE Trans. Ind. Informat.*, vol. 14, no. 2, pp. 403–414, Feb. 2018.
[23] Ministry of Economy. *Trade and Industry (METI), Detail Design of Imbalance Charge for FY2021 and Beyond*. Accessed: Jun. 3, 2021. [Online]. Available: https://www.emsc.meti.go.jp/activity/emsc_system/pdf/037_04_00.pdf
[24] Y. Kataoka, T. Kato, and Y. Suzuoki, "A study on spatial average insolation forecast in electric utility service area using meso-scale model grid point value," *IEEJ Trans. Power Energy*, vol. 133, no. 6, pp. 548–554, 2013.
[25] Y. Yu, J. Cao, and J. Zhu, "An LSTM short-term solar irradiance forecasting under complicated weather conditions," *IEEE Access*, vol. 7, pp. 145651–145666, 2019.
[26] W. Lee, K. Kim, J. Park, J. Kim, and Y. Kim, "Forecasting solar power using long-short term memory and convolutional neural networks," *IEEE Access*, vol. 6, pp. 73068–73080, 2018.
[27] M. Brenna, F. Foiadelli, M. Longo, and D. Zaninelli, "Energy storage control for dispatching photovoltaic power," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 2419–2428, Jul. 2018.
[28] The Institute of Electrical Engineers of Japan. *Recommended Practice for Simulation Models for Automatic Generation Control (IEEJ AGC30 Model)*. Accessed: Jun. 7, 2021. [Online]. Available: https://www.iee.jp/pes/
[29] X. Dui and G. Zhu, "Optimal unit commitment based on second-order cone programming in high wind power penetration scenarios," *IET Renew. Power Gener.*, vol. 12, no. 1, pp. 52–60, Jan. 2018.
[30] Ministry of Economy. *Trade and Industry (METI), The Introduction Amount of Photovoltaic System*. Accessed: Jun. 10, 2021. [Online]. Available: https://www.meti.go.jp/shingikai/santeii/pdf/063_01_00.pdf
[31] Tokyo Electric Power Company (TEPO). *International Comparison of Peak Load*. Accessed: Jun. 10, 2021. [Online]. Available: https://www.tepco.co.jp/corporateinfo/illustrated/power-demand/peak-demand-international-j.html
[32] *Power System Supply and Demand Control Technology*, no. 302, Inst. Elect. Eng. Japan, Tokyo, Japan, 1989, pp. 1–220.
[33] T. Kato, S. Kumazawa, N. Honda, M. Koaizawa, S. Nishino, and Y. Suzuoki, "Development of estimation method of spatial average irradiance fluctuation characteristics considering smoothing effect around observation point," *IEEJ Trans. Power Energy*, vol. 133, no. 1, pp. 91–98, 2013.

RYU ANDO (Student Member, IEEE) received the B.E. degree in electrical engineering from Waseda University, Tokyo, Japan, in 2017, where he is currently pursuing the Ph.D. degree in electrical engineering. His research interests include frequency control, battery control, and renewable energy forecasting. He is a Student Member of the Institute of Electrical Engineers in Japan (IEEJ).

HIDEO ISHII (Member, IEEE) received the Ph.D. degree from The University of Tokyo, Tokyo, Japan, in 1996. He joined Tokyo Electric Power Company, Tokyo, in 1988. He was a Visiting Scientist with Massachusetts Institute of Technology, Cambridge, MA, USA, from 1989 to 1991. Since 2010, he has been engaged as an organizer in major smart grid-related national projects in Japan. He is currently a Professor with the Advanced Collaborative Research Organization for Smart Society (ACROSS), Waseda University, Tokyo. His current research interests include electric energy systems, especially those related to demand response and the integration of renewable energy resources. He has been the Chair of IEC TC 8 SC 8C, since 2020.

YASUHIRO HAYASHI (Member, IEEE) received the B.Eng., M.Eng., and D.Eng. degrees from Waseda University, Tokyo, Japan, in 1989, 1991, and 1994, respectively. In 1994, he became a Research Associate with Ibaraki University, Mito, Japan. In 2000, he became an Associate Professor with the Department of Electrical and Electronics Engineering, Fukui University, Fukui, Japan. He has been a Professor with the Department of Electrical Engineering and Bioscience, Waseda University, since 2009, and the Director of the Research Institute of Advanced Network Technology, since 2010. Since 2014, he has been the Dean of the Advanced Collaborative Research Organization for Smart Society, Waseda University. His current research interests include optimization of distribution system operation and forecasting, operation, planning, and control concerned with renewable energy sources, and demand response. He is a member of the Institute of Electrical Engineers of Japan and a Regular Member of CIGRE SC C6 (Distribution Systems and Dispersed Generation).

GUIPING ZHU (Member, IEEE) received the Ph.D. degree in electrical engineering from Tsinghua University, Beijing, China, in 2006. Since 2007, she has been an Associate Professor with the Department of Electrical Engineering, Tsinghua University, and an Associate Dean with the Department of Electrical Engineering, Tsinghua University, since 2016. Her research interests include energy storage, interactions between EVs and power grids, active distribution networks, and power quality control.