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Dynamic Determination Method of LFC Capacity Using Correspondence Table between LFC Capacity and PV Output Forecast Error in Wide Fluctuating Season of Solar Radiation

Keito NISHIDA[*1], Ryuto SHIGENOBU[1], Masakazu ITO[1], Hisao TAOKA[2]
Norikazu KANAO[3], Hitoshi SUGIMOTO[3]
1: University of Fukui, Japan, 2: Yamato University, Japan
3: Hokuriku Electric Power Company, Japan
*** nishdia.keito@pws.fuee.u-fukui.ac.jp**

SUMMARY

The target for the composition ratio of Renewable Energy (RE) is 36 to 38% by 2030 to achieve a decarbonized society in Japan. However, RE output has a challenge for the power system stability, such as demand-supply imbalance because RE output includes various cycle fluctuations. The RE output is considered the short cycle fluctuations and the long cycle fluctuations. Load frequency control (LFC) reduces the RE output of a cycle of several minutes to 20 minutes. Generally, the constant LFC capacity is known regardless of the PV fluctuations. However, LFC capacity during the daytime is necessary to be determined according to PV capacity level because PV generates in the daytime. On the other hand, the power system can operate with a small LFC capacity during the nighttime because PV output will not happen. Furthermore, the previous research clarified a decrease of frequency deviations by PV forecast error according to the increase of LFC capacity. Thus, this paper proposes a Dynamic Determination method of LFC capacity (DD-LFC) which determines LFC capacity dynamically at each time of the UC by the PV output forecast error. In this paper, a correspondence table for the LFC capacity determination by the PV output forecast error was made using the knowledge that the time stay rate of the standard frequency range differs for each LFC capacity. The procedure of LFC-DD was performed according to the following steps. Firstly, the simulation for the correspondence table was executed with iterative calculation by the model supposing the existing power system. Secondly, the PV output forecast error and the time stay rate of frequency under ± 0.1Hz for each LFC capacity were calculated using the results step 1. Thirdly, an approximate linear between the PV output forecast error and the time stay rate of frequency was obtained for each LFC capacity. Finally, the correspondence table between the LFC capacity and the PV output forecast error was obtained by the approximate linear in step 3. The power supply-demand balance and frequency simulation was executed using the correspondence table. The analyzed day was performed assuming a significant PV output forecast error. LFC capacity was set as a dynamic setting and the constant setting for comparison. The simulation results by DD-LFC showed that LFC capacity was reduced from 379 MW/day to 276 MW/day compared to the constant LFC capacity. Furthermore, the maximum PV installation capacity could be increased from 50.8% to 63.8%. In conclusion, DD-LFC could reveal a reduction in LFC capacity and an increased effect on the maximum PV capacity rate.

KEYWORDS

LFC capacity, Time stay rate of frequency, Dynamic Determination, PV output forecast error, Correspondence table

1. Introduction

The Japanese government mentioned that the target for reducing greenhouse gas to 46% below 2013 by 2030. Since the power generation sector accounts for about 40% of CO2 emissions in Japan, reducing CO2 emissions is vital in this sector. Thus, to achieve the 2030 target, further installation of RE is required compared to the current composition ratio of RE. However, RE output has a challenge for the power system stability, such as demand-supply imbalance because RE output includes various cycle fluctuations. The RE output is considered the short cycle fluctuations and the long cycle fluctuations. The countermeasures against the short cycle fluctuations are system inertia, governor-free control, and load frequency control (LFC). Furthermore, the countermeasure against the long cycle fluctuations is economic load dispatching control. Thus, when the power system stability maintains, the power system operation is required to combine the unit commitment (UC) considering the reserve power with countermeasures against short-period fluctuations. Generally, a constant LFC capacity is known regardless of the PV fluctuations. In previous research, various PV output forecast methods have been proposed [1-5], and the PV output forecast error has been analyzed [6-7]. On the other hand, several studies on the UC [8-10] and LFC model [11-15] are actively performed, and the LFC of micro-grid has been researched [16-17].

Furthermore, the author's previous research clarified increased frequency deviations with increasing PV output forecast error. In addition, when LFC capacity was large, the frequency deviations were decreased regarding increasing PV output forecast error [18]. In other words, LFC capacity is required by the PV output forecast error for further installation of PV capacity while maintaining power system stability. Thus, this paper proposes a Dynamic Determination method of LFC capacity (DD-LFC), which dynamically determines LFC capacity at each time of the UC by the PV output forecast error. To clear the validation of efficacy by using DD-LFC, a UC using DD-LFC is scheduled, and a power supply-demand balance and frequency simulation is executed for the operation on the day. In DD-LFC, an approximate line between PV output forecast error and the time stay rate of frequency is obtained, and a correspondence table for the determination of LFC capacity by PV output forecast error is obtained using this formula. Using DD-LFC, a reduction effect of LFC capacity and an increasing effect of maximum PV installation will be revealed while maintaining the power system stability.

This paper is organized as follows. DD-LFC is given in Section 2. Simulation conditions are shown in Section 3. Simulation results are shown in Section 4. The concluding remarks are made in Section 5.

2. Dynamic Determination method of LFC capacity.

The flow chart of the DD-LFC is as shown in Fig. 1. Firstly, an approximate line between PV output forecast error and the time stay rate of frequency is made at each time of the UC by using the data for the same month of the previous year of the month in which the analysis dates. Secondly, a correspondence table for the determination of LFC capacity by the PV output forecast error is made using the formula in Step 1. Finally, LFC capacity is dynamically determined by PV output forecast error at each time of the UC in the analysis data based on the correspondence table.

2.2 Make an approximate line between PV output forecast error and the time stay rate of frequency.
1. Collect the frequency for each LFC capacity.
2. Calculate the 30 minutes value of the PV output forecast error and the time stay rate.
3. Make an approximate line between PV output forecast error and the time stay rate of frequency.

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2.3 Make a correspondence table for the determination of LFC capacity.

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2.4 Dynamically determination LFC capacity at each time of the UC.

Fig. 1 The flow chart of DD-LFC

Table 1. Electric power generators of the power system analysis model.

Generator	LFC generator	Rated Output [MW]	Minimum Output [MW]	Output Speed [MW/min]	Inertia [s]
Oil #1	○	250	40	3.0	8.0
Oil #2		250	75	3.0	8.0
Oil #3		500	75	12.5	8.0
Oil #4		250	35	3.0	8.0
Coal #1		250	60	5.0	8.0
Coal #2		250	60	5.0	8.0
Coal #3	○	500	100	15.0	8.0
Coal #4	○	700	140	28.0	8.0
Coal #5	○	500	100	10.0	8.0
Coal #6	○	700	140	28.0	8.0
GTCC	○	425	178	20.0	8.0

2.1 Power system analysis model and use data.

The model is assumed in the Hokuriku area in Japan, modified automatic generation control (AGC) model [19]. The models of electric power generators are constructed to concern existing power plants data and shown in Table 1. The LFC generators reserve an output margin of 40 MW from the rated output and the minimum output, respectively. The PV output and the demand data are made by synthesizing the short-cycle fluctuation (1-second value) into the measured PV and demand (1-minute value) for considering an actual condition. To make the forecast PV output, the accurate forecasted irradiance data of the mesoscale model (MSM-GPV) are obtained from JMA. Then, the forecast irradiance is converted to the forecast PV output by using a performance ratio and installed PV capacity. The forecast demand is the average value for 30 minutes of the measured demand. The PV output forecast error is defined as the ratio of the PV output forecast error to the forecast demand and is calculated by using formula (1).

$$\varepsilon_t^{PV} = \frac{PV_t^{\text{out}} - PV_t^{\text{fcst}}}{P_t^{\text{Load}}} \times 100 \qquad (1)$$

where t is each time of the UC ($t = 1, \cdots, 48$), ε_t^{PV} is the PV output forecast error at time t, PV_t^{out} is the PV output at time t, PV_t^{fcst} is forecast PV output at time t, P_t^{Load} is forecast demand at time t.

2.2 Make an approximate line between PV output forecast error and the time stay rate of frequency.

In DD-LFC, an approximate line between the PV output forecast error and the time stay rate of frequency is made for each LFC capacity by using the knowledge that the time stay rate of the standard frequency range differs for each LFC capacity.

2.2.1 Collect the frequency for each LFC capacity.

A power supply-demand balance and frequency simulation are executed by the power system analysis model in section 2.1 to collect the frequency deviations of each LFC capacity. LFC capacity is assumed from 2% to 10%.

2.2.2 Calculate the 30 minutes value of the PV output forecast error and the time stay rate.

LFC capacity is reserved at the UC, and the UC is scheduled every 30 minutes. Thus, the average values for 30 minutes of the time stay rate of frequency under ± 0,1Hz for each LFC capacity are calculated using the frequency in 2.2.1. The average values for 30 minutes of the PV output forecast error are also calculated.

2.2.3 Make an approximate line between PV output forecast error and the time stay rate of frequency.

An approximate line is made between PV output forecast error and the time stay rate of frequency for each LFC capacity by using formula (2). An approximated linear is shown in Fig. 2.

$$F_i^{\pm 0.1} = a_i \varepsilon_t^{\text{PV}} + b_i \qquad (2)$$

where i is LFC capacity at the UC ($i = 2, \cdots, 10$), a_i and b_i are slope and intercept at LFC capacity i, respectively, $F_i^{\pm 0.1}$ is the time stay rate of frequency under ±0,1 Hz, ε_t^{PV} is the PV output forecast error at time t. Note that a_i and b_i are required to calculate by simulation.

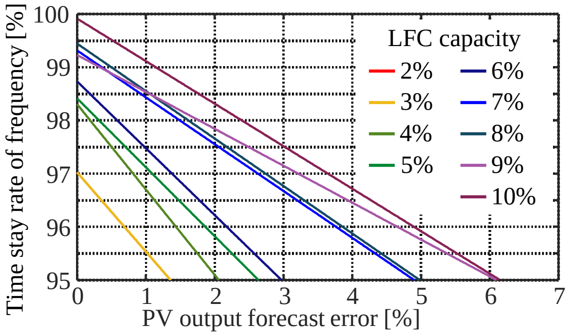


Fig. 2 Approximate liner equations.

Table 2 Correspondence table.

PV output forecast error [%]	LFC capacity [%]
0	2
~ 1.36	3
~ 2.06	4
~ 2.64	5
~ 2.97	6
~ 4.90	7
~ 4.98	8
~ 6.10	9
6.10 ~	10

2.3 Make a correspondence table for the determination of LFC capacity.

The time stay rate of frequency in section 2.2 is required to satisfy the criteria which is 95% or more under ±0.1 Hz. Therefore, the minimum LFC capacity that satisfies the criteria of the time stay rate of frequency is determined by using the formula (3). Finally, the correspondence table between LFC capacity and the PV output forecast error is made using formula (3). The correspondence table is shown in Table 2.

$$i_t^{req} = \{\, i \mid \min\{a_i \varepsilon_t^{\mathrm{PV}} + b_i - \mathrm{F}_0\} \geq 0\} \qquad (3)$$

where i_t^{req} is LFC capacity by the PV output forecast error at time t, F_0 is 95 because of the criteria which is 95% or more under ±0.1 Hz. The correspondence table is shown in Table 2.

2.4 Dynamically determine LFC capacity at each time of the UC.

The PV output forecast error is calculated at each time of the UC on the analysis day using formula (1). Then, LFC capacity is determined by using the correspondence table between the PV output forecast error and LFC capacity.

3. Validation of efficacy by using DD-LFC.

3.1 Simulation procedure.

The simulation can be separated into scheduling and simulation. Firstly, PV capacity is set, and the forecast PV output is made using the forecasted irradiance data. Next, the PV output forecast error is calculated, and LFC capacity at each time of the UC is determined by the PV forecast error using DD-LFC. Finally, a power supply-demand balance and frequency simulation is executed using the model in section 2.1.

3.2 Simulation condition.

The data period to make the correspondence table is November 2018, and the analysis day is November 16th, 2019. Furthermore, the analysis day is assumed that the PV output forecast error is significant. PV capacity increases in 20 MW increments from 1010 MW (current installation at November 2019). When PV capacity is 1010 MW, the profile of demand, PV output is shown in Fig. 3, and the dynamically determined LFC capacity is shown in Fig. 4.

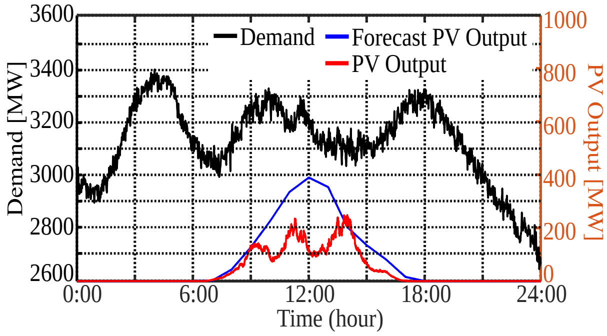


Fig. 3 Profile of demand, PV output.

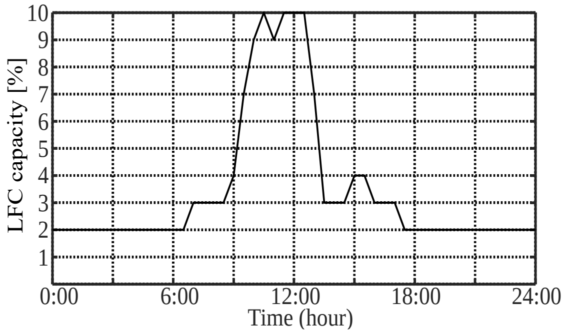


Fig. 4 LFC capacity at the UC.

3.3 Evaluation index.

The maximum PV capacity rate is defined as the ratio of the maximum PV capacity to the maximum demand that satisfies the frequency criteria (① ±0.1 Hz: 95% or more, ② ±0.2 Hz), and is calculated by the formula (4). The PV power generation rate is defined as PV power generation to electricity demand and is calculated using the formula (5).

$$PV_i^{\mathrm{poss}} = \frac{PV_i^{\max}}{\mathrm{L}^{\max}}$$
$$PV_i^{\max} = \{PV_i^{\max} \mid \max(PV_i^{0.1} \cap PV_i^{0.2})\} \qquad (4)$$
$$E_i^{\mathrm{PV}} = \frac{E_{PV_i^{\max}}}{\mathrm{E_{load}}} \qquad (5)$$

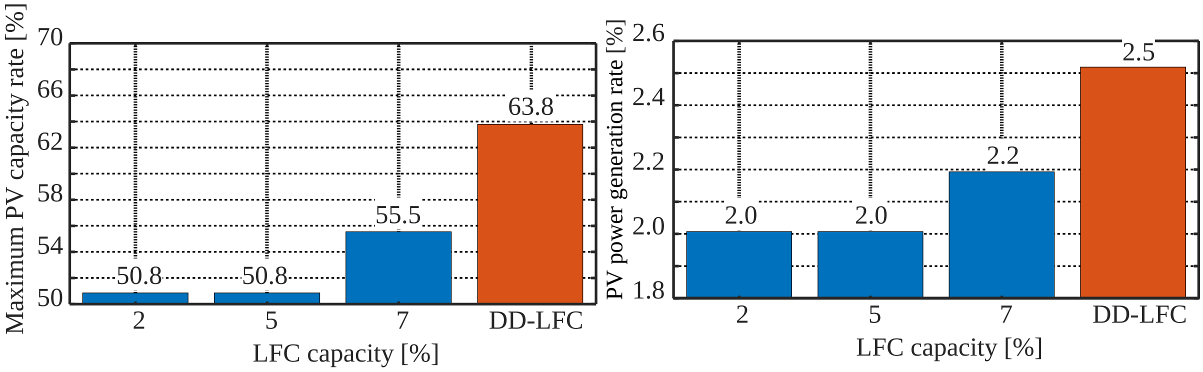
where is i is LFC capacity at the UC (2%, 5%, 7%, dynamic setting), PV_i^{poss} is the maximum PV capacity rate at LFC capacity i, $PV_i^{\max}$ is the maximum PV capacity that satisfies the frequency criteria at LFC capacity i, $PV_i^{0.1}$ and $PV_i^{0.2}$ are PV capacity that satisfies the frequency criteria at LFC capacity i, $\mathrm{L}^{\max}$ is the maximum demand, E_i^{PV} is the PV power generation rate at LFC capacity i, $E_{PV_i^{\max}}$ is the PV power generation with the maximum PV capacity at LFC capacity i, $\mathrm{E_{load}}$ is electric power generation.

4. Simulation result and discussion

The result of the daily average of LFC capacity at the UC, the maximum PV capacity rate and the PV power generation rate by using DD-LFC is shown in Table 3. Then, the maximum PV capacity rate and PV power generation rate by using DD-LFC and the constant LFC capacity are shown in Fig. 5. The maximum PV capacity rate using DD-LFC could be increased from 50.8% to 63.8% compared to the constant LFC capacity 5% as shown in (a), Fig. 5. Therefore, an increased effect of maximum PV capacity rate was 25.6% compared to the constant LFC capacity 5%. Furthermore, the PV generation rate using DD-LFC could be increased from 2.0% to 2.5% as shown in (b), Fig. 5. Therefore, an increased effect of the PV generation rate was 25.0% compared to the constant LFC capacity 5%. On the other hand, when PV capacity was installed at 55% or more, the constant LFC capacity 7% was required for maintaining the power system stability as shown in (a), Fig. 5. Thus, when PV capacity was 55.5%, the reserved LFC capacity of all LFC generators and the daily average of LFC capacity for

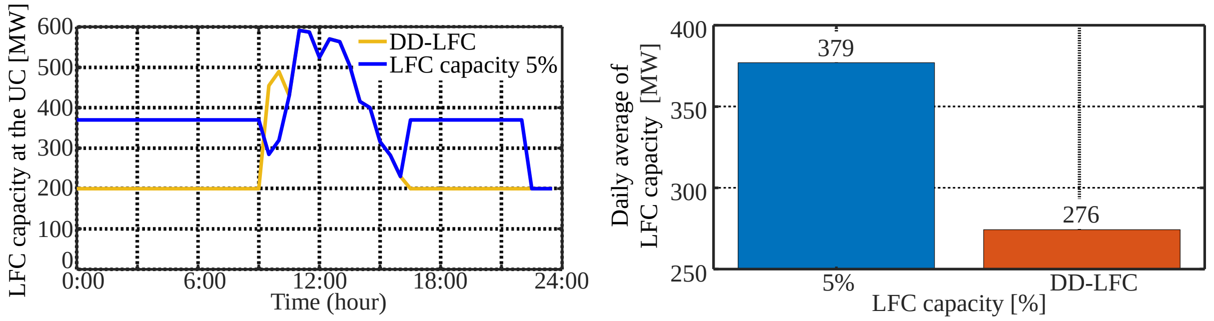
Table 3 Maximum PV capacity rate, PV power generation rate and LFC capacity by using DD-LFC.

Maximum PV capacity rate	63.8%
PV power generation rate	2.52%
Daily average of LFC capacity at UC	3.9%



(a) Maximum PV capacity rate. (b) PV power generation rate.

Fig. 5 The results by using DD-LFC (orange) and the constant LFC capacity (blue).



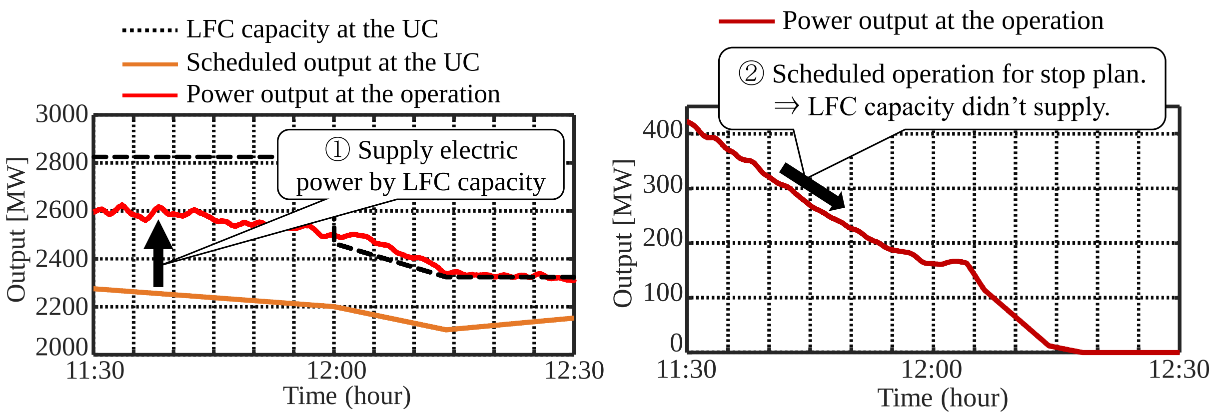
(a) LFC capacity of all LFC generators. (b) Daily average of LFC capacity.

Fig. 6 Compare DD-LFC to the constant LFC capacity 7%.

the cases of DD-LFC and the constant LFC capacity of 7% are shown in Fig. 6. The reserved LFC capacity during the daytime was large for considering the PV output forecast error as shown in (a), Fig. 6. On the other hand, the reserved LFC capacity during the nighttime was small because the PV output forecast error would not happen. Furthermore, the daily average of LFC capacity was decreased 379 MW/day to 276 MW/day as shown in (b), Fig. 6. Therefore, a reduction effect of LFC capacity was 27% compared to the constant LFC capacity 7%.

A reduction effect of LFC capacity and an increased effect of maximum PV installation rate could be revealed by using DD-LFC. Furthermore, the power system stability was maintained when LFC capacity was reserved dynamically at the UC by considering PV output forecast error. From (a), Fig. 5, when the constant LFC capacity was 5% at PV capacity 51.8%, the power system was considered instability by

2019.11.16. PV capacity 51.8%.



(a) Output, scheduled output, LFC capacity. (b) Output of Coal#5.

Fig. 7 The system condition by using the constant LFC capacity 5%.

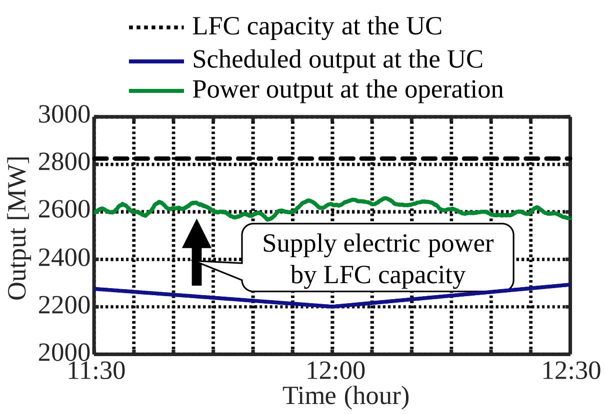


Fig. 8 Output, scheduled output, LFC capacity by using DD-LFC.

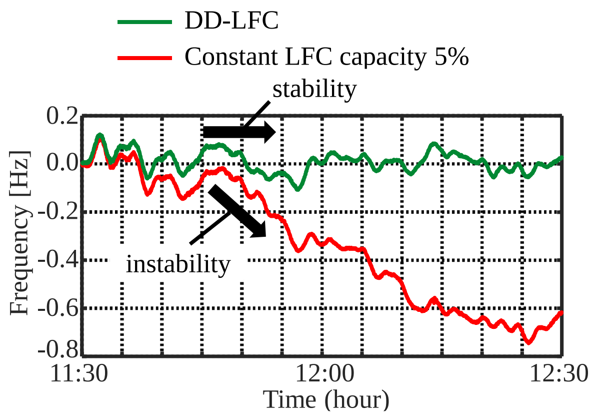


Fig. 9 Frequency.

happening the PV output forecast error. When PV capacity was installed at 51.8%, the efficacy by using DD-LFC is discussed with the frequency and generator output as shown in the following sections. A situation at 11:30 to 12:30 as shown in Fig. 5. Fig. 7 and Fig. 8 show the power output, the scheduled output at the UC, and LFC capacity of all LFC generators. Fig. 9 shows the frequency. Then, the output of Coal #5 is shown in (b), Fig. 7. According to the result of (a), Fig. 7, when the constant LFC capacity was 5%, the electric power was supplied by the reserved LFC capacity reserved of the LFC generators. However, (b) of Fig. 7 showed that Coal#5 output decreased linearly because Coal #5 is scheduled to stop at 12:00. This generator was switched from the LFC generator to the scheduled generator. As a result, LFC capacity of Coal #5 did not supply the electric power, and the frequency decreased because of the supply shortage by PV output forecast error (Fig. 9). According to the result of Fig. 8, when LFC capacity was determined by using DD-LFC, the electric power was supplied by LFC capacity against the power supply shortage by the PV output forecast error. Therefore, the frequency was stable even if the PV output forecast error happened, and the power system stability was maintained (Fig. 9).

5. Conclusion

To achieve the 2030 target, further installation of RE is required compared to the current composition ratio of RE. However, RE output is challenging for the power system stability such as the PV output forecast error. Thus, this paper proposed a Dynamic Determination method of LFC capacity (DD-LFC) which determines LFC capacity dynamically at the UC by the PV output forecast error. In DD-LFC, the correspondence table between LFC capacity and the PV output forecast error was made. Then, LFC capacity was dynamically determined by the PV output forecast error at each time of the UC by using the correspondence table. As the simulation result using DD-LFC, a reduction effect of LFC capacity and an increase of maximum PV capacity rate could be revealed. Furthermore, by confirming the generator output using DD-LFC, the frequency was stable because the electric power was supplied by reserved LFC capacity even if PV output forecast error happened, and the power system stability was maintained. Further consideration will reveal that the reduction effect can be shown even in different seasons.

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Keito Nishida received the B.Eng. degree in electrical and electronics engineering from University of Fukui, Japan, in 2021. He is currently pursuing the M.Eng degree with University of Fukui. His research includes electric power system analysis and stability analysis, renewable energy.

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