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Impact of Power Output Curtailment Control of Photovoltaic Power Generation on Grid Frequency

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Abstract: In a power system with very high penetration photovoltaic power (PV) generation, the curtailment of PV power will be necessary to maintain a power supply and demand balancing. PV power output can be effectively utilized by controlling the curtailment at a certain interval based on forecasting and nowcasting of aggregated power output of PV systems. By using an optimum unit commitment scheduling model, this paper assesses the effect of a scheduled curtailment control at 30 min interval on the reduction of curtailed PV power output in comparison with a fixed curtailment control throughout a day. Then, by using an electricity supply - demand simulation model, this paper discusses the effect of ramp rate control of curtailed PV power output for avoiding the steep change in grid frequency due to the stepwise change in curtailment.

Keywords: Solar energy, electric power systems, load frequency control, load dispatching, load forecasting.

1. INTRODUCTION

In a future power system with very high penetration of photovoltaic power generation (PV), the operation of electric power system will be more complicated. One of the key issue is to preserve enough flexibility of power supply and demand balancing. When the available PV power output is large enough in a very fine day and electricity demand is not so large in middle seasons without heating / cooling demand, surplus power supply may occur. In such a situation, it would be necessary to curtail PV power output to preserve enough balancing capability by operating controllable generators such as conventional fossil fuel thermal power plants. In Kyushu region, Japan, curtailment of PV power output has been applied already since October, 2018. In Kyushu region, curtailment was made by stopping the operation of several numbers of PV power plants throughout a day by informing the request by the day before.

In order to utilize PV power output as much as possible, however, curtailment should be done by applying the upper limit of power output in individual PV instead of stopping the operation. Besides, instead of using the fixed upper limit throughout a day, the curtailed PV power can be reduced by changing the upper limit in consideration of the amount of forecasted electricity demand and the capacity of available controllable generators.

In the case of large scale PV power plants with an online communication network, the upper limit can be changed at small step by the control of system operator at a few minutes interval. However, considering a huge number of PV will be installed, the online control of all PV might be difficult. Therefore, from the practically feasible point of view, the change in the upper limit at a certain interval (e.g. 30 min) should be scheduled throughout a day. Then, the upper limit relative to rated capacity (hereinafter upper limit ratio) should be announced to individual PV by the day before. In this situation with larger interval than on-line control, the stepwise change in the upper limit ratio can be large, resulting in the steep change in residual electricity load given by subtracting PV power output from electricity demand.

Assuming such a situation, by using an optimum unit commitment scheduling model, this paper assesses the effect of scheduled upper limit ratio at 30 min interval on the reduction of curtailed PV power in comparison with a fixed upper limit control for a day. Then, by using an electricity supply - demand simulation model, this paper assesses the impact of stepwise change in PV power output with scheduled upper limit ratio on the frequency of power system. Finally, this paper assesses the effect of limiting a ramp rate of PV power output change (hereinafter ramp rate control) under the curtailment control for avoiding the steep change in grid frequency due to the stepwise change in the upper limit ratio.

2. ASSUMPTIONS ON SIMULATION

2.1 *Assumption on power system*

This paper assumes the rated capacity and number of units of generators as shown in Table I in consideration of electric power system in the Chubu region, Japan. The plant parameters are assumed based on the Japanese Power System Models developed by The Institute of Electrical Engineers of Japan. Although the target capacity of PVS toward 2030 is 64 GW in Japan, this study assumes 100 GW, which corresponds to 16 GW in the Chubu region so as to assume that the curtailment of PV power output is necessary as described latter.

Table 1. Composition of Generator Unit

type	Capacity [MW]	units	UC	EDC	LFC
Hydro	1000	1	no	no	no
Nuclear	3000	1	no	no	no
Coal	1000	4	no	yes	no
LNG-CC	250	24	no	yes	yes
LNG	700	10	yes	yes	yes
LNG	200	3	yes	yes	yes
Oil	500	12	yes	yes	yes
Pumped hydro	250	10	yes	yes	yes
PVS	16000	1	no	no	no

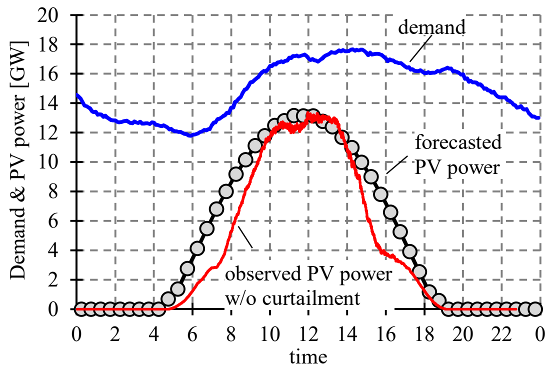


Fig. 1. Assumption on electricity demand and PVS power output (16 GW)

Figure 1 shows the time-series of aggregated PV power output used in this study, which is the available power if no curtailment is applied. However, because the maximum PV power output almost corresponds to 76% of electricity demand, the curtailment is needed to maintain the power supply – demand balancing as described below.

The time-series data of aggregated PV power output was developed based on the ground observation of global horizontal irradiance at 56 points in the Chubu region. The sampling interval is 10 sec. In order to take into account so-called smoothing effect of irradiance fluctuation around the observation point, a low-pass filter (LPF) model developed by Kato et al. (2015) was applied. Besides, for the proper impact assessment on the system frequency, faster fluctuation components of irradiance was added by using a method proposed by Matsumoto et al. (2015), in which faster components is estimated by extrapolating the tendency of magnitude of frequency spectrum. As a result, the aggregated PV power output operating at maximum power point (in other words, without curtailment) $P_M^h(t)$ (t = 0 - 30 min) in the time zone h (at 30 min interval) is given as follows:

$$P_M^h(t) = \sum_{i=1}^{56} P_{Mi}^h(t) = \sum_{i=1}^{56} I_i^h(t) C_i^{PV} \quad (1)$$

where $P_{Mi}^h(t)$ is PV power output operating at maximum power point in the representative territory of observation point i, $I_i^h(t)$ is irradiance at observation point i after applying LPF model and adding faster fluctuation components, C_i^{PV} is total capacity of PV in the representative territory of observation point i.

The time-series data of forecasted PV power output is developed based on Grid-Point-Value of weather forecast by Japan Meteorological Agency. A multi-regression model developed by Kato et al. (2013) was applied to calculate the irradiance from the other weather elements such as cloud cover and relative humidity. The forecast error is large after the sunrise and before the sunset.

Figure 1 shows the time-series data of electricity demand observed in the Chubu region on the same day as irradiance observation. Although the temporal resolution of demand observation is 6 min, the time-series data at 1 sec interval was developed by applying faster fluctuation components was by using the same method used in irradiance data.

2.2 Assumption on curtailment of PV power output

The PV power output curtailment is needed from various points of view, i.e. voltage rise in a distribution network, current limitation in distribution / transmission lines, power supply - demand balancing in a system service area, etc. This paper simply assumes that the curtailment is determined from the power supply – demand balancing point of view.

At first, the system operator calculates the aggregated PV power output which can be supplied to a power system at 30 min interval on the next day by calculating a unit commitment (UC) scheduling in consideration of the forecasted electricity and forecasted PV power output. When the surplus power output is expected, the curtailment of PV power output will be scheduled.

This paper assumes that the upper limit ratio r_c^h in the time zone h is informed to all PV by the day before. The curtailment ratio is given by 1 - r_c^h. From the practical operation point of view, r_c^h should be informed to each PV as a relative value to the rated capacity instead of forecasted PV power output. Therefore, this study calculates r_c^h by dividing the curtailed aggregated power output by the total capacity of PV in the power system.

By using r_c^h, this study calculates the sub-aggregated PV power output $P_{Ci}^h(t)$ in the representative territory of observation point i when the curtailment is applied to individual PV as follows:

$$P_{Ci}^h(t) = \begin{cases} P_{Mi}^h(t) & (P_{Mi}^h(t) < C_i^{PV} r_c^h) \\ C_i^{PV} r_c^h & (P_i^M(t) \geq C_i^{PV} r_c^h) \end{cases} \quad (2)$$

Then, the aggregated PV power output under the curtailment control $P_C^h(t)$ is calculated as follows:

$$P_C^h(t) = \sum_{i=1}^{56} P_{Ci}^h(t) \quad (3)$$

2.3 Assumption on ramp rate control of PV power output

Because the temporal interval of UC scheduling is 30 min in this paper, the acceptable PV power output ratio r_c^h is determined at 30 min interval. Unlike the conventional fossil thermal power plants, the PV power output under the curtailment control can be changed very quickly by changing the operational point on the I-V curve. Therefore, when the change in r_c^h is very large between 30 min interval, the aggregated PV changes significantly, resulting in the steep change in the system frequency.

In order to avoid such a steep change in PV power output, this study assumes that the upper limit of power output change (ramp-rate) is applied to individual PV power generation. As a sensitivity analysis, the ramp-rate X is assumed to be 2 or 5 or 10 %/min (relative to the rated capacity). In addition, this study assumes that the transition of r_c^h to r_c^{h+1} is finished within the transition time T. T is calculated by solving the following equation.

$$\left|P_{Ci}^{h+1}\left(0+\frac{T}{2}\right)-P_{Ci}^{h}\left(29-\frac{T}{2}\right)\right|=C_i^{PV}\times\frac{X}{100} \qquad (4)$$

3. SIMULATION MODELS

3.1 UC scheduling optimization model

This study utilizes UC scheduling optimization model used developed by Kato et al. (2015). The model is formulated as a mixed-integer nonlinear programming. The objective function is the minimization of electricity production cost in a day. The major constraints are as follows.

- Available power output range in rated capacity for Load - Frequency Control (LFC) (5% for thermal power plant and 10 % for pumped hydro power plant) must be larger than minimum requirement (2% of hourly average electricity demand)
- Minimum operation time of thermal power plant (3 hours)
- Initial and final values of reserved water of pumped hydro (50%)

Hydro and nuclear power plant are excluded from UC scheduling.

3.2 Power supply – demand simulation model

This study utilizes a power supply – demand simulation model developed by Kato et al. (2017). The model emulates economic load dispatching control (EDC) and LFC. Figure 2 shows the block diagram. The model is developed using Matlab/Simulink.

In this model, the available capacity of generator by fuel type is determined by using the above described UC scheduling optimization model. EDC signal is determined in every 3 min with the equal incremental cost rule, in which a day-ahead

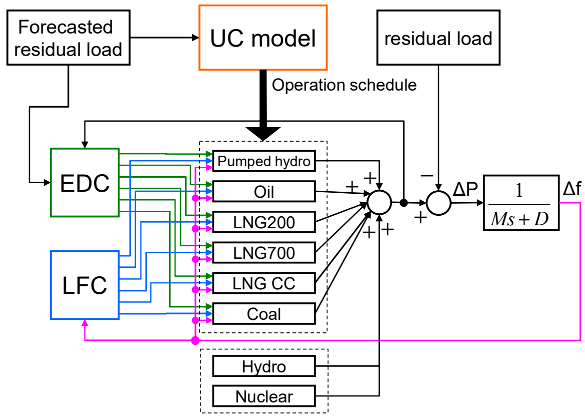


Fig. 2. UC-EDC-LFC simulation model

forecasted residual electricity load is corrected based on the observed total power output of utility generators.

The LFC signal is determined by using a simple PI control based on the frequency deviation, and LFC signal for each generator is determined based on the rated capacity. The power output of each generator is determined based on the sum of load dispatching control signal and LFC signal by considering governor free control, load following capability, and upper/lower power output limit. Droop is set at 4% and 5% for thermal power plant and pumped hydro power plant, respectively. The difference between the sum of power supply and the residual load is translated to the frequency deviation by using a simplified inertia model, where the inertia coefficient M and the dumping coefficient D is set at 9.5 and 2.0, respectively.

Hydro and the nuclear power plant are excluded from EDC and LFC, as a base load power plant. Coal power plant and LNG combined cycle power plant (LNG-CC) are excluded from UC taking the continuous operation for certain period. LFC is not applied to Coal power plant in consideration with the lower load-following capability (3 %/min) than that of other thermal power plants (3.3 %/min).

4. RESULTS OF UC SCHEDULING

Figure 3 shows the result of UC scheduling. Figure 4 shows the change in the upper limit ratio r_c^h together with the change in the upper limit ratio to forecasted PV power output. Figure 5 shows the curtailed aggregated PV power output and the aggregated PV power output without curtailment. Figure 6 (a) also shows the portion of curtailed PV power output. The curtailment is needed from 6:30 to 16:30, and r_c^h in this period ranges between 60% - 80%. As a result, a day cumulative PV power supply is 65% of that without curtailment. The change in r_c^h is large at 8:30, 9:00, 9:30, 11:30, 12:00, 13:00, and 13:30. Therefore, when the ramp-rate X is not small enough, the steep change in grid frequency may occur at those periods.

As a comparison, this study calculated the acceptable PV power output ratio fixed throughout a day r_c^{day}. As shown in Figure 6 (b), a day cumulative PV power supply with day r_c^{day} is 63%, which is 2% smaller than that using scheduled r_c^h with

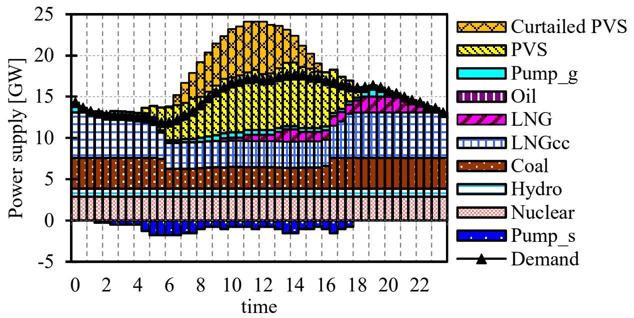


Fig. 3. Result of UC scheduling

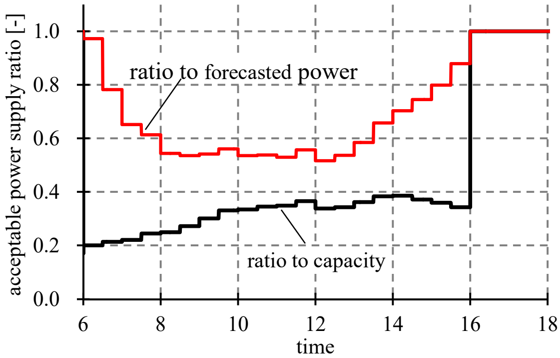


Fig.4. Change in upper limit ratio r_c^h

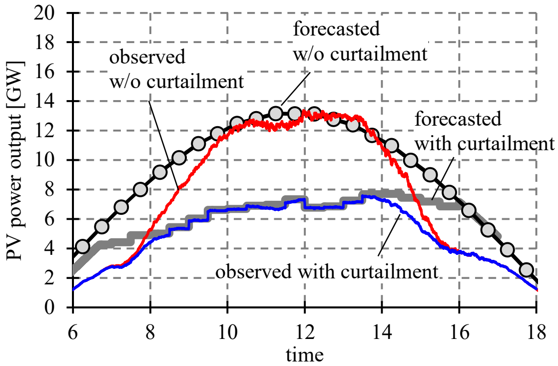
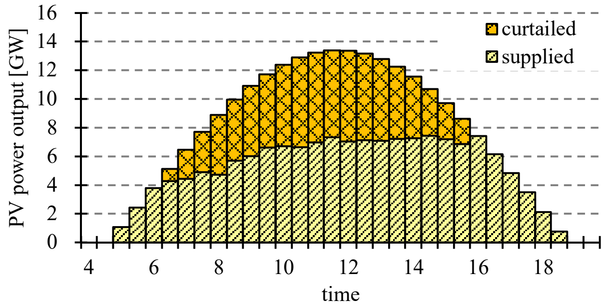
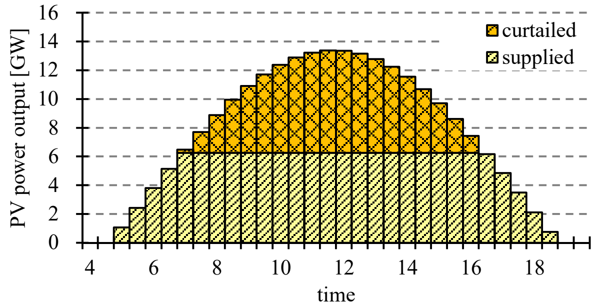


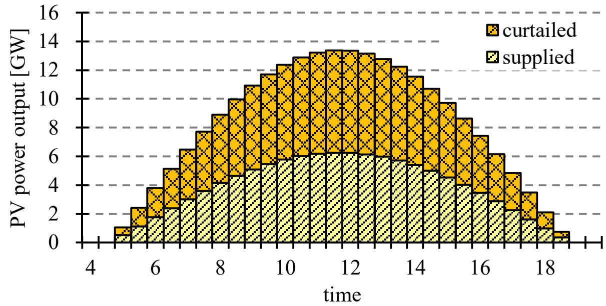
Fig.5. Change in curtailed PV power output



(a) curtailment with scheduled upper limit in 30 min interval



(b) curtailment with fixed upper limit



(c) curtailment by reduced number of operating PV

Fig. 6. Difference in acceptable PV power output by curtailment method

30 min interval. When the electricity production cost to compensate for the reduced PV power output is 7 kWh/yen, 18 x 10^6 yen is saved in a day by the change in the upper limit ratio to forecasted PV power output.

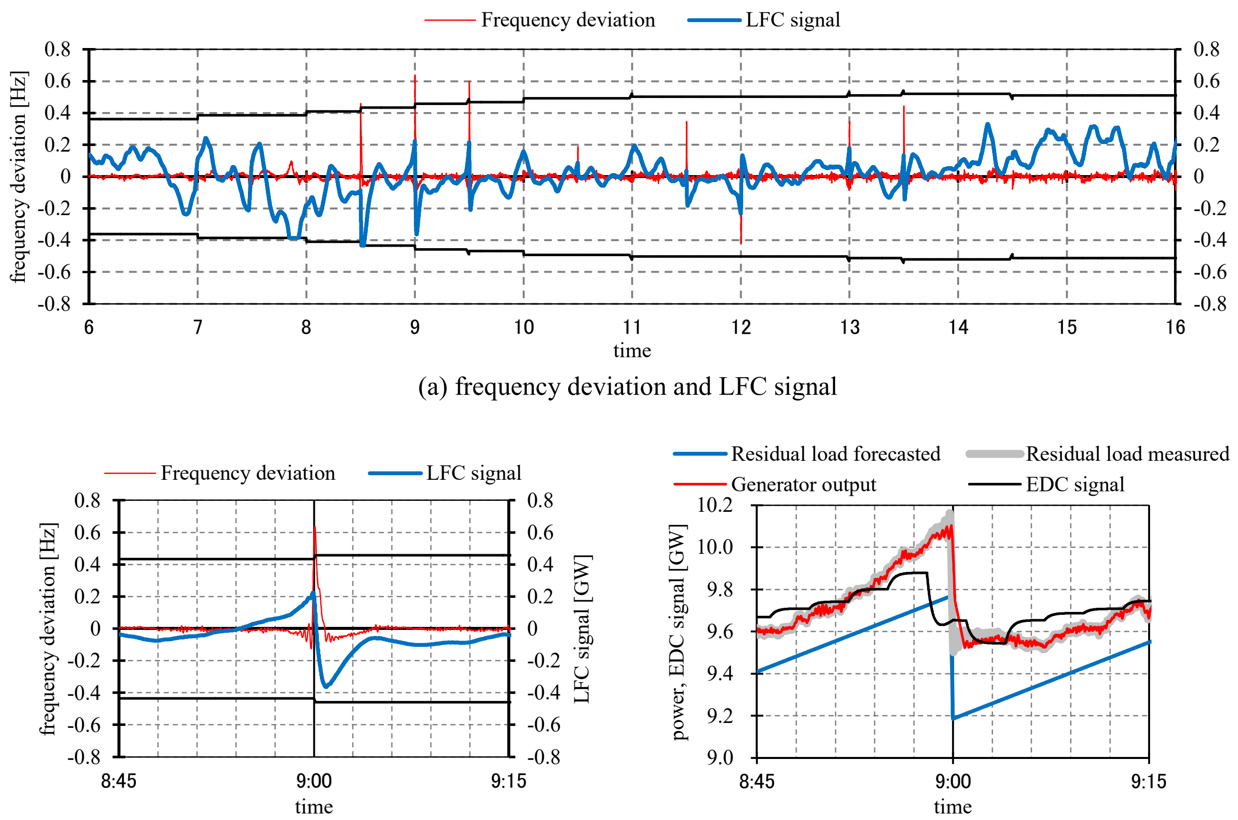
In addition, this study also calculated the acceptable PV power output when then curtailment takes place by reducing the number of operating PV as shown in Figure 6 (c). A day cumulative PV power supply is only 47%, which is 16% smaller than that using scheduled r_c^h with 30 min interval. When the electricity production cost to compensate for the reduced PV power output is 7 kWh/yen, 151 x 10^6 yen is saved in a day by the change in the upper limit ratio to forecasted PV power output.

The results show that the change in r_c^{day} contributes to increase the useful PV power output, hence to reduce the fossil fuel consumption to meet the electricity demand.

5. RESULTS OF EDC - LFC SIMULATION

Figure 7 (a) shows the result of power supply - demand simulation, in which the ramp-rate of PV power output change under the curtailment control is 10%/min. As a result, the steep change in the grid frequency occurs at 8:30, 9:00, 9:30, 11:30, 12:00, 13:00, and 13:30 because the change in r_c^h is large at those periods as shown in Figure 4.

Figure 7 (b) and (c) shows the change in LFC signal and EDC signal focusing on 8:45 - 9:15, respectively. Because the increase in r_c^h is scheduled at 9:00, the decrease in residual load (= demand - PV power) is forecasted. Therefore, EDC signal provided at 8:57 decreased due to the reduction in the forecasted residual load at 3 min latter, while the residual load is still increasing. In order to compensate for the increasing gap between the increasing residual load and decreasing EDC signal, the LFC signal increases toward 9:00. However, because the PV power output is decreased significantly and



(a) frequency deviation and LFC signal

(b) frequency deviation and LFC signal in 8:45-9:15 (c) power supply/demand and EDC signal in 8:45-9:15

Fig. 7. Simulation results (upper limit of power output change in curtailment operation: 10 %/min)

steeply at 9:00, the frequency increases sharply. Such a steep change in PV power output can take place because PV power output is controlled by inverter and no inertia exists in PV unlike conventional fossil thermal generators using rotating machine. This is also the reason for the steep increase or decrease in frequency at the other periods.

In order to avoid such a steep change in the grid frequency, the change in PV power output should be properly controlled by setting suitable upper limit of power output change rate or ramp-rate. Figure 8 shows the results in the case of X = 2 %/min. Because of smaller ramp-rate of PV under the curtailment control, the steep changes in frequency are mitigated throughout a day. The suitable value of ramp-rate can be determined in consideration of grid characteristics and scheduled change in aggregated PV power output at every 30 min.

6. CONCLUSIONS

In a power system with high penetration photovoltaic power (PV) generation, the curtailment of PV power will be necessary to maintain a power supply and demand balancing. PV power can be effectively utilized by controlling the curtailment at a certain interval based on forecasting and nowcasting of aggregated power output of PV systems. By using an optimum unit commitment scheduling model, this paper assessed the effect of a scheduled curtailment control at 30 min on the reduction of curtailed PV power in comparison with a fixed curtailment control throughout a day. As a result of numerical simulation for a day in which the curtailment is necessary, a day cumulative PV power supply can be increased by 2 % compared to the case with the curtailment using the fixed upper limit throughout a day. Besides, a day cumulative PV power supply can be increased by 16 % compared to the case with the curtailment by reducing the number of operating PV.

Then, by using an electricity supply - demand simulation model, this paper discussed the effect of ramp rate control of curtailed PV power for avoiding the steep change in grid frequency due to the stepwise change in curtailment hence the steep change in residual electricity load. The result shows that the ramp-rate control of PV under the curtailment control is necessary for avoiding the steep change in frequency. The ramp-rate can be determined in consideration of grid characteristics and scheduled change in aggregated PV power output at every 30 min.

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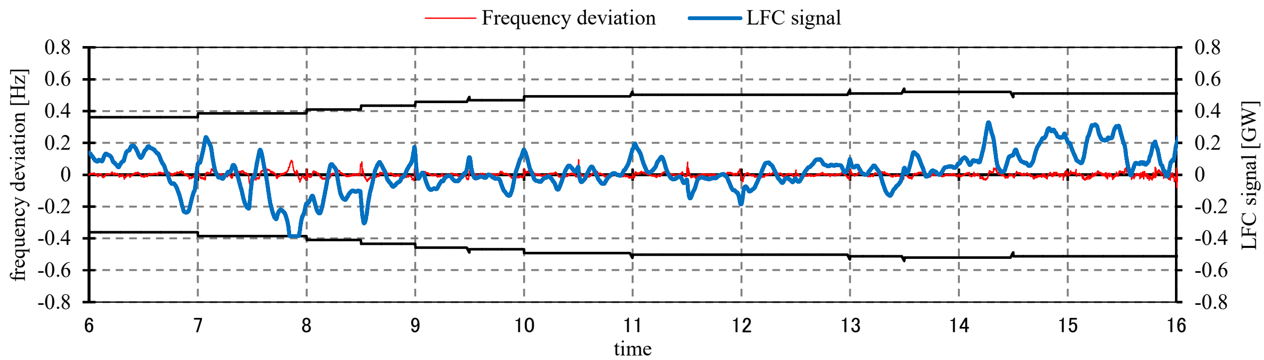
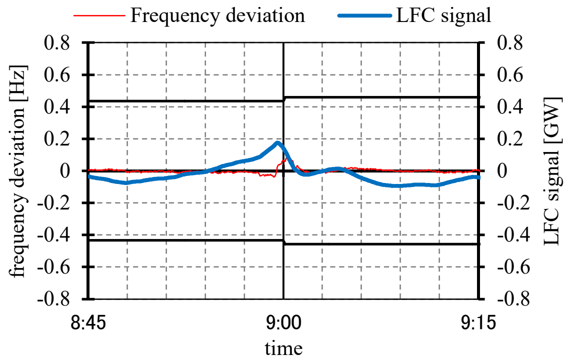
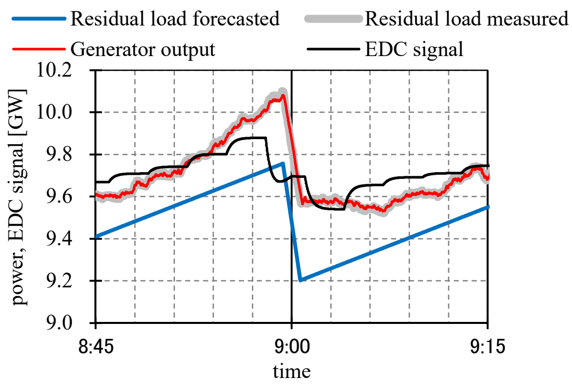


(a) frequency deviation and LFC signal



(b) frequency deviation and LFC signal in 8:45-9:15



(c) power supply/demand and EDC signal in 8:45-9:15

Fig. 8. Simulation results (upper limit of power output change in curtailment operation: 2 %/min)

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