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# Modelling of Aggregated Power Output of Photovoltaic Power Generation in Consideration of Smoothing Effect of Power Output Fluctuation around Observation Point

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**Abstract.** High penetration photovoltaic power generation system (PVS) may cause negative impacts on the frequency control of electric power system. In the impact assessment of high penetration PVS on the system frequency, the proper preparation of time-series data of aggregated PVS power output in electric power system service area is essential. However, the available data points are limited compared to the huge installation points of widely dispersed PVS in a power system service area. Therefore, this study proposes a modelling of aggregated PVS power output based on a low-pass filter (LPF) which is capable to take into account a smoothing effect of power output fluctuation around individual observation point. Then, the proposed model is applied to estimate the spatial average irradiance in the central region (called the Chubu region) in Japan by using the irradiance data observed at 61 points. The reduction in the short-cycle fluctuation is evaluated in comparison to the time-series data calculated by the simple average of 61 points data. Finally, the usefulness of proposed model is discussed in the situation that the aggregated PVS power output in electric power system service area must be curtailed due to the surplus power supply in the electric power system.

## Key words

photovoltaic power generation system, irradiance, smoothing-effect, curtailment

## 1. Introduction

In Japan, the capacity of photovoltaic power generation system (PVS) is increasing rapidly toward the target of 64 GW by 2030 after the implementation of feed-in-tariff scheme in 2012. The high penetration of PVS, however, would affect the stable operation of electric power system and cause negative impacts such as the voltage rise in distribution system, the surplus power supply during middle season of low electricity demand, the shortage of generator capacity for the load frequency control (LFC), etc. Therefore, various grid integration studies of PVS are conducted to investigate the acceptable capacity of PVS and the effective measures for higher penetration [1]-[5]. One of the important points in such the integration studies is to utilize the appropriate time-series data of aggregated power output of PVS in electric power system service area depending on the purpose of study.

When the high penetration of PVS is realized, PVSs are widely dispersed in the electric power utility service area. In such the situation, the power output fluctuation would be different among PVSs. As a result, the aggregated power output fluctuation of high penetration PVS would be smoothed, reducing such the negative impacts as well as the required measures. In order to estimate the time-series data of aggregated PVS power output properly, the utilization of multi-point observation of irradiance or individual PVS power output is essential. However, the available data points are limited compared to the huge installation points of widely dispersed PVS in a power system service area. Therefore, this study proposes a modelling method of aggregated PVS power output employing a low-pass filter (LPF) which takes into account a smoothing effect of power output fluctuation around individual observation point.

First, the proposed model to calculate the spatial average irradiance is introduced after the explanation of data set used in this study. Then, the reduction in short-cycle fluctuation of spatial average irradiance by applying the proposed model is evaluated in comparison to the time-series data calculated by the simple average of observed data. Finally, the usefulness of proposed model is discussed in the situation that the aggregated PVS power output in electric power system service area must be curtailed due to the surplus power supply in the electric power system.

## 2. Data

In order to develop a model to estimate spatial average irradiance, this study utilizes time-series data of global horizontal irradiance observed at 61 points in the central region (called the "Chubu region") in Japan. Figure 1 shows the location of observation points. The observation points are dispersed almost evenly according to the population distribution, excepting for Nagoya City area and Matsumoto City area. The distance between neighbouring two observation points varies between 4.2 km and 138 km depending on the combinations, and the average distance is 22 km. The data observed from July 1st in 2010 to October 5th in 2010 (92 days) is used to develop the proposed model. The data observed from September in 2010 to August in 2011 (363 days) is used to evaluate the reduction in short-cycle fluctuation of spatial average irradiance by applying the proposed model. In addition, the data observed in July 27th in 2013 is used to discuss the usefulness of proposed model in the situation that the aggregated PVS power output in electric power system service area must be curtailed due to the surplus power supply in the electric power system.

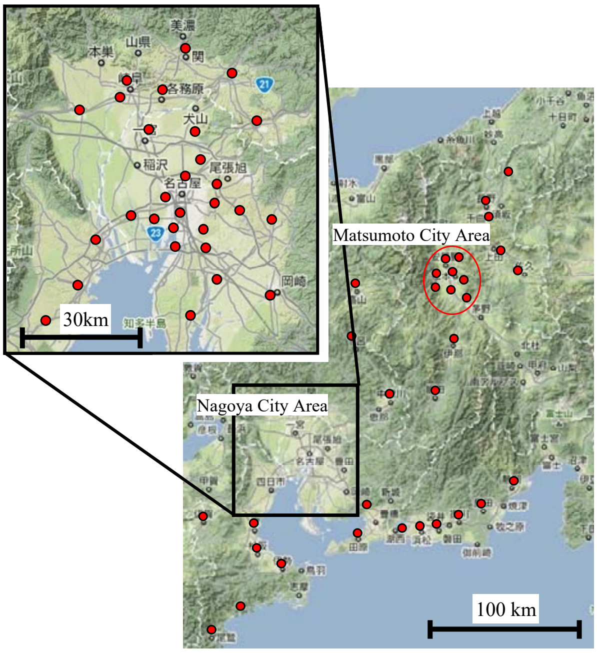


Fig. 1. Location of multi-points observation of global horizontal irradiance.

## 3. Proposed Model

### A. Transfer Hypothesis[6]

A method for evaluating the aggregated PVS power output fluctuation has been proposed in ref.[6]. By analyzing the observed data, it is revealed that the long-cycle fluctuations of PVS power outputs of different locations are coherent each other, while the short-cycle fluctuations are random. Based on this characteristics, the linear spectrum of ensemble average irradiance $S_{tra}(f)$, which is the average spectrum for various days with different weather conditions, is given as follows.

$$S_{\mathrm{traN}}(f)=\left|\frac{S_{\mathrm{cohN}}(f)+j\cdot T_X\cdot f\cdot S_{\mathrm{ranN}}(f)}{1+j\cdot T_X\cdot f}\right| \tag{1}$$

In ref.[6], eq.(1) is called as "Transfer Hypothesis". $S_{tra}(f)$ is expressed by two components, i.e. the coherent component $S_{coh}(f)$ and the random components $S_{ran}(f)$. $T_x$ is the shortest cycle of which the fluctuation can be considered coherent among different $N$ locations. In the cycles shorter than $T_x$, therefore, the random component increases when the cycle becomes shorter. $S_{coh}(f)$ is given by eq.(2), assuming that all fluctuation cycle components are coherent each other among different $N$ locations.

$$S_{\mathrm{cohN}}(f)=\frac{1}{N}\sum_{i=1}^{N}S_i(f) \tag{2}$$

$S_{ran}(f)$ is given by eq.(3), assuming that all fluctuation cycle components are independent each other among different $N$ locations.

$$S_{\mathrm{ranN}}(f)=\frac{1}{N}\sqrt{\sum_{i=1}^{N}\{S_i(f)\}^2} \tag{3}$$

$T_x$ is determined so that the route mean square error between $S_{tra}(f)$ and $S_{mea}(f)$, which is the linear spectrum of the time-series data of ensemble average irradiance of $N$ points, is minimized. In addition, by considering the nature characteristics of irradiance fluctuation, the cycle Ty is given as follows.

$$T_y=T_x/\sqrt{N} \tag{4}$$

The fluctuation components shorter than $T_y$ can be considered as independent among different $N$ locations. Besides, the linear spectrum of ensemble average irradiance $S_{tra}(f)$ regarding the fluctuation components shorter than Ty becomes the same as $S_{ran}(f)$ given by eq.(3) because the contribution of imaginary part in eq.(1) is large enough. Note that the linear spectrum of ensemble average irradiance $S_{tra}(f)$ given by eq.(1) is the average spectrum for various days with different weather conditions.

### B. Low-Pass Filter Model

Based on "Transfer Hypothesis", this study proposes a modelling method of aggregated PVS power output employing LPF which takes into account a smoothing effect of power output fluctuation around individual observation point. "Transfer Hypothesis" is a method to present the linear spectrum of ensemble average irradiance fluctuation of $N$ points by using the time-series data observed at $N$ points. Then, based on the fact that the short-cycle fluctuation can be calculated by using the so-called $1/\sqrt{N}$ rule, the transfer hypothesis is modified so that the linear spectrum of ensemble average fluctuation of ensemble average irradiance of $N$ points is presented by using the linear spectrum $S_A(f)$ at the available only one observation point. In addition, the transfer hypothesis is modified as follows so that the smoothing effect around observation point can be taken into account.

$$S_{\mathrm{cen}}(f)=\left|\frac{S_A(f)+j\cdot T_X\cdot f\cdot\dfrac{S_A(f)}{\sqrt{M}}}{1+j\cdot T_X\cdot f}\right| \tag{5}$$

$S_{cen}(f)$ is the linear spectrum of time-series data of ensemble average irradiance of $M$ points and is given by the linear spectrum of single observation point. $M$ is the total number of points including both single actual point and some dummy points included in the observation point-representative area, and is determined as follows.

First, the boundary of observation point-representative area is determined by using the Voronoi decomposition for each observation point. Then, based on the Mesh-statistical data provided by the Statistics Bureau and the Director-General for Policy Planning of Japan, the total number $B$ of 0.5 x 0.5 km blocks is calculated. The block in which at least 30 households live in a detached-house is taken into account so that the area not suitable for the installation of PVS is excluded. The size of observation point-representative area $A$ is given by $B$ x 0.5 x 0.5. Next, based on the fact that the irradiance fluctuations shorter than 32 min at two observation points can be considered as independent each other when the distance between two points is longer than 5 km, which was revealed in our previous study [7], it is assumed that sin gle actual point and some dummy points are located at the lattice point of 5 x 5 km mesh. Finally, $M$ in eq.(5) is given by eq.(6).

$$M = \frac{B \times 0.5 \times 0.5}{5 \times 5} = \frac{A}{5 \times 5} \quad (6)$$

According to the size of the observation point-representative area, the LPF gain $G(f)$ to exclude the short cycle fluctuation of observed irradiance is given by $S_{cen}(f)/S_A(f)$ as shown in eq.(7).

$$G(f) = \frac{S_{cen}(f)}{S_A(f)} = \left| \frac{1 + j \cdot T_X \cdot f \cdot \frac{1}{\sqrt{M}}}{1 + j \cdot T_X \cdot f} \right| \quad (7)$$

By using the time-series data of irradiance observed around Nagoya City area shown in Figure 1, it is verified that eq.(7) is applicable at most to the circle area of some hundreds km$^2$ area [7]. In addition, $T_x$ and $T_y$ are formulated as a function of the size of observation point-representative area. Therefore, if the size of observation point-representative area is smaller than some hundred km$^2$, the spatial average irradiance within the area can be determined by taking the smoothing effect around the observation point into account.

Figure 2 shows examples of filter gain according to the size of the observation point-representative area. When the area size is small, almost no smoothing effect is taken into account even in short cycle fluctuation. On the other hand, when the area size is large, e.g. 500 km$^2$, the fluctuation of spatial average irradiance at 0.0008 Hz (22 min cycle) is reduced to 22% of that of observed irradiance fluctuation.

*C. LPF applied irradiance fluctuation*

By calculating LPF gain for individual observation point $i$ (=1 – 61) according to the size of point-representative area, and by using the observed irradiance $I_i(d, t)$ in the day $d$ (= 1 – 363), the spatial average irradiance of individual point-representative area $I_i'(t)$ is estimated as follows by taking into account the smoothing effect around the observation point.

$$I_i'(d,t) = F^{-1}[G(f) \cdot F[I_i(d,t)]] \quad (8)$$

where $F[\ ]$ is the operator of Fast Fourier Transform (FFT) and $F^{-1}[\ ]$ is the inverse operator of FFT.

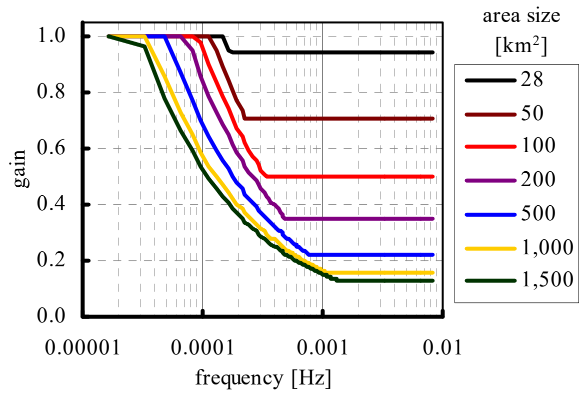


Fig. 2. An example of filter gain.

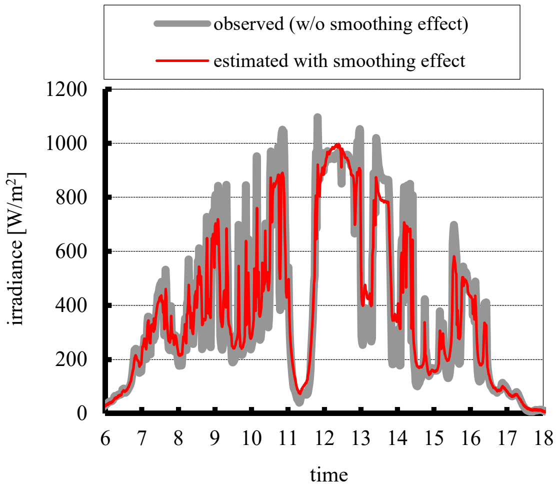


Fig. 3. An example of observed irradiance and estimated irradiance by using low-path filter.

Figure 3 shows an example of daily change in the observed irradiance and the LPF applied-irradiance. In this example, the size of observation point-representative area is about 500 km$^2$, and the fluctuation of spatial average irradiance shorter than about 30 min is estimated to be only 20 % of observed irradiance. Although the width of short cycle fluctuation is reduced due to the LPF, the fundamental fluctuation profile throughout a day is unchanged.

## 4. Spatial Average Irradiance in Utility Service Area

By using the proposed modelling, this study calculates a spatial average irradiance in the electric power utility service area as an ensemble average of filtered irradiance of each observation point. As discussed above for $M$ value, the contribution of each observation point depending on the effective area size should be taken into account. In this study, by taking the weight value $w_i$ into account, the weighted ensemble average irradiance $I(d,t)$ is estimated as the spatial average irradiance in the Chubu region by using eq.(9).

$$I(d,t)=\sum_{i=1}^{N} w_i I_i'(d,t) \qquad (9)$$

As shown in eq. (10), $w_i$ is determined as the ratio of number of detached houses in the area $i$ against the total number of detached houses in the electric power utility service area of the Chubu region in Japan.

$$w_i = H_i \Big/ \sum_{i=1}^{N} H_i \qquad (10)$$

Figure 4 shows examples of total spatial average irradiance of with and without the proposed LPF model. The short-cycle fluctuation is reduced by applying the proposed LPF model.

The reduction in short-cycle fluctuation is evaluated by using the hourly standard deviation (Std) of spatial average fluctuation of 32 min cycle or shorter. Figure 5 shows the hourly Std of spatial average irradiance fluctuation with and without using LPF model. When the LPF model is not applied, the annual average value of hourly Std is 6.5 W/m$^2$, and the largest hourly Std reaches 32 W/m$^2$. On the other hand, when the LPF model is applied, the annual average value of hourly Std is only 3 W/m$^2$, and the hourly Std is less than 5 W/m$^2$ for about 80 % days in a year. As a result, on average of a year, the short-cycle fluctuation of spatial average irradiance with applying the proposed LPF model is estimated almost half of that of simple average irradiance without applying the LPF model.

## 5. Curtailed Aggregated PVS Power Output

When the extremely high penetration of PVS is realized, the total electricity supply from operating generators may exceed the electricity demand even when all generators are operated at the lowest output. In such a situation, the curtailment of PVS power output would be necessary to make an electricity supply – demand balancing. In order to prepare the time-series data of curtailed aggregated PVS power output for the impact assessment of PVS power output fluctuation in such a situation, multiplying the curtailment factor to the original power output data is one of the easiest way. However, in the real world, the curtailment is applied to individual PVS instead of aggregated PVS in electric power system service area. When the power output of individual PVS is smaller than the requested curtailment level, the power output is not curtailed actually. Therefore, the time-series data of aggregated PVS power output in curtailment situation should be prepared using irradiance data observed at multiple points.

In this study, the time-series data of aggregated PVS power output in curtailment situation is calculated. The assumption is that the curtailed power in electric power system service area is determined in a day-ahead unit commitment (UC) scheduling based on the forecasted aggregated PVS power output and the forecasted electricity demand. Figure 6 shows the time-series data of aggregated PVS power output when all PVS is operated at maximum power point without curtailment and electricity demand used in this study. This study utilizes the electricity demand observed in July 27$^{th}$ in 2013 in the central region in Japan. The number of observation point is 56 instead of 61 in the above described study. The total PVS capacity $C_{PV}$ is 20 GW in the Chubu region, which corresponds to the assumption on the total PVS capacity of 130 GW in Japan. The time-series data

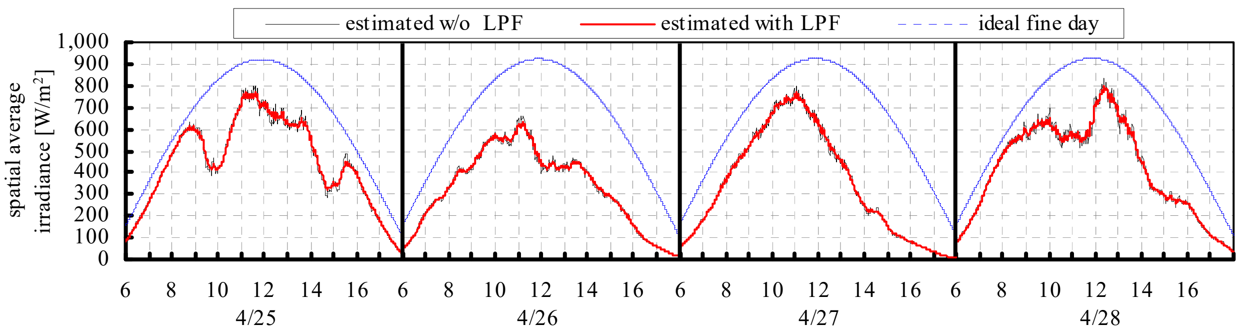


Fig.4. Examples of daily change in spatial average irradiance.

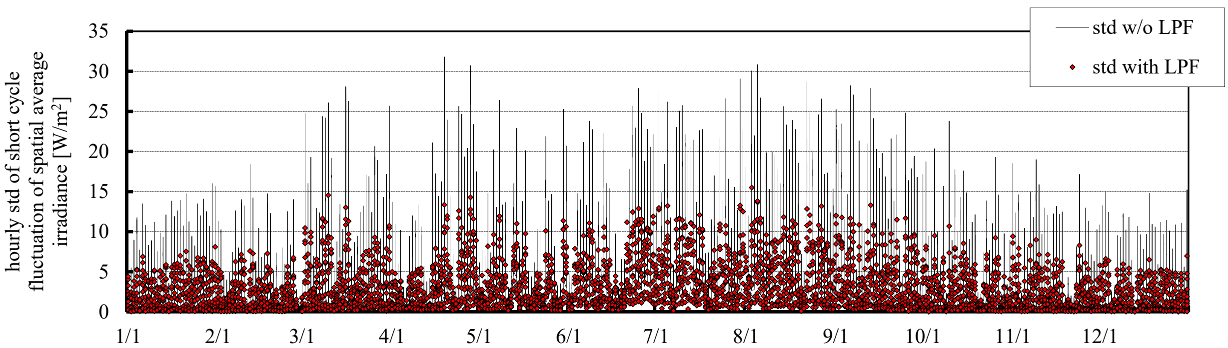


Fig.5. Hourly standard deviation of short cycle spatial average irradiance fluctuation.

of aggregated PVS power output in electric power system service area when all PVSs are operated at maximum power point without curtailment $P_M^h(t)$ is calculated as follows. The temporal resolution is 1 sec $t = 0 - 3599$).

$$P_M{}^h(t) = \sum_{i=1}^{56} P_{Mi}{}^h(t) = \sum_{i=1}^{56} \eta C_{PV_i} I_i{}^h(t) \qquad (11)$$

where $C_{PVi}$: capacity of PVS in each observation point-representative area $i$, $\eta$: system performance ratio of individual PVS (=80%), $I_i^h(t)$: spatial average irradiance in observation point-representative area $i$ calculated using the proposed LPF model, $P_{Mi}(t)$: aggregated PVS power output in each observation point-representative area $i$. The prefix $h$ shows time step at 30 min interval.

The assumption on calculating curtailment of PVS power output is that the amount of curtailment of aggregated PVS power output at time step $h$ is determined a day before based on a UC scheduling and the acceptable power supply ratio to the installed capacity $r_{ca}(h)$ is announced to all PVSs. This study calculated the UC scheduling on the day shown in Figure 6 by using the UC optimization model developed in our preceding study [8]. Figure 7 shows the result. Some amount of aggregated PVS power output must be curtailed to maintain the power supply and demand balance. Figure 8 shows the acceptable power supply ratio to the installed capacity $r_{ca}(h)$ and to the forecasted power output $r_{pa}(h)$. $r_{pa}(h)$ reduces to 55 % of the forecasted PVS power output toward the noon and recovers to 100 % at 16:00 when the forecasted surplus power supply is cleared. According to the change in $r_{pa}(h)$, $r_{ca}(h)$ increases to 36 % around the noon from 20 % at 6:00 and is kept at 35 – 40% for several hours until the forecasted surplus power supply is cleared at 16:00.

Then, this study calculated the curtailed aggregated PVS power output $P_{Ci}^h(t)$ in observation point-representative area $i$ as follows.

$$P_{C_i}{}^h(t) = \begin{cases} P_{Mi}{}^h(t) & \left(P_{Mi}{}^h(t)/C_{PV_i} < r_{ca}(h)\right) \\ C_{PV_i} r_{ca}(h) & \left(P_{Mi}{}^h(t)/C_{PV_i} \geq r_{ca}(h)\right) \end{cases} \qquad (12)$$

Because $r_{ca}(h)$ changes step-wisely as shown in Figure 8, $P_{Ci}^h(t)$ also changes step-wisely, which would affect the system frequency. In order to avoid such the impact on system frequency, this study assumes that the maximum change rate of $P_{Ci}^h(t)$ between the time steps. The maximum change rate of 2 % of installed capacity is used in this study.

The aggregated PVS power output $P_C^h(t)$ when all PVSs are operated taking into account the requested curtailment ratio $r_{ca}(h)$ is calculated as follows.

$$P_C{}^h(t) = \sum_{i=1}^{56} P_{Ci}{}^h(t) \qquad (13)$$

As a comparison, this study calculated the curtailed aggregated PVS power output by using $P_M^h(t)$ and $C_{PV}$ of the aggregated PVS instead of $P_{Mi}(t)$ and $C_{PVi}$ in each observation point-representative area $i$. In order to evaluate the usefulness of above mentioned proposed model, $P_M^h(t)$ is calculated based on the observed irradiance without applying the proposed model.

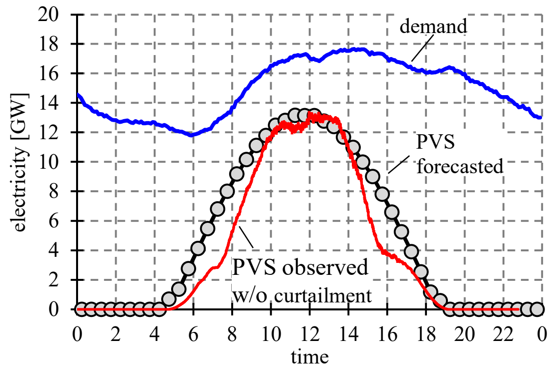


Fig. 6. Time-series data of aggregated PVS power output and electricity demand.

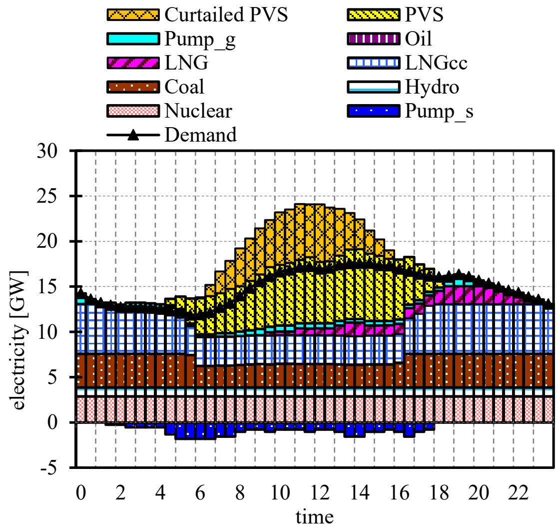


Fig. 7. Result of UC scheduling.

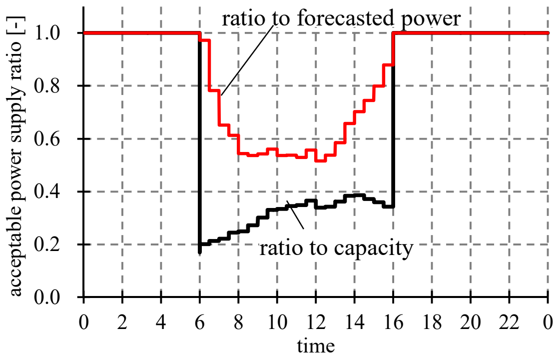


Fig. 8. Change in acceptable supply ratio of aggregted PVS power output to installed capacity.

Figure 9 shows time-series data of curtailed aggregated PVS power output calculated with different methods. The two time-series data are not so different each other between 9:00 – 14:00 and almost the same as the pre-determined level in the UC scheduling, because the acceptable power supply rate to the installed capacity $r_{ca}(h)$ is small. On the other hand, the difference is large before 9:00 and after 14:00. Because the aggregated power output in each observation point-representative area is small and fluctuating, the smoothing effect among different areas is large before 9:00. As a result, the

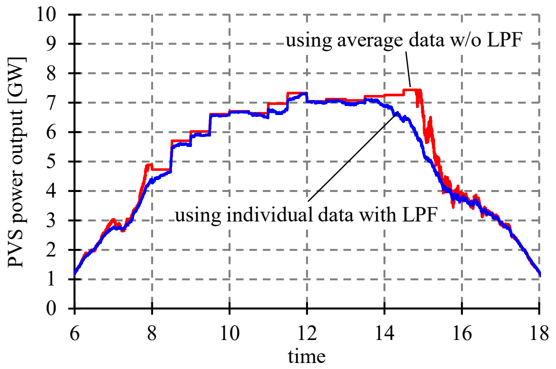


Fig. 9. Difference in time-series data of curtailed aggregated PVS power output by data processing method.

curtailed aggregated PVS power output in electric power system service area is smaller than the pre-determined level in the UC scheduling. When the curtailed aggregated PVS power output in electric power system service area is calculated based on the aggregated PVS power output and without using LPF model, however, the curtailed aggregated PVS power output is almost the same as the pre-determined level in UC scheduling.

The difference between two time-series data is large also after 14:00, because the smoothing effect among various areas is large. Besides, the reason for the large smoothing effect is large fluctuation of observed irradiance, the effect of LPF is large. Therefore, the short-term fluctuation is large even with the curtailed power output when it is calculated based on the aggregated PVS power output and without using LPF model. If such a time-series data with large short-term fluctuation is used in the impact assessment of high penetration PVS on the power system frequency, the impact would be over evaluated. In other words, the proposed model to calculate the time-series data of aggregated PVS power output is useful for the impact assessment on the system frequency even in the situation that the aggregated PVS power output must be curtailed due to the surplus power supply.

## 6. Conclusion

This study proposed a modelling method of aggregated PVS power output employing a LPF which takes into account a smoothing effect of power output fluctuation around individual observation point. The result showed that the hourly standard deviation of spatial average fluctuation of 32 min cycle or shorter is estimated almost half of that of simple average irradiance without applying the LPF model. Then, this study applied the proposed model to calculate the curtailed aggregated PVS power output and discussed the usefulness of proposed model. The comparison with the time-series data calculated based on the aggregated PVS power output and without using LPF model showed that the proposed model is useful even for the curtailment situation.

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