European Association for the Development of Renewable Energies, Environment and Power Quality (EA4EPQ)

International Conference on Renewable Energies and Power Quality (ICREPQ'12)
Santiago de Compostela (Spain), 28th to 30th March, 2012

Evaluation of Short-cycle Power Output Fluctuation of High-Penetration Photovoltaic Power Generation Systems using Multi-Points Insolation Data

T. Kato[1], S. Kumazawa[1], Y. Suzuoki[1], N. Honda[2], M. Koaizawa[2] and S. Nishino[2]

[1] Department of Electrical Engineering and Computer Science
Nagoya University
Furo-cho, Chikusa-ku, Nagoya, 464-8603 (Japan)
Phone/Fax number: +81 52 789 5373/+81 52 789 2108, e-mail: tkato@nuee.nagoya-u.ac.jp
[2] Electric Power Research & Development Center
Chubu Electric Power Co., Inc.
20-1, Kitasekiyama, Ohdaka-cho, Midori-ku, Nagoya, 459-8522 (Japan)
Phone/Fax number: +81 52 621 6101/+81 52 624 3994, e-mail: Koaizawa.Masakazu@chuden.co.jp

Abstract. By using the multi-points observation data of insolation, this study evaluated the short-cycle fluctuation of total power output fluctuation of high-penetration photovoltaic power generation system (PVS). First, this study evaluated the practical usability of so-called 1/√N rule. The results suggest that the observation points should be placed with at least 20 - 30 km interval so that the average insolation fluctuation around the point is calculated by applying 1/√N rule. Then, taking the smoothing-effect around the observation point into account, this study estimated the total power output fluctuation of high penetration PVS. The horizontal global insolation data observed for a year at 61 points in the Japan central area was utilized. As the result, the total power output fluctuation including only shorter cycles than 32 min is smaller than 1 % of the installed capacity for most of the period in a year. Although the absolute value of short-cycle fluctuation itself may not be significant even if 8 GW of PVS is installed, the reduction in the contribution of controllable utility power plant due to the HP-PVS may cause the difficulty of LFC.

Key words

photovoltaic power generation system, load frequency control, insolation, smoothing-effect, central limit theorem

1. Introduction

Photovoltaic power generation system (PVS) is one of the promising techniques for reducing the fossil fuel consumption and mitigating the carbon dioxide emission. The Japanese government has set the target capacity in 2030 at 53 GW. However, the high penetration of grid-connected PVS may cause some negative impacts on the electric power utility. For example, if a number of PVS are installed within a small district, the operation voltage of distribution network may exceed the regulation range. During the middle season, in which the electricity demand is much smaller than in the summer and winter seasons, the power supply of high penetration PVS (HP-PVS) may result in a surplus power, affecting the operation of base-load power plants. Besides, because of the nature of power output fluctuation, HP-PVS may increase the requirement on the power plant capacity for the load frequency control (LFC).

For the cost-effective mitigation against such the negative impacts, the proper evaluation of apparent fluctuation of electricity demand including power output of HP-PVS as negative demand is very important. Because the primary reason for the power output fluctuation of HP-PVS is the movement of clouds, there would be the time-difference in the power output fluctuation pattern among PVSs if PVSs are dispersed in the service area of electric power utility, and the average power output fluctuation would be reduced, called as a "smoothing-effect". In the impact assessment of HP-PVS, therefore, the precise evaluation of the total power output fluctuation by considering the smoothing-effect is essential. However, currently, the number of observation points of insolation or PVS power output is not enough. Therefore, we need to develop a method useful for evaluating the total power output fluctuation of HP-PVS by using only the data observed at the limited points.

Focusing on the impact assessment regarding the LFC, this paper proposes a method to estimate the standard deviation (Std) of the short-cycle fluctuation of total power output of HP-PVS. First, the proposed method is explained, followed by the discussion of the practical usability of so-called 1/√N rule on which the proposed method is based. Then, by assuming that PVSs are dispersed according to the spatial distribution of detached-house, the Std of total power output fluctuation of HP-PVS is estimated. Finally, the increase in the required capacity of the load frequency control of the utility due to the HP-PVS is discussed.

2. Approach

If the number of observation points of the insolation or PVS power output is large enough, we can estimate the total power output fluctuation of HP-PVS as a simple ensemble average of observed data, taking the so-called power output smoothing-effect among PVSs into account adequately. However, currently, the number of observation points of insolation is not enough. Although this paper utilizes the insolation data observed at 61 points as shown below, the number is not enough considering the large service area (about 39,000 km^2) of electric power utility in which the observation points are placed. Therefore, the smoothing-effect within the area around each observation points should be taken into account so that the total power output fluctuation can be evaluated properly by using the insolation data of inadequate number of observation points.

In this study, we propose the method to evaluate the hourly standard deviation (Std) of total power output fluctuation of HP-PVS by taking the smoothing-effect around observation point into account. The proposed method supposes that the multi-points insolation data is available, while the number of points is not enough. Focusing on the impact of HP-PVS on LFC, this study deals with the fluctuation cycle components shorter than 32 minute by using the Fast Fourier Transform (FFT).

First, by using Voronoi decomposition, the border line within which the observed insolation represents the insolation characteristics is determined. In this study, such the area is referred to as observation point-representing area. If there are N observation points, the service area of electric power utility is divided into N area. Figure 1 shows the schematic figure of Voronoi diagram. Although the actual Voronoi diagram would be very complicated due to the random location of observation points, the Voronoi diagram shown in Figure 1 consists of square areas of the same size for the simplicity.

Then, for taking the smoothing-effect around observation point into account, the proposed method supposes followings. Each observation point-representing area

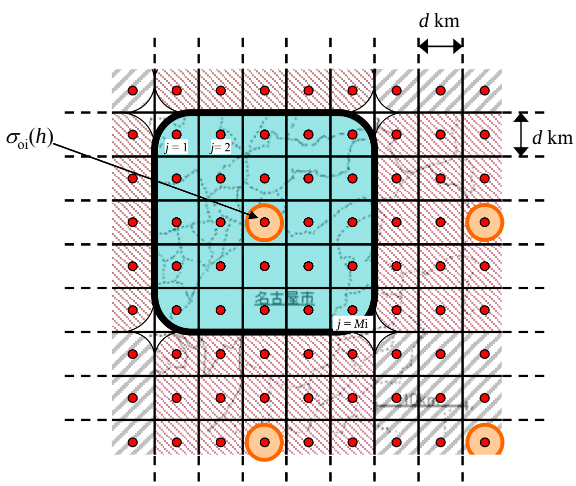


Fig.1. Modeling of observation point-representing area

consists of M blocks. The procedure to determine the number M is described later. As an example, M = 25 in Figure 1. The distance between center points of neighbouring two blocks is d km. The Std of insolation fluctuation at j-th block during the period h is $\sigma_j(h)$ [kW/m^2].

The distance between two points d is the most important value in the proposed method, and must be determined so that the insolation patterns at two points can be considered as independent. Because this study focuses on the impact of HP-PVS on the LFC, the value of d is determined by considering the independence of the insolation fluctuation including only shorter cycles than 32 minute. Our previous study regarding the independency of insolation fluctuation between two observation points revealed that the insolation fluctuation including only cycles shorter than 32 minute is considered independent when the distance between two points is longer than 5 km – 10 km [1][2]. Therefore, in this study, the size of each block is assumed to be 5 km x 5 km.

If $\sigma_j(h)$ is available for all M_i blocks in the i-th observation point-representing area, the Std of average insolation fluctuation in the i-th area $\sigma_{Ii}(h)$ is given based on the independence of insolation fluctuation among blocks by using the addition theory of variance as follows.

$$\sigma_{Ii}(h) = \frac{1}{M_i}\sqrt{\sum_{j=1}^{M_i}\sigma_j(h)^2} \qquad [\mathrm{W/m^2}] \qquad (1)$$

From the practical point of view, however, it seems difficult to estimate the individual Std for each block. On the other hand, if the probabilistic characteristics of insolation fluctuation is the same for all M blocks as $\sigma_{oi}(h)$ at the observation point while the actual time-varying changes are different each other, $\sigma_{Ii}(h)$ is given as follows by using the so-called 1/√N rule.

$$\sigma_{Ii}(h) = \frac{\sigma_{oi}(h)}{\sqrt{M_i}} \qquad [\mathrm{W/m^2}] \qquad (2)$$

In the real world, because the Std slightly vary among blocks even within the small area, the so-called 1/√N rule or the central limit theorem in other words is not applicable from the theoretical point of view. As discussed below, however, the 1/√N value would be still useful from the practical point of view if the area is not so large.

By applying eq.(2) to the individual observation point, if the area size is not so large, the Std of short-cycle fluctuation can be calculated for each point-representing area. Besides, considering the inadequate number of observation points, the actual time-varying changes are different each other among the observation points. Therefore, the Std of total average insolation fluctuation σ_I is also calculated based on the addition theory of variance. However, we should take into account another factor due to the inadequate number of observation points, i.e. the difference in contribution of each observation point due to the difference in the size of representing-area. Therefore, by using the weight factor w_i, therefore, σ_{Iave} is given as follows.

$$\sigma_I(h) = \sqrt{\sum_{i=1}^{N}\left(w_i \sigma_{Ii}(h)\right)^2} \quad [\mathrm{kW/m^2}] \tag{3}$$

Details to determine the weight factor are described later.

Finally, by using the Std of insolation fluctuation on the tilted surface σ_{ti} instead of σ_{oi}, and by assuming the total capacity of HP-PVS P_{tot} and the performance ratio of individual PVS η, the Std of total power output fluctuation of HP-PVS is given as follows based on the addition theory of variance.

$$\sigma_{PV}(h) = \eta P_{tot} \sqrt{\sum_{i=1}^{N}\left(w_i \frac{\sigma_{ti}(h)}{\sqrt{M_i}}\right)^2} \quad [\mathrm{MW}] \tag{4}$$

η should be determined by considering several factors, i.e. module type, season, temperature, inverter efficiency, MPPT mismatch, etc. For the simplicity, however, this study assumes that η is fixed at 0.8 independently of such the factors.

3. Multi-Points Insolation Data

We have started the multi-points observation of global horizontal insolation in the japan central area (Chubu area). In this study, the data at 61 points observed during Sep/2010 –Aug/2011 is utilized. 61 points are selected so that the distance to the nearest points is larger than about 5 km. Although the data sampling interval is 1 second, this study utilizes the 1 minute average value.

As an example regarding the short-cycle fluctuation characteristics of observed insolation, Figure 3 shows the frequency distribution of the hourly Std for a year at five observation points, i.e. point A1, M1, N1, G, and S shown in Figure 2. Although the five points widely dispersed in the Japan central area, the frequency distribution of short-cycle fluctuation is not different so much among points.

4. Practical Usability of 1/√N rule

By using the insolation data observed at 10 points, i.e. A1, A2, A3, A4, M1, M2, N1, N2, G, and S shown in Figure 2, this study discussed the practical usability of 1/√N rule to estimate the Std of spatial average insolation fluctuation by comparing following two Stds.

$\sigma_E(h)$: Std of ensemble average insolation observed at N_x points included within the circle area of radius x km. The center point is chosen from the above mentioned 10 points.

$\sigma_N(h)$: Std calculated by eq.(5) by using only Std of the center point $\sigma_i(h)$ (i = A1 – S).

$$\sigma_N(h) = \frac{\sigma_i(h)}{\sqrt{N_i}} \quad [\mathrm{kW/m^2}] \tag{5}$$

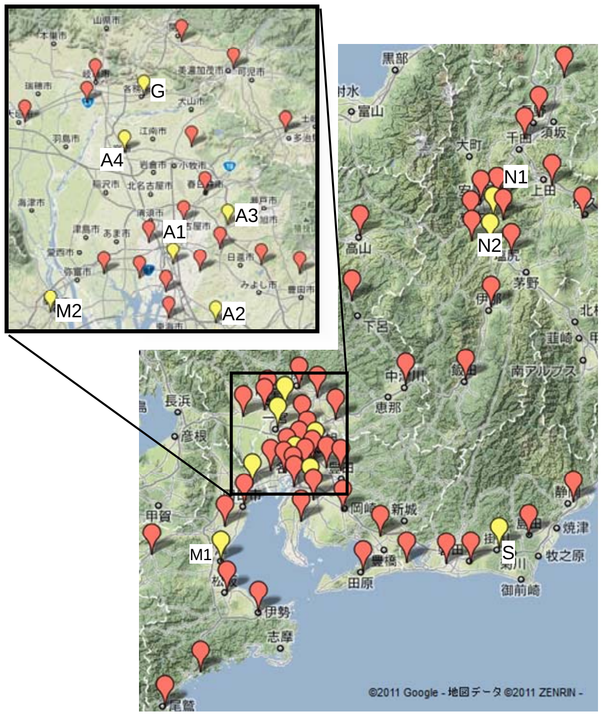


Fig.2 Insolation observation points

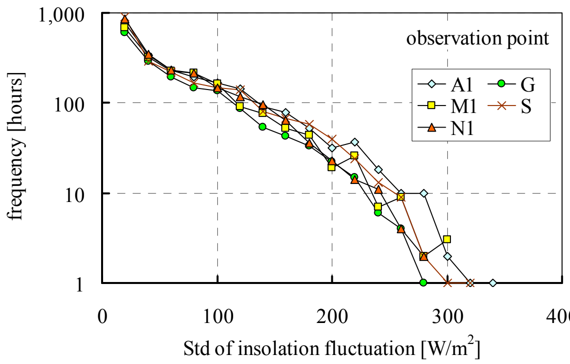
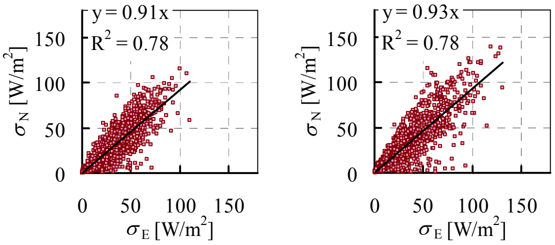


Fig.3 Examples of frequency distribution of short-cycle insolation fluctuation standard deviation

If $\sigma_N(h)$ is close to $\sigma_E(h)$, the 1/√N rule would be practically usable to estimate the Std of spatial average insolation fluctuation.

By using the data between 9:00 – 15:00 for a year, this study calculated $\sigma_E(h)$ and $\sigma_N(h)$ for the above mentioned 10 points. Figure 4 shows examples of the σ_E - σ_N correlation diagram regarding the circle area of 10 km radius in the case of center point A1 and G. The R^2 value of regression line is 0.78 in these examples. Although this value is not large enough, we could conclude that the Std of spatial average insolation fluctuation can be estimated with such the accuracy by using the Std of only one point.

We calculated R^2 value by changing the area radius for 10 different center points. Figure 5 shows R^2 value of regression line of σ_E - σ_N correlation diagram as a function of area size. Excluding the case of N1 and N2, which are located in the Matsumoto Basin area, R^2 value



(a) center: A1 (b) center: G

Fig.4 Examples of σ_E - σ_N correlation diagram regarding area of 10 km radius

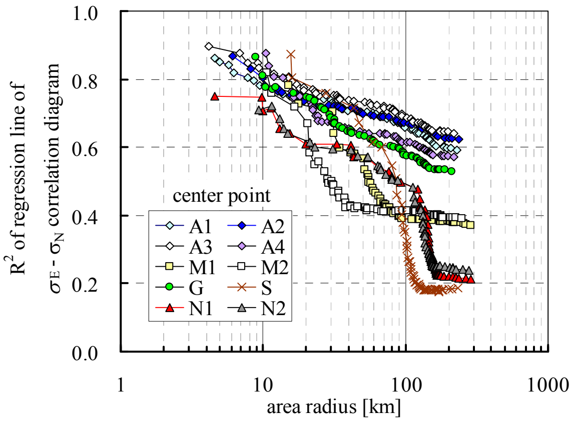


Fig.5 R^2 value of regression line of σ_E - σ_N correlation diagram as a function of area size

is larger than 0.8 within the circle area of 10 km radius. Even though the area size is the same, the difference in weather condition is much larger in the Matsumoto Basin area than in the Plain area, in which other points are located, because of the sudden change in weather due to the influence of mountain. As the result, from the stochastic evaluation point of view, excluding the location like N1 or N2, 1/√N rule would be useful to estimate the Std of spatial average insolation for the circle area of radius 10 km.

5. Effective Size of Observation Point-Representing Area

In order to apply the proposed method, the number of blocks M_i and the weight factor w_i must be determined for individual observation point-representing area. Because the proposed method assumed that the observation point-representing area consists of blocks of 5 km x 5 km as mentioned above, the number of blocks M_i is given by taking the area size S_i into account.

When S_i is determined based on the actual geographical size, M_i would be overestimated because there would be many places in which the installation of PVS is impossible such as mountain, forest, river, etc. Considering that PVSs will be dispersed according to the spatial distribution of detached-house, this study determines S_i based on the number of 0.5 km x 0.5 km area A_i in which at least X households inhabit in detached-house. The effective size of

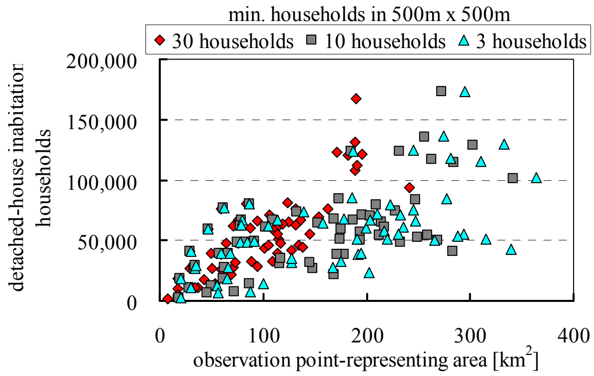


Fig.6 Relation between observation point-representing area size and involved households inhabiting in detached-house

observation point-representing area Si is given by A_i x (0.5 x 0.5). As a sensitive analysis regarding the degree of smoothing-effect around the observation point, the X value (minimum number of detached house) of 3, 10, and 30 is utilized.

Figure 6 shows the relation between Si and the number of involved households H_i inhabiting in detached-house. When X is assumed to be 3 so that sparse area is included, the maximum value of effective area Si reaches 364 km^2. This size corresponds to the circle area of radius 11 km. Considering the above mentioned result regarding the practical usability of 1/√N rule, 1/√N rule can be applied to all 61 observation points in this study.

By using A_i, the number of point-representing area M_i is given as follows.

$$M_i = \frac{S_i}{5 \times 5} = \frac{A_i \times (0.5 \times 0.5)}{5 \times 5} \tag{6}$$

By using H_i, the weight factor w_i is given as follows.

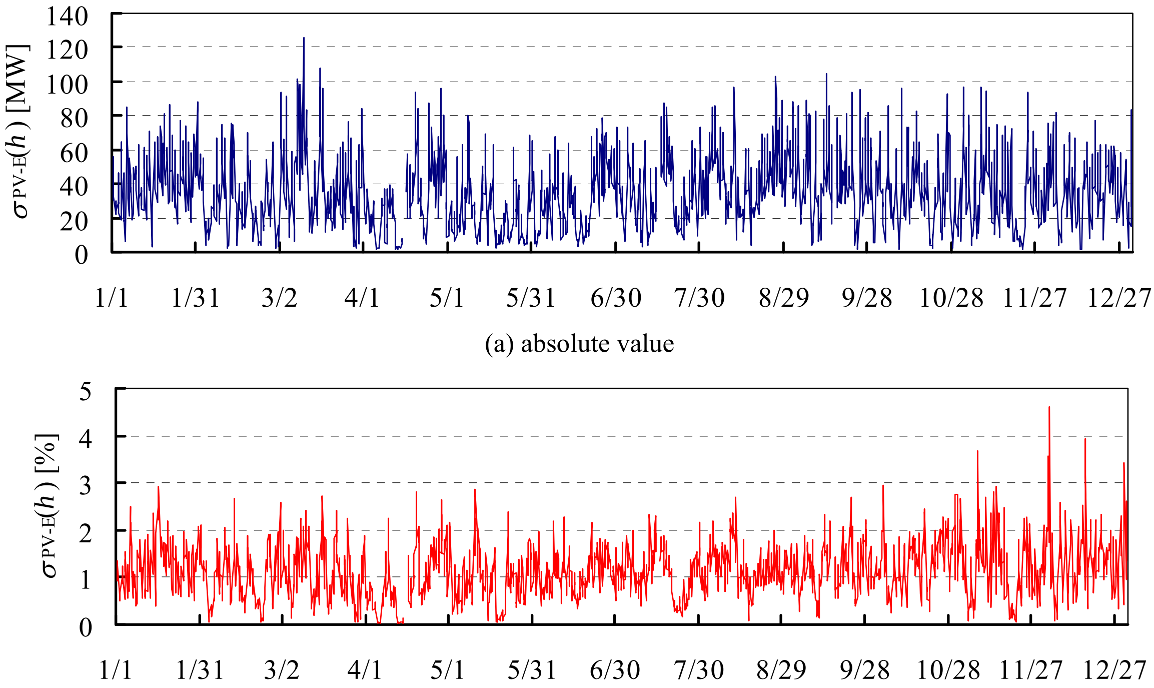
$$w_i = H_i \Big/ \sum_{i=1}^{N} H_i \tag{7}$$

6. Short-Cycle Total Power Output Fluctuation of HP-PVS

A. Assumption

By using the proposed method, this paper estimates the Std of total power output fluctuation of HP-PVS dispersed in the electric power utility service area in central area in Japan, in which the electricity supply to residential sector is done by single electric power utility. The record of the maximum electricity demand in the Japan central area is 27 GW in 2008.

Considering that the Japanese government has set the target capacity by 2030 at 53 GWp, this study assumes that total capacity of PVSs in the Japan central area is 8 GWp. This value reaches about 30 % of maximum electricity demand.



(a) absolute value

(b) relative value to hourly total power output

Fig.7 Change in hourly standard deviation of short-cycle fluctuation of HP-PVS $\sigma_{PV}(h)$ for a year (total capacity of PVS: 8GWp)

B. Results

Based on the above assumptions, this study calculated the hourly Std of short-cycle fluctuation of total power output of HP-PVS $\sigma_{PV}(h)$ by using eq.(4). $\sigma_{ti}(h)$ is the hourly Std of insolation fluctuation on the tilted surface (35 degree, south) and is calculated for every one hour between 9:00 and 15:00 (6 hours/day) for a year (Sep/2010 – Aug/2011). Because there are some days with observation error at some points, the Voronoi diagram to determine the observation point-representing area is rebuilt depending on the number of available points.

Figure 7 (a) shows the change in $\sigma_{PV}(h)$ for a year, in which the effective area size is determined by counting Although $\sigma_{PV}(h)$ tends to be large in March, the annual change in $\sigma_{PV}(h)$ is not so large, ranging between 10 MW and 80 MW. Figure 7 (b) shows the change in $\sigma_{PV}(h)$ relative to the hourly total power output of HP-PVS. The relative value ranges mainly between 1 – 2 %, and tends to be large in December because of relatively small power output of HP-PVS compared with other months.

Figure 8 shows the difference in $\sigma_{PV}(h)$ by degree of smoothing effect around observation points. By considering the smoothing effect around observation point, $\sigma_{PV}(h)$ decreases to almost half. The difference in $\sigma_{PV}(h)$ by degree of smoothing effect is small.

C. Impact on LFC

Considering the typical load factor in Japan, the minimum electricity demand would be about 25 % of the maximum.

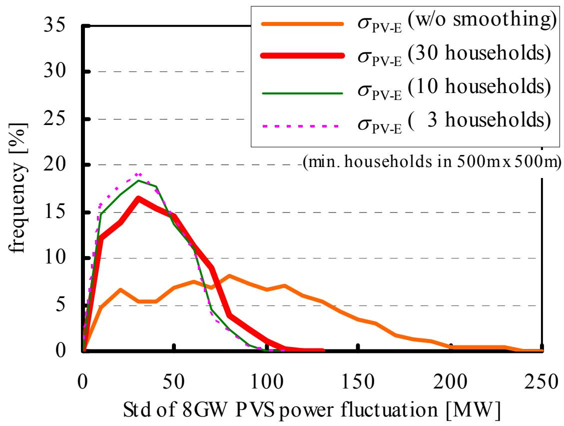


Fig. 8 Difference in Stds regarding short-cycle power output fluctuation of HP-PVS by degree of smoothing effect around observation points

Because the required capacity of LFC generator is a few percentages of the demand, depending on the time of the day or seasons, it would be between 200 and 800 MW in the central area of Japan. In this study, the amount of required capacity for LFC in the case without HP-PVS is used as the reference to evaluate the Std of short-cycle power output fluctuation of HP-PVS.

By using the data of electricity demand in the Japan central area observed in 2001, this study compared the Std of actual electricity demand fluctuation $\sigma_D(h)$ and the Std of apparent electricity demand fluctuation $\sigma_{appD}(h)$ including the power output of HP-PVS as negative electricity demand. Note that observation year of the insolation and the electricity demand is different due to the unavailability of the recent electricity demand. Therefore, the comparison in this study should be understood as a part of probabilistic evaluation. Two types of relative value of $\sigma_{appD}(h)$ are calculated as follows.

$$\sigma_{appD}(h) = \frac{\sqrt{\sigma_D(h)^2 + \sigma_{PV}(h)^2}}{Ave_D(h)} \quad [\%] \qquad (6)$$

$$\sigma_{appD}(h) = \frac{\sqrt{\sigma_D(h)^2 + \sigma_{PV}(h)^2}}{Ave_D(h) - Ave_{PV}(h)} \quad [\%] \qquad (7)$$

The first one is the relative value against the hourly average electricity demand $Ave_D(h)$. The second one is the relative value against the hourly apparent electricity demand $Ave_D(h)$ – $Ave_{PV}(h)$ including hourly HP-PVS power output as negative electricity demand. The reduction of apparent electricity demand viewed from electric power utility means the reduction in the contribution of controllable utility power plant due to the HP-PVS.

Figure 9 shows the correlation diagram between $\sigma_D(h)$ and $\sigma_{appD}(h)$. The relative value of $\sigma_{appD}(h)$ against the actual electricity demand $Ave_D(h)$ is not different from $\sigma_D(h)$ for most of the period, because Std of short-cycle fluctuation of HP-PVS power output ranging between 10 – 80 MW is very small compared with the electricity demand.

On the other hand, $\sigma_{appD}(h)$ relative to the apparent electricity demand $Ave_D(h)$ – $Ave_{PV}(h)$ is larger than $\sigma_D(h)$ by 0.5 – 1.0 %. The value itself is not so significant, suggesting that the impact of the power output fluctuation on LFC of local electric power utility would not be the matter. However, the reduction in the contribution of controllable utility power plant due to the HP-PVS may affect LFC for a very few periods with the large fluctuation. As mentioned above, this study is a part of probabilistic evaluation. Further study is required by using the data of electricity demand and multi-points insolation both for several years.

Conclusion

By using the multi-points observation data of insolation, this paper proposed a method to calculate the standard deviation (Std) of total power output fluctuation of high penetration PVS (HP-PVS). The main results are as follows.

- From the stochastic evaluation point of view, the estimation of the Std of ensemble average insolation among area by calculating the 1/√N value would be useful for the area of radius 10 km.
- The total power output fluctuation including only shorter cycles than 32 min is smaller than 1 % of the installed capacity for most of the period in a year.
- Although the absolute value of short-cycle fluctuation itself may not be significant even if 8 GW of PVS is installed, the reduction in the contribution of controllable utility power plant due to the HP-PVS may affect LFC.

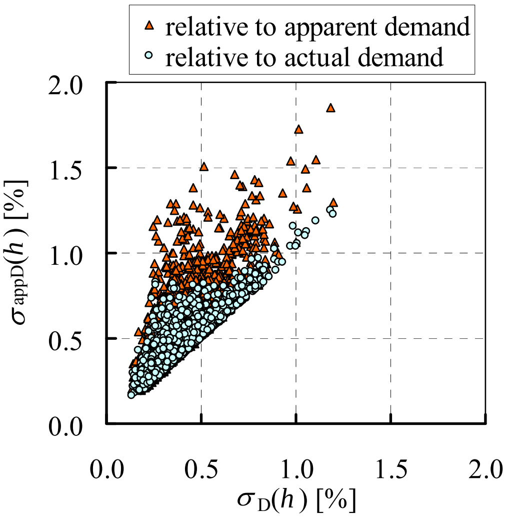


Fig. 9 Correlation diagram between Std of actual electricity demand fluctuation and Std of apparent demand fluctuation including PVS power as negative electricity demand

As a future work, we will evaluate longer cycle fluctuation of HP-PVS and discuss the impact on the stable operation of electric power system.

Acknowledgement

This work was partially supported by Grant-in-Aid for Scientific Research (B), No. 21360127 and the Environment Research and Technology Development Fund (E-1105) of the Ministry of the Environment, Japan.

References

[1] T. Kato, T. Inoue and Y. Suzuoki: “Evaluation of Total Power Output Fluctuation of Photovoltaic Power Generation Systems of Large-scale Penetration Based on Central Limit Theorem”, Proc. of 25th European Photovoltaic Solar Energy Conf. and Exhibition, 5BV.4.35 (2010)

[2] T. Kato, T. Inoue and Y. Suzuoki: “Estimation of Total Power Output Fluctuation of High Penetration Photovoltaic Power Generation System”, Proc. of The 2011 IEEE PES General Meeting, 2011GM1076 (2011)

[3] T. Kato and Y. Suzuoki, “Geographical Distribution of Potential Capacity of Residential Photovoltaic Power Generation System – A Case study for 5 Prefectures in Chubu Area in Japan –”, Proc. of Int. Conf. and Exhibition of Renewable Energy, No.-PV-042 (2008)