An Evaluation Method of the Fluctuation Characteristics of Photovoltaic Systems by Using Frequency Analysis

Norihiro KAWASAKI, Takashi OOZEKI, *Kenji OTANI, and Kosuke KUROKAWA
Kosuke KUROKAWA Lab, Tokyo University of Agriculture and Technology,
2-24-16 Naka-cho, Koganei, Tokyo, 184-8588 Japan
Phone: +81-42-388-7445, Fax: +81-42-388-7445, E-mail: norihiro@cc.tuat.ac.jp
*National Institute of Advanced Industrial Science and Technology (AIST)

Abstract

Short time fluctuations in solar irradiance will become an important issue with regard to future embedded photovoltaic (PV) systems. From the viewpoint of considering an intensive PV installation on the certain area, the output of the systems will be provide stable by the equalization of irradiance fluctuation. In this paper, a new estimation method of irradiance fluctuation, which based on the combination of the Fourier transform and the Wavelet transform methods, is described.

Keywords

PV system, the smoothing effect, fluctuation characteristic, Fourier transform, Wavelet transform

1. Introduction

The output of PV systems has a short-term fluctuation due to weather fluctuation. It may give undesirable effects on an individual power system, and it makes the capacity value (kW value) of the PV system be low. To clarify these phenomena, authors have studied "the smoothing effect" which is smooth the area total irradiance. Fluctuation of PV output is sensitive as for a few PV systems, however fluctuation of total output in clustering PV systems is not remarkable because there is spatial-inhomogeneity of irradiance field in certain area. According to the smoothing effect, the capacity value of PV systems is indicated to increase, and problems for utility occurred by fluctuation of PV output power can be alleviated. Therefore, it is very important to quantitative this effect and to develop a new evaluation method.

Several important studies of the smoothing effect have already been approached based on irradiation data. One of the papers describes a definition of the irradiance fluctuation degree by using original parameter, moving average and standard deviation of irradiance data, and demonstrates improvement in kW value [1]. In another paper, the magnitude of the fluctuation and speed of fluctuation are defined, and the forecast of Load Frequency Control (LFC) capacity is evaluated [2]. Both studies have developed simulation methods of the smoothing effect based on irradiation as relation between smoothing effect, area size and the value of the number of PV systems in a distribution network. Furthermore, the evaluation method is prospected to be more mathematical and to consider several time scales, and also it is necessary to demonstrate accuracy of simulations by using data obtained in real system. However, both studies are not used a real measurement data of the distribution network.

Purpose of this paper is to develop a new evaluation method for smoothing effect. The evaluation method uses Fourier transform and Wavelet transform [3] for frequency analysis. Measured data will be able to obtain from February 2004. This study is a part of “Demonstrative Research on Clustered PV Systems”, funded by New Energy and Industrial Technology Development Organization (NEDO).

2. Measured Data

Irradiance data has been recorded by one minute sampling. Irradiance data used in analysis was obtained by the special monitoring system that consists of nine synchronized monitoring terminals Oct 1995 to December-1997 (Fig 1). Those terminals have been installed on a grid which covers an area measuring about 4km x 4km at 140 ° 05’58” eastern to 140 ° 09’05” eastern and 36 ° 02’58” northern to 36 ° 05’30” northern. The size of the grid is decided by considering the size of typical urban distribution network [1].

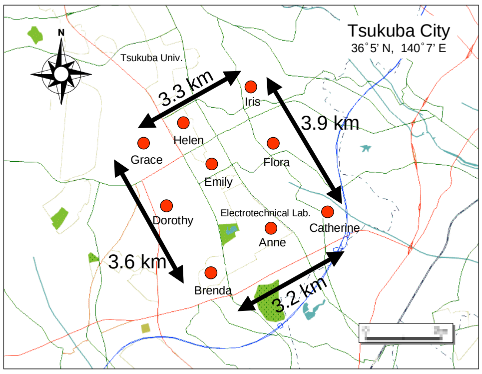

Fig 1. Location of 9 terminals of Area Irradiance Monitoring System

3. Approach

Applying the Fourier transform and the Wavelet transform can derive frequency domain properties of the recorded fluctuation patterns. Unlike for Fourier transform, Wavelet transform is localized in time by frequency analyzing. In other words, Fourier transform has only frequency information, and Wavelet transform has time information and frequency information. However, if either of them is chosen, authors think that the fluctuation characteristic cannot be grasped correctly. Because Fourier transform gives fluctuation for the whole one day, and Wavelet transform gives fluctuation for a local time. Both of them are important in order to understand by fluctuation characteristics. The flow of the calculation is shown in Fig.2.

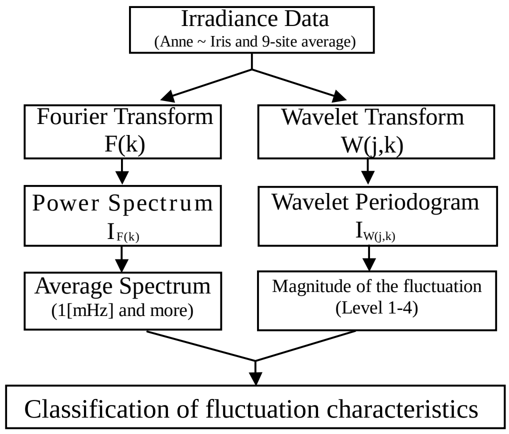

Fig 2. Flow chart of the evaluation process

3.1. Fourier analysis

The Fourier transform of discrete data is given by the following formula.

$$F(k) = \sum_{n=0}^{N-1} f(n) e^{\frac{-j2\pi kn}{N}} \qquad (1)$$

Power spectrums ($I_{F(k)}$) are calculated from the square of the coefficients of Fourier spectrum (F(k)).

$$I_{F(k)} = \frac{1}{N} |F(k)|^2 \qquad (2)$$

The maximum frequency is 1/120 [Hz] (= 8.33×10^{-3} [Hz]) base on the sampling theorem, because irradiance data has been recorded by one minute sampling. This time, the power spectrum more than 1x10-3[Hz] was averaged that is as an example. This is defined as “Average spectrum”. This corresponds to the frequency domain of LFC (Load Frequency Control). Average spectrum can know the degree of a distribution of the fluctuation speed in one day. There is so much fluctuation that this value is large.

3.2. Wavelet analysis

Wavelet transform W of a signal f(n) is calculated as the inner product of f(n) and the scaled and shifted wavelet base $\psi_{j,k}(n)$:

$$W(j,k) = \sum_{n=0}^{N-1} f(n)\psi_{j,k}(n) \qquad (3)$$

$$\psi_{j,k}(n) = \frac{1}{2^{j/2}}\psi\left(\frac{n-k}{2^j}\right) \qquad (4)$$

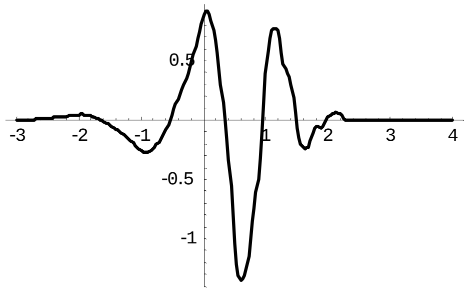

Fig.3. Daubechies 4 (Wavelet function)

Daubechies 4 (Fig.3.) has been chosen as a wavelet function ($\psi_{j,k}(n)$). Wavelet periodograms are calculated from the square of the coefficients of wavelet spectrum (W(j,k)).

$$I_{W(j,k)} = \left|W(j,k)\right|^2 \qquad (5)$$

This time, the fluctuation cycle for 1 - 16 minutes was observed as an example. This corresponds to a level 4 from a level 1. Furthermore, this corresponds to the frequency domain of LFC. The maximum of spectrum is looked for from these periodogram (Fig.4.). The maximum of a periodogram is detected and the width of irradiance fluctuation of this time is calculated. This is defined as “Magnitude of fluctuation”. The magnitude of fluctuation is not necessarily max of the day, because frequency band is limited. The greatest magnitude of fluctuation can be calculated for the target frequency.

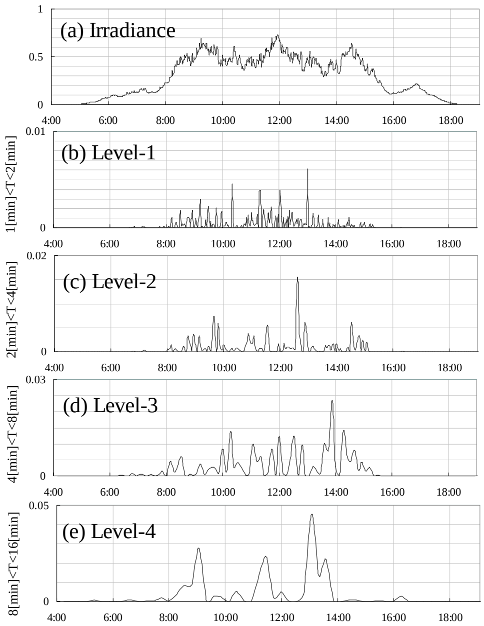

Fig.4. Wavelet Periodogram;
average of nine-sites measurements
(19 August 1997).

4. Results and Discussion

Result of the flow chart is shown in Fig.5. ((a)-3, (b)-3, (c)-3, (d)-3) and Table.1. The horizontal axis serves as Magnitude of the fluctuation, and the vertical axis serves as Average spectrum in Fig.5. Four patterns of a clear weather day (97/8/10), a cloudy after fine weather day (97/8/19), a slightly clouded sky day (97/7/4), and a rainy weather day (97/7/10) performed analysis.

(1) Clear day

The real measured data of 10th July (see Fig. 5-a) has been set for evaluation standards as a clear day. Average spectrum and Magnitude of the fluctuation is respectively distributed over the range about 0.005 $x10^{-3}$ and about 0.05 [kW/m^2] on this pattern. As a result, these fluctuations of irradiance are the smallest among four patterns. But as for three points of Brenda, Helen, and Iris, Magnitude of the fluctuation is larger than other points, according to influence of the shade by the building. Influence of the shade by the building is contained on irradiation of 9-site average, according to the smoothing effect.

(2) Slightly cloudy day

There is fast and small fluctuation on each point in area. Average spectrum is distributed over the range about 1.0 $x10^{-3}$ to $1.4*10^{-3}$, Magnitude of the fluctuation is distributed over the range about 0.2 to 0.4 [kW/m^2]. As compared with clear day, Average spectrum is 200 or more times, and the Magnitude of fluctuation is 10 or more times. Therefore, irradiance of each point had a sharper fluctuation. Irradiance of 9-site average is the waveform that removed fluctuation as if LPF pass to irradiance of each point. Compared irradiance of 9-site average of this day with irradiance of clear day, Average spectrum is about 30 times, and the Magnitude of fluctuation is the about the same. Average spectrum decreases to about 1/10 and this means that short and fast fluctuation is contained, according to the smoothing effect.

(3) Cloudy, fine later day

Irradiance of this day has much quick and big fluctuation. Irradiance fluctuation of each point in area is intense. Average spectrum is distributed over the range about 5 to 9 $\times 10^{-3}$, magnitude of fluctuation is distributed over the range about 0.2 to 0.6 [kW/m^2]. As compared with clear day, Average spectrum is 1400 or more times, and the Magnitude of the fluctuation is 30 or more times. Therefore, irradiance of each point had a very sharp fluctuation. Compared irradiance of 9-site average of this day with irradiance of clear day, Average spectrum is about 130 times, and the Magnitude of fluctuation is the about 3 times. Average spectrum decreases to about 1/12 and the Magnitude of the fluctuation decreases to about 1/4, according to the smoothing effect. This means that the smoothing effect is acquired well.

(4) Rainy day

On the whole, irradiance is small on this day. Therefore, since the absolute value of fluctuation becomes small, an average spectrum and the range of fluctuation become small inevitably: Average spectrum is distributed over the range about 0.02 $x10^{-3}$ to 0.07 $x10^{-3}$, Magnitude of the fluctuation is distributed over the range about 0.02 to 0.07 [kW/m^2]. As compared with clear day, Average spectrum is 1400 times, and the Magnitude of the fluctuation is 30 times. Therefore, irradiance of each point didn't have very sharp fluctuation. Compared irradiance of 9-site average of this day with irradiance of clear day, Average spectrum is about 2 times, and the Magnitude of fluctuation is the about 1/2. The smoothing effect is not obtained on this pattern.

Table.1. Relation of Average Spectrum and Magnitude of the fluctuation

	Clear		Slightly cloudy		Cloudy, fine later		Rainy	
	1 site individual	9 site average	1 site individual	9 site average	1 site individual	9 site average	1 site individual	9 site average
Average Spectrum ($x 10^{-3}$)	0.00465	0.00448	1.021	0.129	7.22	0.572	0.0508	0.00891
Magnitude of the fluctuation [kW/m^2]	0.0170	0.0565	0.221	0.212	0.615	0.175	0.0605	0.0352

* 1 site individual: Anne

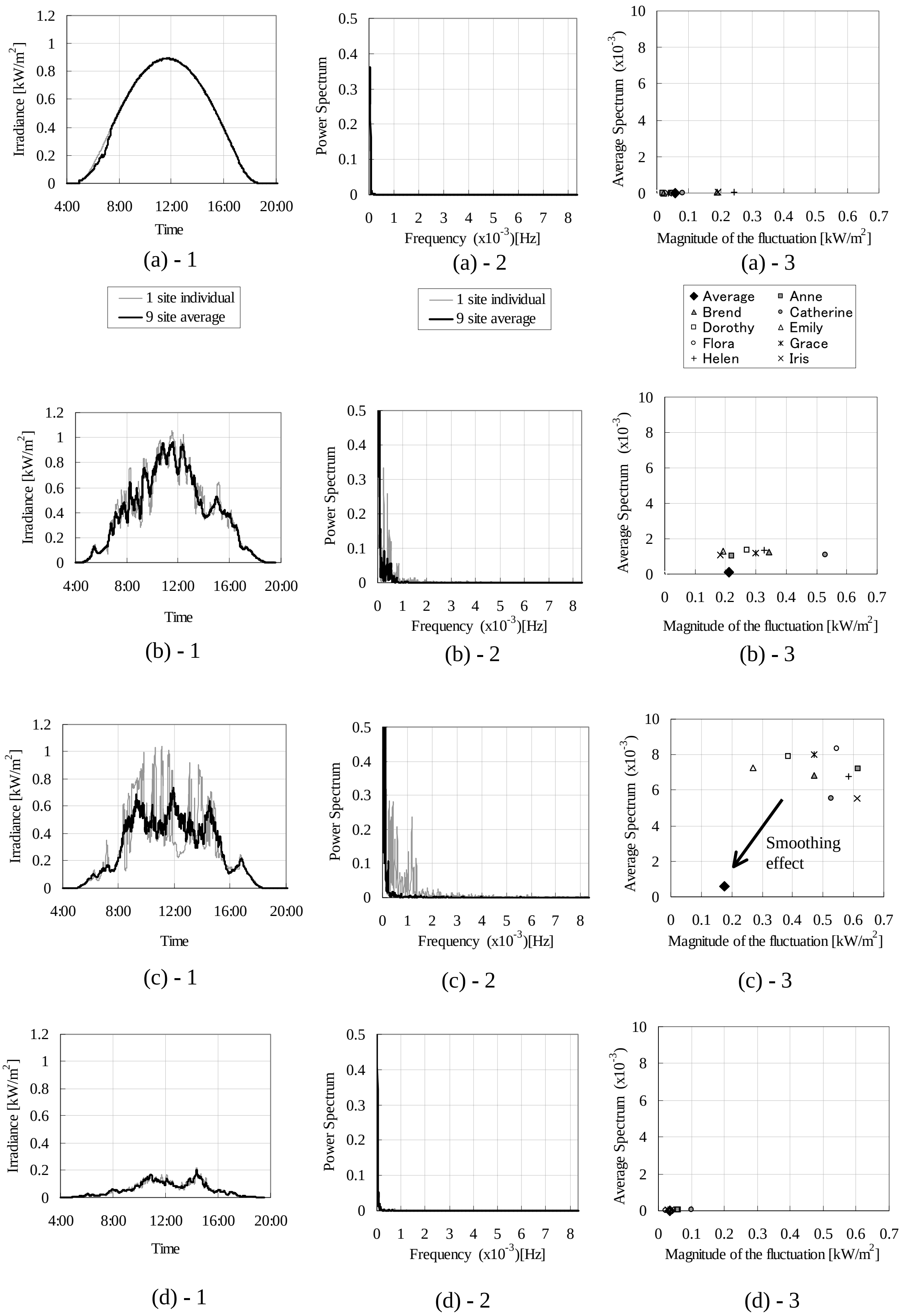

Fig.5. Classification of fluctuation characteristic; relation of Average Spectrum and Magnitude of the fluctuation.
(a): 10 July 1997, (b): 4 July 1997, (c): 19 August 1997, (d): 10 August 1997
1: Irradiance data, 2: Result of Fourier Transform, 3: Fluctuation characteristic

(5) Summary of results

Figure 5 (b) and (c) are influenced by the short time moving cloud, because irradiance drops and spikes caused by passing fast clouds. (c) was deadened by the smoothing effect to level of (b). This is the effect of “the smoothing effect”. Scarcely (a) and (d) are influenced by the short time moving cloud, this fluctuation characteristic is very small value. Author arranges the fluctuation patterns according to intensity: (c) > (b) > (d) > (a) This turn is the same as the turn that the smoothing effect is obtained. The smoothing effect can be quantified every fluctuations frequency by using frequency analysis of Fourier transform and Wavelet transform.

5. Conclusion

In this study, authors verified the smoothing effect using frequency analysis of Fourier transform and Wavelet transform base on using irradiation data. From results, authors obtained the smoothing effect; c>b>d>a (in order of effect) This turn is equal to the irradiance fluctuation. Because of them, it is confirmed that the more irradiance fluctuates, the more the smoothing effect is effective. Moreover, the smoothing effect can be quantified by this evaluation method. In the future, authors will model the simulation to consider the smoothing effect in actual grid including area size, the distance of station, and number of PV system.

Acknowledgments

This work was supported by NEDO as a part of the “Demonstrative Research on Clustered PV Systems” under METI.

References

[1] K.Otani, J.Minowa, and K.Kurokawa, ”Study on Areal Solar Irradiance for Analyzing Areally-Totalized PV Systems,” Solar Energy Materials and Solar Cells,47, pp.281-288,1997.

[2] S.Yanagawa, et al., “Evaluation of LFC Capacity for Output Fluctuation of Photovoltaic Power Generation Systems Based on Multi-point Observation of Isolation,” T. IEE Japan, Vol.121 No.9 pp.1094-1102, 2001.

[3] A.Woyte, R.Belmans, and J.Nijs, “Analysing Short-time Irradiance Fluctuations By Their Characteristic Time Scales” WCPEC-3, Osaka, Japan, 11-18 May 2003

Category: VI, Poster presentation P-220