Temperature Fluctuation Analysis of Photovoltaic Modules at Short Time Interval

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ABSTRACTS

Photovoltaic (PV) array temperature and ambient temperature change constantly, and the current of the array is influenced by the change of the irradiation and the temperature. Many past papers described models for estimating PV module temperature. However, those models dealt with fluctuation of PV module temperature as hourly value at steady state. In order to monitor the temperature in a second level interval, we have established experimental equipment that can monitor the temperature on the second time interval scale and established a model to simulate PV module temperature. This paper presents that fluctuation of the PV module temperature can be estimated by using a heat transfer model, and demonstrates that PV module temperature influences on the output voltage at a short time interval.

Keywords: PV module, Temperature fluctuation, Simulation

Introduction

PV modules, which installed outside are constantly influenced by irradiance from the sun, ambient temperature, wind and radiation to ambient objects. The conversion efficiency of PV modules are also under influence of the temperature coefficient which is about -0.4 - -0.5 [%/degC]. Thus it is unable to ignore decrease of generated electricity following temperature rise. Previously, the authors developed an I-V curve simulator, which supply light to simulate PV module output[1], and proved that rapid fluctuation of the PV module output voltage has possibility to give negative impact on maximum power point (MPPT) control of inverters for PV system[2]. In order to precisely evaluate or develop MPPT control methods, it is indispensable to understand fluctuation behavior of PV module output at short time interval. While the PV module current depends on the irradiation, the PV module voltage is influenced by the solar cell temperature; therefore it is necessary to know about the variation of cell temperature.

A large number of studies about PV module temperature have been made, as many researchers have interested in this subject. Yukawa et al. (1996) established an estimated equation of PV array temperature based on the heat transmission engineering[3]. Nishikawa (1999) found an estimated equation of stand-off type PV array by experimental result used for a demonstrative test facility[4]. Akaki et al. (2001), analyzed the effects of solar cell temperature by experimental results applying regression analysis[5]. D. L. King et al (1997) identified a relationship between irradiation and module PV temperature rise with experimental results of various types of PV modules[6]. A. D. Jones demonstrated fluctuation of PV module temperature at unstable weather conditions[7]. These estimated models are able to precisely estimate PV module temperature comparatively at steady state and 1 hour condition. However, these models are not suited for estimating PV module temperature at short time interval, so called non-steady heat conduction. Therefore, the authors developed a simulation model for PV module temperature fluctuation at short time interval, and verified it with the actual experimental data.

THE PV MODULE TEMPERATURE ESTIMATE MODEL

Fig. 1. shows an overview of PV module temperature simulation model of this study.

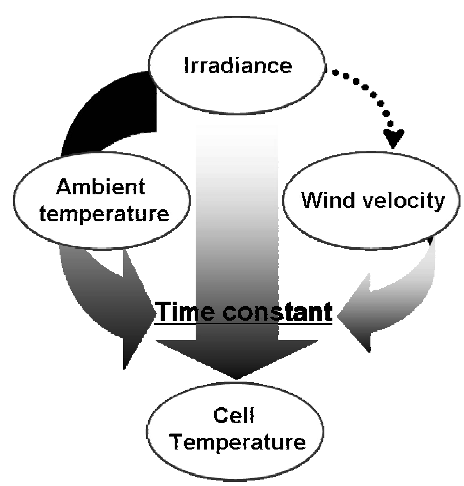

Fig.1. Image of the PV module temperature simulation model

The temperature of PV module mainly depends on three factors: 1) irradiance, 2) ambient temperature influenced by irradiance and 3) wind with a certain amount of time constant. This model simulates the "target temperate" at steady state from irradiance, ambient temperature, wind speed and velocity and PV module temperature corrected in the previous step, and estimates the PV module temperature using transient analysis at unsteady condition after estimating the temperature time constant.

Estimated by steady heat conduction

Estimation method of PV module temperature at steady state was investigated with taking into account the heat radiation and heat transfer from the PV module. Thermal conduction model of PV module is shown in Fig.2

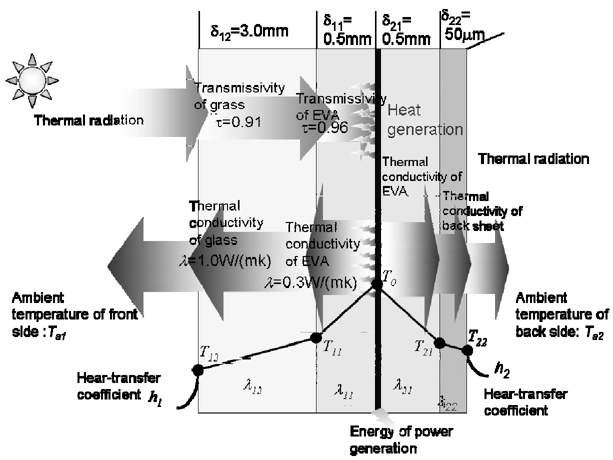

Fig.2. Thermal conduction model of PV module

It is considered that energy from the irradiance is equal to the sum total of generated electric energy generated by PV module, heat transfer to ambient air, radiated energy for celestial and ambient body at steady state, based on the heat balance of PV module. As the front and back side structure of PV module are different, the model was studied by applying it to front and backside separately to investigate predominant of effects of wind.

- Heat transfer in case of wind effect on the front side of PV module is predominant

$$G_A \cdot (1-\mathrm{h}) \cdot \mathrm{e}_1 = \frac{T_0 - T_a}{\frac{\mathrm{d}_{11}}{\mathrm{l}_{11}} + \frac{\mathrm{d}_{12}}{\mathrm{l}_{12}} + \frac{1}{h_1}} + \mathrm{se}_2\left(T_0^4 - T_a^4\right) \tag{1}$$

- Heat transfer in case of wind effect on the backside of PV module is predominant

$$G_A \cdot (1-\mathrm{h}) \cdot \mathrm{e}_1 = \frac{T_0 - T_a}{\frac{\mathrm{d}_{21}}{\mathrm{l}_{21}} + \frac{\mathrm{d}_{22}}{\mathrm{l}_{22}} + \frac{1}{h_2}} + \mathrm{se}_2\left(T_0^4 - T_a^4\right) \tag{2}$$

- Calculation procedure of heat transfer coefficient

$$h = Nu \cdot \frac{\mathrm{l}}{d} \tag{3}$$

G_A: irradiance

H: module conversion efficiency

ε_1: transmission of glass

ε_2: radiation ratio

T_0: cell temperature

T_a: ambient temperature

δ_{11}: thickness of EVA

λ_{11}: thermal conductivity of EVA

δ_{12}: thickness of glass

λ_{12}: thermal conductivity of glass

δ_{21}: thickness of EVA

λ_{21}: thermal conductivity of EVA

δ_{21}: thickness of back sheet

λ_{21}: thermal conductivity of back sheet

σ: Bolzmann number

Nu: Nusselt number

d: distance from the edge

Evaluation of non-steady heat conduction

The process of reaching the target temperature at steady state, which calculated in the previous section, is estimated by using "Transient heat conduction model"[8].

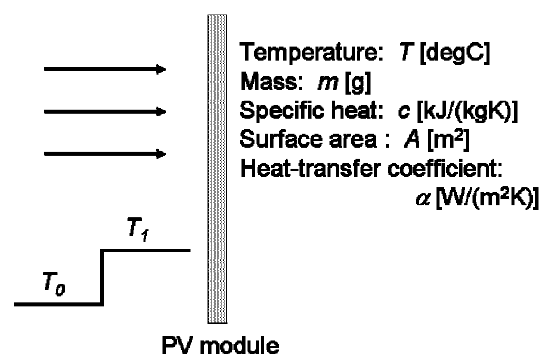

Fig. 3. Transient heat conduction model using pointed heat capacitance method

A PV module with superficial area (*A*), mass, (*m*) and specific heat (*c*), was placed in steady airflow, at initial stage, the PV module temperature and ambient temperature are equal. When ambient temperature varied suddenly from "T_0" to "T_1", the response of the PV module temperature (temporal response) was calculated. If the thermal conductivity of "*k*" is enough large, the temperature distribution of the PV module is assumed to uniform, and the PV module temperature is considered to change only by the function of time. The PV module temperature, which is in transient state at one time instant, is "*T*", heat transfer coefficient is "*α*" and the heat quantity of transmitting air to PV module at short time interval "d_τ" is:

$$\alpha A(T_1 - T)\mathrm{d}\tau \tag{4}$$

This equation equals to storage heat of the energy "*mcdT*". In other words:

$$\alpha A(T1 - T)\mathrm{d}\tau = mc\mathrm{d}T \tag{5}$$

At this point, "*dT*" is temperature rise of PV module. Consequently:

$$\mathrm{d}T = -\mathrm{d}(T_1 - T) \tag{6}$$

$$\frac{\mathrm{d}(T_1 - T)}{T_1 - T} = -\frac{\alpha A}{mc}\mathrm{d}\tau \tag{7}$$

Integrate of this expression:

$$\therefore \quad \ln\left(\frac{T_1 - T}{T_1 - T_0}\right) = -\frac{\alpha A}{mc}\tau \tag{8}$$

At this point $\tau_C = \dfrac{mc}{\alpha A}$ is a time constant of this series.

Therefore the response of the PV module temperature can be described in below:

$$T(\tau) = T_1 - (T_1 - T_0)e^{-\frac{\alpha A}{mc}\tau} \tag{9}$$

As this method dose not depend on the finite element and other methods, which is frequently used for non-steady heat conduction analysis, and it can simulate PV module temperature in simple and easy way with higher accuracy.

OVERVIEW OF EXPERIMENT

In order to verify the accuracy of this heat transfer simulation method, indoor and outdoor experiments were carried out.

Indoor experiments

In order to clarify the temperature fluctuation of PV module, indoor experiments were carried out. At the indoor experiments, the PV module was heated up using direct current power source until the temperature of PB module were stabilized. Then, the PV module was cooled down until the temperature was stabilized. The airflow from the air blower to study effect of wind, has four level of wind force: "Calm", "Light air", "Light breeze" and "Gentle breeze" and each level was used to measure the variation of the PV module temperature. Moreover, in order to eliminate the influence of radiant heat, the indoor experiments were carried out in a dark place and convective airflow except the wind from air blower were eliminated as much as possible. Figure 4 shows the outline of the indoor experiments.

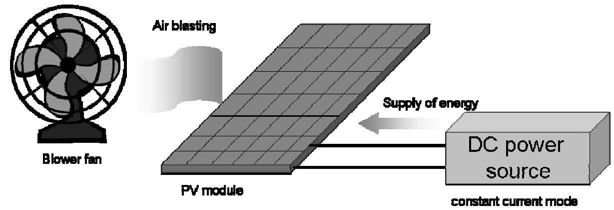

Fig.4. Overview of the indoor experiment

Outdoor experiments

In order to measure actual variation of PV modules temperature, outdoors exposure experiments of PV modules was carried out. In these experiments, the irradiance was measured by the current of the reference PV cell, because measurement of irradiance with thermopile type pyranometer is affected by the delay of response speed. The wind velocity was measured with a slight breeze anemometer with 0.2 m/s of cut-in wind velocity since the PV module temperature variation at low wind velocity was important. The PV modules temperature was measured with a thermocouple, which was attached to the central part of backside, where a part of the back sheet was peeled. Open-circuit voltage of PV modules was also measured. All the data were measured on one-second interval. Figure 5. shows the outline of the outdoor experiments.

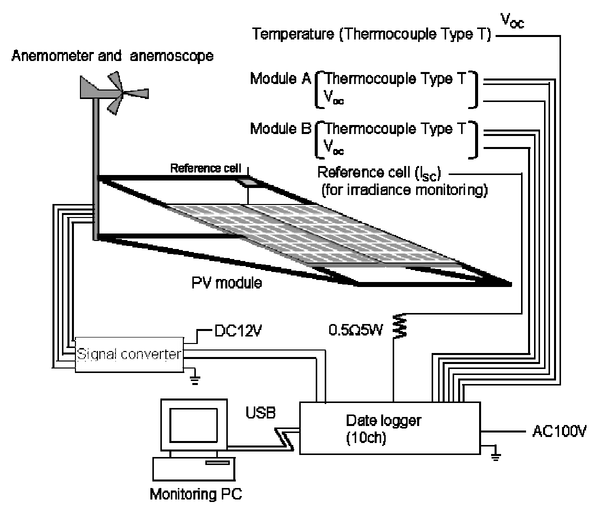

Fig. 5. Overview of the outdoor experiment

RESULTS

Figure 6 shows the results of indoor experiments.

In the indoor experiments, air was blown to both front and backsides, the simulated model was optimized in order to improve the accuracy of simulation at each side. The Comparison between measured and simulated values were validated by applying “root mean square error (RMSE)”.

Then, simulated model was verified by using outdoor experimental data. Figure 7 shows the result of comparison between simulated and experimental data collected on March 28th, 2004. For the purpose of reference, ambient temperature, irradiance and wind velocity data were inserted to the Figure 7. It shows that this model can simulate PV module temperature with high accuracy.

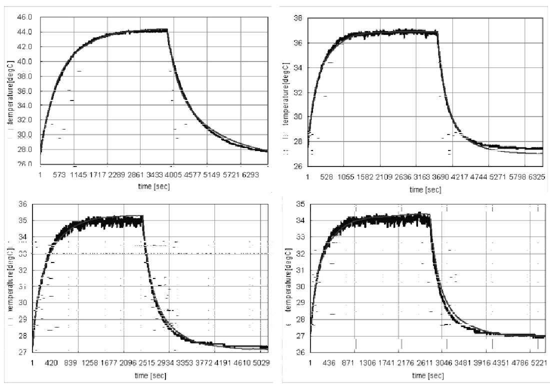

Fig. 6. Experimental results at the indoor experiment

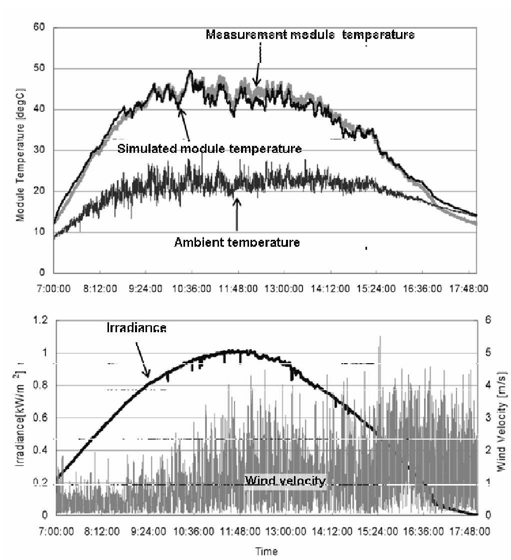

Fig.7. Comparison of the measured and simulated data (March 28, 2004)

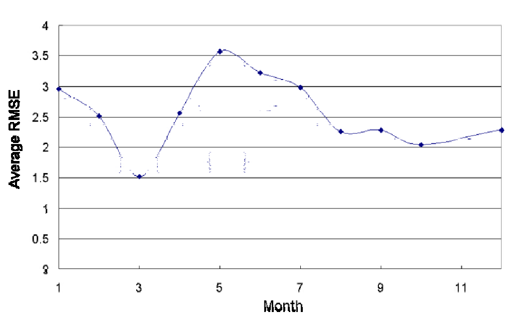

Fig.8. RMSE of the simulated data through one year

Figure 8 shows the RMSE of experimental results using annual data. Even though, complete evaluation of the simulated data is difficult due to missing of experimental data, the developed model can generally simulate PV module temperature with high accuracy through one year. It is validated that the model is also effective for annual data.

CONCLUSIONS

In this study, behavior of PV module temperature was characterized in one-second interval and the simulation model for dynamic variation of PV module temperature was established. It is assumed that highly accurate simulation of PV module temperature will be achieved by employing the established model into simulation of PV systems.

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