A Study on Suppression of Photovoltaic Power Output Fluctuation by Using Thermal Radiative Cooling/Heating System

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***Abstract*—The suppression of photovoltaic power generation output fluctuation has been investigated by using thermal radiative cooling/heating system. The thermal radiative cooling/heating system is novel equipment that can provide an energy-saving, comfortable and healthy living environments by utilizing heat pump technology and an active radiative heat transfer. The characteristic of this system is to maintain the thermal environment with respect to power fluctuations. Photovoltaic power generation has a characteristic that the amount of power generation varies according to the weather. When a large amount of photo-voltaic power generation is installed, the short-term supply and demand imbalance occurs, which causes the frequency deviation. Then, a method to suppress such power fluctuation by thermal radiative cooling/heating system is proposed. As a result of the numerical experiment, the proposed method shows efficient suppression performance.**

***Index Terms*—photovoltaic power generation, thermal radiative cooling/heating system, heat pump, power control**

I. Introduction

Recently, the introductions of renewable energy such as solar power generation and wind power generation and the energy-saving measures have attracted a great deal of interest since energy consumption around the world has been continuously increasing. As energy-saving measures on the demand side, the cooling and heating system has been much attention, because it accounts for one quarter of the energy consumption in the residential sector in Japan [1]. Among them, the thermal radiation type heating and cooling systems have been studied for the concern about energy conservation and energy management in buildings [2]-[6]. Therefore, the thermal radiative cooling/heating system with an active use of radiative heat transfer and heat pump technology for the thermal energy supply has been investigated on performance evaluation concerning energy conservation as our topics [7]-[10]. This thermal radiative cooling/heating system is able to maintain the room temperature even when the electric power fluctuates, because the system carries out heat exchange and heat transfer via water by heat pump. Therefore, this system can be expected to be applied to power management by using it as a controllable load equipment.

On the other hand, with regard to the introduction of renewable energy, photovoltaic (PV) power generation has been drastically introduced in Japan in recent years. When a large amount of PV power generation is introduced, there is a concern that problems such as occurrence of surplus power, lack of frequency adjustment power due to output fluctuation, and voltage rise in the distribution system may occur in the electric power system. In particular, PV power generation has characteristics that its output fluctuates depending on the weather, so it is difficult to predict power output of PV power generation at present, and the frequency may deviate due to short-term supply-demand balance collapses.

The introduction of energy storage system such as storage batteries is considered as output fluctuation compensation equipment for power system stabilization [11]-[13]. However, the introduction amount of the energy storage system is limited since the installation and maintenance costs of the energy storage system are high. Therefore in order to contribute to system stabilization, methods of controlling consumed electric power by using consumer’s equipment as a controllable load have attracted much attention. As a device used as a controllable load, it is desired that the influence on the convenience of the customer is small. Therefore, the heat load devices that can store energy relatively easily are candidates for controllable loads. Then, the research on output fluctuation compensation using heat pump air conditioners and heat pump water heaters as controllable load devices has been conducted [14]-[18].

In this paper, we investigate whether short-term output fluctuation of PV power generation can be suppressed by using thermal radiative cooling/heating system which maintains room temperature with respect to power variation. The actual measurement data of PV power generation output in one day with remarkable fluctuation is used for a numerical simulation. The effect of suppression of PV power output fluctuation is

Manuscript received May 31, 2018; revised December 27, 2018, accepted December 27, 2018.
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doi: 10.18178/ijeetc.8.3.146-151

investigated by carried out the dynamic simulation of the room temperature variation with respect to the power fluctuation.

II. Thermal Radiative Cooling/Heating System

A. Characteristics

The proposed thermal radiative cooling/heating system used in this work is composed of the indoor units of heat sinking radiators and an outdoor unit which contains the heat pump and the heat exchanger. Fig. 1 shows the block diagram of the proposed system. In the case of heating, the heat is absorbed from the atmosphere by the heat pump. Hot water is produced by transferring the heat in the heat exchanger. The room is warmed by circulating the hot water inside the radiator. For transferring the heat in the room, the heat transfer by radiation has been actively utilized. On the other hand, in the case of cooling, which is the reverse process of heating, cold water is produced in the heat exchanger by releasing heat into the atmosphere using the heat pump. The circulation of the cold water into the radiator brings a cooling effect in the room. Moreover, a ceramic material coating with high emissivity in far-infrared region applied to the room walls, ceiling and the surface of the radiators. This coating is expected to increase the radiant heat transfer effect. The characteristics of the thermal radiative cooling/heating system are indicated as follows: It is comfortable because there is no feeling of air flow which is usually caused by warm or cold air. In addition to that, the temperature variations in the room are small. Also, it is safer for health because it prevents dust whirling up in the room. There is no mechanical noise other than water circulation in the radiator. Dehumidification effect can be expected during cooling process of the system. Thus, this system can provide comfortable and healthy living environments.

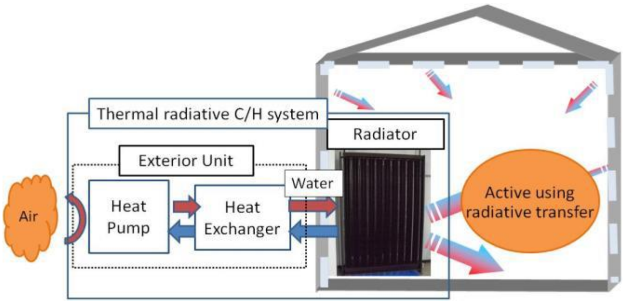


Fig. 1. Schematic illustration of the thermal radiative cooling/heating system.

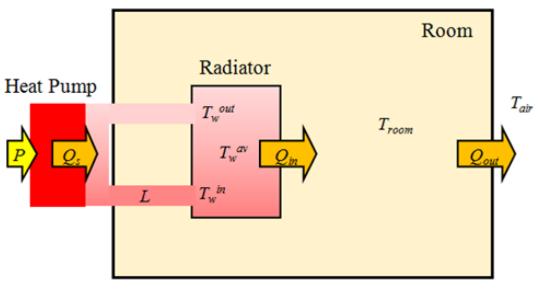


Fig. 2. Configuration diagram of the heat transfer model.

B. Construction of Heat Transfer Model

Here, the construction of the heat transfer model which is the basis of the dynamic simulation of room temperature variation is explained. Fig. 2 shows the configuration diagram of the heat transfer model. The model consists of three parts; (i) the performance of heat pump which determines the power consumption and total heat amount, (ii) the radiation performance of the radiator with respect to the supply heat amount to the room, and (iii) the heat insulation performance of the room which determines the amount of heat for maintaining the room temperature.

First, the performance of the heat pump is described. This performance relates the total heat amount Q_s [W] supplied by the cooling/heating system and the power consumption P [W]. The supplied heat amount Q_s is expressed by the difference between the inflow water temperature T_w^{in} [℃] to the radiator and the outflow water temperature T_w^{out} [℃] at the flow rate L [L/min.] of water, and given by

$$Q_s = LC_p\rho\left(T_w^{\ in} - T_w^{\ out}\right)\times\frac{1000}{60} \tag{1}$$

here C_p and ρ is the specific heat capacity and the density of water, respectively. The values of them are using 4.18 kJ/kgK and 1.00 kg/L. The power consumption P at this time is related to the supplied heat amount Q_s by the coefficient of performance (COP) of the heat pump. The COP of the system used in this research can be formulated as a relationship between the outside air temperature T_{air} [℃] and the average water temperature T_w^{av} [℃] from the previous measurement results [10], and given by

$$\mathrm{COP} = 0.05 + 0.072T_w^{av} + \mathrm{COP}_0 \tag{2}$$

Secondly, the radiation performance of the radiator is described. The heat amount Q_{in} [W] transferred from the radiator to the room is assumed to consist of a radiation component Q_r [W] and a convection component Q_c [W]. According to the Stefan-Boltzmann law, the radiation component Q_r is proportional to the difference of the fourth power of temperature and given by

$$Q_r = S\varepsilon\sigma\left(T_w^{\ 4} - T_{room}^{\ 4}\right) \tag{3}$$

Here S (m^2) is the effective area of the radiator (assuming the radiation surface is a rectangle), and σ is the Stefan-Boltzmann constant. The value of the constant is 5.67×10^{-8} W/m^{2}K. The emissivity ε is determined as ε=1.05 from actual measurement results [10]. On the other hand, the convection component Q_c is proportional to the difference of temperature and given by

$$Q_c = Sh\left(T_w - T_{room}\right) \tag{4}$$

where h is heat transfer coefficient, which is a coefficient for convection. The value of h varies with flow rate of water. In the steady state, the heat amounts Q_s and Q_{in} correspond.

Thirdly, the heat insulation performance of the room is explained. The heat amount Q_{out} [W] released to the outside is generally expressed by the difference between T_{room} and T_{air} and given by

$$Q_{out} = QA\left(T_{room} - T_{air}\right) \tag{5}$$

where Q [W/m^{2}K] is the coefficient of heat loss and A (m^2) is the floor area. However, since the room used in this study is not all surrounded by outside air, the heat amount Q_{out} is used following equation,

$$Q_{out} = Q'A\left(T_{room} - T_{air}\right) + Q_{out0} \tag{6}$$

where Q' is a modified heat loss coefficient, and Q_{out0} is a correction term. Then, the room temperature varies with time according to the difference between the heat amount Q_{in} transferred from the radiator to the room and the heat amount Q_{out} discharged to the outside.

Based on the above heat transfer model, a dynamic simulator is constructed. The changes in room temperature are simulated when the electric power is changed. The simulated change in room temperature shows a good agreement with the measured value in the room where the thermal radiative cooling/heating system is installed.

III. Results of Suppression of Photovoltaic Power Fluctuation

In this research, suppression of short-term power fluctuation of PV power generation has been considered by using thermal radiative cooling/heating system with maintaining room temperature against disturbance. The actual measurement data of one day where the fluctuation is remarkable is used as the output fluctuation of PV power generation. By verifying the room temperature fluctuation range by performing dynamic simulation of room temperature fluctuation against the power fluctuation, the effect of suppressing PV fluctuation is demonstrated.

A. Method of Division of Variable Component of Photovoltaic Power Generation

Here, a method of dividing the fluctuation component from the output of PV power generation is described. The output of PV power generation is used data corresponding to the rated capacity of 1 kW based on the actually measured PV power generation amount. Fig. 3 shows the output data of the day's PV power generation in clear weather and partly sunny weather. The PV output data on a partly sunny day fluctuate greatly in the short-term, because the sun appears or hides in the clouds. To verify the suppression of fluctuations in PV power generation, the PV output data of the day where the fluctuation is remarkable are used.

By applying a low pass filter to this PV output waveform, it separates into a long-term component and a short-term component. The waveforms are shown in Fig. 4 (a) and (b). In the long-term component, it is found that the fluctuation component of the short-term (the frequency band of governor-free, Load Frequency Control (LFC)) is suppressed. The fluctuations in the frequency band of the governor-free and LFC are suppressed, so that short-term supply-demand balance is maintained in the power system, the frequency deviation problem is solved, even when a large amount of PV power generation is installed. On the other hand, in the short-term component, the fluctuation range is very large and it is large enough to correspond to the rated capacity.

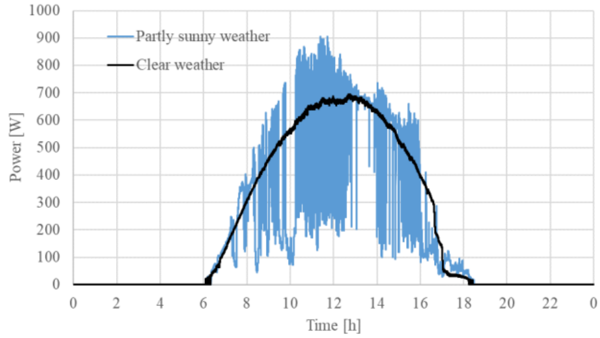
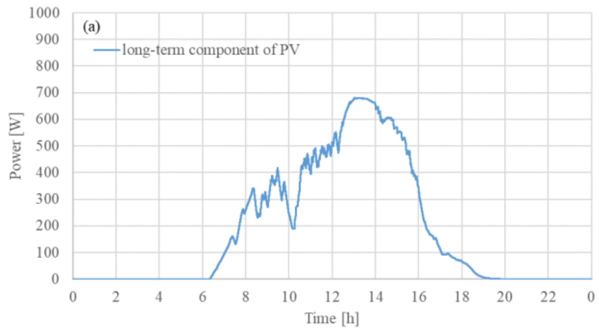
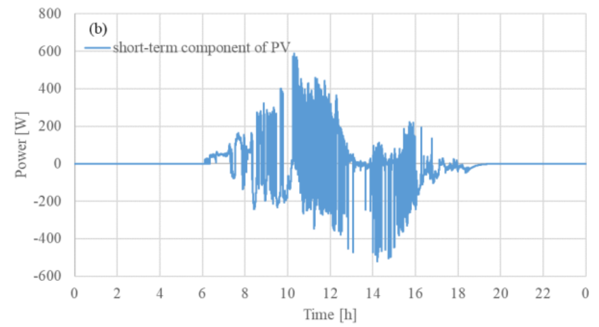


Fig. 3. PV output data in clear weather (August 2nd) and partly sunny weather (August 10th).



(a)



(b)

Fig. 4. PV output in the partly sunny weather: (a) A long-term component and (b) a short-term component.

B. Dynamic Simulation of Room Temperature with Power Fluctuations

Assuming a room where the temperature is kept constant by using the thermal radiative cooling/heating system, the variation range of the room temperature has been verified when the short-term fluctuation component of PV power generation is superimposed on the input power of the thermal radiative cooling/heating system. The assumed room is with a floor area of about 50 m^2 and a height of 2.6 m, which is the same standard room as the room where the thermal radiative cooling/heating system is actually installed. The thermal radiative cooling/heating system has a maximum power consumption of 1.4 kW in the case of cooling and has sufficient cooling capacity. By simulating the dynamic room temperature change, the power consumption required for constant room temperature is estimated. Assuming that the outdoor air temperature is constant at 32 ℃, it can be estimated that the required power is 600 W to keep the room temperature at 26 ℃ (comfort zone) in this supposed room.

The power obtained by adding the fluctuation component of the PV power generation output to the base power of 600 W is input to the thermal radiative cooling/heating system. The input power and room temperature change at that time are shown in Fig. 5 and Fig. 6, respectively. The input power includes fluctuation components of PV power generation output corresponding to the rated capacity of 500 W and 1 kW.

The changes in room temperature are eliminated short period fluctuations seen in input power. It seems that the room temperature change reflects a change corresponding to a change in the moving average of the input power for a long time. The maximum value of room temperature is 26.44 ℃ at 16:30, in the case of adding a fluctuation component of the PV with a rated capacity of 1 kW. The reason for this temperature rise is that input power at around 16 o'clock is almost below 600 W, and its moving average (about 1.5 hour average) is also less than 600 W.

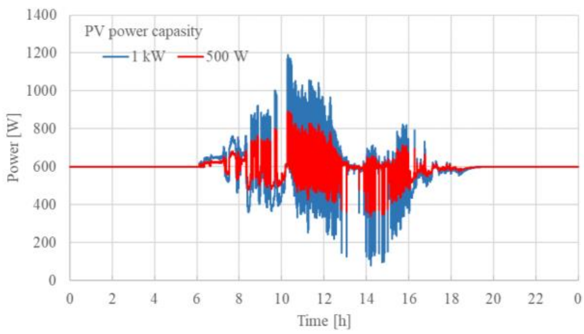


Fig. 5. Input power to the thermal radiative cooling/heating system.

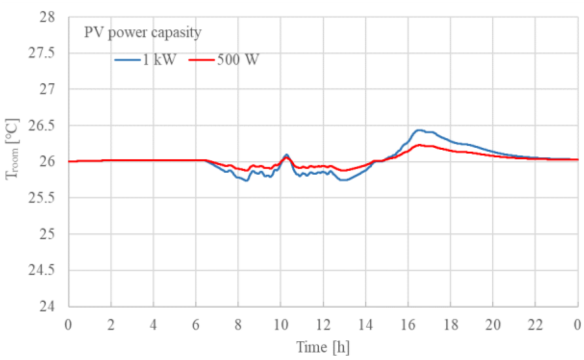


Fig. 6. Room temperature changes operating the thermal radiative cooling/heating system with power including the power fluctuation.

The variation range of the room temperature is 0.35 ℃, which is very small when a fluctuation component of the PV power generation with a rated capacity of 500 W is added. Even when a fluctuation component of the PV with a rated capacity of 1 kW is added, the variation range of the room temperature is 0.7 ℃ and the maximum value at room temperature is 26.44 ℃. These are the amount of change in which the comfort of the room is sufficiently maintained.

Next, the results for the case of another day are shown. Fig. 7 shows the output data of another day's PV power generation in partly sunny weather. The PV output data also fluctuate greatly in the short-term, because the sun appears or hides in the clouds. The change in room temperature is simulated when the short-term fluctuation component of the PV power generation output is added to the base power of 600 W as the input power to the thermal radiative cooling/heating system.

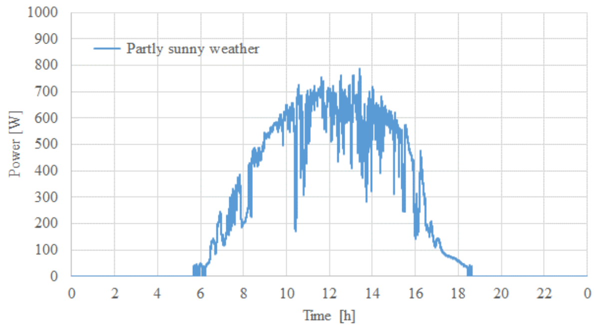
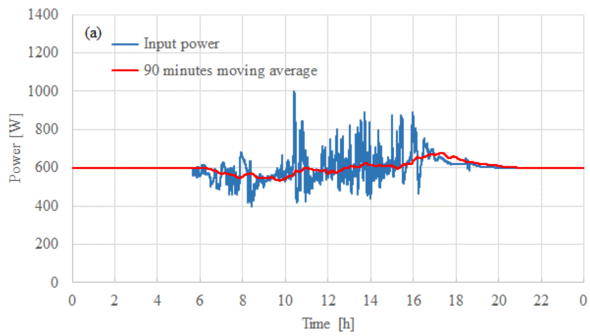
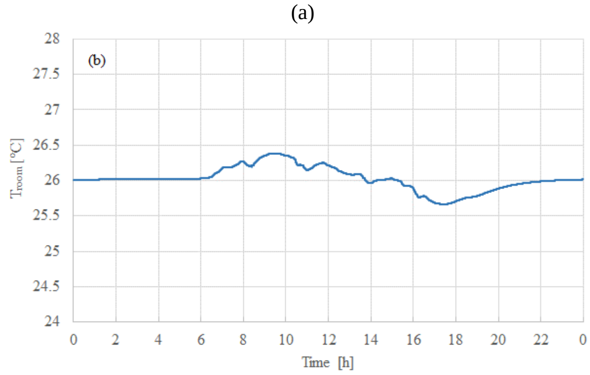


Fig. 7. PV output data in partly sunny weather (June 1st).



(a)



(b)

Fig. 8. Room temperature change: (a) Input power to the thermal radiative cooling/heating system with the 90 minutes moving average and (b) room temperature changes operating the thermal radiative cooling/heating system with power including the power fluctuation.

The input power and the simulated room temperature change are shown in Fig. 8 (a) and (b), respectively. The change in room temperature in this case is also eliminated short period fluctuations seen in input power. The changes in room temperature are thought to reflect the long-term fluctuation component of the input power. Fig. 8 (a) shows the 90 minutes moving average of input power as an additional line. Thus the long-term components remain in the input power. It seems that room temperature is changing corresponding to the long-term change of the input power. The variation range of the room temperature is 0.72 ℃, which is very small. The maximum value of room temperature is 26.38 ℃. In this case as well, the amount of change is sufficient to maintain the comfort of the room.

Thus, even in the case of adding a short-term fluctuation component of PV power generation with a rated capacity of 1 kW, it is possible to maintain the comfort of the room by using the thermal radiative cooling/heating system with the heat pump the maximum power consumption of 1.4 kW. That is, it is found that the thermal radiative cooling/heating system is an effective device for suppressing fluctuation of PV power generation output.

IV. Conclusion

The suppression of PV power generation output fluctuation has been studied by using thermal radiative cooling/heating system. First, a dynamic simulation model was constructed based on the heat transfer model in order to investigate the room temperature change with respect to the input power of the thermal radiative cooling/heating system. At that time, the parameters were determined so as to reproduce the characteristics maintained at room temperature against the power fluctuation in this system. Secondly, the short-term fluctuation component of PV power generation is extracted by the low pass filter so as to include the period of governor-free and LFC region. When this short-term fluctuation component was superimposed on the input power of the thermal radiative cooling/heating system, the changes in room temperature were investigated by dynamic simulation. As a result, it was found that even in the case of adding a short-term fluctuation component of PV power generation with a rated capacity of 1 kW, it is possible to maintain the comfort of the room in the thermal radiative cooling/heating system with the maximum power consumption of 1.4 kW. Although fluctuation of the outside air temperature is not taken into consideration this time, it was found that the thermal radiative cooling/heating system can suppress output fluctuation of PV power generation with sufficient capacity. That is, the thermal radiative cooling/heating system is considered to be one of the equipment that can expect the effect of suppressing fluctuation of PV power generation.

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