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Temperature measurement of solar module in outdoor operating conditions using thermal imaging

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ABSTRACT

In this paper, a method to determine the operating temperature of photovoltaic module in outdoor conditions using thermal imaging is presented. Importance of temperature in PV module performance is well known at design and monitoring level. As manufacturer provide module specifications at STC (25 °C, 1 KW/m^2) and the outdoor conditions are different, so in order to know the change in actual output of PV module and to track maximum power point with temperature in real time, it is important to determine the exact temperature of PV module in outdoor operating conditions. Existing techniques to determine the OOT have many drawbacks as discussed in paper. To overcome those drawbacks, a non-invasive and more accurate technique is suggested to measure module temperature in operating conditions. An experimental setup was established in outdoor and infrared images of PV module were captured using a Flir Infrared camera. These images were further processed quantitatively to calculate the temperature of module. To validate the results, actual field output data was compared to values calculated with the help of well-established relations available in literature at different temperatures calculated using existing techniques. Parameters calculated using thermal imaging method were most nearer to the actual field output data.

1. Introduction

Photovoltaic(PV) module temperature is one of the key parameter which needs to be determined precisely in order to estimate the output of PV power system at design level. The output of a PV module decreases considerably with an increase in temperature. For instance, a value lesser by 5 °C may result in over prediction of 2.25 percent in expected output DC power, which may be a significant value for large solar systems [1].

Manufacturer rating of PV module is provided at STC (Standard Test Condition), 25 °C with irradiance of 1 KW/m^2 [2]. However in outdoor environment conditions, module operates at a higher temperature. During summer, as ambient temperature increases, real output of module decreases as compared to the values mentioned by manufacturer rating [3]. For performance assessment, monitoring and, Outdoor Operating Temperature (OOT) of PV module need to be determined. The value of OOT is of more importance to fetch maximum power from PV module i.e. to operate module at maximum power point, operating temperature can be used to determine voltage at maximum power [4]. Module temperature may also be used to determine the degradation rate of a PV module [5,6]. Hence operating temperature of a PV module is an important parameter and needs to be determined as accurate as possible.

A survey of relevant literature provides dozens of correlations relating PV Cell temperature (T_c) to the ambient temperature (T_{amb}), solar irradiation and local wind speed [7]. Since all these parameters are highly variable with time, PV module output is extremely sensitive to these variables. Considering the thermal environment of a photovoltaic cell, semiconductor (p-n junction) temperature is of primary interest. This is a difficult task as PV cells cannot be directly probed in fielded modules.

A commonly used method is to determine the junction temperature by measuring open circuit voltage across the solar module [8] as given by Eq. (1)

$$V_{oc} = \frac{KT}{q}\ln\left(\frac{J_{sc}}{J_o} + 1\right) \tag{1}$$

where J_{sc} is short circuit current density and T is the junction temperature. Advantage of this method is that it gives average junction temperature across the whole module but the issues with this method it is an open circuit method cannot be used in grid connected conditions in real time.

Another method used is to rely on discrete locations temperature measurement of a solar panel by attaching a temperature measurement

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probe (RTD Sensor) (as shown in Fig. 2) on the back surface of module before encapsulation [9]. Drawback of this method is that it does not give the average temperature of the module as the cells where temperature probes are located do not represent the overall temperature distribution pattern of panel. Another problem is that temperature given by this method may differ considerably from actual average temperature of PV module due to the encapsulation on PV cells. As an example, the relative temperature coefficient of power for crystalline silicon modules is typically −0.45%/°C; therefore, if your measured back-of-module temperature is 7 °C low, expected dc power output will be over-predicted by about 3.2%, which is a significant amount for large PV systems.

Another established procedure to determine the PV cell operating temperature involves use of normal operating cell temperature (NOCT). This method is for open rack mounted modules with a sunlight angle of 45° and at fixed condition (Irradiance: 800 W/m^2, Cell Temperature: 45 °C, Air Temperature: 20 °C, Wind Velocity: 1 m/s, Mounting: open back side). Since the value of irradiance and temperature changes almost at every instant in outdoor environment, hence using NOCT may not give accuracy in results [10,11].

In the present work, a non-invasive method using infrared (IR) images of PV module has been used to measure the operating temperature of the PV module. Color pattern of IR images has been used to model the temperature of whole panel.

Although IR imaging has been already used for PV module condition monitoring and fault detection such as overheating [12–14], cracks and damage in a solar panel, but most of the work has been a qualitative application of infrared imaging. Active and passive thermography as performance assessment tool has been used Botsaris et al. [15]. In the proposed work, IR images have been analyzed quantitatively to determine the temperature of PV module in outdoor conditions. Information extracted from the thermal signature of PV module was utilized to calculate average temperature. Proposed method overcomes the drawbacks of existing methods.

(1) This method gives the averages temperature of PV module by taking in consideration each and every cell of PV panel, and hence more accurate as compared to discrete location temperature measurement method.
(2) As the method gives the temperature of the PV module at the instant at which IR image was taken, so varying environmental parameters do not make an impact on calculations.
(3) It is a non-invasive method and can be used in variable environment conditions as compared to other methods.

Apart from the above advantages, thermal imaging temperature measurement method can be used for maximum power point tracking by determining the voltage and power with the help of temperature measured in real time operating condition [16,17]. In the present work, Voltage and power calculated at maximum power point using a well-established empirical relation at three different temperatures i.e. Temperature calculated with Infrared imaging, NOCT and Back of panel temperature measurement is compared with actual field output data.

Rest of the paper is organized as follows. In Section 2, proposed algorithm is given. Implementation of experimental work, results is given in Section 3. In Section 4, comparison between proposed method and other methods and possible future improvement in the proposed techniques is discussed.

2. Proposed algorithm

In the present work, a novel algorithm has been suggested to calculate the temperature of a PV module using Infrared images in outdoor environment conditions. Every object above absolute zero temperature emits thermal radiations. These radiations are emitted in electromagnetic spectrum in Infrared range and can be detected by an Infrared detector using an IR Camera (as shown in Fig. 1). Intensity of emitted radiations depends on the temperature of object. More the temperature of object more will be the emitted radiation power as given by Eq. (2). Boltzmann law gives the thermal radiation power radiated by a body in terms of temperature as

$$P_r = \in \sigma A T^4 \tag{2}$$

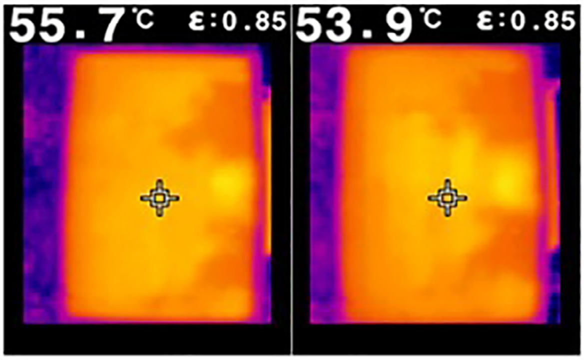

Fig. 1. Infrared images of a solar module.

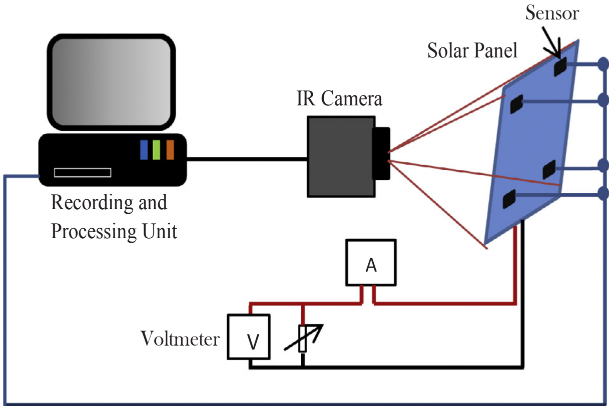

Fig. 2. Experimental setup.

An IR camera detects infrared radiations in the same way as done by visible camera in visible spectrum. Infrared image gives a signature of temperature distribution on the surface of object. Variation of color pattern on IR images varies with change in temperature. To calculate average temperature using IR images, color intensity of each pixel was converted into corresponding temperature. This conversion of pixel intensity to temperature was done with the help of an established relation through camera calibration.

Proposed algorithm is divided into two parts.

2.1. Calibration of IR camera i.e. to devise an equation to convert pixel intensity into corresponding temperature

Step 1: Fifteen different IR images of a PV module were taken by focusing the IR camera at different points (P_1, P_2, P_3,…P_{15}). Some of the images are shown in Fig. 1.
Step 2: Intensity (I_1, I_2, I_3,…I_{15}) corresponding to each point is determined by MATLAB Tool, and corresponding temperature (T_1, T_2, T_3,…T_{15}) as indicated by IR camera of each marked point were determined. (Temperature shown 54.0 °C at upper left corner of Fig. 4 is the temperature of point P_1 and intensity level at point P_1 is 197), similarly all 15 points temperature and intensity was taken.
Step 3: Regression analysis of Intensity and Temperature values (taken in Step 2) was done in order to formulate an equation between Intensity and Temperature as in the form given below: