Photovoltaic Modules Operating Temperature Estimation Using a Simple Correlation

A. M. Muzathik[1, 2]

[1]Mechanical Engineering Department, Faculty of Engineering, South Eastern University of Sri Lanka, Oluvil, Sri Lanka

[2]Maritime Technology Department, Universiti Malaysia Terengganu, 21030 Kuala Terengganu, Terengganu, Malaysia

muzathik64@yahoo.com

***Abstract*-The operating cell temperatures of photovoltaic (PV) modules directly affect the performance of the PV system. In this study, an effective new approach for estimating the operating temperature of a photovoltaic module is presented. The developed model is simple and does not need any complicated calculations. The proposed approach uses a simple formula to derive the PV cell temperature from the environmental variables such as ambient temperature, irradiance and wind speed. Effectiveness of the new temperature estimation procedure is investigated through some conducted simulations in MATLAB/Simulink environment and its validity is verified by experiment on a UNI-SOLAR US-64 solar photovoltaic modules. It was found that, in general, the model tends to give better results of temperature prediction. From the results, the predicted PV cell temperatures show a good correlation with the measured data. The *MBE, NMBE, RMSE, NRMSE* and correlation coefficient of predicted and measured PV cell temperatures are -0.3490 ^{o}C,-0.7328%, 1.3571 ^{o}C, 2.8492% and 0.9763, respectively. The statistical results show that the model can be used to predict the PV cell temperatures with an error of less than 3%. As a conclusion, the PV cell temperatures can be estimated using a new linear model based on the steady state approach prediction as**

$$T_{\mathrm{mod}\,ule}\left({}^{o}C\right)=0.943\times T_{\mathrm{ambient}}+0.0195\times Irradiance-1.528\times WindSpeed+0.3529\,.$$

Keywords- Operating PV Cell Temperature; Photovoltaic Module; Linear Model; Temperature Prediction

I. INTRODUCTION

The physical process in which a photovoltaic (PV) cell converts sunlight into electricity is known as the photovoltaic effect. A PV cell is a semiconductor diode that converts visible light into direct current (DC). Some PV cells can also convert infrared (IR) or ultraviolet (UV) radiation into DC electricity. One single PV cell produces up to 2 watts of power at approximately 0.5V DC, too small even for powering wristwatches or pocket calculator. Many PV cells are connected together to form modules (panels) to increase power output which are further assembled into larger units called arrays. This modular nature of PV enables to build systems with different power output for different types of applications. Crystalline silicon solar cells were the first type of PV cells to be widely commercialized [1]. They are very stable and do not deteriorate significantly with time. Silicon is in short supply and it may affect manufacturing this type of PV cells.

Photovoltaic cells are an integral part of solar-electric energy systems, which are becoming increasingly important as alternative sources of utility power. Approximately 45% of the cost of a silicon cell solar module is determined by the cost of the silicon waffer. Thus efforts are being made to use less silicon in the manufacture of solar cells. This is being done by making the cells thinner and making them more efficient. The Copper Indium Gallium di-Selenide (CIGS) thin-film solar cell recently reached 19.9 percent efficiency, setting a new world record for this type of cell. Multi-crystalline silicon-based solar cells have shown efficiencies as high as 20.3 percent [1-4].

Temperature of PV cells is one of the most important parameters for assessing the long term performance of PV module systems and their annual amounts of electrical energy production [5]. This temperature depends on many parameters such as the thermal properties of materials used in PV module encapsulation, types of PV cells, configuration of PV modules' installation and climatic conditions of the locality [6-8]. Typically, a PV module's efficiency strongly depends on its cells' operating temperature. Increasing cell temperatures during operation generally deteriorates the performance of the PV module in electricity generation [5].

Two models commonly used for predicting the temperature at the back surface of the PV module are: the nominal operating cell temperature (NOCT) model and the Sandia National Laboratory temperature prediction (SNL) model. Both are formulated empirically based on a steady state approach [5]. However, accuracies of both models are questionable in some conditions, particularly when they are totally different from the specified conditions as assumed by the models. Many studies have been made to evaluate the suitability of the above two models under various conditions [7, 9-11], particularly for solar hybrid applications. The studies showed that two models give satisfactory results, but they are not suitable when the cooling of the PV modules is poor [6-7, 9-10]. Further, these studies were not conducted in the study area of Kuala Terengganu, Malaysia (4° 13.6′ N latitude 103^{o} 26.1’ E longitude). Few studies have investigated the suitability of two models in this region where the climatic conditions are vastly different from the climate conditions of the standard condition of the tested area.

An outdoor experimental testing facility was set up under the climatic conditions of Kuala Terengganu, Malaysia (4°13.6' N latitude 103°26.1' E longitude and 5.2 m altitude). The facility consisted of a testing rig of a 64 W polycrystalline silicon PV module mounted on the wooden frame as shown in Fig. 1. The installed polycrystalline silicon cells were encapsulated by laminated glass. Generated electricity of the module was connected to a battery of 24V DC fixed voltage, which served as an external load of the PV module.

Fig. 1 UNI-SOLAR ® US-64 solar photovoltaic panels

II. PV SYSTEM MATHEMATICAL MODELING

The performance of solar cell is normally evaluated under the standard test condition (STC), where an average solar spectrum at air mass (AM) 1.5 is used, the irradiance is normalized to 1000 W/m^2, and the cell temperature is defined as 25° C [12]. To satisfy the requirement of temperature and insolation in STC, the test usually needs specified environment and some special testing equipment, such as an expensive solar simulator. Simple experiments may not be sufficient to reproduce accurately the solar cell electrical characteristics. In this study, the modeling method is based on the specification data provided in the manufacturers' datasheets.

In this study the single-diode model or the so-called four-parameter model, includes a photocurrent source, a parallel diode and a series resistor R_S is considered. The primary solar cell equivalent circuit contains a current source with parallel diode, as presented in Fig. 2.

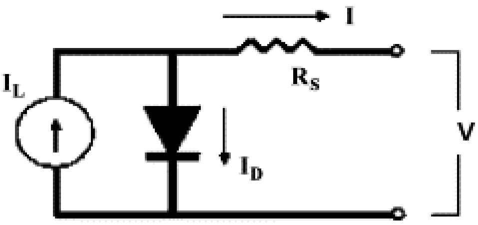

Fig. 2 Equivalent circuit of the four-parameter model

Generally, in case of the single-diode model the four-parameter determination is difficult, due to the exponential equation of the diode p–n junction. The solar model was developed through the coupled multi-physical photovoltaic energy conversion processes by Liu and Dougal [13].

Applying Kirchoff laws, the cell terminal current is expressed by

$$I = I_L - I_D \quad (1)$$

where I is the PV cell output current (A), I_L the photo current (A) and I_D the diode current (A).

The light current depends on both irradiance and temperature [1]. It is measured at some reference conditions as written in Equation 2 as

$$I_L = \left(\frac{G}{G_{REF}} \right) \left(I_{L,REF} + \mu_{ISC} \left(T_C - T_{C,REF} \right) \right) \quad (2)$$

where $I_{L,REF}$ is the light current at reference condition (A); G, G_{REF} the irradiance, actual and at reference condition (W/m^2); T_C, $T_{C,REF}$ the cell temperature, actual and at reference condition (K); μ_{ISC} the manufacturer supplied temperature coefficient of short-circuit current (A/K).

The diode current is given by Shockley equation as [14]

$$I_D = I_0\left[\exp\left(\frac{q(V+IR_S)}{\gamma.kT_C}\right)-1\right] \tag{3}$$

where V, terminal voltage (V); I_0, reverse saturation current (A); γ, shape factor; R_s, series resistance (Ω); q, electron charge 1.602×10^{-19} C; k, Boltzmann constant, 1.381×10^{-23} J/K.

The reverse saturation current is

$$I_0 = DT_C^3\exp\left(\frac{-q\varepsilon_G}{AkT_C}\right) \tag{4}$$

where D, diode diffusion factor; ε_G , material bandgap energy (1.12 eV for Si, 1.35 eV for GaGs); A , completion factor.

The reverse saturation current is actually computed by taking the ratio of Equation 4 at two different temperatures, thereby eliminating D. Similar to the determination of I_L, I_0 is related to the temperature and the saturation current estimated at some reference condition

$$I_0 = I_{0,REF}\left(\frac{T_C}{T_{C,REF}}\right)^3\exp\left[\left(\frac{q\varepsilon_G}{kA}\right)\left(\frac{1}{T_{C,REF}}-\frac{1}{T_C}\right)\right]. \tag{5}$$

And thus the I–V characteristic is described by

$$I = I_L - I_0\left[\exp\left(\frac{q(V+IR_S)}{\gamma.kT_C}\right)-1\right]. \tag{6}$$

While R_s and γ are assumed to be constant, I_L is a function of irradiance and cell temperature and I_0 is a function of temperature. The cell temperature can be determined from the ambient temperature and with the help of some standard test information.

Matti et al., Skoplaki and Palyvos investigated several formulations for polycrystalline PV module temperature calculation using a simple method of energy balance, environmental parameters, etc [15, 16]. Skoplaki et al proposed a simple working nonlinear equation for the PV operating temperature using environmental parameters [17]. Michael et al. [18], Armstrong and Hurley [19] modeled the nominal operating PV cell temperature based on outdoor weathering. A number of other implicit equations for PV module temperature found in the literature, some of them require extra information beyond what is provided by the module manufacturer [20]. Schwingshackl et al. [21] studied the wind effect on PV module temperature using different techniques for an accurate estimation.

In order to predict the energy production of PV modules, it is necessary to predict the module temperature as a function of ambient temperature ($T_{ambient}$), wind speed and total irradiance. The cell temperature can be determined by the following relationship [1, 15-22]:

$$T_{\text{module}}\left({}^oC\right) = a\times T_{ambiant} + b\times Irradiance - c\times WindSpeed + d\ . \tag{7}$$

where a, b, c and d are system-specific regression coefficients, $T_{ambient}$ is given in (℃), irradiance in (W/m^2) and wind speed in m/s.

There are numerous works in literature which deal with the assessment and comparison of estimation models. The most popular statistical parameters are the mean bias error (*MBE*) and the root mean square error (*RMSE*) to evaluate the accuracy of the estimated data [15-21].

III. PHOTOVOLTAIC SYSTEM, DATA AND METHOD

A. Photovoltaic System

The PV array, installed on a mounting structure (wooden frame) of the PV system, consists of 16 amorphous PV modules, facing south with the optimum designed slope angle of latitude. In this project, two modules are connected in series to form a substring. It is determined by the selected DC voltage (24V) and the PV module voltage output (16.5V DC at the maximum power point); and then 8 sub strings (2 PV modules each) are connected in parallel to form one array.

The technical characteristics of the PV module under standard testing conditions are listed in Table 1. A temperature sensor of a K-type thermocouple was installed at the midpoint of the rear surface of the PV module for measuring its temperatures. Electrical signals were recorded automatically by a data logger for data collections. A weather station was also installed nearby the testing rig. A pyranometer was mounted on the same plane of the PV module's surface to measure solar irradiance falling on the surface of the PV panel. A four-blade propeller anemometer with a wind vane was used to measure wind speeds and direction. A temperature probe was used for measuring the ambient temperature. The measurements were sampled every 10 s and then averaged over 1-minite periods.

TABLE 1 SIMULATION PARAMETERS OF PV MODULES (UNI-SOLAR® US-64)

Conditions	Data provided by the manufacturers
Rated Power *P* (W)	64
Operating Voltage V_{MP} (V)	16.5
Operating Current I_{MP} (A)	3.88
Open Circuit Voltage V_{OC} (V)	23.8
Short Circuit Current I_{SC} (A)	4.80
Temperature Coefficient of I_{SC}	0.001/ ^{o}K
Temperature Coefficient of V_{OC}	-0.0038/ ^{o}K
Temperature Coefficient of P_{max}	0.0021/ ^{o}K
Temperature Coefficient of I_{MP}	0.001/ ^{o}K
Temperature Coefficient of V_{MP}	-0.0031/ ^{o}K

B. Solar and Wind Data

In this study, the global solar radiation, wind speed, wind direction and air temperature data collected from the Renewable Energy Station, Universiti Malaysia Terengganu (UMT) from 2008 to 2010 was considered. The geographical co-ordinates of the study site are 4° 13.6′ N latitude 103^{o} 26.1’ E longitude and 5.2 m altitude. The data were measured at one minute intervals and averaged. The row and hourly averaged data were stored on computer. In addition to the Renewable Energy Station data, secondary data were obtained from Malaysian Meteorological Department for the Terengganu Airport station (5^{o} 10.0’ N latitude 103^{o} 6.0’ E longitude) which is nearly 2 km southeast to the study area. The surface air temperature and the global solar radiation measurement instruments were set at 3 m above the ground level. The wind speed measurement instrument was set at 18 m above the ground level. The sensors were regularly checked and calibrated against reference sensors maintained at the station and suppliers to ensure the quality of the data collected. There were missing and invalid measurements in the data. The missing and invalid measurements, accounting for less than 0.50% of the whole database of each data, were replaced with the values of preceding or subsequent hours of the day by interpolation. The integrated hourly time-series data from multiple months, excluding incomplete data were combined for validation. Data were manually validated to remove outlier events due to failure of instruments, power failure, etc. which is accounted around 0.10% and statistically analyzed.

C. Experimental Data

The time series data were collected from test-bed experiments covering the research period from 2008 to 2010. The test performance data include voltage and current of the PV array, voltage, power consumption of the loads, the incident solar radiation, wind speed, PV array temperature and the ambient temperature around the PV modules using sensors and instruments. The sensors and instruments were regularly checked and calibrated against reference sensors to ensure the quality of the data collected. In addition to this, the collected data were frequently checked using standard measuring instrument. There were missing and invalid measurements in the data. Further, the data were manually validated to remove outlier events due to failure of instruments, etc. They were excluded from the analysis.

D. Method

Using Equation 7, the PV cell temperature was estimated and compared with corresponding experimentally measured values during the study period from the study area. The estimated and measured values were analyzed using the statistical tests of MBE, NMBE, RMSE, NRMSE and correlation coefficient. A program was developed using MATLAB to analysis the PV cell temperature estimations. The maximum likelihood method was used for this purpose. The model was checked with repeated runs and different sequences, as required for the prediction of PV cell temperature.

IV. RESULT AND DISCUSSION

The values of solar radiation on a horizontal plane, the wind speed and the ambient temperature in 2008 are plotted in Figures 3 to 5, respectively which were used to predict the PV cell temperature.

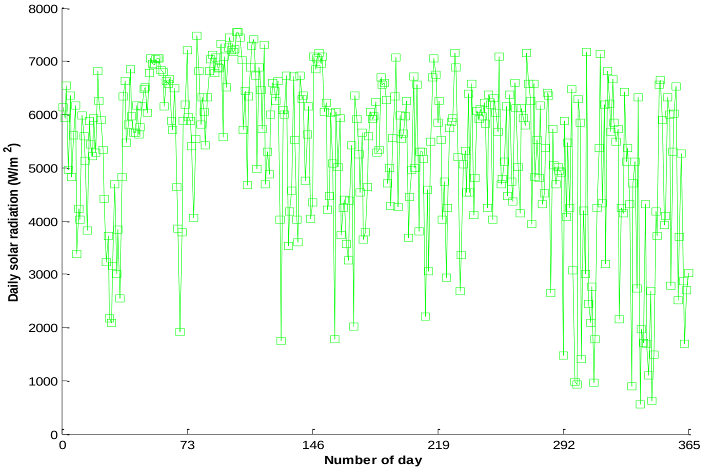

Fig. 3 Daily mean values of solar radiation

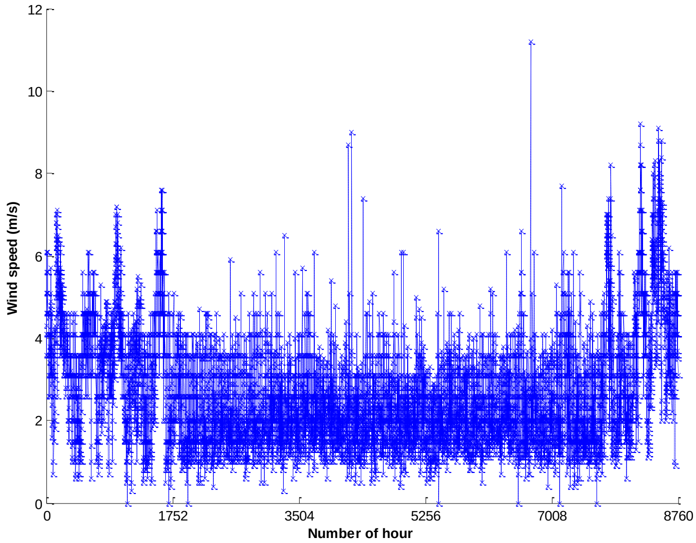

Fig. 4 Hourly mean values of wind speed

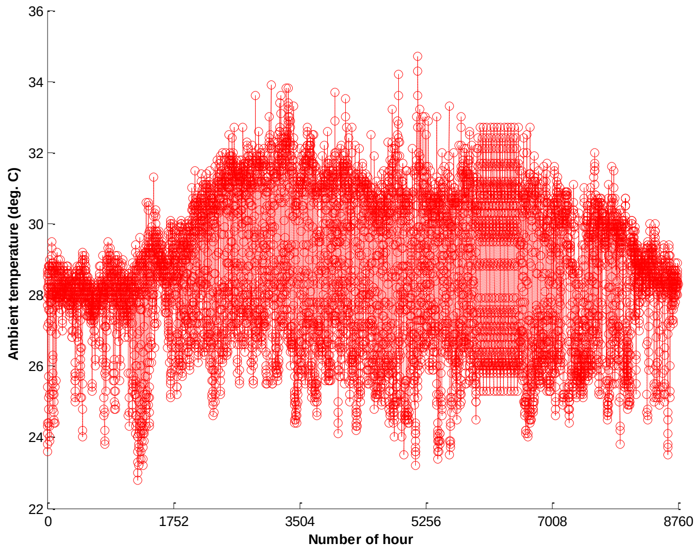

Fig. 5 Hourly mean values of ambient temperature

The temperature of PV cells is one of the most important parameters used in assessing the performance of PV systems and their power output. The cell temperature depends on several parameters which are mentioned in 3rd paragraph of Section I, mainly local climatic conditions. A PV module's efficiency depends largely on its cells' operating temperature. PV-cell temperatures are very difficult to measure since the cells are tightly encapsulated in order to protect them from environmental degradation. The temperature on the back surface of PV modules is commonly measured and substituted for the cell temperature, assuming that these temperatures closely match [23].

In this study, the accuracy of the model was determined using the data measured at Terengganu in the periods between 2008 and 2010. By using the data, the regression constants a, b, c and d were determined for the model. The regression constants a, b, c and d were obtained using curve fitting tool of MATLAB. The PV cell temperature prediction "New Model" was developed using experimental data obtained during study period from the study area based on the linear temperature prediction model as

$$T_{\text{module}}\left({}^{o}C\right)=0.943\times T_{ambient}+0.0195\times Irradiance-1.528\times WindSpeed+0.3529.$$

According to the statistical test results, it can be seen that the estimated values of PV cell temperature using the model are in favorable agreement with the measured values. Fig. 6 shows plot of measured and predicted PV cell temperature using "New Model" for the five continuous days in August 2008. The daily high temperatures, with daily highs around 35 ℃ and daily low temperatures are around 22 ℃ throughout the study period. Over the course of the study period, the length of the day is varying about 0.50 hours with 11:50 hours to 12:20 hours of daylight. In general, the sky is clear or not cloudy with little variation in this period. Over the course of the study period typical wind speeds vary from 0 m/s to 6 m/s, rarely exceeding 8 m/s. The wind is most often out of the south west (21%), south (18%), north east (17%) and east (15%).

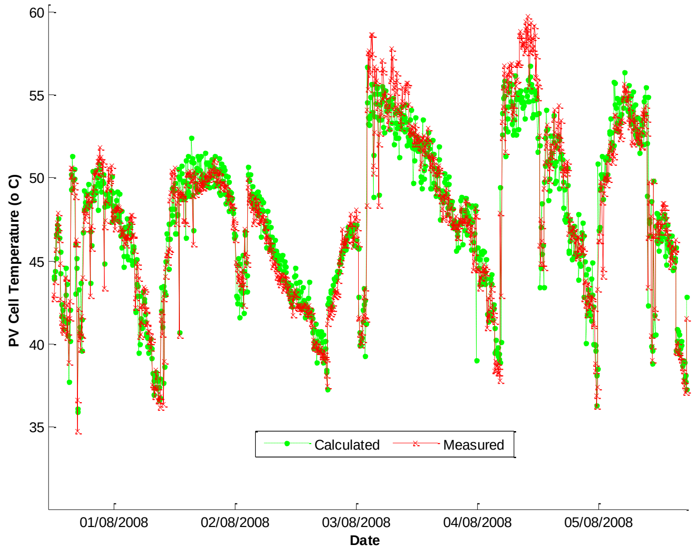

Fig. 6 Measured and predicted PV cell temperature

The calculated and measured PV cell temperature values show that they co-vary in a linear fashion, with a correlation coefficient of 0.9763, as is shown in Fig. 7.

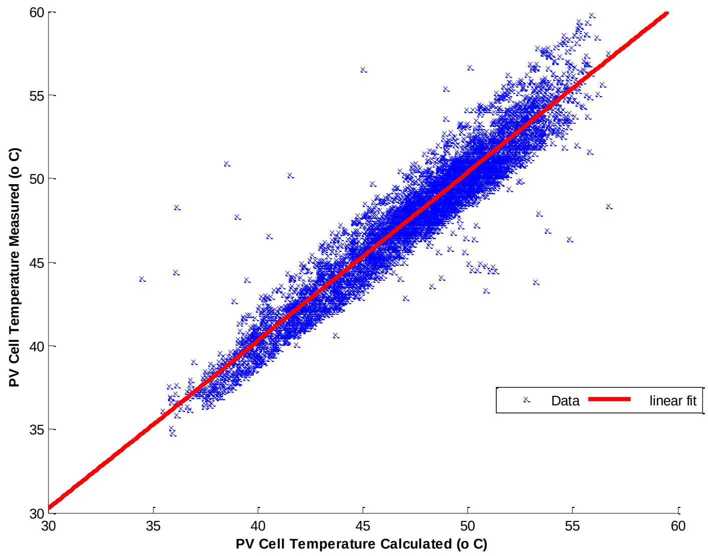

Fig. 7 Correlation between measured and predicted PV cell temperature

It can be seen from Figs. 6 and 7, that the predicted PV cell temperatures show a good correlation with the measured data. The *MBE*, *NMBE*, *RMSE*, *NRMSE* and correlation coefficient of predicted and measured PV cell temperatures are -0.3490 ^{o}C,-0.7328%, 1.3571 ^{o}C, 2.8492% and 0.9763, respectively. The percentage errors are very small. In this analysis more than 4630 PV cell temperature data collected five continuous days in August 2008 were used. The above statistical results show that the "New Model" can be used to predict the PV cell temperature with an error of less than 3%. With this new model, one could accurately estimate the PV cell temperature for Terengganu state.

V. CONCLUSION

PV cell temperature is an important parameter for PV power output. The investigation of the model for its suitability in the temperature prediction under a tropical climate showed that PV cell temperature can be estimate using the linear mode. The total percentage error of the expected temperature would be less than 3% in this study. Therefore, it can be concluded that the accuracy of the predicted temperatures are adequate for renewable solar energy applications and can be used at the study area and similar tropical climatic condition areas where ambient temperature remains relatively constant throughout the day.

Therefore, based on the statistical results a new simple linear model, given below is recommended to estimate PV cell temperatures for research area and in elsewhere with similar climatic conditions areas. The present work will help to advance the state of knowledge of PV renewable solar energy to the point where it has applications in the estimation of PV cell temperature.

$$T_{module}\left(^{o}C\right) = 0.943 \times T_{ambient} + 0.0195 \times Irradiance - 1.528 \times WindSpeed + 0.3529$$

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