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Insolation-oriented model of photovoltaic module using Matlab/Simulink

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Abstract

This paper presents a novel model of photovoltaic (PV) module which is implemented and analyzed using Matlab/Simulink software package. Taking the effect of sunlight irradiance on the cell temperature, the proposed model takes ambient temperature as reference input and uses the solar insolation as a unique varying parameter. The cell temperature is then explicitly affected by the sunlight intensity. The output current and power characteristics are simulated and analyzed using the proposed PV model. The model verification has been confirmed through an experimental measurement. The impact of solar irradiation on cell temperature makes the output characteristic more practical. In addition, the insolation-oriented PV model enables the dynamics of PV power system to be analyzed and optimized more easily by applying the environmental parameters of ambient temperature and solar irradiance.

Keywords: PV model; Insolation-oriented; Matlab/Simulink

1. Introduction

Nowadays, people are much concerned with the fossil fuel consumed at the present high rate as well as the environmental damage caused by the conventional power generation. Renewable energy resources will play a significant role in the world energy supply in the upcoming future. Among the renewable energy resources, solar energy is the most essential and prerequisite resource of sustainable energy because of its ubiquity, abundance, and sustainability. Regardless of the intermittency of sunlight, solar energy is widely available and completely free of cost. Recently, photovoltaic (PV) system is well recognized and widely utilized to convert the solar energy for electric power applications. It can generate direct current (DC) electricity without environmental impact and emission by way of solar radiation. Being a semiconductor device, the PV system is static, quite, and free of moving parts. These characteristics make it need very small operation and maintenance costs.

PV cell represents the fundamental conversion unit of a PV power generator system. Solar insolation, PV's cell temperature and operating voltage strongly influence the output current and power characteristics of PV. With nonlinear characteristics, PV model is first built to design the maximum power point tracker (MPPT) for PV system applications. Many mathematical PV models for in computer simulation have been built for over the past three decades (Angrist, 1982; Tsai et al., 2008). These models elaborately describe the output characteristics mainly affected by the solar insolation, cell temperature, and load voltage. In fact, the infrared (IR) region of the solar spectrum with about 42% solar energy generates waste heat and contributes to the increase of operating temperature in conventional semiconductor- based solar cells. The cell temperature is mainly dependent on the irradiance intensity and ambient temperature (Messenger and Ventre, 2000). In addition, the increase in irradiance would enhance the photocurrent but results in

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Nomenclature

A	ideal factor
E_G	bang-gap energy of the semiconductor used in the cell (in eV).
I_{PH}	light-generated current or photocurrent in ampere (A)
I_{RS}	cell's reverse saturation current in ampere (A) at reference temperature and solar radiation
I_S	cell saturation of dark current in ampere (A)
I_{SC}	cell's short-circuit current in ampere (A) at 25 °C and 1 kW/m^2 of solar insolation
k	Boltzmann's constant (=1.38 × 10^{-23} J/K)
K_I	cell's short-circuit current temperature coefficient
N_P	parallel number of cell
N_S	series number of cell
q	electron charge (=1.6 × 10^{-19} °C)
R_S	series resistance in ohm (Ω)
R_{SH}	shunt resistance in ohm (Ω)
t_C	center time of Gaussian function in hour
T_{Amb}	ambient temperature in Kelvin (K)
T_C	cell temperature in Kelvin (K)
T_{Ref}	cell's reference temperature in Kelvin (K)
T_{NOCT}	nominal operating cell temperature (NOCT) in Kelvin (K) for operating at open circuit with the following conditions: ambient temperature of 20 °C, AM 1.5 irradiance, $\lambda = 0.8$ kW/m^2, and wind speed less than 1 m/s

Greek letters

σ	standard deviation of Gaussian function
λ	solar insolation in kW/m^2
λ_{max}	maximal radiation intensity at a given time (in kW/m^2)

additional temperature degradation of PV current and power outputs (Patel, 1999). The previous work (Tsai et al., 2008) found that all PV models are built without considering the effect of sunlight intensity on cell temperature. This motivates me to develop a sunlight intensity-oriented PV model by taking the insolation effect on cell temperature into consideration. Recently, a number of powerful component-based electronics simulation software packages, such as SPICE and Matlab/Simulink, have become popular in the design and development of power electronics applications. A solar cell library that was new in R2008b is in SimElectronics 1.3 toolbox of Simulink. However, these models implemented by SPICE and Matlab/Simulink are not suitable for real applications because that they do not consider the effect of sunlight intensity on cell temperature. To integrate PV models with the wind turbine models in Matlab/Simulink SimPowerSystem tool is more suitable for analysis and design of renewable power system. Based on the generalized PV model (Tsai et al., 2008), this paper further implements a novel PV model by directly taking the effect of sunlight intensity on cell temperature.

The main contribution of this paper is the implementation of an insolation-oriented PV model, which can justify the user's strategy of MPPT algorithm by taking account of the sunlight insolation effect on the cell temperature. The verification of the proposed PV model has bee confirmed by conducting a series of measurement through an experimental rig.

2. Photovoltaic models

PV cell consists of a p–n junction fabricated in a thin wafer or layer of semiconductor. Basically, photovoltaic conversion is a direct electromagnetic radiation conversion into electrical power. Being exposed to the sunlight, photons with energy larger than the band-gap energy of the semiconductor are absorbed and create some electron–hole pairs proportional to the incident radiation. Under the influence of the internal retarding electric fields of the p–n junction, these carriers are swept apart and create a photocurrent which is directly proportional to solar irradiance. PV system naturally exhibits nonlinear I–V and P–V characteristics which depend upon the solar insolation and cell temperature.

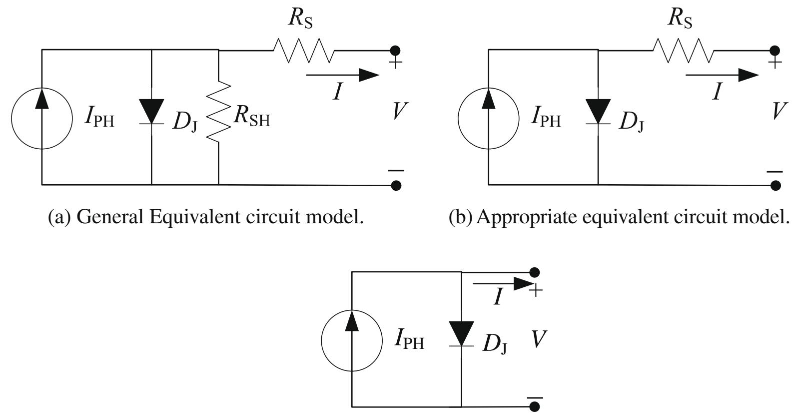
2.1. PV cell model

A general mathematical description of I–V output characteristic for a PV cell has been studied for over the pass three decades. The equivalent circuit model is shown in Fig. 1a. The model consists of a photo current, a diode, a parallel resistor expressing a leakage current and a series resistor describing an internal resistance to the current flow. The I–V characteristic equation is given as follows (Enrique et al., 2007; Villalva et al., 2009)

$$I = I_{PH} - I_S\left[\exp\left(\frac{q}{kT_CA}(V + IR)\right) - 1\right] - \frac{V + IR_S}{R_{SH}} \quad (1)$$

where I_{PH} is a light-generated current or photocurrent, I_S is the cell saturation of dark current, q stands for an electron charge (=1.6 × 10^{-19} °C), k is the Boltzmann's constant (=1.38 × 10^{-23} J/K), T_C is the cell's operating temperature in Kelvin (K), A is an ideal factor, R_{SH} is the shunt resistance, and R_S is the series resistance. The photovoltaic current mainly depends on the insolation intensity and cell's operating temperature as follows (Enrique et al., 2007; Villalva et al., 2009)

$$I_{PH} = [I_{SC} + K_I(T_C - T_{Ref})]\lambda \quad (2)$$



(a) General Equivalent circuit model.

(b) Appropriate equivalent circuit model.

(c) Simplified equivalent circuit model.

Fig. 1. Different models of PV solar cell.

where I_{SC} is the cell's short-circuit current at 25 °C and 1 kW/m^2 of solar insolation, K_I is the cell's short-circuit current temperature coefficient, T_{Ref} is the cell's reference temperature, and λ is the solar insolation in kW/m^2. On the other hand, the cell's saturation current varies with the cell temperature, which is described as (Enrique et al., 2007; Villalva et al., 2009)

$$I_S = I_{\text{RS}}\left(\frac{T_C}{T_{\text{Ref}}}\right)^3 \exp\left[\frac{qE_G}{kA}\left(\frac{1}{T_{\text{Ref}}} - \frac{1}{T_C}\right)\right] \tag{3}$$

where I_{RS} is the cell's reverse saturation current at a reference temperature and a solar radiation, E_G is the bang-gap energy of the semiconductor used in the cell. The ideal factor A as listed in Table 1 depends on PV technology (Hua and Shen, 1998), which is selected as 1.3 for polycrystalline silicon (poly-Si) in this paper.

The shunt resistance R_{SH} is inversely related with shunt-leakage current to the ground. In general, the PV efficiency is insensitive to the variation in R_{SH}, which can be assumed to approach infinity without leakage current. On the other hand, a small variation in R_S will significantly affect the P–V output power. The appropriate model of PV solar cell with suitable complexity is shown in Fig. 1c (Hua and Shen, 1998; Bellini et al., 2009). Eq. (1) can be rewritten as

$$I = I_{\text{PH}} - I_S\left[\exp\left(\frac{q}{kT_CA}(V + IR_S)\right) - 1\right] \tag{4}$$

Table 1
Factor A dependence on PV technology.

Technology	A
Si-mono	1.2
Si-poly	1.3
a-Si:H	1.8
a-Si:H tandem	3.3
a-Si:H triple	5
CdTe	1.5
CIS	1.5
AsGa	1.3

For an ideal PV cell, there are neither series loss nor leakage current, i.e. $R_S = 0$ and $R_{\text{SH}} = \infty$. Then the equivalent circuit of PV solar cell can be simplified as in Fig. 1c (Messenger and Ventre, 2000). Finally, Eq. (1) can be simplified to be

$$I = I_{\text{PH}} - I_S\left[\exp\left(\frac{qV}{kT_CA}\right) - 1\right] \tag{5}$$

2.2. PV module and array model

In general, the power output of a typical PV cell is less than 2 W at 0.5 V output voltage. Therefore, PV cells are connected in a module of series–parallel configuration to produce enough high output power and voltage. For photovoltaic systems, a PV array is a group of several PV modules which are electrically connected in series and parallel circuits to generate the required current and voltage. The equivalent circuit for the solar module arranged in N_P parallel and N_S series branches is shown in Fig. 2a. The terminal equation for the current and voltage of the cell array becomes as follows (Veerachary et al., 2002; Veerachary and Shinoy, 2005; Kim and Youn, 2005; Kim et al., 2006).

$$I = N_PI_{\text{PH}} - N_PI_S\left[\exp\left(\frac{q}{kT_CA}\left(\frac{V}{N_S} + I\frac{R_S}{N_P}\right)\right) - 1\right] - \frac{\frac{N_P}{N_S}V + IR_S}{R_{\text{SH}}} \tag{6}$$

In fact, the PV efficiency is sensitive to small change in R_S but insensitive to the variation in R_{SH}. For a PV module or array, the series resistance becomes apparently important and the shunt resistance approaches infinity which is assumed to be open. An appropriate equivalent circuit for all PV cell, module, and array is generalized and expressed in Fig. 2b. It can be shown that $N_S = N_P = 1$ for a PV cell. Then Eq. (6) can be rewritten to be

$$I = N_PI_{\text{PH}} - N_PI_S\left[\exp\left(\frac{q}{kT_CA}\left(\frac{V}{N_S} + I\frac{R_S}{N_P}\right)\right) - 1\right] \tag{7}$$

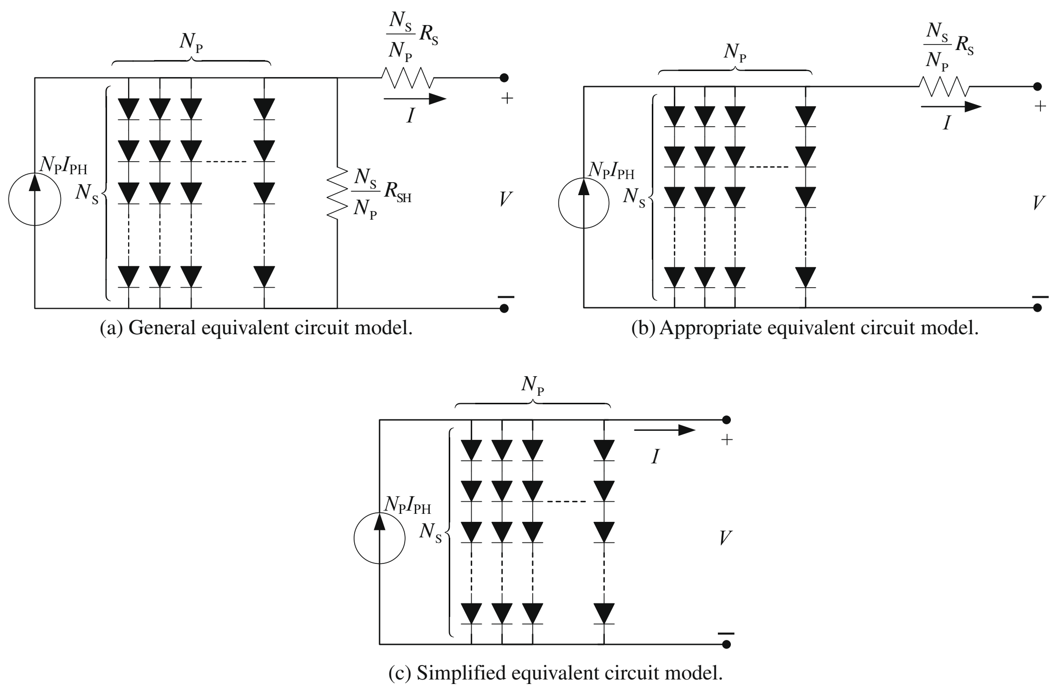


Fig. 2. Different models of solar module in N_P parallel and N_S series branches.

The most simplified model is depicted in Fig. 2c. The equivalent circuit is described by the following equation (Wasynczuk, 1989; Hussein et al., 1995)

$$I = N_P I_{PH} - N_P I_S \left[\exp\left(\frac{qV}{N_S k T_C A} \right) - 1 \right] \tag{8}$$

2.3. Effect of sunlight intensity on cell temperature

Bing illuminated with radiation of sunlight, PV cell converts part of the photovoltaic potential directly into electricity. However, the remaining power of the photon will result in heating of the cell and elevate the temperature of the cell. Therefore, the cell can be expected to operate above ambient temperature, and the cell temperature is a function of ambient temperature and sunlight irradiance. As PV cells being mounted into modules, the modules are generally housed on metal, and are then covered with antireflective coating to minimize the reflection as well as a special laminate for mechanical protection. The fraction of absorbed sunlight is not converted to electricity and this makes the overall cell temperature vary with the solar insolation. The variation of cell operating temperature can be quantitatively evaluated and quite accurately estimated with a linear approximation that (Messenger and Ventre, 2000)

$$T_C = T_{\text{Amb}} + \left(\frac{T_{\text{NOCT}} - 20}{0.8} \right) \lambda \tag{9}$$

where T_{Amb} is the ambient temperature, and T_{NOCT} is the nominal operating cell temperature (NOCT) for operating at open circuit with the following conditions: ambient temperature of 20 °C, AM 1.5 irradiance, $\lambda = 0.8$ kW/m^2, and wind speed less than 1 m/s.

3. Insolation-oriented model and simulation

3.1. Determination of PV parameters

Taking Solarex MSX 60 PV module for an example, the key specifications are listed in Table 2. To examine the PV manufacturer's product specifications can determine all of the model parameters. The most important parameters widely used for describing the cell electrical performance are the open-circuit voltage V_{OC} and the short-circuit current I_{SC}. Given the PV open-circuit voltage V_{OC} at reference temperature, the reverse saturation current at reference temperature can be approximately obtained without taking the shunt-leakage current into consideration

$$I_{\text{RS}} = \frac{I_{\text{SC}}}{\exp\left(\frac{qV_{\text{OC}}}{kAT_{\text{Ref}}} \right) - 1} \tag{10}$$

Table 2
Solarex MSX 60 specifications (1 kW/m^2, 25 °C).

Characteristics	Spec.
Typical peak power (P_p)	60 W
Voltage at peak power (V_{pp})	17.1 V
Current at peak power (I_{pp})	3.5 A
Short-circuit current (I_{sc})	3.8 A
Open-circuit voltage (V_{OC})	21.1 V
Temperature coefficient of open-circuit voltage	−73 mV/°C
Temperature coefficient of short-circuit current (K_I)	3 mA/°C
Approximate effect of temperature on power	−0.38 W/°C
Nominal operating cell temperature (NOCT)	49 °C

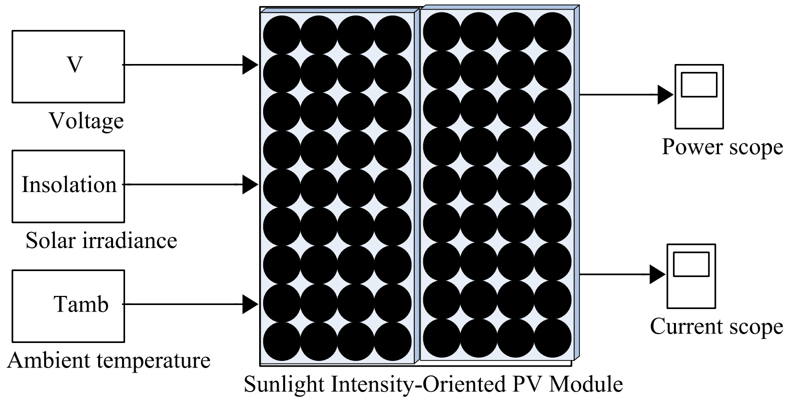


Fig. 3a. Masked insolation-oriented PV module.

On the other hand, Eqs. (2)–(4) are implicit and nonlinear; therefore, it is difficult to arrive an analytical solution by giving a set of model parameters at a specific temperature and irradiance. Ignoring the small diode and ground-leakage currents with zero-terminal voltage, the short-circuit current I_{SC} is equal to the photocurrent I_{PH}.

3.2. Model building and performance analysis

An insolation-oriented model of PV module is built by using Matlab/Simulink to illustrate and verify the nonlinear *I–V* and *P–V* output characteristics of PV module, which takes the effect of irradiance intensity on cell temperature into consideration. The block diagram of the proposed model is implemented and shown in Figs. 3a and 3b. The symbol $f(u)$ in the Function block library shown in Fig. 3b is a built-in function notation in Simulink. Each function uses a notation with a meaningful lettering to make it readable and maintainable. The cell temperature that is a linear approximation function of ambient temperature and insolation in Eq. (10) is implemented in the insolation-oriented cell temperature function. Saturation current function stands for the implementation of Eq. (3). To make the novel PV model easier to use and understand, an image file of PV icon is used as a masking icon. The icon is also shown in Fig. 3a. In addition, the masked model is designed to have a dialog box as shown in Fig. 3c, in which the parameters of PV module can be configured in the same way for the Simulink block libraries.

For an insolation-oriented model of PV module, the variations of cell temperature affected by sunlight irradiance is taken into consideration and the effect on the output current and power can be studied simultaneously. Both *I–V* and *P–V* output characteristics of PV module at various insolation and temperatures are carried out and the results are shown in Figs. 4a and 4b. Comparing the maximal output power

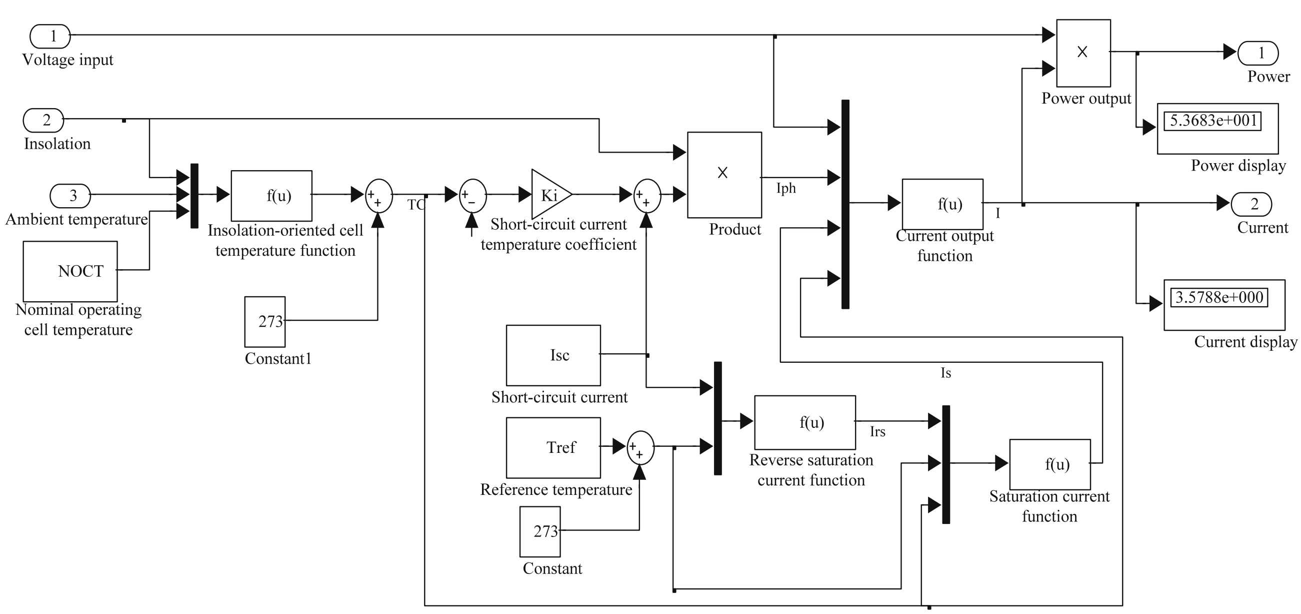


Fig. 3b. Subsystem implementation of insolation-oriented PV module.

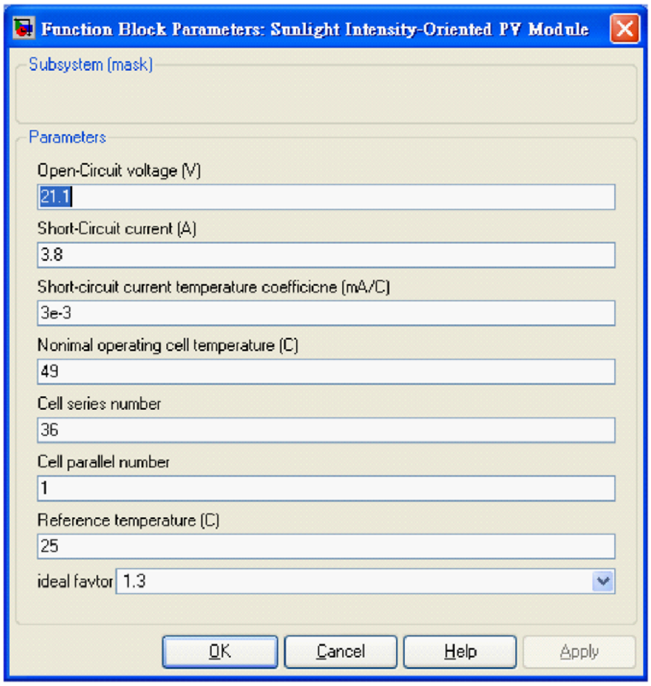


Fig. 3c. Dialog box of insolation-oriented PV module.

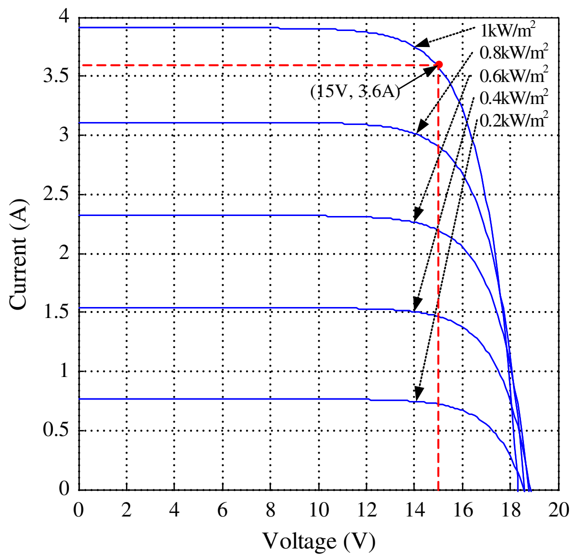


Fig. 4a. I–V output characteristics with different λ.

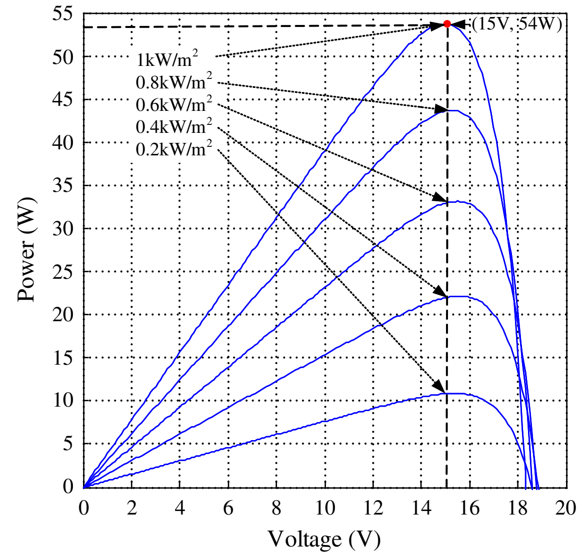


Fig. 4b. P–V output characteristics with different λ.

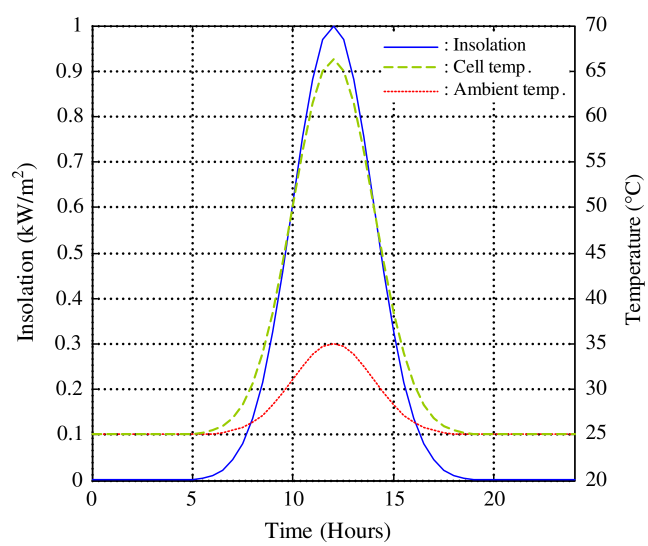


Fig. 5. Sunlight intensity, ambient and cell temperature in the form of Gaussian function for a sample day.

in Fig. 4b with that without taking the effect of sunlight intensity on cell temperature (Messenger and Ventre, 2000; Tsai et al., 2008), the increase of cell temperature would decrease the cell performance, which proves the prediction. On the other hand, the operating voltage of MPPT for different sunlight intensities is closed and approximately about 15 V. Taking the effect of sunlight intensity on cell temperature, the operating voltage of the PV module can be fixed at 15 V for a near MPPT operation without MPPT devices (Huang et al., 2006).

3.3. Simulation results

For easy implementation, the solar radiation intensity for a sample day is assumed to be a function of Gaussian function distribution defined as (Messenger and Ventre, 2000)

$$\lambda(t) = \lambda_{max} \exp\left[-\frac{(t-t_C)^2}{2\sigma^2}\right] \tag{11}$$

where λ_{max} is the maximal sunlight intensity at a given time, t_C is the center time, and σ is the standard deviation of Gaussian function. Fig. 5 shows a plot of the Gaussian function distribution for the solar radiation intensity for a sample day with the conditions: $\lambda_{max} = 1\ \mathrm{kW/m^2}$, $t_C = 12$, and

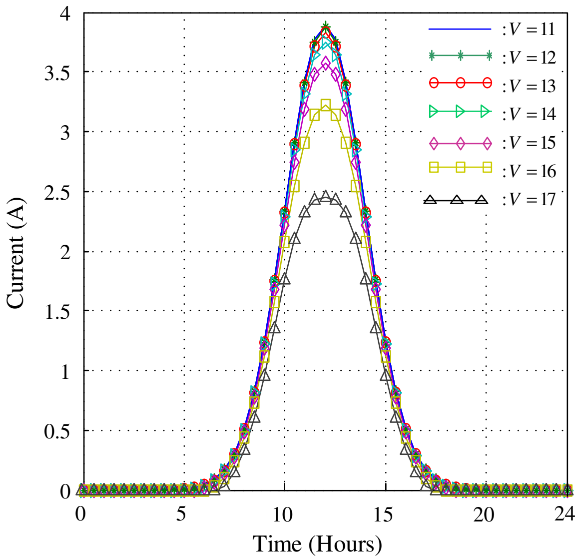


Fig. 6a. Current characteristics during a sample day for different voltage.

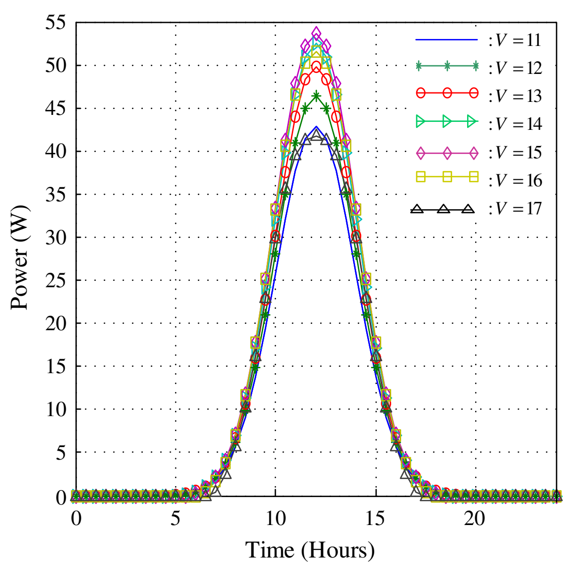


Fig. 6b. Power characteristics during a sample day for different voltages.

$\sigma = 0.5$. The peak of sunlight intensity occurs at noon. In addition, the ambient temperature for such a sample day is assumed to be a Gaussian function distribution. For variations in solar irradiance and ambient temperature, the cell temperature can be estimated by Eq. (10). Both ambient temperature and cell temperature are also shown in Fig. 5. For an insolation-oriented model of PV module, the cell temperature is affected by sunlight irradiance. For different output voltage, the output current and power are obtained in Figs. 6a and 6b for a sample day. Furthermore, for easy comparisons, both total electricity and mean output power for various output voltage of a sample day are calculated and depicted in Fig. 6c. Note that the maximum electricity is 265.1208 W h and the maximum power is 11.0467 W through the course of a sample day, which occurs with the output voltage fixed at 15 V.

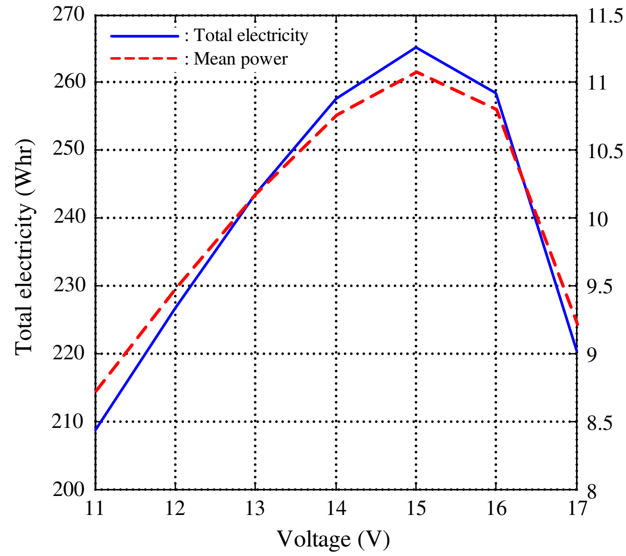


Fig. 6c. Total electricity and mean power for various output voltages.

4. Experimental verification

4.1. Experiment set-up

In order to further verify the correctness of the proposed PV model, the experiment is conducted. As illustrated in Fig. 7, the experimental rig consists of one Siemens SM46 PV module, one MPPT controller, one storage battery, one electric fan as a load, and some measurement instrumentations. A cover of glass that is transparent and ventilatory is use to shelter the PV module from wind. This makes sure that the wind speed is less than 1 m/s to meet the NOCT conditions. The experimental rig was set-up in the Energy Research and Development Center (ERDC) of Da-Yeh University in Taiwan. The PV module was placed in a south-facing position and at an inclination angle of 23.5°. One light meter Lutron LX-1102 was fixed at the same inclination of the PV module to measure incident solar irradiation on the PV plate. One TES-1314 thermometer with dual input channels was used to measure ambient temperature and the temperature of glass cover over PV cell as the reference to the cell temperature. Two CIE 8050 multimeters were respectively arranged in parallel to measured working voltage and in series to measure output current. The output power of PV module was then obtained.

4.2. Measurement results and model validation

A 9-h measurement of the experiment set-up was tested from 8:00 to 17:00 for each day from 2009/5/26 to 2009/7/26. All observations of sunlight intensity, temperatures, working voltage and output current of PV module were recorded at 1-h intervals. The hourly variations of sunlight intensity and ambient temperature for a typical day (2009/07/1) in the summer months are depicted in Fig. 8. In order to check the *n*-MPPT assumption, the operating

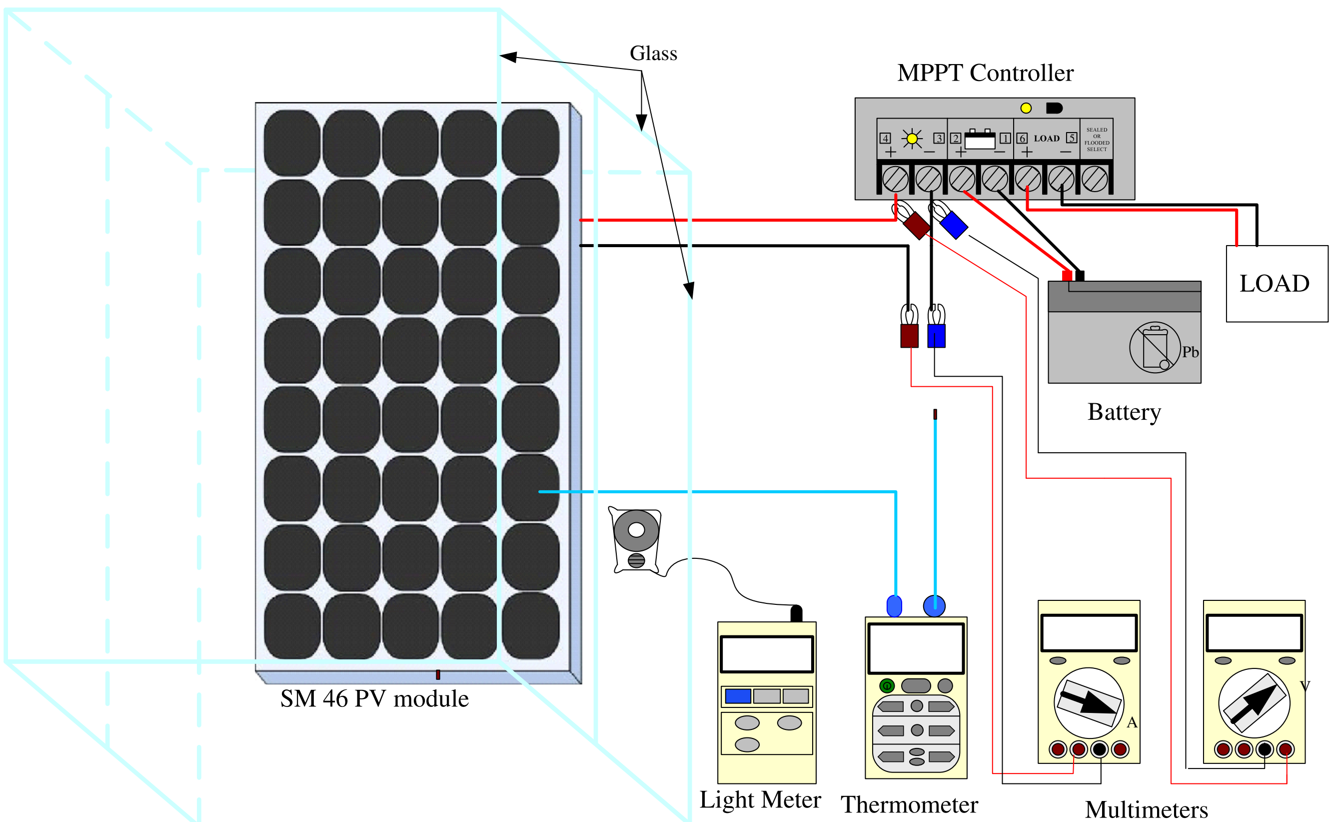


Fig. 7. Schematic diagram of experimental rig.

voltage of the proposed model is fixed at 13.2 V. The output current and power of simulated results can be obtained with the solar insolation and ambient temperature. The operating voltage and current of experimental results are directly measured by the multimeters. The output power is then the product of measured current and voltage. The experimental and simulated results of the change in the PV cell temperatures and *P–V* output power are shown in Fig. 9a and b. Fig. 9a shows the measured temperatures of PV module approximate to the simulated ones of the proposed PV model. The difference is generally less than 2.29 °C and the standard deviation is 1.28 °C. On the other hand, both measured and simulated results for the output power of PV module are approximately the same as shown in Fig. 9b. The difference is less than 1.06 W and the standard deviation is 0.32 W. This proves the near-MPPT assumption. As mentioned previously, both cell temperature and output power of the proposed PV model generally close to the measured ones. The accuracy of simulated values will fall within two times the standard deviation of the measured values.

5. Conclusions

A conventional PV model takes sunlight irradiance and cell temperature as input parameters. In fact, the cell temperature is mainly affected by solar insolation and ambient temperature. The proposed model taking ambient temperature as reference input makes the insolation-oriented model be easily evaluated by taking the effect of irradiation intensity on cell temperature into consideration. The model has been implemented using Matlab/Simulink and has masked icon and dialog like Simulink block libraries. The

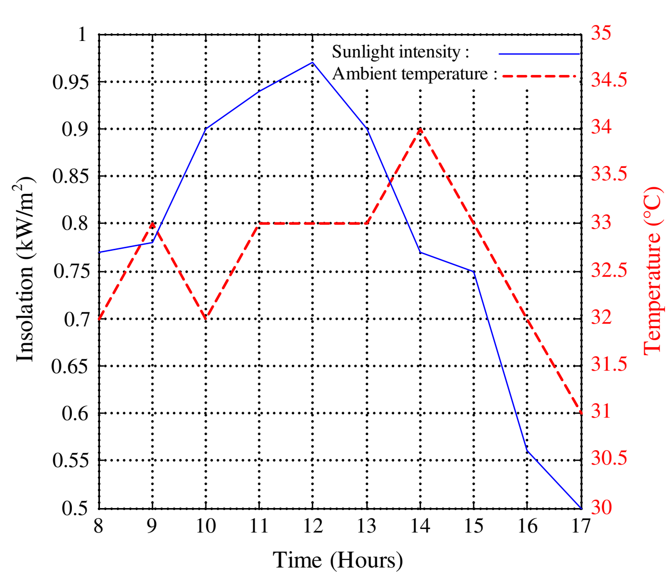
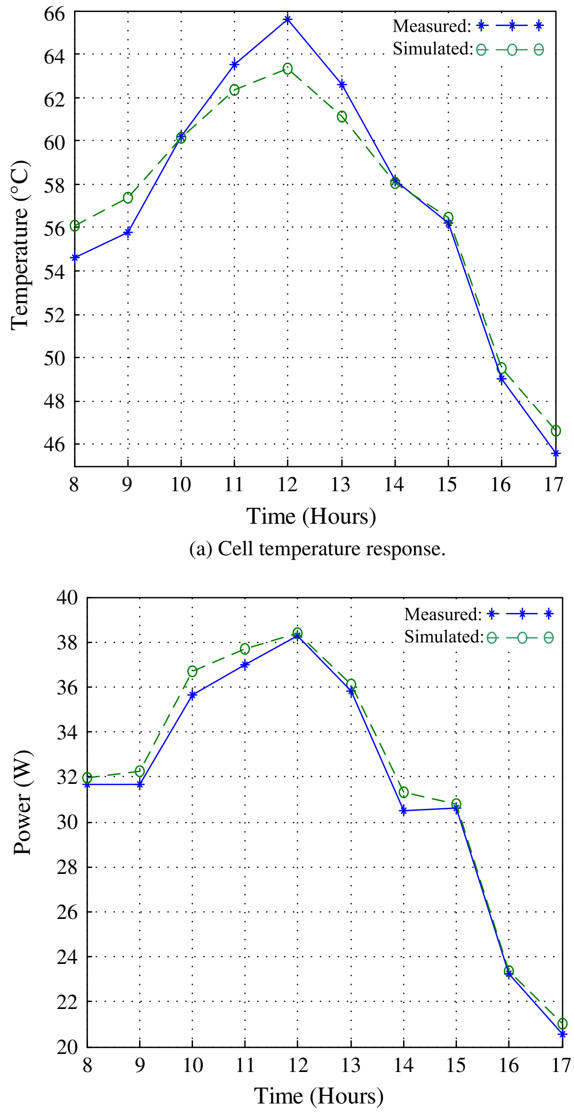


Fig. 8. Hourly variation of sunlight intensity and ambient temperature of a typical day.



(a) Cell temperature response.

(b) Output power response.

Fig. 9. Cell temperature and output power of SM46 PV module in response to hourly variation of sunlight intensity and ambient temperature of a typical day.

proposed model is verified through an experiment set-up to make sure the correctness and usability. On the other hand, taking the effect of sunlight intensity on cell temperature into consideration, the operating voltage of the PV module might be fixed for near MPPT operation without MPPT devices.

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