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CHARACTERISTICS APPROACH OF THIN-FILM CIGS PV CELLS WITH CONVENTIONAL MONO-CRYSTALLINE SILICON MODEL

Syafaruddin[1,*], Faizal Arya Samman[1], Alfian[1], Muh. Aksa Idris[1]
Siti Hamnah Ahsan[2] and Satriani Latief[3]

[1]Department of Electrical Engineering
[2]Department of Civil Engineering
Universitas Hasanuddin
Jalan Perintis Kemerdekaan Km. 10 Tamalanrea, Makassar 90245, Indonesia
*Corresponding author: syafaruddin@unhas.ac.id

[3]Department of Architecture
Universitas Bosowa 45 Makassar
Jalan Urip Sumoharjo Km. 4, Makassar 90231, Indonesia

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Abstract. *The behavior and characteristics performance of photovoltaic (PV) module technology can only be simply obtained through mathematical modeling and simulation. This paper demonstrates the approach characteristics modeling of thin-film CIGS PV cells adopting the conventional mono-crystalline Silicon model. The proposed model is then simulated under variations of irradiance and cell temperature in single PV module and under the uniform and partial shading conditions of 4 × 3 PV array with series-parallel (SP) connections. The simulation results indicate that the model of mono-crystalline Silicon can be simply used to approach the performance output of thin-film CIGS PV technology.*

Keywords: Photovoltaic (PV), Modeling and simulation, CIGS PV cells, Monocrystalline Silicon cells

1. **Introduction.** There has been significant increase in photovoltaic (PV) systems applications worldwide since the last decade. The technology has reached mature stage denoted by increase in capacity spreading from stand alone to grid connected systems. One of the important causes of this phenomena is the rapid development of solar cells technology. In the solar cell markets, the conventional Silicon cells by means poly-crystalline and mono-crystalline Silicon are still dominating due to the reasonable price and efficiency and well-known setup installation. Then the solar cells based Silicon technology is now developed with low cost thin-film and amorphous Silicon starts entering the market. The other thin-film and tandem solar cells, such as CdTe, CIS, CIGS have also appeared in wide range of applications with high capacity per module and good efficiency energy conversion and prominent cost reductions. Especially, the Copper Indium Gallium Diselenide (CIGS) technology has not yet widely been used in the field PV system applications compared with other module types. Consequently, the output characteristics according to the variability of environmental factors are rarely found, except what the manufacturers provide to the users. In addition, the material composing CIGS technology is more complex than conventional crystalline Silicon PV technology that consequently affecting the complexity of electrical characteristic modeling.

The output characteristic of Silicon solar cells is non-linear to the variations of irradiance and cell temperature. Under constant temperature, the short circuit current is directly proportional to the irradiance level and the open-circuit voltage. However, the increase in voltage level is logarithmic in comparison with short-circuit current. If the temperature is increased, the diffusion voltage in p-n junction is reduced and resulted in decrease in open-circuit voltage of -2.1 mV/K, while the short-circuit current increases by approximately 0.01%/K due to the enhance mobility carriers within the cell. The increase in temperature causes slightly increasing in short-circuit current and relatively strong decreasing of open-circuit voltage. As a result, the output power is reduced with increasing temperatures. These characteristics are commonly known in photovoltaic system practices as the wide-spreading implementation of crystalline Silicon photovoltaic modules.

In comparison, the output characteristic of CIGS thin-film solar cells is totally different with conventional crystalline Silicon cells in terms of variations of irradiance and cell temperature. The output power of CIGS solar cell is not much changed by the fluctuation on sunlight intensity including partially shaded conditions. Also, the cell temperature does not affect the reduction in open-circuit voltage and consequently not influence the output power. The CIGS technology is tandem solar cells which are composed of Copper, Indium, Gallium and Diselenide materials with different band gap energy on top of one another. The materials on top may absorb the sunlight wavelength between 300-740 nm, while the material on bottom may wavelength between 740-1050 nm. Such design is mainly to maximize the effective utilization of wavelength entering the surface of photovoltaic cells in order to increase the efficiency power conversion.

Several modeling and simulation have been proposed to improve the electrical output characteristic of CIGS thin-film solar cells technology including the cell efficiency. For instance, by annealing process to increase the open-circuit voltage and to improve the fill factor performance of solar cells [1], by processing with quantum dot solar cells [2] and thermal cracking system in initial process of Selenium flux [3]. Another proposed method is to improve the micromachining process of CIGS in order to optimize the energy density [4]. On the other hand, the temperature dependence of the open-circuit voltage is eliminated by shunt-current-eliminated diode current [5]. The efforts are mostly to improve the thin-film cells performance through the fabrication process of cells. In fact, the accurate modeling is quite difficult because of the complexity materials composing the thin-film CIGS which is confirmed by the analytical modeling and simulation of CIGS [6].

This paper proposes the approximate modeling of thin-film CIGS using conventional crystalline Silicon Solar cells model. The comparison performance between the crystalline Si and CIGS solar cells is provided in the introduction part. Then, systems modeling is explained in the following part. Finally, the proposed modeling has been tested for different connection of 4×3 PV array CIGS thin-film with series-parallel (SP) connection.

2. **Systems Modeling.** Appropriate modeling is supposed to represent the physical components of real systems. The basic component of solar cell is the p-n junction materials connected as the p-conducting base material and n-conducting layer on top side. The solar cell with illumination is considered as the current source parallel with diode. The current source or photocurrent (I_{ph}) is proportional to the sunlight intensity (photon energy), while the solar cell without irradiation is considered as ordinary semiconductor diode; that is way the diode is in parallel with photocurrent in order to maintain the photon incident. Actually, the capacitance effect exists in parallel with diode resulted in the depletion layer of each p-n junction; however, the capacitance is typically neglected for solar cell modeling. In addition, the series resistance (R_s) represents the contacts, cables and resistance of the semiconductor materials. The parallel resistance (R_p) is characterized by leakage currents at photovoltaic cell edges. Ideally, the series and parallel resistances for good mono-crystalline Silicon have values of zero and infinity, respectively.

In comparison, the thin-film CIGS (Copper Indium Gallium Diselenide) PV cells have very different characteristics with conventional mono-crystalline Silicon PV cells and are more complicated than other types of photovoltaic cells. Consequently, the technical performance of CIGS is better than others, especially that the output power performance is not affected during partially shaded condition. In this thin-film technology, CIGS acts as a p-type and CdS as n-type semiconductor. The equivalent circuit of thin-film CIGS PV cells is shown in Figure 1. The complex modeling thin-film CIGS PV cell is simplified into model of mono-crystalline Silicon PV cells by modifying the series resistance (R_s) and parallel resistance (R_p). The series resistance (R_s) is the submission of the resistance in ZnO:Al layers($R_{ZnO:Al}$), resistance of the Mo layers (R_{Mo}), discrete resistance (R_d) and additional resistance at the contact ZnO:Al/Mo (R_c). Meanwhile, the parallel resistance (R_p) is represented by internal resistance of the CIGS material [7]. Thus, the equivalent circuit in Figure 1 is simplified with general equivalent circuit of photovoltaic cells shown in Figure 2.

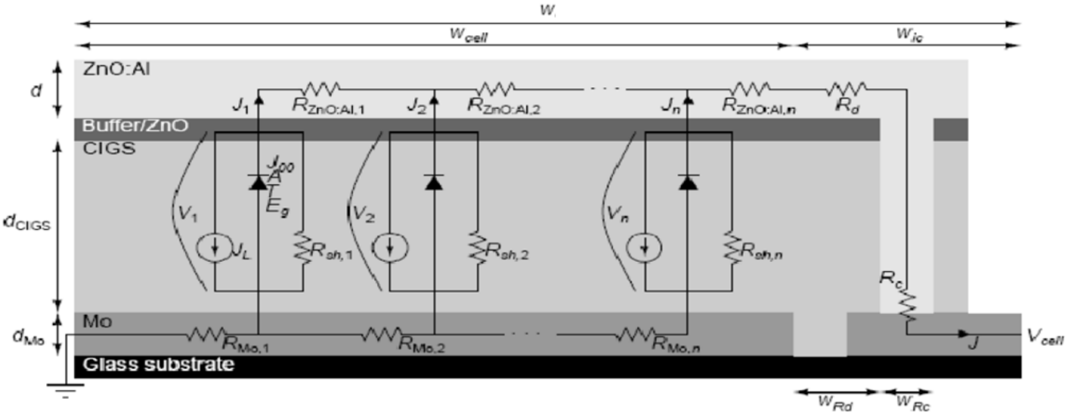


FIGURE 1. The equivalent circuit of thin-film CIGS solar cell [7]

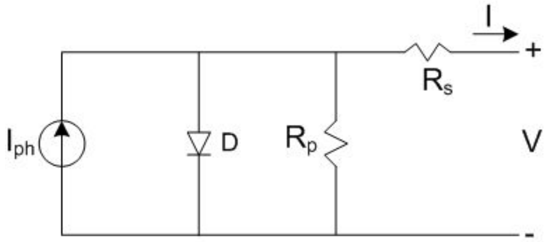


FIGURE 2. Simplified equivalent circuit using model of mono-crystalline Silicon PV cells

According to Figure 2, the photocurrent (I_{ph}) as the current source in the equivalent circuit is influenced by solar irradiation (G) and cell temperature (T_c). The I_{ph} can be calculated as follows:

$$I_{ph} = (1 + (T_c - T_{cref})\mu_{Isc})\, I_{phref} \left(\frac{G}{G_{ref}}\right) \tag{1}$$

where the characteristic parameters of PV module are denoted with μ_{Isc} (short circuit current coefficient) within the range of 10^{-4} and I_{phref} (photocurrent reference by means of the maximum produced photocurrent); while G_{ref} and T_{cref} are the solar irradiance and cell temperature at standard test condition (STC: 1000 W/m^2, 25°C), respectively.

Meanwhile, in the diode component, it flows the diode saturation current (I_0) which is highly affected by the cell temperature (T_c) including its reference (T_{cref}). The diode saturation current (I_s) is calculated using the equation as follows:

$$I_s = I_{0ref}\left(\frac{T_c+273}{T_{cref}+273}\right)^3 e^{\left(\frac{1}{T_{cref}+273}-\frac{1}{T_c+273}\right)\frac{Eg.q}{n.k}} \tag{2}$$

where E_g is the band gap energy of cell, n is the diode ideality factor, q is the electron charge of 1.6×10^{-19} C and k is the Boltzmann constant of 1.381×10^{-23} J/K. Meanwhile, the reference of diode saturation current (I_{0ref}) can be calculated as follows:

$$I_{0ref} = \frac{I_{sc}}{e^{qV_{oc}/NnkT_c}-1} \tag{3}$$

where V_{oc} is the open-circuit voltage, I_{sc} is the short-circuit current, and N is the number of cells connected in series.

If the terminal is short circuited and the parallel resistance (R_p) is high enough, the total current I that flows in the output terminal is calculated as:

$$I = I_{ph} - I_s\left(e^{\frac{qV}{NnkT_c}}-1\right) \tag{4}$$

where V is the terminal voltage. The current I in Equation (4) indicates the non-linear relationship to sunlight intensity by means of irradiance (G) and cell temperature (T_c).

In this research, the thin-film CIGS PFM-2K PV module comprising 36 connected in series is used. The PV module specification is shown in Table 1. In order to investigate the response of proposed modeling under partially shaded conditions, two bypass diodes are utilized in the output terminal [9,10]. The first bypass diode is connected in terminal of the 1st cell to 18th cell, while the other one is connected in the terminal of remaining cells. The single PV module representation with bypass diode and the electric circuit representation are shown in Figure 3.

TABLE 1. The model parameters of thin-film CIGS PFM-2K [8]

Short circuit current coefficient, μ_{Isc}	−0.03% per ℃
Photocurrent reference, I_{phref}	12.8 A
Diode ideality factor, n	2.72
Voltage of band gap energy for CIGS	1.2 V
Terminal voltage, V	23.3 V

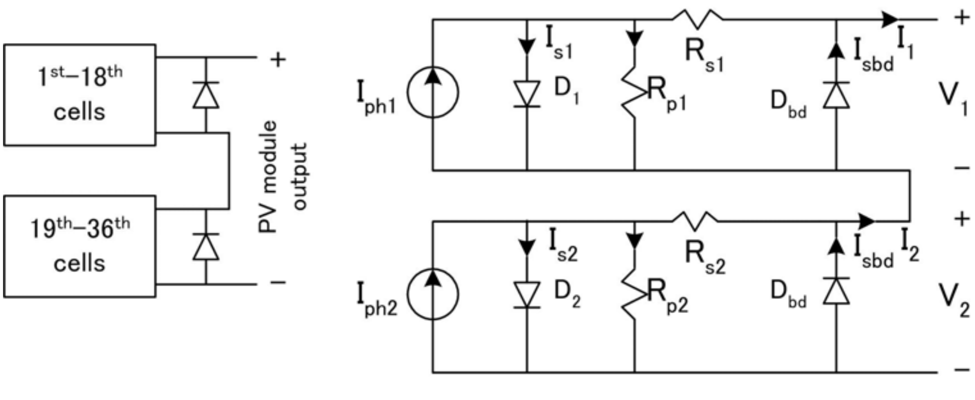


FIGURE 3. Single PV module configuration including the electric circuit representation

From the PV module equivalent circuit in Figure 3, there are four equations with four unknown variables that can be derived in order to obtain the I-V and P-V characteristics. With simply using Kirchhoff's Current Law (KCL) and Kirchhoff's Voltage Law (KVL), then those equations in (5)-(7) are solved.

For $i = 1, 2$

$$\begin{aligned} &-I_i + I_{ph}(i) - I_s(i)\left[\exp\left(\frac{q(V_i) + I_i R_s(i)}{18n(i)kT(i)}\right) - 1\right] - \frac{V_i + I_i R_s(i)}{R_p(i)} \\ &+I_{sbd}\left[\exp\left(\frac{q(-V_i)}{n_{bd}kT_{bd}}\right) - 1\right] = 0 \end{aligned} \tag{5}$$

$$V_1 + V_2 - V_{load} = 0 \tag{6}$$

$$I_1 - I_2 = 0 \tag{7}$$

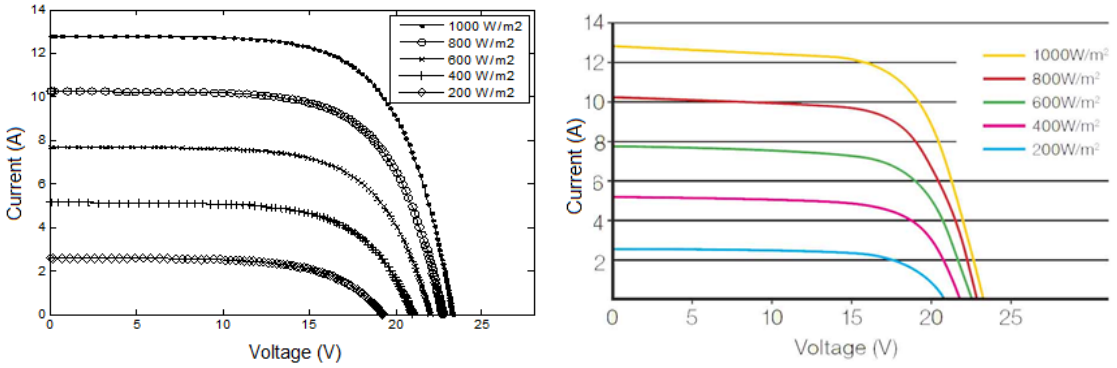
For the bypass diodes components; the $I_{sbd} = 1.6 \times 10^{-9}$ A, $n_{bd} = 1.0$ and $T_{bd} = 35$℃ are selected [9]. As the proposed model in a modular model, this approach makes it easy to construct the modeling and simulation of large-scale PV array with different configurations such as series-parallel (SP) connection.

The nature characteristics of PV modules under shading conditions when bypass diodes are connected in module terminal are explained as follows. Under partially shaded conditions, the shaded cells behave as a load instead of generator that leads to the hot spot problem. The way to avoid the hot spot effect in this case is by driving the current of non-shaded cells through the bypass diode. Under shading condition, the bypass diode in the shaded part will be in the forward bias voltage and conducts current produced by the non-shaded part. Meanwhile, the reverse bias voltage is generated in the bypass diode connected to the non-shaded part. However, the connection of bypass diodes will change the uniform I-V and P-V characteristics of the module, resulting in multiple peaks. In [11], two kinds of bypass diode connections are introduced based on the manufacturer recommendation, called overlapped and non-overlapped cells. The deformation of module I-V characteristics is bigger when the shaded parts show low slope in reverse bias condition until the bypass diode starts to conduct.

Regarding the bypass diode connection type, the shaded parts can cause to force the optimum operating voltage to abnormally low voltage region on the I-V curve. From this view point, the non-linear characteristic of I-V curve can mislead the inverter in searching the MPP and the inverter cannot distinguish between global and local MPPs. Series connected PV modules are normally carrying the same current. However, it is not all the case, and then the bypass diode is connected to allow the current of non-shaded parts flowing in bypass diode of shaded modules [12]. Once a bypass diode is activated, the operating voltage will change to be low in the P-V curve.

3. **Validation and Testing.**

The proposed model of using the equivalent circuit model mono-crystalline Silicon PV module for modeling the thin-film CIGS PV module is validated under standard test condition of cell temperature (25℃), while the irradiance is varied between 200 W/m^2 and 1000 W/m^2. The I-V curves for both proposed model and data sheet of thin-film CIGS PFM-2K PV module are presented in Figure 4. The overall figures are almost the same, except that the fill factor of mono-crystalline Silicon PV module is still higher than the thin-film CIGS PV module. In addition, the open-circuit voltage in mono-crystalline Silicon model is reduced at irradiance of 200 W/m^2 compared to the thin-film CIGS PV module characteristics. This might be the drawbacks of our proposed method where the curve accuracy is reduced under lower irradiance intensity. Nevertheless, the characteristics of thin-film CIGS module are reasonably enough to be approached using mono-crystalline Silicon model.



(a) Proposed model (b) Data sheet

Figure 4. The *I*-*V* curves between proposed model and data sheet

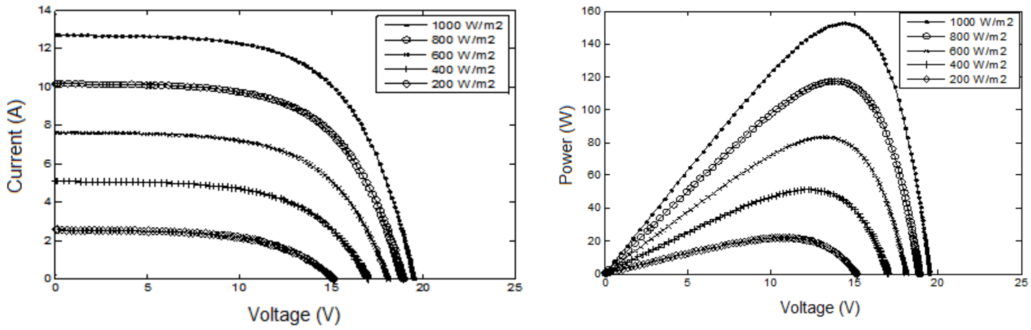
Table 2. The electrical parameters under standard test condition (STC: 1000 W/m^2, 25°C)

Electrical parameters	Proposed model	Data sheet	Error percentage (%)
P_{mp} (W)	199.8	200	0.1
V_{mp} (V)	17.83	17.8	0.17
I_{mp} (A)	11.21	11.2	0.09
V_{oc} (V)	23.3	23.3	0
I_{sc} (A)	12.8	12.8	0

The accuracy of model validation is shown in Table 2. In this table, all electrical parameters such as power, voltage and current at maximum power point, open-circuit voltage and short-circuit current are compared between the proposed model and data sheet of thin-film CIGS PV module under standard test condition (STC: 1000 W/m^2 and 25°C). The results show that the maximum error percentage is confirmed of 0.17% which indicates that the proposed model can be used to do testing and simulation of different input scenarios on PV module of thin-film CIGS technology and different array configuration, such as series parallel (SP) connection including normal irradiance and partial shading conditions.

4. **Simulation Results and Discussion.** In this section, several simulation scenarios of thin-film CIGS technology are presented according to the real practice and implementation of photovoltaic systems. The first scenarios consider the operation of photovoltaic module with constant cell temperature of 50°C, while the irradiance is varied between 200 W/m^2 and 1000 W/m^2. Following this scenarios, the irradiance is kept constant of 1000 W/m^2, while the cell temperature is varied from 20°C to 50°C with the increment of 5°C. Both testing results are presented in the characteristics of *I*-*V* and *P*-*V* curves. Then the simulation scenario is extended into PV array configuration of 4 × 3 with series-parallel (SP) connection under normal irradiance and partially shaded conditions.

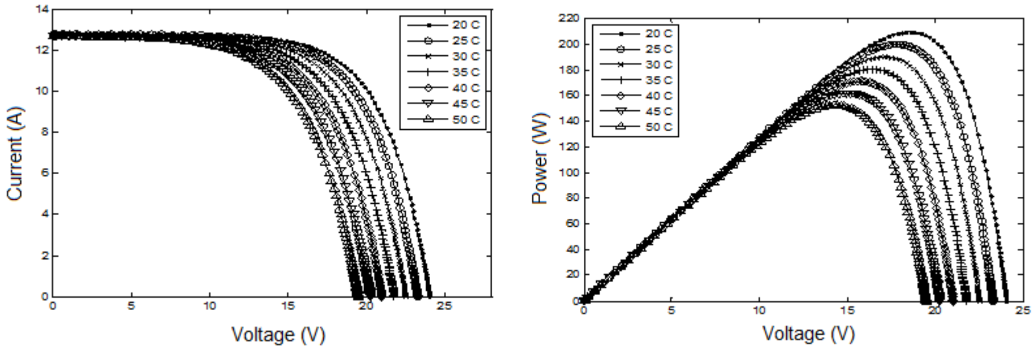
Figure 5 shows the *I*-*V* and *P*-*V* curves of thin-film CIGS PV module technology with constant cell temperatures of 50°C, while the irradiance (E) is varied between 200 W/m^2 and 1000 W/m^2 with the step increasing of 200 W/m^2. The comparison of these characteristics is to the constant temperature of 25°C, and it can be seen that the open-circuit voltage is much further decreased. It is due to the initial approach in original model of mono-crystalline Silicon about the effect of negative voltage temperature coefficient



(a) *I*-*V* curves

(b) *P*-*V* curves

FIGURE 5. Simulation results of constant $T_c = 50$℃, $E = 200\text{-}1000$ W/m^2



(a) *I*-*V* curves

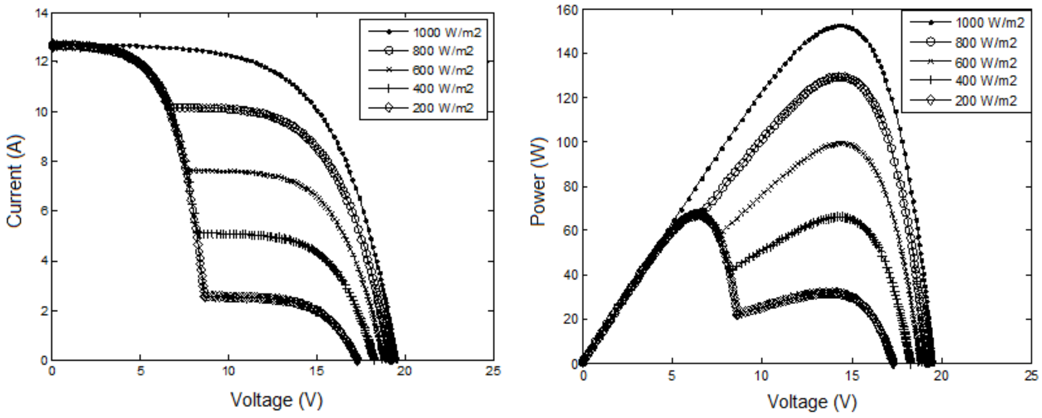
(b) *P*-*V* curves

FIGURE 6. Simulation results of constant $E = 1000$ W/m^2, $T_c = 20\text{-}50$℃

where there will be voltage reduction in increasing of cell temperature. The open-circuit voltage reduction is about 3-4 Volt and consequently the reduction in output power (*P*-*V* curve), although the short-circuit current increases with the increase in irradiance. Therefore, if the assumption is about no effect of temperature variation to open-circuit voltage in thin-film CIGS technology, then the additional voltage of this reduction should be provided in the proposed model.

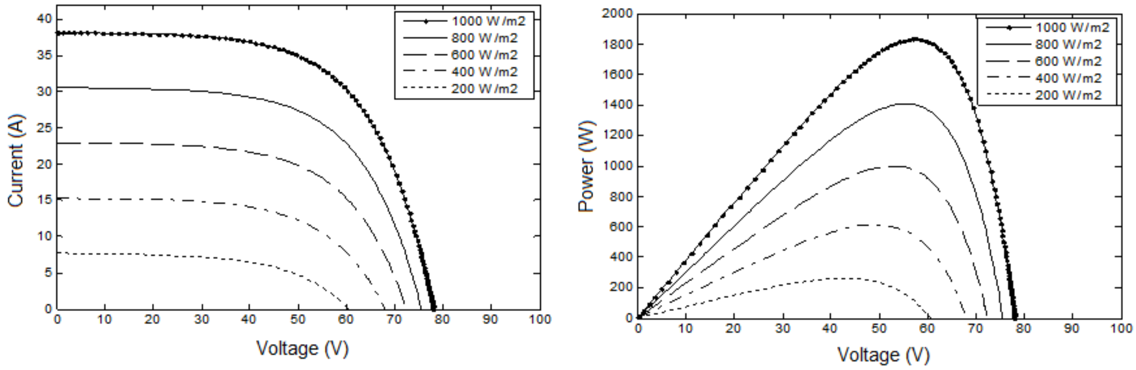
In the following scenario, the electrical *I*-*V* and *P*-*V* characteristics of thin-film CIGS PV module are simulated with constant irradiance of 1000 W/m^2 and cell temperature is varied from 20℃ to 50℃ by increment of 5℃. It can be seen at standard test condition (STC) of 1000 W/m^2 and 25℃, the open-circuit voltage is about 23.5 V. This voltage is reduced when the cell temperature increases due to the significant value of negative voltage temperature coefficient in mono-crystalline Silicon PV module. At cell temperature of 50℃, the open-circuit voltage is reduced below 20 V; while the short circuit current does not change significantly when the cell temperature is fluctuated. The current, voltage and power variation can be viewed in Figure 6.

Under PV module testing, the partial shading operation is simulated by varying the irradiance of 1st-18th cells in Figure 3 from 200 W/m^2 to 800 W/m^2, while the irradiance in 19th-36th cells is kept 1000 W/m^2 under 50℃ of cell temperature. The results of *I*-*V* and *P*-*V* curves measurement are shown in Figure 7. The results show that there are two peak power points and it is important to operate the controller at the maximum power point. The significant output power can be gained when the first part of module is shaded at 200 W/m^2 if the controller can shift the operating voltage from conventional threshold voltage



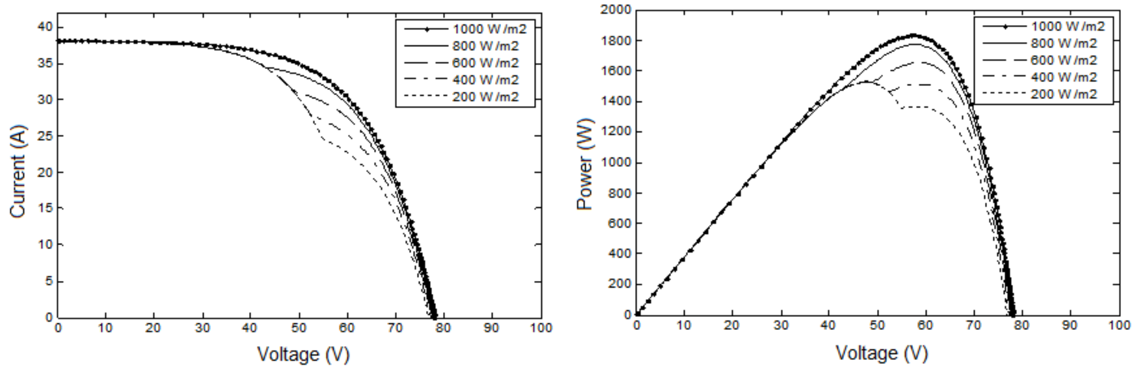
(a) *I*-*V* curves (b) *P*-*V* curves

FIGURE 7. The partially shaded scenario based PV module measurement



(a) *I*-*V* curves (b) *P*-*V* curves

FIGURE 8. Uniform irradiance conditions of SP 4 × 3 PV array configuration



(a) *I*-*V* curves (b) *P*-*V* curves

FIGURE 9. The partially shaded conditions of SP 4 × 3 PV array configuration

operation. Special control method should be deployed under this condition. Meanwhile, under the remained shading condition, the performance of conventional controller can still be acceptable.

The last scenario of testing is the comparison operation between uniform irradiance and partially shaded conditions under constant cell temperature of 50℃ of series-parallel

(SP) configuration of 4 × 3 PV arrays. The cell temperature is notified as the common temperature operation of PV array. The uniform irradiance operation condition of irradiance varying from 200 W/m^2 to 1000 W/m^2 is shown in Figure 8. In this result, the short-circuit current is folded three times, the open-circuit voltage is increased four time from the PV module based measurement and consequently, the maximum output power may reach 12 times (about 1800 W). Meanwhile, the partially shaded condition is tested by varying the irradiance from 200 W/m^2 to 1000 W/m^2 in one module. In Figure 9, it is obtained of the similar results to the shading scenario in PV module measurement where the shading of one module with 200 W/m^2 requires special controller in order to reach the better maximum power. Meanwhile, the performance of conventional controller and special designed controller will be almost similar in the remaining shading scenario. If the number of shaded module increased, of course the shifting optimum voltage occurs and consequently the special designed controller is totally needed.

5. **Conclusions.** This paper has proposed approached modeling of thin-film CIGS PV technology adopting the model of conventional mono-crystalline Silicon PV technology. In general, the technology of thin-film CIGS is much more complex than the mono-crystalline Silicon denoted by complex composing material structure and equivalent circuit. The validation shows that the approached model of conventional mono-crystalline Silicon PV technology is good enough to represent the electrical characteristic model thin-film CIGS PV module. The proposed model has been tested with PV module base under standard test condition, constant temperature of 50℃, constant irradiance of 1000 W/m^2 and partial shading operation. In addition, the proposed model has also been tested on 4 × 3 PV array with series-parallel connection under uniform and non-uniform irradiance conditions. The overall results show the model performance is highly affected by the negative voltage temperature coefficient of mono-crystalline Silicon where the open-circuit voltage decreases with high temperature. Nevertheless, the accuracy has been confirmed high to indicate that the approached model of Silicon may be used to CIGS model with some voltage adjustment, especially under low irradiance level.

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