Experimental Analysis for Temperature Effect on Amorphous Silicon (A-Si) Photovoltaic Module Using Automatic Load Selection System

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Abstract— Temperature and solar irradiance are the two dominating cardinals that determine the electrical performance of Photovoltaic (PV) module. In this paper, an experiment is conducted considering Amorphous Silicon (A-Si) PV module in both indoor and outdoor condition to investigate the temperature effect on A-Si module's performance in terms of efficiency and output power through an automatic resistor selection system. The experimental result shows that A-Si PV module has small temperature coefficient effect; however it has higher effect on solar radiation coefficient. A comparison analysis is evaluated with different models to validate the experimental data.

Keywords- Amorphous silicon; photovoltaic module efficiency; temperature effect; module operating temperature

I. INTRODUCTION

The key finding of the solar energy by Southeast Asia Bangkoker, Thailand was that thin film module technology is competitive in terms of technical and economical performance in Southeast Asia region [1]. Moreover, one of the thin film aging and largest manufacturer companies, First Solar has forecasted to reduce the price (US$0.40/W) by 2017 with increased efficiency [2]. Due to the competitive price of advanced thin film modules, lower temperature coefficient, enhanced efficiency [3], flexible, frameless mounting structure, and lower weight over the crystalline modules, the thin film becomes more attractive for residential feed in tariff or standalone application in tropical countries. A comparison among different commercial module efficiencies is shown in Fig. 1. This data depict that First Solar offered 15% efficient thin film by 2017 which could reach equal efficiencies of other crystalline modules.

Yamawaki et al. have experimented in order to inspect the differences of the generated powers for the roof azimuth [4]. Based on their report, an automated measuring system was proposed for this analysis and considered Amorphous Silicon (A-Si) Photovoltaic (PV) module which was installed on the roof top of the wooden house. The outcome of the analysis was based on total power production varies for azimuths which are 97.9% (east), 89.7% (west), 78.1% (north), and 100% (south). However, the aftermath of the analysis result may be different on location and also time of the year due to the latitude of the sun. Considering cell temperature as a central factor on output power and electrical efficiency of the PV module, Skoplaki et al. have proposed models applicable for arbitrary mounting where the mounting parameter was determined by a variable [5]. Another research conducted on two types of thin film modules namely CdTe and CIGS where the researchers developed and executed a test plan to probe transitory electrical behavior and performance of these modules and applied it to several groups of modules totaled number of 28. The result showed that CIGS and CdTe module type stabilize quickly within the first two exposure steps [6]. The effects of temperature on PV modules investigated by [7] where the researchers have used basic equation to relate among electrical efficiency, solar irradiance, ambient and cell temperature. The simulation has shown the linear and inversely proportional relation between module efficiency and ambient temperature.

From these literature analysis, it is seen that the real data analysis on performance of A-Si type PV module has not been conducted yet considering the temperature effect. In this paper, we have taken in to account A-Si module and analyzed performance based on the variation of the load, both in indoor (where ambient temperature was controlled to

![Fig. 1 Module efficiencies offered by manufactures (Source: GTM research PV pulse, April 2014)]
be constant to 25°C and outdoor climate condition (variable temperature). The performance was analyzed in order to study the temperature effect on efficiency and output power of A-Si module. To conduct this experiment, a microcontroller based automatic resistor selection system was developed for hourly data collection.

II. TEMPERATURE EFFECT ON PERFORMANCE OF PV MODULE

Thin film solar module certainly performs less efficiently compare to mono/poly-crystalline module when Standard Temperature Condition (STC) measurement is considered (STC measurement: 25°C ambient temperature, 1000W/m² solar irradiance, 1.5 air mass, 1m/s wind speed). However, in real climate condition, the efficiency and output power vary due to high ambient/cell temperature, intermittent solar flux, wind speed, air mass, and humidity. Due to this variation, many researchers have proposed models for obtaining module efficiency and output power.

A. Effect on Efficiency

A-Si module possesses the thermal recovery effect and the generating power has an effect with the increase of the module temperature. Similarly the generating powers on the crystalline or polycrystalline solar cells have significant negative effect with the increase of cell temperature. In order to find the temperature effect on efficiency, traditional PV electrical efficiency is measured by the following (1) [8]:

$$\eta_c = \eta_{T_{ref}}[1 - \beta_{ref}(T_c - T_{ref})]$$  \hspace{1cm} (1)

Another temperature effect formula is proposed by [9] mentioned in (2) as follows:

$$\eta = \eta_{T_{ref}}[1 - \beta_{ref}(T_c - T_{ref}) + \gamma \log_{10}(G_T)]$$  \hspace{1cm} (2)

Then the model is proposed by [10] shown in (3).

$$\eta = 0.94 - 0.00043\left[\frac{T_a - \beta_T}{22.4+8.7\omega} - 25\right] \pm 2.6\%$$  \hspace{1cm} (3)

where, $\eta$ is the instant module efficiency, $\eta_c$ is the module efficiency, $\eta_{T_{ref}}$ is the module efficiency at the reference temperature, $\eta_{NOC}$ is the module efficiency at normal operating cell temperature, $\beta_{ref}$ is the temperature coefficient, (for A-Si: 0.0025K⁻¹), $T_{ref}$ is the reference temperature (298.15K), $T_c$ is the module operating temperature (K), $T_a$ is the average day ambient temperature (K), $G_T$ is the solar irradiance on module plane (W/m²), $\gamma$ is the solar radiation coefficient which is equal by 0.12, $\beta_T$ is the total solar irradiance received (W/m²)/day length (hour) and $\omega$ is the wind speed drive through module surface (m/sec).

B. Effect on Output Power

The prediction of PV module performance in terms of electrical power output in the field, that is, the deviation from the standard test conditions reported by the manufacturer of the module, can be modeled. The correlation among output power, voltage, current, cell temperature and solar irradiance form many mathematical models to PV module output power. Some of them are as follows:

$$P = V_r I_r [1 - \frac{G_T - 500}{2 \times 10^4} + \frac{C_T}{4 \times 10^4}(50 - T_c)^2]$$  \hspace{1cm} (4)

Equation (4) determines the relation for predicting output power using module/cell current-voltage, harvested solar irradiance, cell temperature and a parameter ($C_T$) related to cell temperature [11]. The model for predicting output power shown in (5) considers module reference efficiency, surface area, cell temperature, and harvested solar irradiance [12].

$$P = \eta_{T_{ref}} A G_T [1 - 0.0045(T_c - 298.15)]$$  \hspace{1cm} (5)

Lastly considered another model for output power is mentioned in (6) [13].

$$P_{max} = P_{max,ref} \frac{G_T}{G_{T_{ref}}} [1 + \gamma(T_c - 25)]$$  \hspace{1cm} (6)

where $V_r$ is the module output voltage (V), $I_r$ is the module output current (A), $A$ is the module surface area (m²), $P$ is the module output power (W), $P_{max}$ is the module maximum power (W), $P_{max,ref}$ is the module maximum power at reference temperature (°C), $G_{T_{ref}}$ parameter is 1 when the $T_c < 50°C$ and 3 for $T_c \geq 50°C$ and $G_{T_{ref}}$ is the Reference solar irradiance (W/m²).

III. EXPERIMENTAL SETUP

A Flexible type A-Si PV module capacity 0.72W 230mmx74mm (lengthxwidth) with different 13 loads was chosen. Fig. 2 shows experimental layout while installing equipment and collecting data. It includes an automatic resistor selection system that can read PV output voltage in every one hour interval for all different loads. The automatic resistor selection system is consisted of transistor relay driver circuits and data collection and characteristics analysis of the flexible PV module. The transistor relay driver circuit which is shown in Fig. 2(a) includes a 6V supply battery, 13 transistors (BC337), the 13 resistors which are connected to the base of each transistor, 5V relays and freewheeling diode (1N4007) that eliminate back-EMF which is generated by relay’s coil when the relay switches off and as a result it protects the transistor. A programmable Arduino UNO microcontroller board to control which switch should be on and which switched must be off.

Data collection and characteristics analysis of the flexible PV module is shown in Fig. 2(b). The microcontroller program in Arduino UNO is developed in such a way that the system wakes up in every hour interval and reads the 13 different voltages produced by the PV module across the 13 different resistive loads and the current pass through each load. Moreover, the value of ambient temperature and humidity nearby the A-Si flexible PV module is also collected. Then it goes to the ‘sleep’ mode. The ‘sleep’ mode enables the program to consume less energy from the supply battery, thus increases the lifespan of the battery and reduces
the functionality of the microcontroller sub-systems. The data is saved into a non-volatile memory card (e.g. SD card) attached with the Arduino UNO. Finally, the data are collected from the SD card at the day end for further analysis. The position of the A-Si module is on fixed plane with 15° tilted.

IV. DATA COLLECTION AND ANALYSIS PROCESS

Instead of using a static single load, different 13 loads are chosen for dynamic analysis of PV module. This provides an ability to produce the V-I curve of the PV module. Moreover, we distribute the resistive load values as 10, 20, 51, 100, 200, 510, 1k, 2k, 5.1k, 10k, 20k, 51k and 100kΩ, in order to cover a wide range of resistance variation in logarithmic scale. Therefore, we can find a dynamic maximum power point (MPP) as a function of load resistance where the internal resistance of PV module varies due to the irradiation and temperature at different hours of a day during data harvesting. Also, we have used Arduino UNO embedded board to develop the resistor selection system; it allows using only its 13 digital pins to control the 13 relays.

In this study, graphs of produced voltage, current and output power when the resistive load varied between 10 to 100kΩ, from 8AM to 5PM are extracted. Based on these information, the dynamic V-I curve of the PV module is plotted. Therefore, the MPP which is dynamic as a function of time can be taken out from two graphs (V-I curve and output power vs. resistive load). All graphs are produced for indoor and outdoor installation of A-Si PV module.

V. RESULT AND ANALYSIS

The characteristics of A-Si is analyzed based on outdoor and indoor condition where outdoor climate condition is hot-humid (maximum ambient temperature was 34.7°C 60% humid) and indoor temperature was maintained 25°C 50% humidity.

Fig. 3(a) shows this result of produced voltage by A-Si PV module vs. variation of resistive load from 10 to 100kΩ when the PV module installed indoor. Fig. 3(b) shows the same result for outdoor condition. It can be observed that the PV module can produce more voltage in lower resistive load when it is installed outdoor. For instance, the median of the produced voltage at 10Ω resistive load in indoor condition is 0.15V. However, this value is increased to 1V for outdoor condition. The reason is that the PV module can receive more irradiation in outdoor condition which may result more produced voltage in lower load resistance.

In both of indoor and outdoor conditions there is positive correlation between variations of the resistive load and the produced voltages. The rate of this positive correlation is low in the first decade. But it is significantly increased for the second decade and again it reduced for the next two decades (saturated). In indoor condition the produced voltage is saturated for loads which are greater than 5kΩ, but in outdoor condition, this saturation occurs where the resistance is higher than 1kΩ. The median voltage at saturation point of 5kΩ for indoor condition is 8.975V, but the median 8.975V is produces at saturation point of 1kΩ for outdoor condition.

The PV module can produce maximum median of 9.09V in indoor and 9.28V in outdoor condition where the load is maximum at 100kΩ. The maximum voltage at 1PM where the load of 100kΩ is connected to the PV module can be read...
9.20V for indoor condition and 9.37V for outdoor condition. In the afternoon for outdoor condition with the same amount of irradiation, a lower voltage is produced. The reason is that the voltage production is reduced by increasing the ambient temperature. This effect is less significant for indoor condition which the ambient temperature is controlled to be constant.

Fig. 4(a) shows the result of the current vs. variation of resistive load from 10 to 100kΩ when the PV module is installed indoor. Fig. 4(b) shows the same result for outdoor condition. It can be observed that the PV module can produce more power when it is installed outdoor. For instant, the maximum power at 1PM in indoor condition is 113.3mW. However, this value is increased to 571.8mW for outdoor condition. The reason is that the PV module can receive more irradiation for outdoor condition which may result producing more power.

In both indoor and outdoor conditions, the MPP is varying by changing the time. For instant, in indoor condition the MPP at 1PM is happened where the resistive load is 510Ω, but the MPP at 5PM is occurring where the resistance of the load is 1KΩ. The same thing occurred for outdoor condition. The MPP at 1PM is happened where the resistive load is 51Ω, but the MPP at 5PM is changed to where the load resistance is 510Ω.

The maximum current of 21mA occurs at 1PM where the minimum load of 10Ω is connected to the PV for indoor condition. However, the maximum current of 129mA is passed through the resistive load of 10Ω at 1PM for outdoor condition. In the afternoon for outdoor condition with the same amount of irradiation, a lower current can be supplied. The reason is that the current reduced by increasing the ambient temperature. This effect is less significant for indoor condition which the ambient temperature is controlled to be constant.

Fig. 5(a) shows the result of the produced power vs. variation of resistive load from 10 to 100kΩ when the PV module is installed indoor. Fig. 5(b) shows the same result for outdoor condition. It can be observed that the PV module can produce more power when it is installed outdoor. For instant, the maximum power at 1PM in indoor condition is 113.3mW. However, this value is increased to 571.8mW for outdoor condition. The reason is that the PV module can receive more irradiation for outdoor condition which may result producing more power.

In both indoor and outdoor conditions, the MPP is varying by changing the time. For instant, in indoor condition the MPP at 1PM is happened where the resistive load is 510Ω, but the MPP at 5PM is occurring where the resistance of the load is 1KΩ. The same thing occurred for outdoor condition. The MPP at 1PM is happened where the resistive load is 51Ω, but the MPP at 5PM is changed to where the load resistance is 510Ω.
Same as the results for the produced voltage and the current, in the afternoon for outdoor conditions with the same amount of irradiation, a lower power can be generated. The reason is that the power generation reduced by increasing the ambient temperature. This effect is less significant for indoor condition which the ambient temperature is controlled to be constant.

Fig. 6(a) shows the result of the I-V curve in different times from 8AM until 5PM when the PV module is installed indoor. Fig. 6(b) shows the same result for outdoor condition. By comparing between the indoor with the outdoor results, significant differences can be observed. The V-I curve can significantly be affected by the effects of the irradiation and temperature. The irradiation changes by varying the time and changing the sun angle, but with the same amount of irradiation during morning and afternoon, different voltages and current can be produced. This phenomenon is less significant for indoor condition that the temperature is controlled to be constant. The reason is that the higher temperature during afternoon significantly reduces the efficiency and performance of the A-Si PV module.

In Fig. 5 and Fig. 6, the change of the line which show the maximum power in indoor and outdoor conditions can be observed. It is found that the internal resistance of the A-Si PV module can be reduced by increasing the irradiation and reducing the ambient temperature. However, the effect of increasing the irradiation is more significant.

Table 1 presents the efficiency comparison between the outdoor experimental and different models from the literature. The obtained efficiency from the experimental result is approximately similar to (1) (18.11% difference), and (3) (8.50% difference); however (2) does not validate our experimental obtained efficiency (38.82% difference). Then Table 2 compares between the experimental outdoor and indoor characteristics key features and it shows outdoor experiment achieves better efficiency (3.12%) compare to indoor results (1.1%) even though the indoor temperature was maintained 25°C. The STC result is according to the datasheet of the manufacturing company which is always at the best performance. The obtained FF for both indoor and STC is similar whereas outdoor shows slightly weaker performance. The analysis shows that A-Si module has not any significant effect on cell temperature.

Table 3 shows the experimental outdoor result and different models based on output power. Output power of the PV module is analyzed based on Max, Min, and Avg data.
Temperature is not only key factor that effect on PV module output power and overall module efficiency but also other environmental factors are significant. Rather the experimental analysis conducted on A-Si module with respect to variation of the load shows that cell temperature at 25°C and reduced solar irradiance yield only 27.4% of its maximum efficiency. In contrast, outdoor experimental with ample solar irradiance but fluctuate and high cell temperature produces 78% of its maximum efficiency. All the data are validated considering different models where our data error rate is within 18.5%.

VI. CONCLUSION

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REFERENCES


Table 1: Comparison between outdoor and different models in terms of efficiency due to temperature effect

<table>
<thead>
<tr>
<th>Experimental avg. cell temp. (°C)</th>
<th>Experimental efficiency (%)</th>
<th>Obtained efficiency from models (%)</th>
</tr>
</thead>
</table>

Table 2: Comparison among STC, outdoor and indoor results

<table>
<thead>
<tr>
<th>Key features</th>
<th>STC</th>
<th>Outdoor</th>
<th>Indoor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{oc}$ (V)</td>
<td>10.5</td>
<td>9.5</td>
<td>9</td>
</tr>
<tr>
<td>$I_{sc}$ (A)</td>
<td>0.125</td>
<td>0.125</td>
<td>0.02</td>
</tr>
<tr>
<td>$V_{max}$ (V)</td>
<td>7.2</td>
<td>5.25</td>
<td>7.7</td>
</tr>
<tr>
<td>$I_{max}$ (A)</td>
<td>0.11</td>
<td>0.105</td>
<td>0.015</td>
</tr>
<tr>
<td>Module efficiency (%)</td>
<td>4.0</td>
<td>3.12</td>
<td>1.1</td>
</tr>
<tr>
<td>Fill factor</td>
<td>0.6</td>
<td>0.5</td>
<td>0.6</td>
</tr>
</tbody>
</table>

$V_{oc} =$ Open circuit voltage; $I_{sc} =$ Short circuit current $V_{max} =$ Maximum voltage; $I_{max} =$ Maximum current

Table 3: Comparison between outdoor and different models in terms of output power due to temperature effect

<table>
<thead>
<tr>
<th>Variables obtained from experiment</th>
<th>Experimental avg output power (W)</th>
<th>Obtained output power from models (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{oc}$ = 0.02 V</td>
<td>0.019 (Min)</td>
<td>Eq. (4): 0.052 [11]</td>
</tr>
<tr>
<td>$C_{p1}$ = 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\min G_{c} =$ 77 W/m$^2$</td>
<td>0.22 (Avg)</td>
<td>Eq. (5): 0.27 [12]</td>
</tr>
<tr>
<td>$T_c =$ 306.22 K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A =$ 0.017 02 m$^2$</td>
<td>0.56 (Max)</td>
<td>Eq. (6): 0.551 [13]</td>
</tr>
<tr>
<td>$\min G_{c,2}$ = 35.6 W/m$^2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(Avg.)T_c =$ 316.882 K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{max,ref} =$ 0.72 W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_c =$ 46.17°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$G_{c} =$ 820 W/m$^2$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Max=Maximum, Min=Minimum, Avg=Average

where (4), (5), and (6) are followed respectively. Considering Max, Min, and Avg data, the obtained experimental output power 0.56, 0.019, 0.22 W where the percentage differences are 1.63% (6), 18.5% (5), and 63.41% (4) respectively. The overall analysis presents that our experimental analysis validates with most of the considered models.