A Low-cost Device for Measuring the PV Module Performance

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Abstract—This paper presents the design and construction of a low-cost device for PV module performance assessment. This device able to measure the PV module output parameters: open circuit voltage (Voc), short circuit current (Isc), module maximum power (Pmax) and efficiency (η). The device is designed and constructed with simple electronic components. A Matlab/Simulink based mathematical model of PV module was developed to compare the performance of the device. The performance testing experiment had been done with a standard 40W PV module under direct Sun light for five different irradiance levels. The performance testing experiment had been done with a standard 40W PV module under direct Sun light for five different irradiance levels of 150 W/m², 910 W/m², 950 W/m², 990 W/m² and 1020 W/m². The value of Voc, Voc, Pmax and η obtained from the constructed device shows nearly agreeable result with the values obtained from the LIV tester and Matlab/Simulink simulation. The device is portable and can be used to test the PV module performance estimation where PV module performance testing facility is not available.

Index Terms—Solar PV module, performance testing, device construction, Matlab/Simulink model, LIV tester. (key words)

I. INTRODUCTION

Among the renewable energy resources such as wind, geothermal, solar, tidal, biomass etc, and solar energy is the most promising alternative energy source. Solar cells or photovoltaic (PV) cells convert sunlight directly into electricity. They are basically made of PN junction. A single solar cell produces small amount of voltages in the range of 0.5 to 0.8 volts depending on the semiconductor materials and the processing technology. This low voltage cannot be used in commercial purpose. PV module is formed by connecting 36 to 72 PV cells in series. These modules can be interconnected in series and/or parallel to form a PV system [1].

The study the behavior of solar PV module for different field condition in the laboratory is an expensive and time consuming task. The LIV tester is equipment that provides illumination approximating natural sunlight. The purpose of the LIV tester is to provide a controllable indoor test facility under standard test conditions, used for the testing of solar panels. But LIV tester is extremely expensive and not available everywhere worldwide as well as in our country. Thus, there are crying need everywhere to measure the output performance of the required PV panel.

A Matlab/Simulink based modeling of solar PV module for performance testing is presented in this paper. This developed model allows the prediction of PV module behavior under different field conditions such as temperature and irradiance and investigates I-V and P-V characteristics. To measure the PV module maximum power (Pmax) and efficiency (η), a low cost device was designed and constructed. This device can measure and monitor solar PV module parameters. This device measures PV parameters of a solar panel: open circuit voltage (Voc), short circuit current (Isc) and irradiance on the panel and temperature. The maximum power and efficiency obtained from a PV module can be calculated using the value obtained from this device. The device shows almost similar values of the PV module parameters which was measured by the LIV tester and obtained from simulation.

The Matlab/Simulink model will be discussed first, then the design and construction of the device and finally a comparison of PV module performance obtained from LIV tester, device and simulation will be shown together for final comparison to show that the device is working efficiently.

II. DESIGN AND CONSTRUCTION OF THE DEVICE

A. Components used in the device

Main components of the device are current sensor (ACS712T), temperature sensor (LM 35), miniature silicon photodiode (BPW 34), microcontroller, LCD etc.

B. Hardware development and operation

In this study PIC 16F690 was chosen as microcontroller which operates based on a program created using mikroC software. Voc of PV panel is measured by voltage divider technique. Voltage across the small valued resistor provided the analog voltage input for analog to digital converter (ADC) port on microcontroller. Device block diagram is given in Fig. 4.

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ADC converted the analog voltage into digital forms. $I_{sc}$ of PV module is measured by ACS712T, which converts the current to equivalent voltage and ADC converted it into digital forms. LM35 changes the output voltage with the changes of temperature. It is also connected to ADC. Irradiance is converted to current by BPW 34. A current to voltage converter circuit converted the current to voltage and connected to ADC for transcription into digital form. All the inputs processed by microcontroller and measured values are displayed into the LCD.

### III. MATLAB/SIMULINK BASED MATHEMATICAL MODEL

To determine the PV module’s behavior theoretically at different irradiance a mathematical model is developed based on some equation.

#### A. Equivalent circuit of a solar cell

A solar cell converts light which means a flow of photons, to electric current. The equivalent circuit of a PV cell is as shown in Fig. 1:

![Fig. 1: Equivalent circuit of a solar cell](image)

The current source $I_{ph}$ represents the cell photocurrent. $R_{sh}$ and $R_{s}$ are the intrinsic shunt and series resistances of the cell, respectively. Usually the value of $R_{sh}$ is very large and that of $R_{s}$ is very small.

PV cells are grouped in larger units called PV modules which are further interconnected in a parallel-series configuration to form PV arrays.

#### B. Equation for developing PV module in Simulink

According to this single diode model the relationship between cell current and voltage can be determined by using following formula[1]:

$$I_{pv}=I_{ph}-I_{o}[\frac{q(V_{pv}+I_{pv}R_{s})}{AKT}-1]-\frac{(V_{pv}+R_{s}I_{pv})}{R_{sh}}$$

(1)

If we think for PV module with $N_{p}$ number of parallel and $N_{s}$ number of series cell the equation of output current [1] of PV module is given below

$$I_{pv}=N_{p}I_{ph}-N_{o}[\frac{q(V_{pv}+I_{pv}R_{s})}{N_{o}A KT}-1]-\frac{(V_{pv}+R_{s}I_{pv})}{R_{sh}}$$

(2)

Where $V_{pv}$ is output voltage of a PV module (V)

$I_{pv}$ is output current of a PV module (A)

$I_{ph}$ is the light generated current in a PV module (A)

$I_{o}$ is the PV module saturation current (A)

$A$ is an ideality factor which is between 1-2. For this simulation 1.5 taken[4].

$k$ is Boltzman constant $= 1.3805 \times 10^{-23}$ J/K

$T$ is the module operating temperature in Kelvin

$q$ is electron charge $= 1.6 \times 10^{-19}$

Generally the values of the open-circuit voltage ($V_{pv}$), short-circuit current ($I_{sc}$), maximum power point ($P_{max}$), current and voltage at the maximum power point, ($V_{mp}$ and $I_{mp}$) are provided in the manufacturer’s datasheet under standard Test conditions (STC) (irradiance = 1000 W/m², temperature = 25°C, air mass = 1.5).

The photocurrent ($I_{ph}$ ) can be determined by the following equation[3].

$$I_{ph} = [I_{sc} + K_{i}(T - 298)] \times G$$

(3)

$K_{i}$ short circuit current coefficient[3]=0.0017 A/$^\circ$C and $G$ irradiance

The diode saturation current can be determined from the following formula[2].

$$I_{o} = I_{rs} \left[\frac{T}{T_{r}}\right]^{3} \times e^{-\frac{qE_{g}}{AK} \left[\frac{1}{T} - \frac{1}{T_{r}}\right]}$$

(4)

The proposed simulation model of solar module is based on the simulation of solar cell as the smallest building block. The simulation model is based on equation (1-4) in Matlab/Simulink environment. In the simulation model it was taken 36 cell are series connected and 1 in parallel. Series resistance ($R_{s}$) and shunt resistance ($R_{sh}$ ) was taken from the module data sheet. In our simulation model we have changed the value of open circuit voltage from 0 to $V_{pv}$ of the particular module using signal builder block. The irradiance was varied using signal builder block at fixed temperature. Again the temperature was varied at a fixed irradiance by a signal.
builder block. Then from the simulation, I-V characteristics graph P-V graph characteristics of the module was obtained. The internal block diagram and final Simulink block diagram of the module are shown in Fig. 2 and Fig. 3.

![Fig. 2: Internal block of PV module based on equation (1-4)](image1)

![Fig. 3: Final simulink block diagram of the PV module with input P-V curve and I-V curve at different irradiance obtained from the simulation. P_max and efficiency then calculated.](image2)

**IV. PERFORMANCE OBSERVATIONS**

Upon completion of prototype device, the performance is compared with the commercially used LIV tester. A standard 40 W PV module is selected for test. Table 1 provides the specification of the PV module.

<table>
<thead>
<tr>
<th>Maximum power (P_max)</th>
<th>40.7 W (Measured at standard test conditions: 25°C, 1000W/m² irradiance, AM 1.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage at maximum power (V_mp)</td>
<td>17.2 V</td>
</tr>
<tr>
<td>Current at maximum power (I_mp)</td>
<td>2.37 A</td>
</tr>
<tr>
<td>Open circuit voltage (V_oc)</td>
<td>21.1 V</td>
</tr>
<tr>
<td>Short circuit current (I_sc)</td>
<td>2.53 A</td>
</tr>
<tr>
<td>Number of cells in the PV module</td>
<td>36</td>
</tr>
</tbody>
</table>

Each cell area: 11cm × 7cm = 77 cm²
Total area occupied by the cell of the PV module = 36 × 77 cm² = 2772 cm²
The field test result from device is presented in Fig. 5 and the measured results with LIV system is presented in Fig. 6.

![Fig. 5: Result from device for a irradiance level](image3)

![Fig. 6: Result from LIV tester for irradiance 990 W/m²](image4)

The module output parameters at different irradiance level has been obtained from LIV tester and presented in Table 2.
device provides $V_{oc}$ and $I_{sc}$ for different irradiance level and presented in Table 3. The power and efficiency from the device were calculated using simple formula.

**TABLE II. SUMMARY OF THE RESULT OBTAINED FROM LIV TESTER**

<table>
<thead>
<tr>
<th>Irradiance (W/m²)</th>
<th>Data from LIV tester</th>
<th>$V_{oc}$ (V)</th>
<th>$I_{sc}$ (A)</th>
<th>FF</th>
<th>$P_{max}$ (W)</th>
<th>$\eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>16.61</td>
<td>0.19</td>
<td>0.667</td>
<td>2.175</td>
<td>0.874</td>
<td></td>
</tr>
<tr>
<td>910</td>
<td>17.65</td>
<td>1.98</td>
<td>0.612</td>
<td>21.44</td>
<td>7.736</td>
<td></td>
</tr>
<tr>
<td>950</td>
<td>17.55</td>
<td>2.16</td>
<td>0.574</td>
<td>21.72</td>
<td>7.854</td>
<td></td>
</tr>
<tr>
<td>990</td>
<td>17.64</td>
<td>2.14</td>
<td>0.577</td>
<td>21.88</td>
<td>7.878</td>
<td></td>
</tr>
<tr>
<td>1020</td>
<td>17.98</td>
<td>2.18</td>
<td>0.583</td>
<td>22.87</td>
<td>8.250</td>
<td></td>
</tr>
</tbody>
</table>

From Table 2 and Table 3 it is evident that prototype device provides almost agreeable result with the measured values of commercial LIV tester. As there is a little difference in the two results a percentage of error was calculated to quantify the performance of the device with the commercial LIV tester. Error measurement for prototype device is tabulated in Table 4. The percentage of error between measured value of a quantity $x_o$ and its actual value $x$ is given by the following formula.

$$\text{Percentage error (PE)} = \frac{x_o - x}{x} \times 100\%$$

**TABLE IV. PE OF DEVICE FOR $V_{oc}, I_{sc}$**

<table>
<thead>
<tr>
<th>Observation</th>
<th>PE of $V_{oc}$ (%)</th>
<th>PE of $I_{sc}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-3.67</td>
<td>-3.26</td>
</tr>
<tr>
<td>2</td>
<td>-1.98</td>
<td>-1.02</td>
</tr>
<tr>
<td>3</td>
<td>-2.56</td>
<td>0.925</td>
</tr>
<tr>
<td>4</td>
<td>-1.92</td>
<td>-1.4</td>
</tr>
<tr>
<td>5</td>
<td>-2.66</td>
<td>0</td>
</tr>
</tbody>
</table>

The device showed acceptable result for both $V_{oc}$ and $I_{sc}$. The PE is smaller with higher irradiance level. For further more investigation a simulation has been done with Matlab/Simulink with the same condition for comparison purpose. The I-V and P-V curve obtained from simulation for observation 1 at irradiance level of 990 W/m² shown in Fig. 7 and Fig. 8 respectively.

**Fig. 7: I-V curve from simulation**

**Fig. 8: P-V curve from simulation**

Similarly, Four more simulations were done at irradiance 150 W/m², 910 W/m², 950 W/m², 990 W/m², 1020 W/m². Comparison of $P_{max}$ and $\eta$ using LIV tester, prototype device (calculated value) and simulation for five different observations is given in Fig. 9 & Fig. 10.

**Fig. 9: Comparison of module power measured by LIV tester, device and simulation**

**Fig. 10: Comparison of module power measured by LIV tester, device and simulation**
From the comparison shown in Fig. 9, it has been shown that the LIV tester, simulation and prototype device (calculated value) provides almost same efficiency for a particular irradiance value. The device shows quite agreeable result compared with the LIV tester and simulation.

From Fig. 10, it is also found that the module efficiency measured by the device is quite similar as obtained from the LIV tester and from simulation. The device shows quite good performance for at measuring the module efficiency. After final comparison, it is found that the device can measure maximum power and efficiency obtained from a particular a PV module quite effectively and constructing of this device requires a very low cost as compared to the LIV tester.

V. CONCLUSION

The performance of the 40W PV module had been tested with five different irradiance level under direct sun light at 150 W/m², 910 W/m², 950 W/m², 990 W/m², 1020 W/m². Then the performance of this prototype device has been compared with LIV tester and the result obtained from the simulation. The result obtained from the device shows agreeable results with the measured values from the LIV tester and simulation which confirms that this device can be successfully used for the PV module performance checking in a low cost where LIV tester is not available. This device is also portable which is very helpful if it is required to check the PV module performance in a remote area where lab facility is not available.

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REFERENCES


