



Designing and Construction of a Solar Panel Simulator Capable of Simulating Partial Shading Conditions

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A B S T R A C T

Given the increasing popularity of solar energy and producing its accessory equipment in Iran, like DC/DC converters, and since for studying and comparing converter's performance or developed algorithms to extract the maximum power from converter, it is necessary to test it under uniform conditions, but due to various interfering factors such as hourly, daily, and spatial variation of solar radiation intensity or unpredictable shading on panels, the tests have to be performed using a simulator. Therefore this paper derives a new set of relations to simulate the panel's performance under partial shading conditions and a simulator is constructed accordingly. By holding the temperature constant, the converter's performance is studied for both uniform illumination and partial shading conditions. Result of studies carried out for uniform illumination under standard conditions and partial shading in conditions under which one third of cells received 600 w/m^2 and the rest received 1000 w/m^2 , indicated a good agreement between the converter's performance and ideal I-V and P-V curves of solar panel.

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1. Introduction

While solar energy use is increasingly growing, testing the performance of the relevant equipment has turned into one of the most important issues in photovoltaic systems [1]. The commercially available software packages such as P-Spice, DesignPro, Solarpro, Pvcad, and PVsyst are relatively complex and expensive and they barely support the connection of PV arrays to converters [2]. A comprehensive PV system simulator has to be capable of fast yet accurate prediction of P-V and I-V characteristic curves under various conditions including partial shading. Most of the simulators proposed in previous research are developed for uniform radiation conditions. The aim of this study is to design and construct a solar panel simulator capable of simulating partial shading conditions.

A PV simulator is a useful experimental tool for studying PV power generation systems. PV simulator provides for testing new power management algorithms and estimating system's efficiency under dynamic environmental conditions [3]. Recent works on PV simulation are reviewed in the following:

Atlas and Sharaf [4] presented a PVA simulation model to be used in graphical environment of GUI Matlab-Simulink [4]. Their proposed model was a general structure that could be used as a PV source by deploying the appropriate interface circuits and controllers accompanied by wind power, fuel cells, and a small hydro-system.

Ishaque et al. [5] proposed a PV system simulator in MATLAB Simulink environment based on an improved two-diode PV model. The simulator supported large array simulations that

could be interfaced with MPPT algorithms and power electronic converters.

In their study, Lu and Nguyen investigated designing and implementation of a PV simulator using two-switch Buck-Boost converter and a low cost 8-bit microcontroller [6]. Using Multiple Straight Lines method, PV simulator can simulate a PV panel (BP Solar SX-10 model) by an acceptable accuracy. The simulator was tested by resistive loads and a maximum-power point tracker. Results indicated a comparable performance of PV simulator to actual PV panels of the same model.

Tang et al [7] implemented a PV modular simulator using analog circuits as a useful tool for developing a PV module array to test the maximum-power point tracker (MPPT) algorithm. With respect to circuit design, since the simulator contains no specific simulation packages or programmable controller, it can be easily implemented with a low cost and in a small scale.

Vishay Kumar et al. [8] simulated the V-I characteristic of an ordinary PV module (115W Shell) for various temperature and irradiation conditions. This useful simulator could act as a source for testing power converters used to connect PV panels to loads (particularly to the main grid). The simulator could replace real panel in every flexibility level of interest and it could be used to test MPPT algorithm.

Yuan [9] studied a PV digital array simulator that simulated V-I characteristic of a 16 W solar module. In this simulator, S3C2440 and BUCK converter were used as the controller and the main circuit, respectively. Changing the open-circuit voltage control panel, short-circuit current MPP's voltage and current, this system could produce various solar characteristic curves. Results were indicative of a reasonable steady state error and good dynamic performance.

Raja et al. [10] studied the simulation of a PV cell using MATLAB to be utilized under various conditions. Some parameters such as ambient temperature (Ta) and irradiation (G) were adjustable. After implementation of the proposed model using fuzzy controller in MATLAB, results showed a considerable improvement in the simulator's performance compared with a PID controller.

Chang et al. [11] designed and implemented a high-efficiency solar array simulator using LLC resonant DC-DC converter to cut the costs and energy involved in testing a PV system. The proposed simulator used a zero voltage switching.

Results indicated that the simulator could accurately represent PV output characteristics and improve the efficiency of system by around 92.5% of maximum power point (MPP) and make a considerable saving in energy.

2. Materials and Methods

2.1. Panel Model

To simulate panel performance, in this paper a one-diode solar panel model as shown in Fig.1 was used.

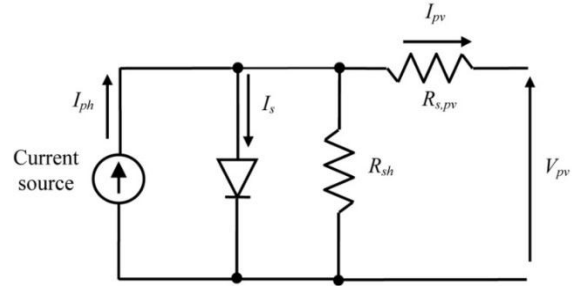


Figure 1. One diode model.

To implement the control method, the panel model can be implemented in either of these ways:

1. Calculating a given number of points and then using them via interpolation and extrapolation
2. Using the mathematical model governing the panel.

Due to requiring less computational effort and having higher accuracy, the former approach was adopted in this paper.

$$I_L = I_{sc} \left[1 - C_1 \left(e^{\frac{V_L}{C_2 V_{oc}}} - 1 \right) \right] \quad (1)$$

$$C_1 = \left(1 - \frac{I_m}{I_{sc}} \right) e^{-\frac{V_m}{C_2 V_{oc}}} \quad (2)$$

$$C_2 = \left(\frac{V_m}{V_{oc}} - 1 \right) \left[\ln \left(1 - \frac{I_m}{I_{sc}} \right) \right]^{-1} \quad (3)$$

Where I_L is the panel's current, V_L is the panel's output voltage, V_{oc} is the open-circuit voltage, I_{sc} is the short circuit current, and V_m, I_m are voltage and current of panel's maximum power point. The value of model parameters under non-STC condition can be obtained by the following relations [12].

$$I'_{sc} = I_{sc} \frac{S}{S_{ref}} (1 + \alpha \Delta T) \quad (4)$$

$$I'_m = I_m \frac{S}{S_{ref}} (1 + \alpha \Delta T) \quad (5)$$

$$V'_{oc} = V_{oc} \frac{S}{S_{ref}} (1 - \gamma \Delta T) \ln(1 + \beta \Delta S) \quad (6)$$

$$V'_m = V_m \frac{S}{S_{ref}} (1 - \gamma \Delta T) \ln(1 + \beta \Delta S) \quad (7)$$

Where α , β , and γ are constant values representing parameters' variability due to changes in temperature and irradiation. Given the values of

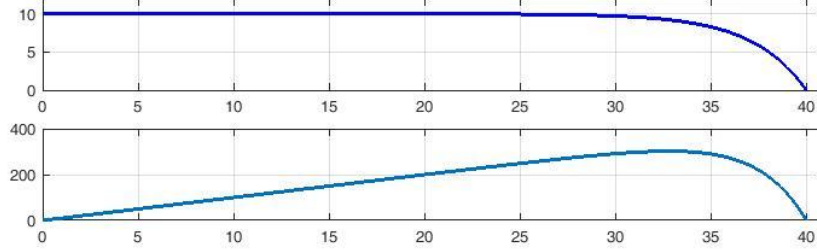


Figure 2. PV & IV curve under STC condition.

Each panel is typically composed of a number of cells connected in series to increase the total voltage. In this series combination, in case of lower current of a cell due to being non-uniformly illuminated or using cells with various specifications, local overheating or “hot spots” are formed which result in lower production, efficiency and life-time of panel. Bypass diodes are used to solve the problem of hot spot heating. There are three of them in parallel with one third of the solar cell array each. When part of the panel is in partial shading condition and its current is lower than other parts, the corresponding bypass diode goes to “bypass” mode and prevents the related problems, however, the panel’s I-V curve may show multiple steps and the P-V curve may exhibit multiple local maxima. Given the fact that equation (1) is derived for uniform illumination conditions, it is not applicable for partial shading conditions. In this situation, the curve is divided into two parts due to the performance of bypass diode in partially shaded string: in the first part, the current of strings under uniform illumination is higher than the current of strings under shading, so the diode “bypass” mode activates. The equation governing the panel in this condition can be written as follows:

$$I_L = I_{sc} \left[1 - C_1 \left(e^{\frac{V_L - V_s}{C_2 V_{oc} \left(\frac{m}{m+n} \right)}} - 1 \right) \right] \quad (8)$$

Where m is the number of equally illuminated strings. When the current of these two strings is equated, diode goes to “off” mode and, from this

these coefficients, the effect of temperature variations can be overlooked by a good approximation. A typical model based on this equation under STC conditions is shown in Fig.2.

point on, the current magnitude is controlled by partially shaded strings. This can be shown by:

$$I_L = I_{sc} \left[1 - C_1 \left(e^{\frac{V_L - V_s}{C_2 V_{oc} \left(\frac{n}{m+n} \right)}} - 1 \right) \right] \quad (9)$$

Where n is the number of partially shaded strings and V_s is the shadowed cell voltage. By calculating V_s via equating these two equations, the above equations can be rewritten as the following equation system to model the panel:

$$I_L = I_{sc} \left[1 - C_1 \left(e^{\frac{V_L - V_s}{C_2 V_{oc} \left(\frac{m}{m+n} \right)}} - 1 \right) \right] \quad V_{sc} \leq V_L \leq V_s \quad (10)$$

$$I_L = I_{sc} \left[1 - C_1 \left(e^{\frac{V_L - V_s}{C_2 V_{oc} \left(\frac{n}{m+n} \right)}} - 1 \right) \right] \quad V_{oc} \geq V_L > V_s \quad (11)$$

The curve plotted according to this equation system is shown in Fig.3.

2.2. Implementation

To implement this simulator, a Buck converter as shown in Fig.4 was used. An appropriate value is chosen for the size of inductor L_1 to ensure the operation of the converter in CCM region which results in lower losses. Letting $\Delta I = \%5$ and an operating frequency of 100 KHz, the minimum size of inductor, according to the following relation, is equal to 90 μH , which is considered as 200 μH to ensure the operation of converter.

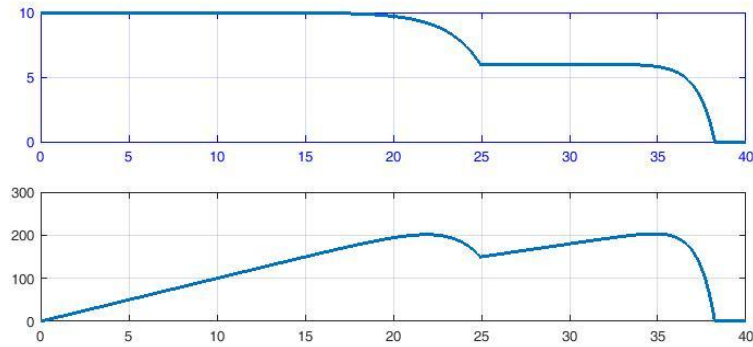


Figure 3. PV & IV curve based on developed eq. when 1/3 of cells are under partial shading.

$$L = \frac{V_{in} \cdot k \cdot (1 - k)}{f_s \cdot \Delta I} \quad (12)$$

Given the allowable voltage variation of 0.5%, the capacitor size of 100 μ F was chosen.

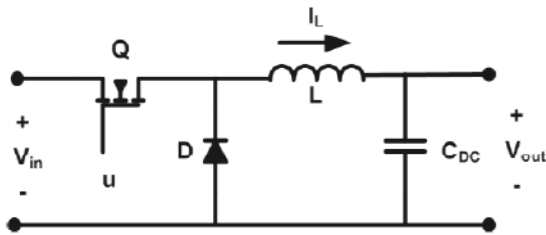


Figure 4. BUCK converter.

The converter specifications are presented in the following table.

Table 1. BUCK Converter specification	
Input Voltage	48 V
Switching freq.	100 KHz
Inductor	200 μ H
Capacitor	100 μ F

This converter is controlled by an ARM microcontroller (STM32 series). The general block diagram of the simulator is illustrated in Fig.5.

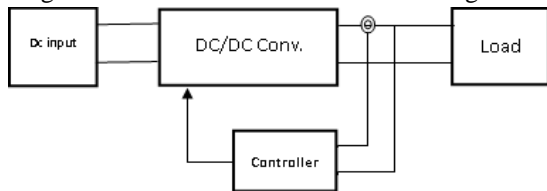


Figure 5. Simulator block diagram.

As it can be seen in this figure, the output current is measured and then its corresponding voltage is calculated by the governing equation of

panel which is subsequently used as the control reference. This reference is compared with the output voltage and, after calculating the error, the duty cycle of switch is adjusted accordingly. The flowchart of the relevant program is depicted in Fig.6.

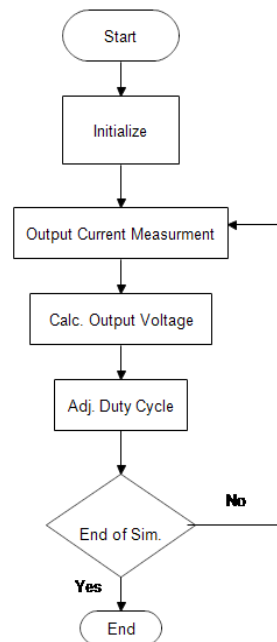


Figure 6. Flowchart of developed code. Simulator hardware Are is shown in Fig.7.

3. Simulation Results

To test the performance of the simulator, a three-string panel with electrical specifications as presented in Table 2 was considered. A variable resistive load of 70 ohm was used to test the performance of the converter.

The test was performed in both uniform illumination and partial shading scenarios and the following results were obtained:

Table 2. Simulated panel characteristic	
Open Circuit Voltage	40 v
Short Circuit Current	10 A
MPP Voltage	33 V
MPP Current	9.5 A

3.1. Uniform illumination scenario

Assuming a temperature of 25 °C and radiation of 1000 w/m², after programming the simulator, resistive loads were used to measure the output voltage and current values for various load levels. The corresponding P-V and I-V curves are plotted in Fig.8.

As it is obvious in this figure, the curve commences from point A corresponding to the open-circuit state and, as the load changes, it moves towards the maximum power point and eventually reaches point B which corresponds the short-circuit state. Due to converter restrictions, the short-circuit point cannot be reached. Comparison of the obtained curve with the ideal one indicates a satisfactory performance of simulator for this scenario.

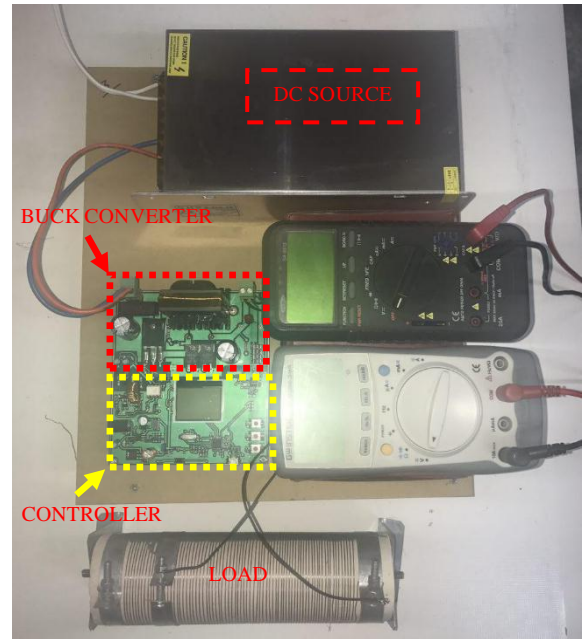


Figure 7. Simulator Hardware.

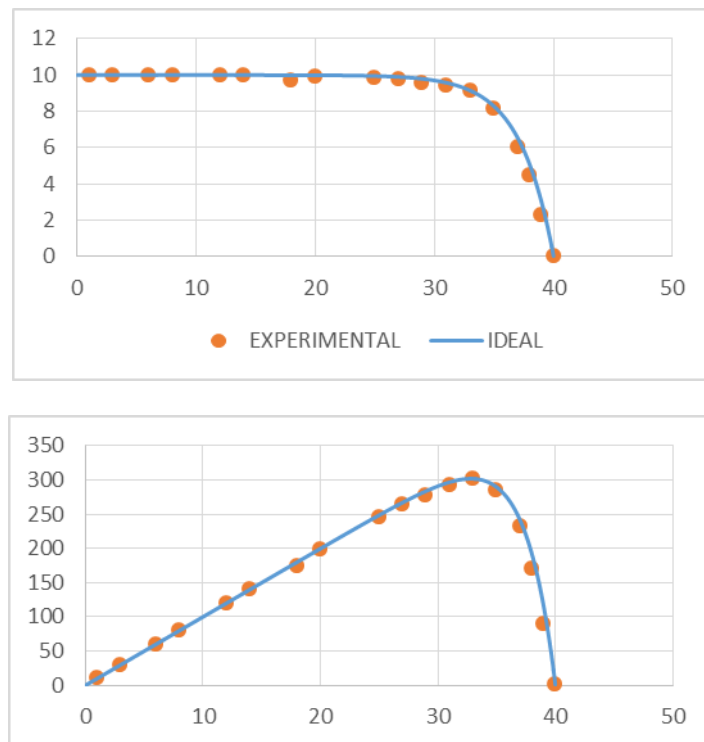


Figure 8. PV & IV curve under STC cond.

3.2. Partial shading scenario

To study the converter's performance in partial shading conditions, assuming irradiation of 600 w/m² for one of the strings and uniform illumination of 1000 w/m² for the other two strings, the simulator was programmed and, after

measuring the output voltage and current, the obtained results were presented in Fig.9. From this figure, the highest resistance which is equivalent to the open circuit commences at point A and as the resistance changes, point B is obtained which is equivalent to GMPP. By further changing the

resistance, the curve reaches points C, D, and F corresponding to LMPP and short circuit. By comparing the results obtained by plotting the characteristic equation, a reasonable performance of the converter can be observed.

4. Conclusion

Given the necessity of using conditions similar to the intensity of radiation and temperature of solar panel to test the performance of the converter, MPPT, or other similar applications, this paper uses the existing equations for the performance curve of solar panel to derive a set of new relations for partial shading conditions. This new set is utilized to construct a converter which is then tested for both standard radiation and partial shading

scenarios. Results of simulator test indicated its high potential to be used as an alternative to the real panel for performing the necessary tests. One of the disadvantages of this simulator is its measurement error for low values which is produced due to using Shant resistance and OP-AMP circuits, but it can be overcome using precise current sensors like LEMs, if economically affordable. Furthermore, a Buck converter with a built-in switch has been used in this simulator through which the whole power is transmitted and this in turn reduces the power of converter. To solve this problem, a higher-power converter and higher number of switches like Half-Bridge and/or Full-Bridge can be used.

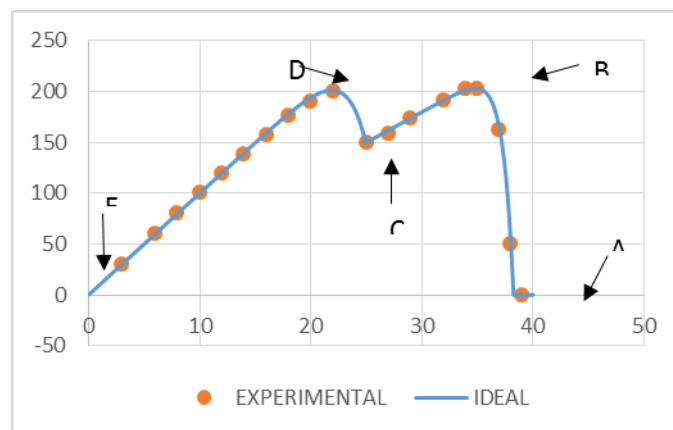
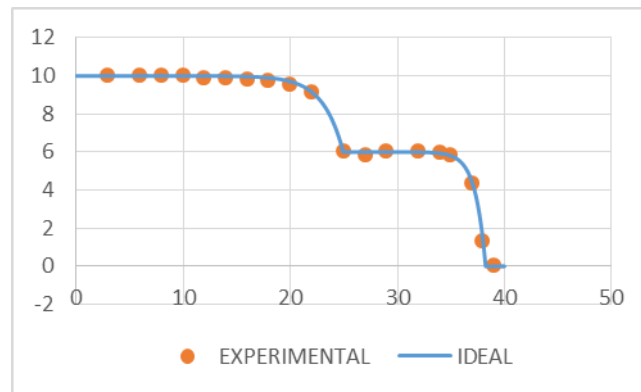


Figure 9. PV & IV curve under irradiation of 600 w/m^2 for one of the strings 1000 w/m^2 for the other two strings.

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