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## Development of a Economic Photovoltaic Array Simulator using an Off-The-Shelf Power Supply.

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### ABSTRACT

In this paper, a solar photovoltaic (PV) array simulator has been developed based on low-cost off-the-shelf components. This paper involves two methods to simulate the solar array characteristic curves namely, (i) an existing off-the-shelf DC power supply method and (ii) an improved version using a piecewise curve-fitting method. In curve-fitting method, the mathematical quadratic polynomial equations are implemented to track the I-V curves when the nonlinearity occurs with an increase in PV array voltage. In the off-the-shelf method, an externally controlled voltage source is injected into the feedback loop using resistors so that it helps in obtaining faster control over the output voltage. This paper is mainly concerned with comparing and analysing the I-V curves generated by these two methods. The system is implemented using MatLab-Simulink model and the characteristics of the PV array have been examined.

**Keywords:** Photovoltaic array, simulator, curve fitting, buck converter, off-the-shelf power supply.

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### INTRODUCTION

Among all the renewable energy resources, solar energy is the most prominent one, because of the features such as inexhaustible, pollution-free, easy to install, noiseless, non-radioactive, etc. [1]. PV source is a developing substitute for electricity which can provide long-term sustainability [2]. It is eco-friendly source and can be used for remote areas. But the installation cost of the solar array is high which is not possible for the initial research. Hence, it is necessary to develop a low-cost solar array simulator (SAS) [3]. Conventionally, to track the maximum power, the output voltage of the solar array is controlled by converters. In SAS, output current is controlled to reproduce the I-V characteristics. Consequently, the current reference is calculated based on the output voltage. The solar array simulator is useful for recreating solar array performance under unachievable conditions like extra-terrestrial solar irradiation and other environmental disturbances [4]. The performance of a solar array has been evaluated by numerous simulators under faulty conditions. Instead of presenting a novel approach to implement a solar simulator, its construction is mainly based on off-the-shelf constant output voltage converter [5]. SAS is mainly used to supply power for various subsystems on the satellite while enabling the testing of the actual solar array of the satellite on the ground. However the major drawback is that their output voltage is able to track fixed reference voltage created by the internal control IC and therefore they are stand-offish [6]. Hence, the SAS must be able to vary its output voltage for reproducing an I-V curve. Hence, the validation is done based on the fastness of control over the output voltage of an off-the-shelf.

In this paper, the PV array is modeled using a single diode model based on literature [7]-[8]. The characteristic of the PV array has been analyzed under different insolation condition. A proper curve fitting method is also presented in this paper to simulate the I-V curve of the PV array which improves the performance of the system having current as the feedback loop. The system is simulated using MatLab-Simulink and the results are analyzed.

### SOLAR ARRAY SIMULATOR

Solar array simulator topology usually presents two stages, namely uncontrolled rectifier and a DC/DC converter. The second one is the most preferred one because, rectifiers introduce harmonic distortion in output current and its voltage is uncontrollable [9]. The solar array simulator is very stable with a fast transient response; hence it is highly recommended for MPPT and inverter performance evaluation. The main drawback of SAS is higher implementation cost which leads to the impossibility of using it for educational laboratories or even a small industry [10]. To overcome these drawbacks, a low-cost off-the-shelf power supply is used to construct an improved simple solar array simulator. The solar array simulator is generally available in two configurations such as stand-alone and system controlled configuration. In this work, a stand-alone configuration is considered. As shown in Figure 1, solar array simulator structure comprises a power stage and control IC.

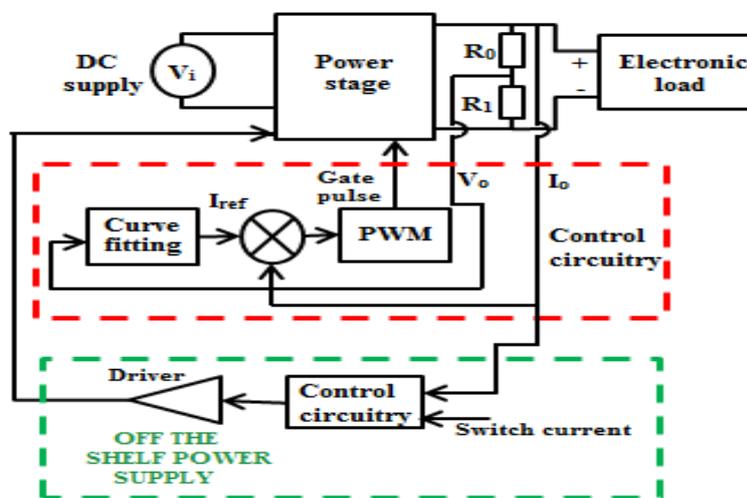


Figure 1. Block diagram of the proposed system

The power stage can comprise of either DC-DC or AC-DC converter depending on the input power supply. The control circuitry generates the regulating signal to the converter in the power stage to trace the I-V curve. The load voltage is usually sensed using a resistive potential divider and is fed into digital signal processor (DSP) based controller; this performs the corresponding PV current fitting equations according to available voltage levels. The output of this gives a current reference  $I_{ref}$ . Generally, switch/inductor currents ( $I_o$ ) are sensed to perform the output current feedback loop. This  $I_o$  is compared with the  $I_{ref}$  to minimize the error if any and is regulated using the PI controller to generate the pulse width modulated (PWM) waveform. This PWM is given to the switch in the converter so that the output current will always track the  $I_{ref}$ . The off-the-shelf power supply control method has been proposed to regulate the output voltage despite the input variation for the varying load. Thus, the I-V curve has traced with the load voltage and the switch circuit without using the curve-fitting equations.

In this paper, the I-V curve has been traced using two methods. The first one is an off-the-shelf power supply and the other is an improved method using curve-fitting. The comparative analysis has been performed for both the methods and the results are presented using MatLab-Simulink model.

### OPERATING MODES OF SAS

There are three modes of operating principle which includes fixed mode, basic mode and table mode [11]. As the hardware part is a power supply, solar array simulator may operate in a fixed mode. So, it will implement the I-V characteristics in a rectangular form [12]. In the basic mode, short circuit current, open circuit voltage, maximum power point current and voltage are given to the simulator and the device calculates the remaining I-V curve points for different weather conditions [13]. In the table mode, the characteristics curve is denoted by the voltage-current points given to the device. Then, a quasi-continuous I-V curve is realized by using interpolation [14]. After selecting the mode and the favourable environmental conditions, the solar array simulator operates in the following manner. The estimated I-V curve is calculated by the software module and then the output current is sensed and given to the power stage. If the environmental conditions changes, I-V curve is again calculated by the software module and which is sent to the power stage is revised accordingly.

### MODELING OF SOLAR ARRAY

The single diode modeling is considered for designing the PV system as shown in Figure 2. The detail PV array modelling is given in [15].

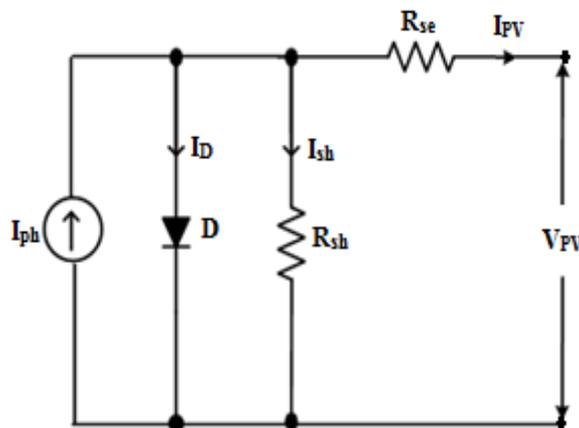


Figure 2. Equivalent circuit of solar cell

The electrical equivalent and the simulated characteristics of a single panel rated for  $P_{mp}=37W$ ,  $V_{mp}=16.54V$  and  $I_{mp}= 2.25 A$  shown in Table 1.

Table 1. Specification of PV array

Parameters	Values
$V_{mp}$ of a single panel	16.54 V
$I_{mp}$ of a single panel	2.25 A
$P_{mp}$ of a single panel	37 W
$V_{oc}$ of a single panel	21.24 V
$I_{sc}$ of a single panel	2.55 A

$$I_{pv} = I_{ph} - I_D - I_{sh} \tag{1}$$

$$I_o = \frac{K_i(T - T_n) + I_{scn}}{\exp\left[\left(K_v(T - T_n) + V_{ocn}\right) / V_{ta}\right]} - I \tag{2}$$

$$I_{pv} = \left[ K_i dT + I_{pvn} \right] \frac{G}{G_n} \tag{3}$$

$$V_{ta} = \frac{N_s aKT}{q} \tag{4}$$

$$I_m = I_{pv} N_{pp} - I_o N_{pp} \exp\left[ \frac{V_t}{N_s} \times \left( R_{se} \frac{N_{ss}}{N_{pp}} I + V \right) \right] - I \tag{5}$$

Where, q - Electronic charge, k - Boltzmann constant, n -Ideality factor or an ideal constant of the diode, T - Temperature of the cell,  $I_0$  - diode saturation current (or) current reverse saturation current,  $R_{se}$  - series resistance,  $R_p$  - shunt resistance.

The I-V characteristics of the PV array are shown in Figure 3.

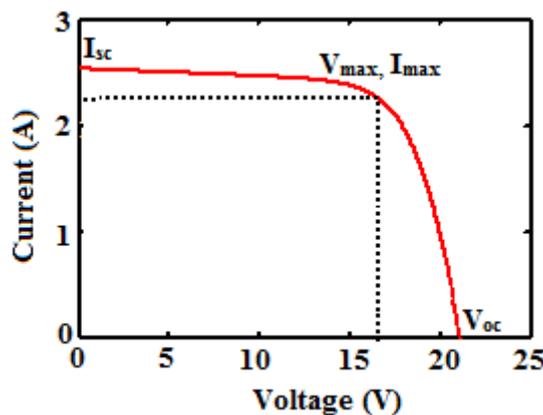


Figure 3. I-V Characteristics of PV array at STC

**CURVE FITTING METHOD**

The PV characteristics are simulated using two methods namely look-up table method and piecewise curve fitting method. The lookup table method is the easiest method of simulating the PV characteristics. But the major drawback of this method is that it requires a large data table in storage space [16]. In a low voltage region, the PV array acts as a constant current source, so the straight line method is the most suitable one to simulate the I-V curve. So for this, piecewise curve fitting method is used. As the voltage increases the non-

linearity of the curve increases so the straight line method is not suitable. For high voltage regions, some quadratic polynomial equations are derived using numerical formulations to simulate the curve [17].

Consider the initial point as A (X<sub>0</sub>, Y<sub>0</sub>) and another point as B (X<sub>1</sub>, Y<sub>1</sub>). The current curve fitting straight line equation to simulate the I-V curve is mathematically formulated as

$$y(x) = \frac{(x - x_1)}{(x_0 - x_1)} y_0 + \frac{(x - x_0)}{(x_0 - x_1)} y_1 \tag{6}$$

For other points, quadratic polynomial current curve fitting equation is derived as follows

$$y(x) = \frac{(x - x_3)(x - x_4)}{(x_2 - x_3)(x_2 - x_4)} y_2 + \frac{(x - x_2)(x - x_4)}{(x_3 - x_2)(x_3 - x_4)} y_3 + \frac{(x - x_2)(x - x_3)}{(x_4 - x_2)(x_4 - x_3)} y_4 \tag{7}$$

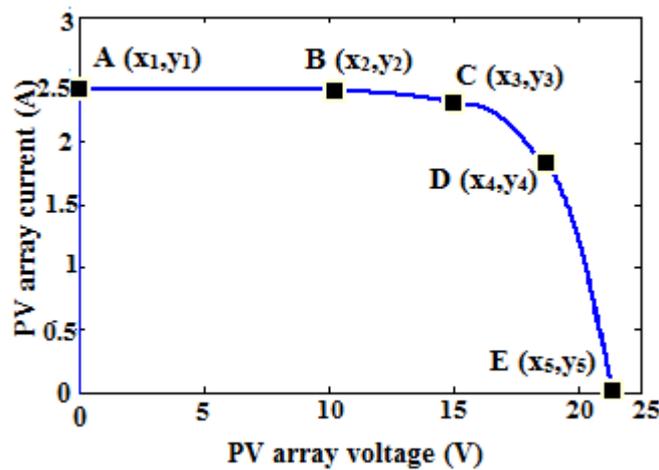


Figure 4. Output I-V characteristic of a PV array structure

Points B to E uses this equation to simulate the curve in high voltage regions. For example, in the curve shown in Figure 4 consider the points B (X<sub>2</sub>, Y<sub>2</sub>) and C (X<sub>3</sub>, Y<sub>3</sub>) then take some intermediate point as F (X<sub>4</sub>, Y<sub>4</sub>) to use the equation (6) and follow the same for other points.

Based on the equations (5) and (6), we can trace the entire I-V curve by considering four intervals from A to E such as (0,13.2), (13.2,16.54), (16.54,18), (18,21.24)

For A to B, the fitting equation is

$$I = -3.04 \times 10^{-3} v + 2.55, v \in [0, 13.2] \tag{8}$$

For B to C, the fitting equation is

$$I = -0.0109v^2 + 0.24492v + 1.1639, v \in [13.2, 16.24] \tag{9}$$

For c to D, the fitting equation is

$$I = 0.3439v^2 - 12.1865v + 109.7392, v \in [16.24, 18] \tag{10}$$

For D to E, the fitting equation is

$$I = -0.22575v^2 + 8.30293v - 74.50992, v \in [18, 21.24] \tag{11}$$

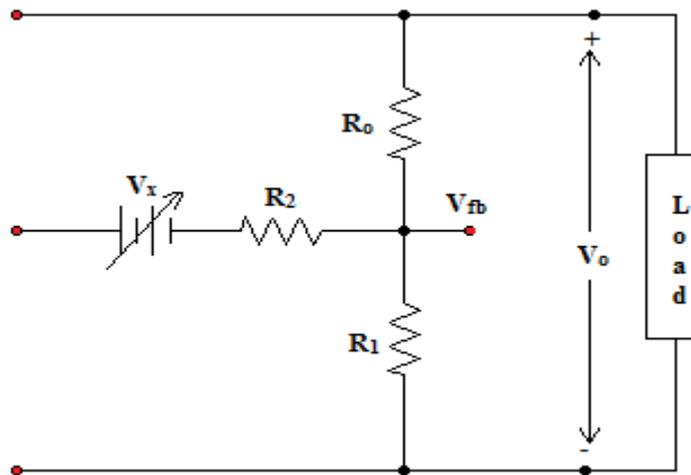
**OFF-THE-SHELF POWER SUPPLY TECHNIQUE**

The main objective of this method is to regulate the output voltage to a predefined value in spite of input voltage variations for variable loads. For the current control loop, the switch current is sensed periodically to limit the current. For voltage control loop, the load voltage is sensed via a voltage divider. The feedback voltage is given by

$$V_{fb} = V_o \cdot R_1 (R_0 + R_1)^{-1} \tag{12}$$

This voltage is then compared with the fixed reference  $V_{Ref}$  voltage and the resultant voltage signal  $V_c$  is applied to generate PWM signal. As a result, the output voltage during the steady state is regulated to

$$V_o = \left(1 + \frac{R_0}{R_1}\right) V_{Ref} \tag{13}$$



**Figure 5. Power Supply Modification**

Such power supply circuits do not allow a dynamic change in their output voltage as the reference voltage is fixed. So, a potentiometer is used in voltage divider for manual variations. But it is difficult to implement this modification as fast controlled voltage tracking is needed. Hence, the power supply is modified as shown in Fig.5. In the point of resistor connection  $R_0$  and  $R_1$ , an external controlled DC source is implemented to regulate the output voltage for a variety of loads. Now the feedback voltage is given by,

$$V_{fb} = \frac{R_1 \parallel R_2}{R_0 + R_1 \parallel R_2} V_o + \frac{R_0 \parallel R_1}{R_2 + R_0 \parallel R_1} V_x \tag{14}$$

The output voltage is now regulated to

$$V_o = \left(1 + \frac{R_0}{R_1 \parallel R_2}\right) \cdot \left(V_{Ref} - \frac{R_0 \parallel R_1}{R_2 + R_0 \parallel R_1} V_x\right) \tag{15}$$

And gain values are  $k_1 = R_1 \parallel R_2 \cdot (R_0 + R_1 \parallel R_2)^{-1}$ ,  $k_2 = R_0 \parallel R_1 \cdot (R_2 + R_0 \parallel R_1)^{-1}$ . Therefore by performing these modifications fast control over the output voltage can be obtained and in order to regulate the output voltage to the power supply voltage  $V$  the injected external voltage  $V_x$  is given by,

$$V_x = \left(1 + \frac{R_2}{R_0 \parallel R_1}\right) \cdot (V_{Ref} - \frac{R_1 \parallel R_2}{R_0 + R_1 \parallel R_2})$$

. Now the injected voltage  $V_x$  is driving the dynamic changes.

### SIMULATION RESULTS AND DISCUSSIONS

The simulated I-V curve using the curve-fitting method using MatLab-Simulink is shown as a solid line in Figure 6. It is observed that the I-V curve for the SAS system can be traced automatically without complications using photovoltaic curve fitting algorithm.

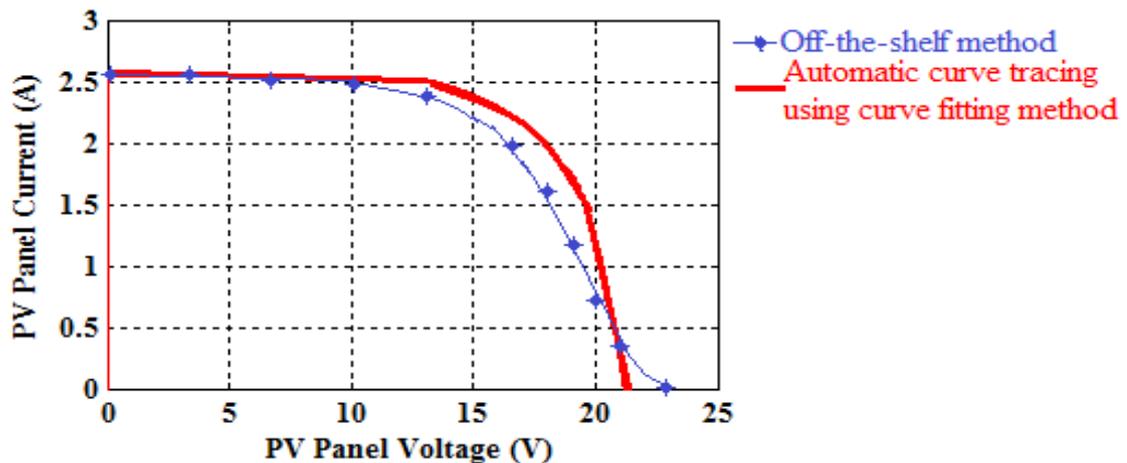


Figure 6. Simulated I-V characteristic curve using curve-fitting method and off-the-shelf method

The off-the-shelf power supply method is implemented and the I-V curve is traced which is shown with manual plotting in Figure 6 and it is compared with curve-fitting method. In this method, the curve cannot be traced continuously instead of the output voltage and current needs to be measured every time and then the curve has to be plotted manually.

### CONCLUSION

This paper provides mathematical modelling of the low-cost solar array simulator. The I-V curves are simulated using piecewise curve fitting method and an off-the-shelf power supply method and the results are compared. Finally, it is concluded that the improved version of off-the-shelf power supply with the curve-fitting method needs only a few technical parameters and results in high accuracy to provide PV array characteristics through simulation. The designed control system requires less memory so that the implementation can be done through any low cost processor. As a result, the solar array simulator can imitate the I-V curves during unachievable environmental conditions and partial shading.

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