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Performance analysis of concentrator photovoltaic dense-arrays under non-uniform irradiance

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ABSTRACT

The paper deals with concentrator photovoltaic dense-arrays under non-uniform solar irradiance. For given measured *I–V* characteristic of InGaP/GaAs/Ge multi-junction solar cells, estimated cell parameters connected to bypass diodes were obtained by using the Newton–Raphson method. Based on the cell parameters, the *I–V* characteristics of arrays were constructed and their performances under non-uniform irradiance were investigated. With the arrays performances analysis, the function of bypass diodes was also analyzed. Under non-uniform irradiance, the photo-generated currents of the cells are different and as a result, the *I–V* characteristic of the array contains steps. The steps may indicate the mismatched cells in the array operating in the negative voltage range and forcing the bypass diodes to conduct. For low dispersion of the non-uniformity of the solar flux, the inclusion of bypass diodes has no effect on the output power of the array; however for high dispersion, the output power decreases because the mismatched cells become reverse biased and dissipate power.

1. Introduction

In concentrator photovoltaic (CPV) systems [1] the incident solar irradiance on the solar cells depends mainly on the optical elements. Under ideal conditions and identical series connected solar cells in the array, the cells operate at the same point on their respective *I–V* characteristic. Any change in the conditions would cause each individual cell to respond equally to the change, and the maximum amount of power is thus extracted from each cell. Therefore, in CPV systems attempts are always made to obtain uniform solar irradiance, and to match the parameters of the cells in the array.

In practice, the solar cells in the CPV array are not entirely matched and therefore are not operating identically due to various reasons related to the cell processed material, quality of the optical elements, tracking errors, uneven heat dissipation, misalignment between the cell and optical elements, and temporary and permanent shading factors such as dust and dew on the external concentrating elements. The uniformity of the solar flux on the array depends very much on the size of the system, having or not having secondary optics, and on other factors as mentioned above. For small arrays (series connected cell), the uniformity is usually better than 10 percent and for large arrays (series and parallel connected cells), the uniformity may vary between 30% and 50%. Therefore, in most cases the irradiance on the cells is non-uniform causing each cell to operate at a different point on the *I–V* characteristic, thus lowering the output power of the system.

Partial shading or non-uniform irradiance on photovoltaic arrays of single junction solar cells has been widely published in [2–5]. Much less has been published on CPV arrays with single junction cells [1] or on multi-junction (MJ) cells [6–8] under partial shading or non-uniform irradiance. A number of articles deal with multi-junction solar cells of dense-array [9–12]. The purpose of the present article is to analyze the performance of CPV arrays under non-uniform solar flux, to understand the importance of connecting bypass diodes to each cell in the array, and to study the effect of bypass diodes on the output power of the arrays. In addition, the purpose is also to estimate the parameter values of MJ cells by curve fitting to measured *I–V* characteristics, and to estimate the parameter values of arrays constructed from the individual cells. A complete study on this subject has not been reported in the literature and is, therefore, the purpose of the article.

To understand the operation of each individual cell and the entire dense-array, the *I–V* characteristics of both the cells and the array ought to be known. The estimated solar cell parameters connected to bypass diodes were obtained for different concentration levels by curve fitting of the measured *I–V* characteristic of InGaP/GaAs/Ge[1] multi-junction solar cell to the theoretical single model equation of the solar cell. Based on the cell parameters, the *I–V* characteristics of different CPV arrays were constructed and their performances under non-uniform irradiance were investigated.

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[1] Data provided courtesy of Spectrolab Inc.

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Under non-uniform irradiance, the *I–V* characteristic of the array may contain steps indicating the amount and the degree of mismatched of cells in the array, and revealing the reverse biased cells forcing the bypass diodes to conduct current in order to protect the mismatched cell from becoming over heated.

2. Multi-junction solar cell model with bypass diode

The single diode model equation (*I–V* characteristic) of a solar cell in the positive voltage and current range may be described as a single diode model by

$$I = I_{ph} - I_0(e^{(V+IR_s)/nV_T} - 1) - \frac{V + IR_s}{R_{sh}} \quad (1)$$

where V and I are the cell terminal voltage and current, I_{ph} is the photo-generated current, I_0 is the diode reverse saturation current, V_T is the thermal voltage, n is the ideality factor, R_s and R_{sh} are the series and shunt resistances, respectively. The vector of this model consists of five parameters:

$$\underline{\lambda} = [I_{ph}, I_0, n, R_s, R_{sh}] \quad (2)$$

A multi-junction cell consists of several sub-cells, each sub-cell possessing its own parameter values. Therefore, the parameters vector in Eq. (2) represents equivalent parameters of a multi-junction cell [7,8]. Under non-uniform illumination, a solar cell in an array may operate at a negative voltage, therefore the above model is extended to include an additional term [2] describing the diode avalanche breakdown at high negative voltage of the cell. The extended cell model is shown in Fig. 1 where the additional term is represented by a current source I_{br}.

The relationship between the cell current and voltage is now given by

$$I = I_{ph} - I_0(e^{(V+IR_s)/nV_T} - 1) - \frac{V + IR_s}{R_{sh}} \underbrace{- \alpha \frac{V + IR_s}{R_{sh}} \left(1 - \frac{V + IR_s}{V_{br}}\right)^{-m}}_{\text{addional term for the negative diode breakdown}} \quad (3)$$

where α is a coefficient ($\ll 1$,~10^{-5}), V_{br} is the junction breakdown voltage of the cell, and m is the avalanche breakdown exponent; where for $\alpha = 0$ we obtain Eq. (2). The expressions for the two parameters α and m are derived in Appendix B.

$$\alpha = \frac{R_s}{R_{sh} - R_s} - \frac{R_{sh} I_0}{nV_T} \quad (4)$$

$$m = \left[- \frac{\ln\left\{ \frac{R_{sh}}{\alpha(V+IR_s)} \left[I_{ph} - I_0(e^{(V+IR_s)/nV_T} - 1) - (V + IR_s)/R_{sh} - I \right] \right\}}{\ln\{1 - (V + IR_s)/V_{br}\}} \right] \quad (5)$$

The parameter vector that describes the solar cell consists now of eight parameters

$$\underline{\lambda} = [I_{ph}, I_0, n, R_s, R_{sh}, \alpha, V_{br}, m]^T \quad (6)$$

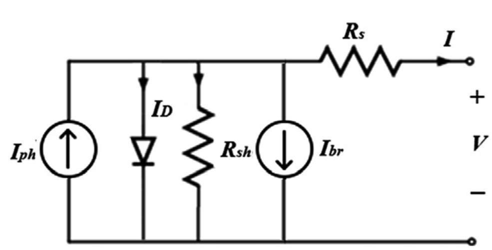

Fig. 1. Equivalent circuit of a single diode solar cell model including avalanche breakdown.

The additional term in Eq. (3) can also be used to describe the characteristic of a bypass diode connected in parallel to the solar cell [2]. In this case the additional term represents the current through the bypass diode and V_{br} is the conduction voltage of the bypass diode. Alternatively, one may use the Shockley diode equation for the additional term in Eq. (3) [13]. The difference between the two ways to describe the function of the bypass diode is in the parameters. The expression of the additional term in Eq. (3) contains parameters of the solar cell (see Eqs. (4) and (5)) and the conduction voltage, V_{br}, representing the conduction voltage of the diode, whereas the Shockley diode equation-representing a real bypass diode-contains parameters of its diode. However, both expressions behave exponentially and with appropriate numerical values for the parameters the characteristics of the additional term and the real bypass diode may describe the same behavior. In the present article, the approach of using the additional term was adopted based on proven good results of the measured and simulated solar cell arrays [2].

2.1. Parameter estimation of MJ cells

A single diode model of a solar cell may be represented by five parameters, Eq. (1), in the positive voltage range (forward bias) or by eight parameters, Eq. (3), in both the positive and the negative voltage range (forward and reverse bias). The cell *I–V* measurements are usually reported for positive currents and voltages, therefore the estimated five parameters are based on the five parameters model, Eq. (2), of the solar cell using a curve fitting procedure (see Appendix A and [14]). For given *I–V* measurements both in the positive and negative voltage range, the estimated eight parameters, Eq. (6) , are based on curve fitting on the eight parameter model of the solar cell. However, for a measured *I–V* characteristic in the positive voltage range only it is possible to generate the additional branch of the *I–V* characteristic for the negative voltage range (represented by the additional term in Eq. (3)) by applying Eqs. (4) and (5) and a given V_{br} on the estimated five parameters. Eq. (3) is used for the estimation of the dense-array parameters and for the array performance analysis under non-uniform irradiance.

Curve fitting was performed on measured *I–V* characteristics of a multijunction cell (see footnote 1) (with no attached bypass diode) containing 220 data points under three irradiance concentrations of 350, 555 and 700 Suns at temperature of 80 °C. The estimated (fitted) cell parameters for each concentration level are detailed in Table 1. Although the measurements of the cell that were provided by Spectolab were for positive voltages only, the eight parameter model, describing the *I–V* characteristics of the cell connected to a bypass diode, includes also the reverse biased region. As a cell in the array may become reverse biased due to a mismatch of cells in the array, the bypass diode starts to conduct slightly less than 0.6 V (for a silicon diode) protecting the cell from becoming damaged. Table 1 shows that the parameters of a solar cell depend on the concentration level, i.e., one need to take into account the variation of all parameters of the cell or of the array in the calculation of the system performance under variation in the irradiance, and not only the value of the photocurrent. The direction of change in the parameter values corresponds to the

Table 1
Estimated parameters of multi-junction cells under different concentrations (at 80 °C).

Suns	I_{ph} (A)	I_0 (A)	n	R_s (Ω)	R_{sh} (Ω)	α	V_{br} (V)	m
50	4.478	4.65E−16	2.62	2.449E−02	4.14E+02	6.28E−05	−0.6	14
555	7.0734	9.26E−16	2.67	1.621E−02	3.16E+02	5.13E−05	−0.6	11
700	8.851	1.42E−15	2.71	1.441E−02	2.02E+02	7.13E−05	−0.6	9
				$\varepsilon^2 = 2.1 \times 10^{-6}$				