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A comprehensive study of dense-array concentrator photovoltaic system using non-imaging planar concentrator

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ABSTRACT

A special modeling method using Simulink has been developed to analyze the electrical performance of dense-array concentrator photovoltaic (CPV) system. To optimize the performance of CPV system, we have adopted computational modeling method to design the best configuration of dense-array layout specially tailored for flux distribution profile of solar concentrator. It is an expeditious, efficient and cost effective approach to optimize any dense-array configuration for any solar concentrator. A prototype of non-imaging planar concentrator (NIPC) was chosen in this study for verifying the effectiveness of this method. Mismatch effects in dense array solar cells caused by non-uniform irradiance as well as sun-tracking error normally happens at the peripheral of the array. It is a crucial drawback that affects the electrical performance of CPV systems because maximum output power of the array is considerably reduced when a current–voltage (*I–V*) curve has many mismatch steps and thus leads to lower fill factor (FF) and conversion efficiency. The modeling method is validated by assembling, installing and field testing on an optimized configuration of solar cells with the NIPC prototype to achieve a conversion efficiency of 34.18%. The measured results are in close agreement with simulated results with a less than 3% deviation in maximum output power.

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1. Introduction

Solar power generation systems, including concentrator photovoltaic (CPV) installations, usually incur a substantial amount of initial investment cost. To offset the cost of expensive semiconductor material and encourage CPV installations, these systems employ comparatively inexpensive optical elements such as mirrors or lenses acting as solar concentrator together with high-efficiency multi-junction solar cells. To further reduce the cost of generated electricity, optimal system design is necessary so that maximum solar energy can be harnessed from CPV cells [1,2]. However, we often find that the delivered electrical power in field conditions is much lower than the array ratings because mismatch losses have affected the current–voltage (*I–V*) and power–voltage (*P–V*) curves of the solar cells. Mismatch factors such as soiling, non-uniform irradiance, shading, temperature variations, cell's quality as well as aging of solar cells, all contribute to serious array power reduction in real site testing [3,4].

Non-uniform distribution of concentrated solar irradiance is one of the significant problems faced by most of concentrator systems, especially around the receiver edges, mainly caused by optical design limitations, structure misalignment, and low tracking accuracy. Over the recent years, many studies can be found discussing on the improvement of solar concentrator optical design to produce more uniform solar illumination at high concentrations [5–10]. Nevertheless, the overall output current of CPV cells connected in a dense array arrangement is very much dependent on the solar flux distribution of a solar concentrator. Due to factors such as sun-shape, circumsolar effect, aberration, imperfection of mirror's geometry etc., it is impossible to produce perfect uniform illumination on the dense-array CPV receiver and hence causing a significant loss in the overall output power and average conversion efficiency [11–16]. Despite the employment of flat mirrors in the non-imaging planar concentrator (NIPC), the resultant flux distribution from simple super-positioning of all flat mirror images is inevitably non-uniform near the peripheral zone. Hence, a specially designed algorithm has been developed to analyze *I–V* curve of different dense-array configurations in order to optimize conversion efficiency and improve overall output power. In our study, the measured solar flux distribution of NIPC prototype is matched to every solar cell's location at the receiver. The measured solar flux distribution shows deviation from a perfect uniform distribution

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owing to various imperfections in practical installation such as mechanical structure and mirror alignment. There are considerable efforts in the study of partially shaded PV array for minimizing mismatch losses through the use of different interconnection methods [17–19]. In this paper, a new approach of Simulink-based computational modeling is proposed to accurately simulate $I-V$ and $P-V$ curves of CPV dense-array. Various possible configurations have been simulated and analyzed based on real flux distribution of the solar concentrator to obtain the best array configuration. An optimized configuration of CPV array has been constructed for the purpose of verification with an NIPC prototype. The methodology and practical demonstration of CPV dense-array performance optimization are reported in detail.

2. Modeling and simulation of dense array CPV system

2.1. Concentrator photovoltaic (CPV) cell modeling

A comprehensive equivalent circuit model for a triple-junction solar cell can be represented by three current sources connected in series [20]. Nonetheless, not all of the parameters that are required by the model can be readily collected from field measurements nor obtained from a standard manufacturer's datasheet. Therefore the two-diode model, a model that is capable of representing CPV cells, is chosen for this study (Fig. 1). The temperature of solar cell was measured as 55 °C using a k-type thermocouple, and this value is applied in our circuit simulation to improve modeling accuracy.

Solar cell block represented by a single solar cell as current source with two exponential diodes, a parallel resistor (R_P), and connected in series with a series resistance (R_S) are arranged into subsystems in Simulink to form an array. The output current, I, can be represented by the equation

$$I = I_{ph} - I_{o1} \times \left(e^{(V + IR_S)/(N_1 V_t)} - 1 \right) - I_{o2} \times \left(e^{(V + IR_S)/(N_2 V_t)} - 1 \right) - (V + IR_S)/R_P \quad (1)$$

where I_{ph} is the solar-induced current, I_{o1} is the saturation current of the first diode, I_{o2} is the saturation current of the second diode, V_t is the thermal voltage, N_1 is the diode ideality factor of the first diode, N_2 is the diode ideality factor of the second diode, and V is the voltage across the solar cell. In Simulink, it is possible to choose either an eight-parameter model in which the preceding equation describes the output current or a five-parameter model. In the
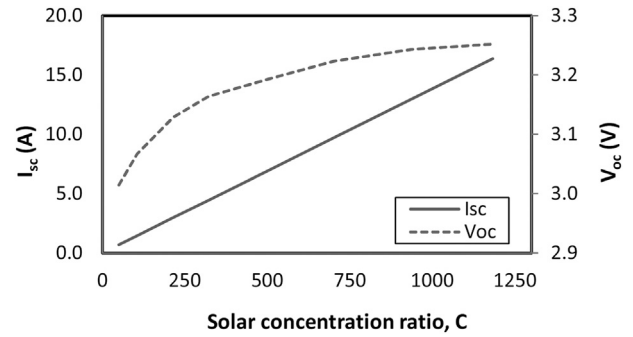
five-parameter model, two simplifying assumptions are made: the first assumption is that saturation current of the second diode is zero in value and the second assumption is that the impedance of its parallel resistor is infinite. The five-parameter model is good enough to perform a reasonably accurate analysis and we have successfully verified it in the field test that will be presented in the later section.

For this study, the five-parameter model is applied to solar cell blocks from SimElectronics, and therefore solar cells are parameterized in terms of short-circuit current (I_{SC}) and open-circuit voltage (V_{OC}). Both short-circuit current and open-circuit voltage values are common parameters which are readily available in a manufacturer's datasheet or measured as field data. To complete the modeling of the entire array, parameters such as short-circuit current (I_{SC}), open-circuit voltage (V_{OC}), diode ideality factor (N), the series resistance (R_S) and irradiance level of each CPV cell are keyed-in to the program.

2.2. Electrical characteristics of solar cell under high concentration

Main electrical parameters of EMCORE's high efficiency Concentrating Triple Junction (CTJ) cells are extracted from the $I-V$ curves of increasing concentration ratios (from 50× to 1182×) from the manufacturer's datasheet using graph digitizing method [21]. This can be achieved by employing WebPlotDigitizer v2.5, or other similar software that are able to automatically follow data lines on a scanned image of high resolution $I-V$ curve (refer to Fig. 23 in Appendix) to extract digitized current, voltage and concentration values. Once the axis limits were set, all necessary data points can
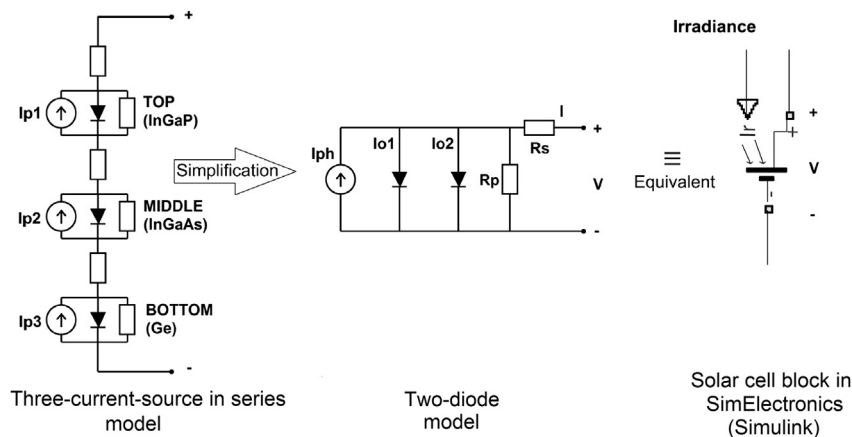
Fig. 2. The relationship of short-circuit current (I_{SC}) and open-circuit voltage (V_{OC}) versus solar concentration ratio from 50× to 1182× for high-efficiency CTJ solar cell.

Fig. 1. A schematic diagram to show the representation of a triple-junction solar cell which is simplified from three-current-source in series model to the two-diode model, which is equivalent to a solar cell block in SimElectronics, Simulink.