Computers and Electrical Engineering 51 (2016) 331–342

Contents lists available at ScienceDirect

Computers and Electrical Engineering

journal homepage: www.elsevier.com/locate/compeleceng

A performance evaluation model of a high concentration photovoltaic module with a fractional open circuit voltage-based maximum power point tracking algorithm☆

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ARTICLE INFO

Article history:
Received 27 May 2015
Revised 13 January 2016
Accepted 13 January 2016
Available online 1 February 2016

Keywords:
High concentration photovoltaic
Performance evaluation model
Fractional open circuit voltage
Maximum power point tracking

ABSTRACT

High concentration photovoltaic (HCPV) modules employing high-efficiency III–V solar cells promise greater system-level efficiency than conventional photovoltaic (PV) systems. Nevertheless, the output power of an HCPV system is very sensitive to rapidly fluctuating tracking errors and weather patterns. The fractional open circuit voltage (FOCV) based maximum power point (MPP) tracking technique benefits from simplified processing circuits with speed response. To investigate the feasibility of using the FOCV technique for MPP estimation on HCPV modules, a theoretical model and simulation are presented in this study. A MATLAB-based MJSC circuit model of an HCPV module with buck-type converter and load is proposed and validated. In addition, the magnitude of the optical loss caused by Fresnel lens shape deformation and air mass (AM) ratio is modeled and quantized. The FOCV technique is then employed and compared with the conventional perturb and observe (P&O) method on the HCPV module under varying irradiance and temperature conditions to study its effectiveness. The results suggest that the FOCV technique could help an HCPV module to attain greater power efficiency.

1. Introduction

High concentration photovoltaic (HCPV) technology has gained growing attention in recent years, with HCPV systems based on multi-junction solar cells (MJSC) representing a breakthrough for solar electricity production by utility companies. In December 2014, the Fraunhofer Institute for Solar Energy Systems ISE announced a new world record of 46% efficiency for an MJSC, with this technology developed by Soitec, CEA-Leti and Fraunhofer ISE [1]. MJSCs are based on a selection of III–V compound semiconductor materials. Each sub-cell of an MJSC converts part of the incoming photons of the sunlight in the wavelength range between 300 and 1750 nm into electricity. To offset the cost of expensive semiconductor materials, small MJSCs are used with comparatively inexpensive Fresnel lenses in an HCPV module. Point-focus based HCPV modules must be always mounted on two-axis solar trackers to help the lens concentrate direct sunlight onto the cells. In order to reduce the cost of the electricity that is produced, it is important that the HCPV module is operated at its maximum power point (MPP), which is tracked by different maximum power point tracking (MPPT) techniques. However, due to the

☆ Reviews processed and recommended for publication to the Editor-in-Chief by Guest Editor Dr. S. D. Prior.

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http://dx.doi.org/10.1016/j.compeleceng.2016.01.009
0045-7906/

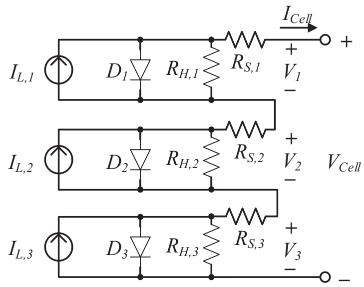

Fig. 1. Single-diode model for a TJSC.

rapidly fluctuating tracking errors caused by varying environmental conditions, a simple MPPT algorithm with fast response is needed for an HCPV system [2].

The most common MPPT methods include the Perturb and Observe (P&O), Incremental Conductance (IC) and Hill Climbing (HC) algorithms. Other soft-computing MPPT techniques include the use of a Fuzzy Logic Controller (FLC), Artificial Neural Network (ANN), Genetic Algorithm (GA) and Evolutionary Algorithm (EA) [3–5]. However, these methods require complex mathematical operations, and therefore a digital signal processor is typically needed to implement them. In contrast, the Fractional Open Circuit Voltage (FOCV) and Fractional Short Circuit Current (FSCI) techniques have simpler algorithms, but their accuracy is limited [2, 3, 6]. The FOCV method exploits the nearly linear relationship between a PV module's open-circuit voltage (V_{OC}) and its voltage at the MPP (V_{mp}) under varying irradiance and temperature levels. Compared with the FSCI technique, the FOCV technique benefits from having less circuit losses [7].

In a previous study, titled "A Rapid Maximum Power Measurement System for High-Concentration Photovoltaic Modules Using the Fractional Open-Circuit Voltage Technique and Controllable Electronic Load", the experiment results demonstrated that the FOCV technique is able to estimate the MPP of the HCPV modules with high accuracy under static conditions [2]. To further build a model for investigating the feasibility of using the FOCV technique for MPP estimation on HCPV modules under dynamic conditions, a theoretical model and simulations are presented in this study. A MATLAB-based MJSC circuit model of an HCPV module with buck-type converter and load is proposed and validated. In addition, the magnitude of the optical loss caused by Fresnel lens shape deformation and air mass AM ratio is modeled and quantized. The FOCV technique is then employed and compared with the conventional P&O method on the HCPV module under varying temperature and irradiance conditions to study its effectiveness. Furthermore, the power loss caused by V_{OC} measurement of the FOCV algorithm is modeled to estimate its effect.

This paper is organized as follows. Section 2 describes the proposed simulation model of an HCPV module and the MPPT algorithms. The effects of temperature and irradiance are discussed. Section 3 presents experimental results and a comparison between two MPPT techniques. Finally, Section 4 concludes this paper.

2. Method

2.1. III–V triple-junction solar cell circuit model

Triple-junction solar cells (TJSCs) are commonly employed in HCPV modules. A TJSC can be considered as being composed of three p-n junction subcells connected in series. Each subcell can be represented by an equivalent circuit model. The commonly used models for a TJSC are single- and two-diode models, both of which are adequate for practical applications, with the *I*–*V* curve having a good fit to the experimental data [8–10]. This study presents a single-diode model for a TJSC as presented in Fig. 1. Based on this, the cell *I*–*V* curve can be mathematically expressed as

$$V_{Cell} = \sum_{i=1}^{3} V_i, \tag{1}$$

$$I_{Cell} = I_{L,i} - I_{0,i}\left\{\exp\left[\frac{q(V_i + I_{Cell}R_{S,i})}{n_i kT}\right] - 1\right\} - (V_i + I_{Cell}R_{S,i})/R_{H,i},\ i = 1, 2, 3, \tag{2}$$

where V_{Cell} and I_{Cell} are the voltage and current of the TJSC, respectively; i indicates the subcells ($1 = $ top, $2 = $ middle, and $3 = $ bottom), I_L is the light-generated photocurrent, I_0 represents the diode reverse saturation current, q is the electrical charge of the electron, n denotes the diode ideality factor, k is the Boltzmann's constant, and T is the absolute temperature. Further, R_S and R_H are the series resistance and shunt resistance, respectively. Assuming the shunt resistance is sufficiently large to be neglected [8], the open-circuit voltage V_{OC} can be obtained by setting $I_{Cell} = 0$

$$V_{OC} = V_T\left[n_{top}\ln\left(\frac{I_{L,top}}{I_{0,top}} + 1\right) + n_{mid}\ln\left(\frac{I_{L,mid}}{I_{0,mid}} + 1\right) + n_{bot}\ln\left(\frac{I_{L,bot}}{I_{0,bot}} + 1\right)\right], \tag{3}$$