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A novel optimal parameters identification of triple-junction solar cell based on a recently meta-heuristic water cycle algorithm

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ABSTRACT

A novel methodology for extracting the optimal parameters of PV module with high efficiency InGaP/InGaAs/Ge triple-junction solar cells (TJSCc) is developed. Such methodology is based on recent meta-heuristic approach of Water Cycle Algorithm (WCA). The TJSC model is represented by single diode model and then a constrained objective function has been derived to be used in the optimization process of optimal parameter estimation. The analysis has been carried out based on high efficiency InGaP/InGaAs/Ge TJSC. The performance of WCA is evaluated and tested for TJSC based PV module operated with various irradiances and temperatures. Finally, a comparison between the proposed methodology and experimental data is carried out. Furthermore; other algorithms are programmed and applied to solve the problem under study like grey wolf optimizer (GWO), antlion optimizer (ALO), mine blast algorithm (MBA), harmony search algorithm (HSA) and the obtained results via these approaches are compared with those obtained by the proposed WCA. The results reveal the validity and superiority of WCA in extracting the optimal parameters of the TJSC based PV module.

1. Introduction

Renewable energy sources (RESs) are being sought in order to diminish the greenhouse emissions and related effects in addition to slow down the depletion of fossil fuel. Therefore, the need for renewable, cleaner, cheaper, safer, more efficient and environmentally friendly energy sources is on the rise. Solar energy is one of the most promising RESs, it is usually harvested by means of solar photovoltaic (PV) or Concentrating Solar Power (CSP) (Rezk and Hasaneen, 2015). PV system has many merits, such as: pollution-free, little maintenance and noise-free. It has been used in many applications such as solar vehicles, street lighting and others (Rezk and El Sayed, 2013). Recently, concentrated photovoltaic systems (CPVSs) gained a great attention due to their high conversion efficiency (Steiner et al., 2014, 2016). CPVSs are based on high efficiency triple-junction solar cells (TJSCs) (Asaf and Appelbaum, 2013). TJSCs that used in CPVSs are different from silicon PV cells science; they can convert solar irradiance to electrical power at high efficiency (Rezk and El Sayed, 2013). TJSCs are one of the most promising photovoltaic devices with 41.6% efficiency (King et al., 2009), their theoretical efficiencies exceed 60% (Law and et al., 2010). Up to date the GaInP/GaInAs/Ge TJSC has achieved an efficiency of 46% (Green et al.) and has become the dominant type of solar cell used in CPVSs. Solar cells have been investigated at both high and low concentrations respectively for terrestrial and space applications. Single-junction PV module manufacturer's datasheet provides the parameters of open circuit voltage, short circuit current, power at MPP, voltage and current at MPP and the temperature coefficients of voltage and current. However, such module needs other parameters such as photon current, saturation current, ideality factor of diode, series resistance and parallel resistance. Such values of these parameters are not specified in the datasheet. The estimation of such parameters is already covered by many researchers such as in Elbaset et al. (2014), Elbaset and Ali (2016). Seven parameters are estimated by the Newton Raphson technique with the aid of initial values that are derived from basic equations of the model and manufacturing data sheet at STC. Newton Raphson and Runge–Kutta Merson iteration methods are used for verifying the capability of the model to fit non-linear output characteristics of *I*–*V* and *P*–*V* (Elbaset et al., 2014). A novel modeling technique for amorphous silicon thin film PV module for determining the impact of changing the solar irradiance on seven parameters of two-diode model and for describing the characteristic curves for each generic condition of operative solar irradiance is proposed in Ref. (Elbaset and Ali, 2016). The proposed model is based on the rate change of seven parameters with respect to irradiance change. The rate change of seven parameters

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is derived from current equation of two-diode model at MPP of different solar irradiance levels. The values of the parameters of the two-diode model are extracted with respect to different solar irradiance levels using precise Runge-Kutta-Merson iterative method. For validating the capability of the proposed technique, three different amorphous silicon and thin film PV modules, U-EA110, MPV95-S, and MST-43LV have been used (Elbaset and Ali, 2016). Two models for the characterization of a multi-junction solar cell are reported in Ref. (Patra and Maskell, 2012). The first model is based on the lumped diode model with an additional term describing the reverse bias region of the multi-junction solar cell. The model contains eight parameters: five parameters describing the I–V characteristic in the positive voltage range and three parameters in the negative voltage range. Such model employed to describe the I–V characteristic of TJSC interconnected with bypass diode (Patra and Maskell, 2012). A technique based on Lambert W-function is employed for determining the parameters of TJSCs at uniform temperature and irradiation. The parameter extraction is applied on two experimental TJSCs simulated with the conventional one containing five parameters at two different concentration ratios. The calculated values are compared with the experimental results showing the accuracy of the proposed approach. The effects of the parasitic resistances on the I-V characteristics are also determined with great matching with the published results (Naorem Santakrus Singh and Avinashi Kapoor, 2014). To the best of our knowledge, even though different optimization techniques have been extensively used for determining the parameters of single-junction solar cell (SJSC), their applications in case of multi-junction solar cells haven't been reported. Several researchers are used meta-heuristic optimization algorithms in extracting the optimal parameters of SJSC (Jacob et al., 2015; AlHajri et al., 2012; AlRashidi et al., 2013; Gong and Cai, 2013; El-Naggar et al., 2012; Askarzadeh and Rezazadeh, 2012; Askarzadeh and Rezazadeh, 2013; Wei et al., 2011; Ma et al., 2013; El-Fergany, 2015; Alireza and Alireza, 2013; Yuan et al., 2014; Chellaswamy and Ramesh, 2016). Such algorithms include; artificial immune system (Jacob et al., 2015), pattern search (AlHajri et al., 2012; AlRashidi et al., 2013), repaired adaptive differential evolution (Gong and Cai, 2013), simulated annealing (El-Naggar et al., 2012), harmony search-based algorithms (Askarzadeh and Rezazadeh, 2012), artificial bee colony (Askarzadeh and Rezazadeh, 2013), chaos particle swarm algorithm (Wei et al., 2011), cuckoo search (Ma et al., 2013), mine blast algorithm (El-Fergany, 2015), bird mating optimizer (Alireza and Alireza, 2013), mutative-scale parallel chaos optimization algorithm (Yuan et al., 2014) and adaptive differential evolution technique (Chellaswamy and Ramesh, 2016). Accordingly, this work suggests a novel methodology for optimal parameters extraction of PV module that contains high efficiency InGaP/InGaAs/Ge TJSCs based on a recently meta-heuristic approach named Water Cycle Algorithm (WCA). Various parameters are estimated and compared with the experimental values. The analysis is limited to three-junction cells only as they represent the status of photovoltaics for which there are published with detailed data.

2. Modeling of InGaP/InGaAs/Ge TJSC

InGaP/InGaAs/Ge TJSC consists of InGaP, InGaAs, and Ge sub-cells as illustrated in Fig. 1. The sub-cells are constructed with decreased energy gaps from the top to the bottom. This structure minimizes the losses due to thermalization of hot carriers and transmission of low energy photons, therefore; increases the solar energy converted into electricity more efficiently than SJSCs (Wen et al., 2012). Multi-junction InGaP/InGaAs/Ge solar cells are known to have an ultrahigh efficiency and are now used for space applications (Nishioka et al., 2006).

Referring to Fig. 1, the solar cell current can be expressed as:

$$I_C = I_{Li} - I_{Di} - I_{shunti} \tag{1}$$

where $i = 1$ for top sub-cell, $i = 2$ for medium sub-cell, and $i = 3$ for bottom sub-cell. The light generated current is given by Tsai et al. (2008):

$$I_{L_i} = RK_C[I_{sc_i} + a(T_c - T_{c,ref})] \tag{2}$$

where $T_{c,ref}$ is the reference temperature in °C, a is the temperature coefficient of the short circuit current A/°C, K_C is the concentration ratio, and R is the solar radiation kW/m^2. The diode current is given by Nishioka et al. (1308):

$$I_{Di} = I_{Oi}\left[\exp\left(\frac{qV_{Di}}{n_i K_B T}\right) - 1\right] \tag{3}$$

$$V_{Di} = V_i + I_C \times R_{Si} \tag{4}$$

$$I_{Oi} = K_i \times T^{(3+\gamma_i/2)}\left[\exp\left(-\frac{E_{gi}}{n_i K_B T}\right)\right] \tag{5}$$

where q is the electron charge, n_i is the diode ideality factor, K_B is the Boltzmann's constant, E_g is the bandgap energy, K and γ are constants, T is the absolute temperature, and R_S is the cell series resistance.

The temperature has an effect on the bandgap energy (E_g). The vibration of the bandgap energy with the temperature can be expressed as (Eltamaly, 2010):

$$E_g(T) = E_g(0) + \frac{\alpha T^2}{T + \beta} \tag{6}$$

If the shunt resistance is big enough, the shunt current can be neglected (Nishioka et al., 2006). Substituting (3)–(5) in (1) gives:

$$I_C = I_{L1} - I_{D1} - I_{shunt1} = I_{L2} - I_{D2} - I_{shunt2} = I_{L3} - I_{D3} - I_{shunt3} \tag{7}$$

The output voltage of the cell, V_C, is given by:

$$V_C = V_1 + V_2 + V_3 \tag{8}$$

Neglecting the shunt current, the voltage V_1, V_2, and V_3 can be expressed as:

$$V_1 = \frac{n_1 K_B T}{q}\ln\left[\frac{I_{L1} - I_C}{I_{O1}} + 1\right] - I_C \times R_{S1} \tag{9}$$

$$V_2 = \frac{n_2 K_B T}{q}\ln\left[\frac{I_{L2} - I_C}{I_{O2}} + 1\right] - I_C \times R_{S2} \tag{10}$$

$$V_3 = \frac{n_3 K_B T}{q}\ln\left[\frac{I_{L3} - I_C}{I_{O3}} + 1\right] - I_C \times R_{S3} \tag{11}$$

Substitute (9)–(11) in (8) gives:

$$V_C = \frac{n_1 K_B T}{q}\ln\left[\frac{I_{L1} - I_C}{I_{O1}} + 1\right] + \frac{n_2 K_B T}{q}\ln\left[\frac{I_{L2} - I_C}{I_{O2}} + 1\right] + \frac{n_3 K_B T}{q}\ln\left[\frac{I_{L3} - I_C}{I_{O3}} + 1\right] - I_C \times R_S \tag{12}$$

where

$$R_S = R_{S1} + R_{S2} + R_{S3} \tag{13}$$

3. An overview of optimization algorithms

In this work the proposed solution methodology is the water cycle algorithm and the obtained results are compared with other four programmed algorithms. Such algorithms include; grey wolf optimizer (GWO), antlion optimizer (ALO), mine blast algorithm (MBA) and harmony search algorithm. This section presents an overview of the used approaches.