Solar Energy 158 (2017) 432–439

Contents lists available at ScienceDirect

Solar Energy

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

Photovoltaic system using Lambert W function-based technique

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ARTICLE INFO

Keywords:
Single diode model
Maximum power point tracker
Lambert W function
Buck converter
Fuzzy logic

ABSTRACT

This article presents a successful simulink model by using the photovoltaic (PV) product along with DC/DC buck converter, lithium ion battery, maximum power point tracker (MPPT) along with loads. The current-voltage (*I-V*) and power-voltage (*P-V*) characteristics of a Kyocera KC200GT product is validated using single diode PV model in conjunction with Lambert W function. Fuzzy logic algorithm is incorporated in MPPT for high tracking accuracy at steady state and better performance to the varying atmospheric conditions. The complete model is simulated under two testing scenarios i.e., sunny and cloudy day conditions. Exact analytical solution technique by using Lambert W function is followed by expressing *I-V* and *P-V* characteristic of PV module by converting into discrete equations. The proposed Lambert W function based mathematical model is accurate and there is a good agreement between calculated and simulated outputs.

1. Introduction

Solar energy is the substantial available, clean and free of emission renewable energy sources that have been gaining increased adoption in recent years. It is estimated that the solar energy received within less than one hour would be sufficient to cover one year of world's energy budget (Lewis, 2007). In a photovoltaic (PV) solar system, the power generating devices are the PV modules, usually called PV panels. For a large-scale PV system, a number of PV panels are connected in series to form a 'string'. A PV solar cell can be represented by either an equivalent single diode circuit (Liu and Dougal, 2002) or a two diode circuit (Gow and Manning, 1999). The single diode model is simple and accurate and widely used (Xiao et al., 2004; Jensen et al., 2010). The *I-V* characteristic of a PV panel is not linear and highly dependent on solar irradiation (Masoum et al., 2002). Because of this nonlinearity, there is a peak point of power corresponding to the voltage at which the PV panel can supply maximum amount of power for an irradiance level. Mathematical modelling of PV module is being continuously improved by many researchers (Veerachary, 2005; Altas and Sharaf, 2007; Chowdhury et al., 2008; Jung and Ahmed, 2010a,b; Nema et al., 2010). The single-diode model presented in open literature is one of the basic equivalent circuits of a solar cell. This model consists of different parameters i.e., ideality factor, series resistance, shunt resistance, photo current and saturation current. Exponential non-linearity of the current equation in the single-diode model causes many problems for evaluating these parameters. Several numerical methods are used to calculate the model parameters (Xiao et al., 2006; Chen et al., 2011). These numerical methods depend on initial values to initiate the process and some cases there may be convergence problems. Analytical methods are one of the powerful methods which express the current and voltage of a PV module or solar cell explicitly. And it takes less computational time due to single iteration (Tamrakar and Gupta, 2015). These methods perform efficiently at standard test conditions (STC) and also under changing environmental conditions. Some of these methods were proposed using the Lambert W function to estimate the parameters of the PV module. Lambert W function is used in literature (Jain and Kapoor, 2005; Ortiz Conde et al., 2006; Singh et al., 2009; Abebe et al., 2009; Fathabadi, 2015) for solving transcendental *I-V* characteristics analytically. Ortiz Conde et al. (2006) analysed a method based on the Lambert W function. In their research, the investigators first calculated Co-content function from the exact explicit analytical expressions and then the model parameters were extracted. Ding and Radhakrishnan (2008) presented an exact explicit solution based on the Lambert W-function to express the optimum load of an illuminated solar cell containing a parasitic series resistance and a shunt resistance. Based on this expression, the optimum load could be calculated directly from the device model parameters. Zhang et al. (2011) expressed a simple fitting method to estimate all the parameters of a solar cell based on the Lambert W function. Various solar devices were analysed including Si solar cells, Si solar modules, standalone organic solar cells, tandem organic solar cells, multi-junction organic solar cells, and dye-sensitized solar cells (DSSCs). Ishaque and Salam (2011) intimated accurate modelling method by using differential evolution for the PV module, and model parameters are computed at any irradiance and temperature

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http://dx.doi.org/10.1016/j.solener.2017.10.007
Received 7 January 2016; Received in revised form 2 August 2017; Accepted 2 October 2017

Nomenclature

I	output current of PV module (A)
V	output voltage of PV module (V)
I_{ph}	photo current (A)
$I_{(ph)n}$	nominal photo current (A)
R_{se}	equivalent series resistance of the PV module (Ω)
R_{sh}	equivalent shunt resistance of the PV module (Ω)
I_{rs}	reverse saturation current of the diode in model (A)
i	ideality factor of the PV module
V_{jnt}	junction thermal voltage of the PV module (V)
$V_{(jnt)n}$	nominal Junction thermal voltage of the PV module (V)
N_s	number of solar cells of a PV module connected in series
K	Boltzmann constant (1.3806×10^{-23} J/K)
T	cell temperature on the PV module (K)
T_n	nominal cell temperature on the PV module (K)
q	electron charge (1.6021×10^{-19} C)
H_g	solar irradiance (W/m^2)
$H_{(g)n}$	nominal solar irradiance (W/m^2)
K_i	current/temperature coefficient (A/K)
I_{sc}	short circuit current of PV module (A)
$I_{(sc)n}$	nominal short circuit current of PV module (A)
V_{oc}	open circuit voltage of the PV module (V)
$V_{(oc)n}$	nominal open circuit voltage of the PV module (V)

point by using manufacturer's data sheet. AlHajri et al. (2012) suggested a new application of pattern search optimization technique for extracting the parameters of solar cell models. The suggested technique is used to solve a transcendental function that governs the *I-V* relationship of a solar cell as there is no direct general analytical solution exists. Femia et al. (2012) proposed a method to calculate analytically the series resistances and shunt resistance using Lambert W function. This method expresses the output current of the PV module as an explicit function of its voltage and presents good performance in convergence. Amrouche et al. (2012) proposed a simple behavioural model for solar module electric characteristics based on the first order system step response for MPPT study and comparison. This model was based on the first order system response equation. Peng et al. (2013) presented a new method to describe the *I-V* and *P-V* characteristics of solar cell and module by using the exact explicit analytical solutions. To extract the parameters, an optimized technique was presented using Lambert W function and polynomial curve fitting. The accuracy of the model was compared with other work and the results were good agreement between the fitted *I-V* curves and the experimental data. Cubas et al. (2014) expressed a method based on analytical formulation which turns the series resistor equation explicitly by using Lambert W function. The expression was used to analyse commercial solar panel performance at different irradiation and temperature levels. Batzelis et al. (2014) presented the characteristic of voltage with respect to current by using the Lambert W function. Authors found that this method combines the versatility and accuracy provided by the single diode model with a significantly faster and more robust execution.

In open literature, several MPPT techniques have been proposed (Kuo et al., 2001; Liu et al., 2008) to maximize the extracted output power from a PV cell with the help of MPPT controller. Tsang and Chan (2013) proposed a novel approach for tracking the maximum power point of PV system by investigating on Model based rapid maximum power point tracking. Bennett et al. (2013) followed a new MPPT algorithm and electrical parameters were optimized and compared with other hill climbing algorithms. Liu et al. (2013) investigated on Neural-network-based maximum power point tracking methods for photovoltaic systems expose to fast changing environments. The proposed digital MPPT system was proved to have high static and dynamic tracking efficiency. Gao et al. (2013) suggested two maximum power point tracking control strategies with variable weather parameters. The authors established direct relationships between the weather parameters and the MPPT control signals.

In present study, by using single diode PV model in conjunctions with Lambert W function, the *I-V* and *P-V* characteristics of a Kyocera KC200GT product has been validated. A simulink model is developed by using the above PV product along with DC/DC buck converter, lithium ion battery, MPPT and loads. Where, loads are represented by number of resistors connected in parallel. Fuzzy logic algorithm is used in MPPT for high tracking accuracy at steady state and better performance to the varying atmospheric condition. Finally, the variation of current, voltage and power of PV module and battery is presented with respect to time. Charging and discharging state of battery is also plotted with progress of time.

2. *I-V* and *P-V* characteristic of PV module in terms of Lambert W function

A PV module consists of number of solar cells. The single-diode model of a PV module is shown in Fig. 1. The *I-V* characteristic of the PV module can be expressed as,

$$I = I_{ph} - \frac{V + IR_{se}}{R_{sh}} - I_{rs}\left[\exp\frac{(V + IR_{se})}{iV_{jnt}} - 1\right] \quad (1)$$

where, $V_{jnt} = \frac{N_s KT}{q}$ is the junction thermal voltage of the PV module consisting of 'N_s' solar cells connected in series, 'I_{ph}' is the photo current generated by the PV module. The photo current depends on the solar irradiation 'H_g' and cell temperature 'T'. The photo current can be obtained using the solar irradiation and the cell temperature as follows.

$$I_{ph} = [I_{(ph)n} + K_i(T - T_n)]\frac{H_g}{H_{(g)n}} \quad (2)$$

where, '$I_{(ph)n}$' is the photocurrent generated by the PV module at the nominal condition (standard test condition- STC); 'T' and 'T_n' are the actual and nominal cell temperature; 'H_g' and '$H_{(g)n}$' are the actual and nominal solar irradiation, respectively. The standard test condition (STC) refers to the conditions as $H_g = 1000$ W/m^2, $AM = 1.5$ spectrum and $T = 25$ °C. Substituting 'I_{ph}' from (Eq. (2)) in (Eq. (1)) results

$$I = [I_{(ph)n} + K_i(T - T_n)]\frac{H_g}{H_{(g)n}} - \frac{V + IR_{se}}{R_{sh}} - I_{rs}\left[\exp\left(\frac{V + IR_{se}}{iV_{jnt}}\right) - 1\right] \quad (3)$$

The above equation can be solved by using Lambert W function and the output current of the PV module is expressed as a function of the PV module voltage as given below.

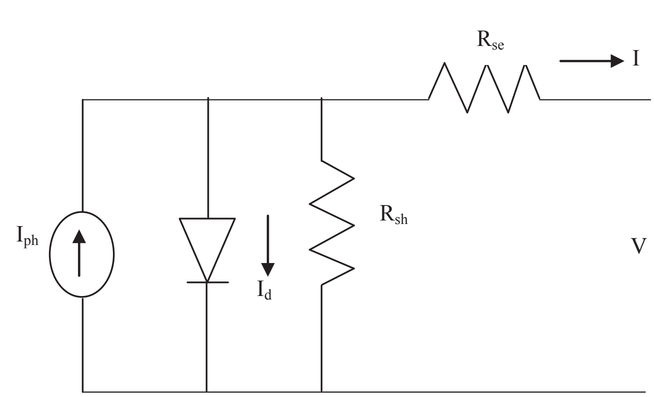

Fig. 1. Equivalent circuit of PV module having single-diode system.