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A new offline method for extracting I-V characteristic curve for photovoltaic modules using artificial neural networks

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ABSTRACT

This paper presents a new I-V curve prediction method using artificial neural networks. The proposed method is based on two artificial neural networks namely generalized regression artificial neural network and cascaded forward neural network. An experiment is set up so as to extract a dataset that includes records of solar radiation, ambient temperature, current and voltage for different photovoltaic modules. The developed model is a general model for all photovoltaic modules whereas the inputs of the model are solar radiation, ambient temperature and datasheet specifications of photovoltaic module (open circuit voltage and short circuit current). Matlab is used to train, test and validate the proposed model. Moreover, the proposed model is validated experimentally. The results show that the proposed model has a high accuracy in predicting I-V curves with average mean absolute percentage error, mean bias error and root mean square error of 1.09%, 0.0229 A and 0.0336 A respectively. Such a model is very helpful in generating I-V curves for different photovoltaic modules.

1. Introduction

The performance of solar cell depends on atmospheric conditions and thus, one of the problems of solar cell is the unpredicted output power due to the variation in solar radiation and solar cell's temperatures. In general a solar cell can be considered as a p-n junction and thus the I-V curve of solar cell provides information on the performance of the solar cell such as the output power. The I-V curve of solar cell represents the relation between solar cell's current and voltage at specific solar radiation and ambient temperature. This characteristic curve provides important performance information about solar cell such as open circuit voltage, short circuit current, maximum rated power, maximum current, maximum voltage, and module's efficiency. These parameters are extremely important for utilizing, testing, calibrating, commissioning, designing, maintaining, and controlling of photovoltaic (PV) systems (Ram et al., 2018).

Measuring I-V characteristic curve of solar cell becomes an important research topic in photovoltaic technology science. The measurement or extraction of I-V characteristic curve can be divided into two categories; online measuring methods and offline measuring methods. The online measuring methods use real devices to measure the current and the voltage of a solar cell or PV module using a specific electric circuit so as to construct I-V curve. These methods utilize many elements such as resistor, capacitor, inductor and switches. The main principle of these methods is to apply varying impedance that varies from a very large value to a very small value so as to extract currents and voltages including short circuit current and open circuit voltage. The varying impedance can be a varying resistor for example, charging or discharging capacitor or inductor or an electronic switch that is controlled by a specific control signal. These methods are well investigated in the literature and commercialized in the market. The advantages of these methods are ability of measuring I-V curve considering site characteristic as well as the ability of diagnosing faults in the system. However, the losses, testing time and the ability of measuring large scale systems are considered the main drawbacks of these methods (Duran et al., 2008). There are many examples of online measuring methods in the literature. Van dykn in Van Dyk et al. (2005) used a variable resistor to measure the I-V curve of a solar cell. Different values of solar cell's current and voltage were measured under different load values. After that, I-V curve was drawn based on these records. However, this method can't achieve the boundary conditions of the I-V curve (open circuit voltage and short circuit current). In addition, it can be only used for solar cells or PV modules with low power capacity. On the other hand, Mahmoud in Mahmoud (2006) extracted the I-V curve by charging a capacitive load. However, here also the open circuit voltage and short circuit current measurement, testing time, and

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Abbreviation list

ANN	artificial neural network
PSO	particle swarm optimization
R_{sh}	shunt resistance
I_d	diode current
q	the electron charge
n	diode's ideality factor
G_{nom}	solar radiation at the reference test
R_s	series resistance
FF	fill factor
GRNN	generalized regression artificial neural network
SR_{new}	solar radiation for the testing condition
SR_{STC}	solar radiation at standard test condition
T_{cell}	cell temperature for the testing condition
T_{STC}	Temperature at standard test condition
STC	Standard test condition
MBE	mean bias error
MAPE	mean absolute percentage error
GA	Genetic algorithm
R_s	series resistance
I_{ph}	photocurrent of the solar cell
$I_{R_{sh}}$	leakage current of the solar cell
k	Boltzmann constant
G	solar radiation
I_o	saturation current of the diode
I_{sc}	Short circuit current
CFNN	cascaded forward neural network
$I_{sc-test}$ is	short circuit current for the testing condition
I_{sc-STC}	short circuit current at standard test condition
$V_{oc-test}$	open circuit voltage for the testing condition
V_{oc-STC}	open circuit voltage at standard test condition
$NOCT$	Nominal Operating Cell Temperature
V_{oc}	open circuit voltage
RMSE	root mean square error

method's applicability for different PV module sizes were considered as limitations to this method. Similarly, Muñoz and Lorenzo in Muñoz and Lorenzo (2006) have extracted the I-V curve by charging a capacitive load. In this method, some of the limitations of the method presented in Mahmoud (2006) were avoided. On the other hand, electronic loads were utilized for I-V curve extraction. Kuai and Yuvarajan in Kuai and Yuvarajan (2006) extracted I-V curve by utilizing several MOSFETs in parallel. The advantages of this method are the high testing speed and the ability of measuring high currents. Moreover, Khatib et al. in Khatib et al. (2017) used DC-DC boost converter to extract I-V curve by modifying the duty cycle of the control signal of boost converter's switch. The advantage of this method is the ability of extracting the I-V curve without needing external devices.

However, in all of the previous methods, the switching losses, the accuracy of the measured I-V curve and the complexity of handling large power scale systems were the main challenges. Therefore, some of the authors have utilized offline methods for predating the I-V curve instead of extracting it using physical devices. The offline methods are usually based on artificial intelligence (AI) or empirical mathematical methods. These methods aim to generate I-V curve of solar cell based on historical experimental data (Khatib, 2016). The most common offline method for generating I-V curve of solar cell is the five parameters model of solar cell. With this model the output current of the solar cell is defined as a mathematical function that contains five parameters (sometimes four or seven). The value of these parameters should be optimized based on historical experimental data (Chin et al., 2015). In general offline methods are accurate and fast. However the major drawback of these methods is the ability to diagnose any fault or abnormal condition in the PV system as they are offline (Chan and Phang, 1987; Ciulla et al., 2014). Examples of these methods can be found the literature. Bai et al. (2014)4 extracted I-V curve based on the five-parameter model using an improved curve fitting technique. Similarly, Levenberg–Marquardt method (Ma et al., 2014; Tossa et al., 2014), Newton–Raphson method (NRM) (Easwarakhanthan et al., 1986), and other numerical techniques (Navabi et al., 2015), are also used to extract I-V curve of solar cell. In addition to that, combined numerical and analytical methods are used for this purpose in Hejri et al. (2014), Villalva et al. (2009). However, these methods have some drawbacks such as complex computation, possible diverges and the dependency of method's accuracy on the initial conditions. Moreover, to achieve accurate methods large training data are required.

Here artificial Intelligence based methods were proposed as alternative methods that overcome the drawbacks of other offline methods. Evolutionary algorithms are proposed for extracting the I-V curve because of their high efficiency, accuracy, and capability to estimate the

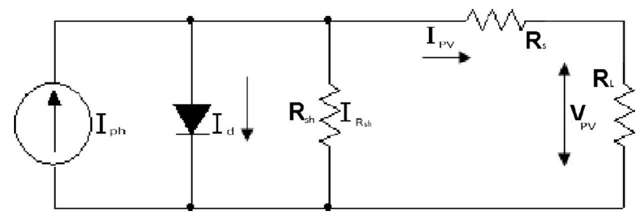

Fig. 1. Solar cell equivalent circuit.

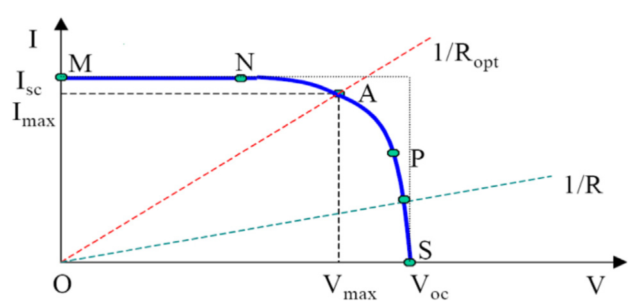

Fig. 2. I-V characteristic curve of a solar cell (Khatib et al., 2017).

parameters of solar cell models (Sharma et al., 2012). The main concept of these methods is to optimize the value of each parameter in the five parameters model based on experimental data. Genetic algorithm (GA) (Dizqah et al., 2014; Moldovan et al., 2009; Ismail et al., 2013; Zagrouba et al., 2010; Appelbaum and Peled, 2014; Jervase et al., 2001), particle swarm optimization (PSO) algorithm (Khanna et al., 2015; Ye et al., 2009; Jing Jun and Kay-Soon, 2012), flower pollination algorithm (Alam et al., 2015), Shuffled frog leaping algorithm (Hasanien, 2015) are used before for extracting the I-V characteristic curve. In addition, improved and hybridized evolutionary are also proposed for this purpose (Ishaque and Salam, 2011; Ishaque et al., 2011; Ishaque et al., 2012; Jiang et al., 2013; Gong and Cai, 2013; Siddiqui and Abido, 2013; Muhsen et al., 2016; Muhsen et al., 2015). For more information regarding these methods, the performance of different evolutionary algorithms that extract the I-V curve of solar cell is discussed by Siddiqui and Abido (2013).

On the other hand, artificial neural networks are used for extracting the I-V curve of solar cells and PV modules (Karatepe et al., 2006; Celik, 2011; Bonanno et al., 2012). The main aim of these methods is to predict the value of model's parameters based on historical experimental data. A number of parameters for the equivalent circuit of the solar cell are assumed. This number could be four, five or seven