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Original Research Article

Evaluation of numerical algorithms used in extracting the parameters of a single-diode photovoltaic model

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ABSTRACT

The current–voltage relationship of the single-diode photovoltaic (PV) cell/panel equivalent circuit model is defined by its implicit nonlinear transcendental equation, which is difficult to solve using analytical methods. This difficulty has led to the development of several algorithms for solving this equation using numerical techniques. This paper investigates and compares three different algorithms commonly employed in solving current–voltage equation of a 5-parameter single-diode solar PV model using manufacturer's data sheet. The comparison is performed based on accuracy (i.e. closeness of the obtained results to experimental values), required computer memory, speed of computation, robustness of the algorithm, and ease of implementation of algorithm. The results reveal that no single algorithm performs best in all the metrics and there will always be a trade-off in the choice of the algorithms based on the user's focus. Villalva algorithm is preferable in terms of robustness whilst T. Esram performs better in the area of computational speed, memory space and ease of implementation. No generic conclusion could be easily made in terms of accuracy as it varies with the PV technology and parameter of interest. The present work can be a potential tool for researchers and designers working in the area of photovoltaic systems, to make decisions related to the selection of the best possible algorithm for the extraction of the characteristic parameters of single-diode 5-parameter PV models.

Introduction

The need to increase the security of energy supply, mitigate environmental pollution and foster job opportunities through the emerging new green technologies in recent years has made clean and renewable energy sources an inevitable option of consideration. There are various types of renewable energy sources with different associated conversion technologies. However, the substantial increase of research and development work in the area of photovoltaic (PV) systems has made the PV one of the fastest growing renewable energy technologies for electricity generation around the world [1]. This increasing attention can be attributed to the ubiquity of the sun, non-polluting nature of photovoltaic systems, increasing efficiency of solar cells, improvements of manufacturing technology of solar panels [2] and the eventual economic long-term benefit for island (stand-alone) and interconnected power systems.

Although PV systems are excellent for clean sustainable power generation, their electrical output varies as a function of ambient environmental conditions (temperature of the photovoltaic cell, the level of solar irradiance) and the operating voltage of the connected load [3,4]. This poses a major drawback in PV system design, since the connected load must operate at the point where maximum power is derived from the PV generators. To achieve the maximum power point operation of a PV system, the changing environmental parameters vis-à-vis the characteristic of PV generators must be adequately matched. Outdoor testing of all commercially available PV modules at different operating conditions in order to obtain their characteristic behaviour is costly, time consuming [5] and really not feasible considering the amount of modules currently available in the market. To surmount this challenge, researchers have developed various mathematical models to understand and predict the effect of these changing conditions on PV electrical output. Amongst these models, the lumped parameter electric circuit based models have proven to be more successful and as a result are widely applied in literature [6].

There are different lumped parameter models which are classified based on the number of diodes [7]. They are single diode model, double diode model [8] and in recent times the three diode

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model [9]. As the number of diode increases, the accuracy of the characteristics of the model improves, however, the mathematical expression required to obtain the output characteristics becomes more complex. The single-diode, 5-parameter model offers the compromise, but it requires solving a number of equations to extract the initial parameters that are applied to the model [6]. This challenge is further complicated by the limited data available in the manufacturer's datasheet.

Several methods have been employed to extract these parameters. Amongst these methods are the artificial neural network, genetic algorithm, the analytical based approach and the numerical methods, and these have shown different levels of accuracy. ANN has been utilised to model PV modules in two basic ways: firstly to predict the equivalent circuit parameters [10], secondly to generate the I–V curves of PV under different weather conditions [11]. Bonanno et al. [12] advanced an ANN based model which takes into account the operating conditions to predict the output power of a PV module. This was further extended by Almonacid et al. [13] by using ambient temperature (instead of module temperature) as part of the input parameter to the model. Furthermore, Karamirad et al. [14] adapted a multi-layer perceptron (MLP) artificial neural networks to predict the operating current and power of the PV module under real operating conditions. In this work, different hidden layers MLP are designed and tested under a varied range of input parameters (the daily total irradiation, air temperature and module voltage). It was demonstrated that the results obtained with ANN were marginally better than the five-parameter model using statistical tools.

GA has also been utilised in the estimation of the PV electrical model parameters. The common objective function when adopting GA for parameter prediction is usually focused on error in the prediction of current at known voltages [15]. Ishaque et al. [16,17] used additional evolutionary algorithms to find the model parameters for a two-diode equivalent electric circuit PV model and found that penalty-based differential evolution showed good accuracy, consistency of solution and required very low control parameters.

Changing the view point from conventional static curve fitting to dynamic system identification, Lihong [18] applied the integral based linear least square identification method to extract all diode model parameter from a single I–V curve. The solution was found to be comparatively accurate, establishing a direct link between the model parameters and I–V curves and does not require either iterative search or approximation. Lambert *W*-function is applied in [19] to approximate the series and shunt resistance and diode quality factor. A reduced-form of the photovoltaic five-parameter model for efficient computation of parameters is applied in [20]. The model is reduced from five to two parameters to define a domain of attraction of the solution space that is analytical. It guaranteed that the nonlinear solver provide physically feasible solution for the parameters at first launch. All the aforementioned methods except the numerical methods are dependent on one or more experimental values that are not normally available in the manufacturers' data sheet.

Some researchers have compared the algorithm used in extracting the parameter of solar PV models. For example, the extraction of the parameters of the single-diode solar cell model using experimental I–V characteristics of Si and Multi-junction solar cells has been performed by Appelbaum and Peled [21]. The extraction was carried out using three different optimisation methods (Newton–Raphson method and the Levenberg–Marquardt algorithm and Genetic algorithm) with the aim of determining which method surpasses the others in terms of data-to-model fitting. Their results revealed that Newton–Raphson method is the most favoured for the extraction of the parameters. In another research, Ciulla et al. [22] compared the I–V and P–V curves at various temperatures and irradiance for a generic PV panel for five different algorithm models which are: Hadj Arab et al. [23] model, De Blas et al. [24], Lo Brano et al. [25], Villalva et al. [26] and De Soto et al. [27] models. The authors showed how the parameters were determined and also highlighted the most important mathematical and physical assumptions that characterised each model and the calculation process. It was revealed that all models perform well when compared with the manufacturer curve at irradiance of 1000 W/m^2 and cell temperature of 25 °C. However, the agreement of the models with the manufacturer curves changes with change in irradiation and cell temperature. The study concluded that Lo Brano et al. model performs best on the overall.

The aforementioned extraction models are compared on the basis of accuracy of the models only. This present study tends to contribute also along this direction by including other metrics in addition to the accuracy of the models for an encompassing comparison of parameter extraction models. This study therefore evaluates the performances of three extraction algorithms (T. Estram, Villalva and Vika algorithms) based on the following metrics: robustness of the algorithms, speed of computation, memory requirement, ease of implementation and accuracy of the algorithms. The choice of these criteria is necessary since the current trend in photovoltaic performance simulation requires high-speed performance estimation to aid real-time optimisation with fast changing environmental conditions. In addition to this is the fact that this optimisation function is usually performed by embedded microcontroller system with limited memory capability.

The performance of these algorithms is evaluated at STC as well as under several temperatures and solar irradiation conditions for six selected photovoltaic panels. The selected PV panels cover six major classes of PV cells: Nexpower Technology NH-100UT (1-a-Si), Polar Photovoltaics TFSM-T-1X (2-a-Si) Xunlight XRU10-74 (3-a-Si) [28], First Solar FS-280 (CdTe) [29], Sunperfect Solar CRM175S125M-72 (mono-Si) [30] and Kyocera Solar KD210GX-LPU (multi-Si) [31].

The single-diode model

The electrical equivalent circuit of a 5-parameter single diode model is depicted in Fig. 1. It consists of a current source anti-parallel with a diode, with a series and parallel resistor connected at the terminal of the diode.

Applying Kirchhoff's law and the Shockley's diode equation to the equivalent circuit in Fig. 1, then, the corresponding mathematical equations for the generated current in the PV cell at a particular operating voltage can be obtained as:

$$I = I_{ph} - I_0\left(\exp\left(q\left(\frac{V + IR_s}{nkT}\right)\right) - 1\right) - \frac{V + IR_s}{R_{sh}} \quad (1)$$

where I_{ph} is the light-generated current, I_o is the diode reverse saturation current, and n is the diode ideality constant. R_s and R_{sh} are used to account for the parasitic series and shunt resistance respectively, k is the Boltzmann's constant and q is the electron charge.

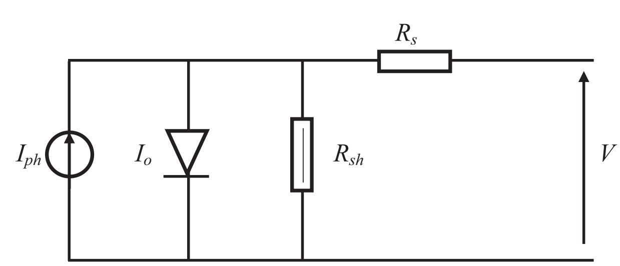

Fig. 1. Equivalent circuit of the single diode, 5-prameter model.