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Modeling and characterization of a grid-connected photovoltaic system under tropical climate conditions

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ABSTRACT

In this study, a three parameter photovoltaic (PV) model operates under tropical weather conditions is developed and characterized. The performance of the PV system model is also assessed. Malaysia weather conditions selected in this case study as a test bed. A mathematical PV model of a small-scale PV system is established. The proposed PV model reliance on, both, the simplicity and accuracy, which based on real data. The potential results obtained based on the designed simulation. The average PV performance based on the comparison of the calculated and actual PV performances was 65.8%. The average inverter performance based on the calculated and actual inverter efficiencies was 97.58%. The accuracy of proposed model verified by using different evaluation criteria and compared with various models from the legacy works. This study could serve as a valuable reference for grid-connected PV system installation in Malaysia and other tropical regions to promote PV implementation.

1. Introduction

Solar energy is clean and environmentally friendly, and it can be harvested from nature freely. These desirable features have promoted the role of PV systems worldwide. However, the high capital cost of such systems has overshadowed their effectiveness. The sun actually provides energy hundreds of times more than the world demands [1]. Capturing this energy and converting it into useful forms, such as electrical power for daily usage, are therefore important. Nevertheless, existing technologies have their own limitations that must be resolved to realize large-scale PV implementation. PV system modeling, characterization, and performance assessment compared with other conventional sources should be enhanced to identify and overcome these limitations [2,3].

Precise PV system modeling has posed a challenge to researchers. A model that can simulate the characteristics of a PV system under specified or non-specified climate conditions should be established. Although several models are based on real weather conditions, they are only effective under specific weather conditions. PV system modeling and characterization are location dependent, and researchers have thus far developed models based on their respective locations and climates. The PV installation site can affect the output power and PV system performance either positively or negatively. Consequently, developing a PV system model that can emulate the characteristics of a PV system that operates under fluctuating weather conditions has become necessary. Thus, the current study develops a high-accuracy and low-complexity PV system model based on real data from a PV system that operates under fluctuating weather conditions.

Numerous researchers have recently conducted studies on PV system modeling and performance assessment under different climate conditions to better understand the impact of climate on the system's performance [4]. Thus, model should consider the performance and characteristics of PV systems under highly uncertain weather conditions.

Many studies on PV system modeling and characterization have also been conducted [5–11]. An approach to determine the model parameters of a single-diode model of a PV panel was proposed in [5]. The influences of both irradiation and temperature on these para-

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meters were also considered; however, the methods for determining the parameter settings in case of instantaneous variations in temperatures and irradiances have not been considered and discussed. A PV system model was established following a simple procedure in [7] to derive the PV system parameters efficiently. Nonetheless, the applicability of utilizing this model is limited because the model does not consider drastic changes in the climate. The four-parameter model was subsequently improved to establish a model that can adapt to the variations in the current voltage characteristics (I–V) under different operating conditions [9]. However, the lack of a practical analysis in the said study made the validation weak. The improved modeling technique in [19] was based on a genetic algorithm-based optimization of several PV panel parameters; the modeling technique was used in establishing single- and double-diode models, between which the single-diode model was more efficient. Another study [11] proposed an improved PV system modeling technique based on a differential evolution algorithm. This method allows for the computation of all the PV parameters at any irradiance and temperature values; however, its computational complexity is high.

A study on the performance of a hybrid PV–fuel cell system was conducted in Malaysia [12]. The results of the study showed that the PV capacity factor was 24.6% and the performance ratio was 66%. The PV performance of an integrated PV–wind hydrogen energy production system was analyzed in [21]. The results showed that the yield factor of this system was in the range of 2.91–3.98 and its performance ratio was in the range of 0.7–0.9. Another study [1] was conducted to investigate the performances of different PV cells, such as monocrystalline silicon (c-Si), multicrystalline silicon (mc-Si), amorphous silicon (a-Si), and copper–indium–diselenide (CIS) solar panels. The study showed that the obtained system efficiencies and performance ratios were in the ranges of 30.1–35.31% and 93.3–109.4%, respectively and asserted that CIS is the most suitable among the PV cell types under the Malaysian weather condition. The said study also determined that the ambient temperature under the standard test condition (25 °C) was inapplicable because its actual average value was 42 °C.

The characterization and performance analysis of a 3kWp monocrystalline grid-connected PV system installed in Selangor, Malaysia, were presented in another study [13]. The 6-month performance data of the system were used to establish accurate mathematical models of the system. Technical criteria were also applied to evaluate the performance of the system and assess its viability and feasibility. The experimental results show that the average efficiency of the PV module was 10.11% and the average efficiency of the inverter was 95.15%. The average monthly PV performance ratio and average capacity factor of the system were 77.28% and 15.70%, respectively. Although PV system modeling and characterization have been studied extensively, an accurate model that is applicable to all tropical countries has yet to be developed. Therefore, developing an accurate model that is applicable to tropical sites is imperative.

In the current study, a 5 kWp grid-connected PV system installed under Malaysia weather conditions. The relevant parameters global solar irradiance, ambient temperature, PV voltage, PV current and efficiency, and inverter efficiency were measured on two particular days. The PV model parameters and effect of the number of these parameters were also reviewed. The average performance value of a PV system in tropical environments was obtained on the basis of comprehensive investigations and the existing literature.

Therefore, the main aim of this study is to develop an accurate PV model. This PV model developed to be distinct on an extremely level of accuracy and an acceptable level of complexity, comparing to PV models presented in literature. In addition, to increase the reliability of the proposed model via its reliance on real data from a PV system operates under fluctuating weather conditions. Lastly, a brief review on the methods of PV modeling and its depending on the number of PV parameters also considered in current study. This study could provide a helpful reference for PV system modeling and installation in tropical climatic regions.

Table 1
Specifications of the proposed system.

Parameter	Value and Units
Number of PV modules	42
Maximum Power (P_{MP})	120 W
Maximum Voltage (V_{MP})	16.9 V
Maximum Current (I_{MP})	7.10 A
Open Circuit Voltage (V_{OC})	21.5 V
Short Circuit Current (I_{SC})	7.45 A

2. PV system modeling and characterization

This section illustrates and demonstrates in detail the methodology for PV system characterization. A five-parameter model was utilized to characterize the PV array. An accurate mathematical model for the PV system was derived by mathematically calculating realistic parameters.

2.1. PV array modeling

A 5 kW PV system consisting of 42 multicrystalline PV modules and installed in Malaysia was considered as the case study. The system specifications are listed in Table 1.

The single-diode model was utilized to model the PV system. Thus, a solar cell was modeled by an equivalent circuit, which consisted of a current source, a diode in reverse mode, and a resistance connected in series. Each model part corresponded to a specific parameter. The cell photocurrent was represented by the current source, which is shown as the solar cell in the model. The output voltage was represented by the diode in reverse mode. The diode saturation current was represented by the shunt resistance. The cell internal losses were indicated by the series resistance.

The solar cells functions similarly to a semiconductor diode under normal conditions or in the absence of sunlight. Thus, the semiconductor diode is represented by a normal diode, whose characteristics (I–V) can be represented by Eq. (1).

$$I_D = I_o\left(.exp^{\frac{q.V_D}{nkT}} - 1\right), \tag{1}$$

where

$$V_D = V + IR_S, \tag{2}$$

I is the PV output current, I_L is the photocurrent, I_o is the diode reverse saturation current, and q is the electron charge value with a value of 1.602×10^{-19} C. Furthermore, k is the Boltzmann constant (1.381×10^{-23} J/K); T is the ambient temperature; V_D is the voltage across the diode terminals; V is the output voltage; R_S is the series resistance; and n is the ideality factor, which is also known as the quality factor or emission coefficient.

When the solar cell is illuminated, an ideal cell is represented by a current generator connected in parallel with a diode. The I–V characteristics were described by Shockley [22] through the following equation:

$$I = I_L - I_D = I_L - I_o(exp^{\frac{q.(V+IR_S)}{nkT}} - 1) - \frac{V + IR_s}{R_{sh}}. \tag{3}$$

The ideality factor (n) commonly ranges between 1 and 2, although it can be larger than 2 under rare conditions, depending on the construction method and semiconductor material. The proposed PV system model included five parameters, namely, I_L, I_o, a, R_s, and R_{sh}.

This model can be applied to an individual cell, a module with several cells, or an array with several modules.

Nonetheless, the following equation was assumed because of the difficulty in determining the accurate value of n: