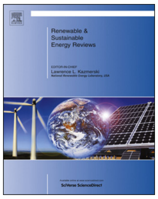
Renewable and Sustainable Energy Reviews 42 (2015) 1047–1054

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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



Performance evaluation and characterization of a 3-kWp grid-connected photovoltaic system based on tropical field experimental results: new results and comparative study

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ARTICLE INFO

Article history:
Received 6 May 2014
Received in revised form
24 July 2014
Accepted 25 October 2014

Keywords:
Photovoltaic system
Modeling of PV system
Performance evaluation
Malaysia

ABSTRACT

In this article, the results on the characterization and performance analysis of a 3-kWp grid-connected photovoltaic (PV) system are presented. Six-month performance data for the system installed at the Universiti Kebangsaan Malaysia campus are used. The analyzed system consisted of a 3-kWp mono-crystalline silicon PV array connected to an indoor 3-kW inverter. Mathematical models for the system are developed based on the collected performance data to provide accurate performance models. In addition, technical criteria are applied to evaluate the performance and to assess the viability and feasibility of the system. The experimental results show that the average efficiency of the PV module is 10.11%, whereas the inverter has the average efficiency of 95.15%. In addition, the average monthly PV performance ratio and average capacity factor of the system are 77.28% and 15.70%, respectively.

Contents

1. Introduction

Currently, the world is facing a significant increase in energy demand and serious environmental issues related to conventional energy sources. Therefore, utilities and customers have extensively accepted the use of pollution-free renewable energy-based generators, including solar energy systems. Solar energy can be efficiently utilized directly to provide heating or cooling of air and water without using any intermediate electric circuitry. Moreover, solar radiation can be converted into electrical energy using photovoltaic (PV) modules. Nonetheless, direct conversion of solar energy into electricity is an efficient manner of utilizing solar energy systems. However, this process needs higher capital cost as compared with conventional energy sources [1].

The PV system is considered an unstable energy source because of the uncertainty of solar radiation. However, performance prediction of these systems is extremely important in many related aspects such as sizing and control of the system. In addition, PV system performance is important for system planning and funding as well as energy market analysis, especially when these systems

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http://dx.doi.org/10.1016/j.rser.2014.10.090
1364-0321/

are incorporated with the electrical power system. Therefore, accurate modeling and characterization of these systems based on experimental results are required. By contrast, the performance of the PV system is a location-dependent variable, which means that the geographical location may affect the performance of the system either negatively or positively. Based on this finding, the performance of these systems much be analyzed under different climate zones for better understanding of the behavioral nature of these systems.

Recently, some studies dealing with PV system characteristic and performance under tropical climates such as Malaysia have been conducted [2]. Based on these studies, the performance of the PV system is highly dependent on the PV module technology, geographic location, and installation configuration. Moreover, environmental parameters such as solar radiation and ambient temperature are extremely important for evaluating system performance over a specific time period [3]. In addition, an accurate system model is required to compare the obtained evaluations with the desired values to justify technical and economic aspects.

In 2003, an assessment has been conducted to address the technical and economic viability of a hybrid PV–diesel generator system installed in a typical secondary school located in East Malaysia [4]. Meanwhile, system simulation-based technical, environmental, and economic evaluations of building-integrated PV systems have been conducted using modeling of a local distribution network at in Petaling Jaya at Selangor, Malaysia [5]. Later, in 2009, an evaluation of a hybrid PV system is conducted [6]. In this research, the performance of a PV/wind/fuel cell system is analyzed. However, simple analysis of PV systems is conducted in this research, whereas most of the focus was on fuel cell performance. Other simulation-based assessments have been reported for a PV–wind–battery system for an existing local distribution system in Kampong Opar, Malaysia [7]. In ref. [8], experimental results were obtained from a comparative study of three different PV module technologies for a grid-connected (GC) system under Malaysia's operating conditions. Based on this research, the performance ratio was approximately 78.2% for polycrystalline, 94.6% for a-Si thin film, and 81% for monocrystalline PV modules. Moreover, the authors concluded that a-Si thin film PV modules showed high performance in terms of final yield, performance ratio, and array/system efficiency of the GC system over the entire monitored period. In ref. [9], the performance of a 5.76-kWp GC PV system installed at the Universiti Kebangsaan Malaysia (UKM), Bangi has been studied. According to ref. [9], the GC PV system at UKM recorded an average module temperature of 39.5 ± 0.6 °C, generated energy at 17.1 ± 0.6 kWh/day, received an incident solar irradiation of 195.8 ± 7.4 kWh/day, exported energy into the grid at 15.6 ± 0.5 kWh, received solar irradiation of 4.1 ± 0.2 kWh/m^2/day, operated at an array efficiency of 8.8 ± 0.2%, operated at an inverter efficiency of 91.2 ± 0.4%, operated at a system efficiency of 8.1 ± 0.2%, has a final yield of 949.0 ± 0.5 kWh/kWp, and has a performance ratio of 63.6 ± 1.0%. In ref. [10], a hybrid PV/fuel cell system is evaluated. The PV power system has been analyzed in terms of power generation and efficiency. However, the authors also focused on analyzing the fuel cell system.

A detailed study on the performance of PV systems in Malaysia was conducted on an off-campus 5-kWp PV system installed at UKM, Malaysia [2]. In this research, the system has been mathematically modeled. Then, the productivity of the system was first evaluated. Afterward, an evaluation of system performance is conducted using specific technical criteria. In addition to this study, the performances of three types of PV systems, namely, concentrating PV system, PV system with sun tracking flat, and fixed flat PV system, installed at Universiti Putra Malaysia, Serdang, Selangor, Malaysia have been evaluated in ref. [6]. In this research, the authors concluded that the PV system with sun tracking flat is the most productive system

In this article, the performance of an in-campus 3-kWp GC PV system is evaluated. The system is composed of 25×120 W polycrystalline silicon PV modules and a 3,000-W direct current/alternating current (DC/AC) inverter. The required data, including solar radiation, ambient temperature, PV panels, and DC/AC inverter output powers, are logged during October 2013 to March 2014 every 1 min. Then, the data are used to develop an accurate mathematical model of the PV system for further performance evaluation.

2. Pv system characterization

To conduct an accurate performance assessment of the PV system, a precise mathematical model of the system is required. Such mathematical model allows characterizing the system for better understanding of the correlation of acquired data for evaluating the actual profitability of the system.

2.1. PV module modeling and characterization

Different methods are used to estimate the required parameters modeling the PV modules. In this article, the five-parameter mathematical model is considered as a reliable and accurate approach to model the 3-kWp PV system [2]. The chosen system consisted of 25 polycrystalline modules. Each module has a maximum power of $120 \pm 3\% \cdot$ W, a maximum current of 6.89 A, a maximum voltage of 17.4 V, an open circuit voltage of 21.5 V, and a short circuit current of 7.63 A. According to refs. [12,13], the mathematical relationship between cell voltage V and cell current I can be expressed as follows:

$$I = I_L - I_0 \cdot \left[\exp\left(\frac{q(V + I \cdot R_s)}{n \cdot kT_c}\right) - 1\right] - \frac{V + I \cdot R_s}{R_{sh}}, \tag{1}$$

where I_L and I_0 are the photocurrent and the reverse saturation current of the diode, respectively, n, k, q, and T_c are the ideality factor, Boltzmann constant, electron charge, and cell temperature (in Kelvin), respectively, and R_s and R_{sh} are the series loss resistance and shunt loss resistance, respectively.

By applying the short circuit and open circuit conditions and some simplifications, I_0 and I_L can be expressed as follows:

$$I_L \cong I_{sc} \cdot \frac{R_s + R_{sh}}{R_{sh}}, \tag{2}$$

$$I_0 \cong I_L - \frac{V_{oc}}{R_{sh}} \cdot \exp\left(-\frac{q \cdot V_{oc}}{nkT_c}\right), \tag{3}$$

where I_{sc} and V_{oc} are the short circuit current and the open circuit voltage of the solar cell, respectively.

To characterize a solar cell accurately, the value of n, R_s, and R_{sh} should be computed first and then substituted in Eqs. (2) and (3) to obtain the I–V characteristic of the PV module expressed in Eq. (1) [7]. Parameters n, R_s, and R_{sh} under the standard test conditions (STC) can be expressed as follows [12,13]:

$$n = \frac{V_{oc} - V_{mp} - I_{mp} \cdot R_s}{kT_c/q \cdot \ln\left(I_{sc} \cdot (R_s + R_{sh}) - V_{oc}/\left(I_{sc} - I_{mp}\right) \cdot (R_s + R_{sh}) - V_{mp}\right)}, \tag{4}$$

$$R_s = \frac{1}{I_{mp}} \cdot \left(V_{oc} - V_{mp} - n \cdot \frac{kT_c}{q} \cdot \ln(\alpha \cdot \beta)\right), \tag{5}$$

$$R_{sh} = \frac{V_{mp} \cdot (V_{mp} - I_{mp} \cdot R_s) - n \cdot kT_c/q \cdot V_{mp}}{(V_{mp} - I_{mp}R_s) \cdot (I_{sc} - I_{mp}) - n \cdot kT_c/q \cdot I_{mp}}, \tag{6}$$

where V_{mp} and I_{mp} are the cell voltage and current at the maximum power point (MPP), respectively, and α and β are