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Simple and easy approach for mathematical analysis of photovoltaic (PV) module under normal and partial shading conditions

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ABSTRACT

This paper presents a detailed modeling and analysis of photovoltaic (PV) module using MATLAB-Simulink. The simulation study utilizes single and two-diode model to represent the PV cell and the results are analysed under normal and partial shading conditions. The PV module performance is influenced by the environmental variables, especially temperature and irradiance level. Under partial shading conditions, the solar irradiance level on each PV cell in a PV system is uneven. This degrades the PV module performance and causes the output characteristic curves to have multiple peaks. Therefore, the PV module is modeled to analyse the performance under such conditions. This paper is divided into two parts. First, a detailed mathematical modeling of PV module using single and two-diode model is analysed during aforesaid conditions. The obtained results are compared in terms of the number of unknown parameters, accuracy, and computation time to justify the advantages and disadvantages of each model. Next, different types of PV modules (i.e. monocrystalline and multi-crystalline) are simulated to justify the precision of the two-diode model as well as the accurateness of the PV simulator.

1. Introduction

A substantial portion of energy is mainly extracted from coal, which is a limited source. Thus, some alternative source of energy is required to compensate the energy shortage. Among all the renewable energy resources, the sustainability, abundancy, ubiquity and inexhaustibility of solar energy make it the most essential resource in recent years [1]. Solar panel plays a vital role in converting solar energy to electrical energy in a photovoltaic (PV) system [2]. The conversion process is known as photovoltaic effect. PV cell is a solid-state electrical device that generates electricity from solar energy by photovoltaic effect. When solar energy strikes a photon, the energy is absorbed by the photon to raise an electron to a higher energy level. The higher energy electron is then flow to the external circuit, thus producing direct current (DC). The DC current produced is processed by the power electronic converters. The converters are also used for the maximum power point tracking (MPPT), load voltage and current regulation, as well as power flow regulation in a grid connected PV system [3]. In order to produce more power, PV module is form by connecting the PV cells electrically. In a PV array, the required voltage and current can be obtained by connecting the modules in series and/or parallel [4]. Solar irradiance level and temperature has an impact on the PV's current and voltage.

PV modules are sensitive towards shading effects. They may be partially shaded by buildings, wildlife or passing clouds, hence the series connection of PV modules is a limiting factor [5]. Shaded cell which generates lower current will limit the current of the whole

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string. The power generated in the normal cell is dissipated in the shaded cell and causes “hotspot” as the shaded cell is reverse biased [6]. Therefore, the overall power generated by the PV system is reduced. In order to reduce such effect, bypass diodes are introduced. The current produced by the normal cell flows through the bypass diode by bypassing the shaded cell and another power peak in the lower voltage region is introduced. An ideal PV cell consists of a diode in parallel to a current source, whereby the output current i.e. photocurrent generated and the irradiance level is directly proportional to each other [7]. The Simplified Single-Diode Model (SSDM) considering the series resistance is proposed by Jeddi et al to overcome the inaccuracy of the ideal PV cell when subjected to environmental changes at low voltages [8]. Due to the imprecision of SSDM at high temperature, the ideal single-diode model considering the series and parallel resistance is proposed by the researchers to overcome the faultiness [8]. The series and parallel resistance take into account the leakage current and internal losses [9]. At low irradiance level, the performance of the ideal single-diode model is inaccurate and hence two-diode model which consider the recombination loss in the depletion region is introduced by Gupta et al. by comprising an extra diode [10]. This provides a better estimation on the PV cell performance.

This paper analysed and compared the performance of a single and two-diode model of PV module with respect to the environmental variables variations, such as temperature and irradiance level. The PV module is mathematically modeled in MATLAB-Simulink environment for the effectiveness of study. Then, the precision of the MATLAB-Simulink simulator is justified by analysing the results of the monocrystalline and multi-crystalline PV modules. Section II presents a comprehensive mathematical modeling of the single and two-diode model PV module. Section III is divided into two parts. The first part discusses the simulation results of each model under standard test conditions (STC) with varying temperature and irradiance level whereas the second part discusses the model’s performance under partial shading conditions. Next, a comparative study is made between the single and two-diode PV module from different manufacturers and the results are tabulated. Section IV concludes the presented work.

2. Mathematical modeling of PV module

Monocrystalline, multi-crystalline and thin film photovoltaic (PV) cell technologies are used to develop the solar panels which are available in the market today. Single and two-diode model PV module are commonly used to model the output current-voltage (I–V) and power-voltage (P-V) characteristic. Single-diode PV cell model has the simplest configuration whereby a constant current source is in parallel to a diode [7], considering the series and parallel resistance. Despite its simplicity, the prediction of the PV cell performance is inaccurate during adverse conditions [7]. Therefore, two-diode model is introduced to improve the precision of the output characteristics.

2.1. Single-diode model

Fig. 1 shows the electrical configuration of the single-diode model PV module. Five unknown parameters, namely photoelectric current, I_{ph}, diode saturation current, I_o, series resistance, R_s, parallel resistance, R_p and ideality factor, A are needed to be extracted from the information given in the datasheet in order to plot the output characteristic curves. Eq. (1) to eq. (5) are used to calculate I_o and I_{ph}, whereby A is assumed to be 1 [11]. R_s and R_p are attained through iteration by calculating both of them simultaneously [3]. The iteration process stops when the calculated maximum power, $P_{mp,C}$ matches the experimental maximum power, P_{mp} (from the datasheet). The maximum power point matching is achieved by iteratively increasing R_s and computing R_p concurrently using Eq. (6). Eq. (6) is derived from Eq. (1) at maximum power point conditions. The flowchart describing the iteration process is shown in Fig. 2.

The loss in the depletion region due to the electron-hole pair recombination at low voltages is not considered in the single-diode model and hence, the performance is not accurate under partial shading conditions [7].

$$I = I_{ph} - I_o\left[\exp\left(\frac{V + IR_s}{AV_t}\right) - 1\right] - \frac{V + IR_s}{R_p} \tag{1}$$

$$V_t = \frac{N_s kT}{q} \tag{2}$$

$$I_{ph} = \frac{G}{G_n}\left[I_{sc} + K_i(T - T_n)\right] \tag{3}$$

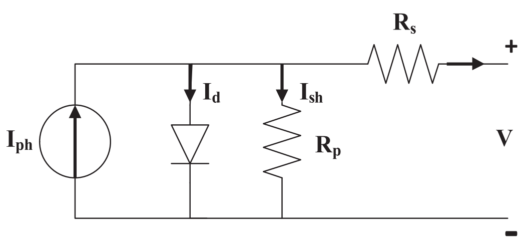

Fig. 1. Electrical Configuration of a Single-Diode Model PV Module.