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Linear equivalent models at the maximum power point based on variable weather parameters for photovoltaic cell

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HIGHLIGHTS

- The voltage-current characteristic of PV cell at the MPP of PV system has been linearized.
- Two linear equivalent models of PV cell have been proposed.
- The relationships between linear model parameters and VWP have been found.

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ABSTRACT

In order to sweep completely the obstacle to the whole linearization of photovoltaic (PV) system with non-linear PV cell, in this paper, the voltage-current characteristic of PV cell at the maximum power point (MPP) is linearized and two linear equivalent models including Thevenin equivalent model and Norton equivalent model are proposed. On the basis of this work, the whole linearization of PV system is workable and reasonable, and then the conventional linear theories or laws can be used to study PV system conveniently. Meanwhile, in this work, the direct relationships between three linear model parameters and variable weather parameters (VWP) were found, which ensures the strong adaptation of these proposed models to the varying weather conditions. Finally, some simulation experiments verify that these proposed models are feasible and available in practical application, illustrate that the characteristics of three linear model parameters are influenced by varying weather conditions and unaffected by varying load, and show that PV system using the proposed Thevenin equivalent model has the same maximum power point tacking (MPPT) stead-state performance and similar MPPT transient-state performance with the conventional four-parameter model under fast varying weather conditions.

1. Introduction

Nowadays, a lot of works have been done to study the various equivalent circuits of photovoltaic (PV) cell. In these circuits, on the one hand, the one-diode model and two-diode model have been studied more widely than others in practical application. An identification method based on the one-diode model of PV cell was presented by Laudani et al. [1]. A developed one-diode model which allows the prediction of PV cell behaviour under different physical and environmental parameters was analyzed by Salmi et al. [2]. A simplification method of the current two-diode mathematical equation, which has the advantages of the stronger adaptation to the varying weather conditions and more accurate matching in all important voltage-current ($V-I$) points, was presented by Ishaque et al. [3]. On the other hand, these two models have been also used more widely, especially to the maximum power point tacking (MPPT) technique. An adaptive fuzzy controller for MPPT was designed on the basis of the one-diode model by Guenounou et al. [4]. A new MPPT method with irradiance measurement based on two-diode model has been proposed by Bayod-Rújula and Cebollero-Abián [5]. A MPPT method using cuckoo search has been presented by Ahmed and Salam [6]. According to these literatures, it is known that the advantages of the one-diode model mainly include its simple circuit and convenient use while its $V-I$ characteristic is less accurate than the two-diode model which has the more complicated circuit

Abbreviations: PV, photovoltaic; MPP, maximum power point; VWP, variable weather parameters.

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structure. In practical application, the one-diode model is also called as the five-parameter model [1] and is usually simplified as the four-parameter model [7,8] to make its use more convenient. However, these models as well as others can still not solve the question about non-linear characteristic of PV cell satisfactorily. For this reason, hitherto the last obstacle to using conventional linear theories to study PV system with linear direct-current/direct-current (DC/DC) converter (or inverter) is still not swept. To resolve this difficulty, in this paper, two linear equivalent models of PV cell at the maximum power point (MPP) of PV system are proposed.

Besides these above-mentioned existing models, hitherto, there are some works especially to study the mathematical equations of PV cell. A new set of matrix equation of PV cell was proposed by Kadri et al. [9]. A mathematical manipulation that uses the mean value theorem was presented by Rodriguez and Amaratunga [10]. To calculate nominal operation cell temperature, some results for different PV modules were obtained by García and Balenzategui [11]. However, the relative complexity is existed in these presented mathematical equations based on the non-linear characteristics of PV cell, which makes the practical application of these study results difficult and inconvenient. Therefore, the second aim of proposing these linear models is to make the use of the mathematical equations of PV cell more convenient through simplifying them as the simplest linear Thevenin model and Norton model.

With respect to the output characteristics of PV cell, under fast varying weather conditions, it is very difficult to ensure the proposed linear models approximate to the conventional model as well as possible. To solve this problem, the key technique of the variable weather parameters (VWP) methods can be taken into account. The principle of the VWP methods can be described as follows: the controller can make PV system operating around MPP according to the MPP control signal calculated directly by some mathematical functions of solar irradiance (S), cell temperature (T) and load (R_L). In Refs. [12,13], three basic VWP methods was proposed, in which the direct relationships between MPP control signal and S, T, R_L, were first built successfully. In Ref. [14], a new VWP method based on input resistance of PV system was also presented. On the basis of these works, in this paper, through finding out the relationships between S, T and linear model parameters, these proposed models can change reliably with the varying weather conditions, which is one of the main works and innovations.

When it is comes to the existing MPPT methods, a lot of works have been done. Through the MATLAB simulation experiments, the performance comparison of different MPPT methods was made by Mohanty et al. [15]. Similarly, a comparative study of different MPPT methods was also done by Liu et al. [16]. To acquire higher efficiency, the conventional perturb and observe (P&O) method was improved by Ahmed and Salam [17]. In Ref. [18], the P&O method was applied in a closed plant factory by Jiang et al. In order to optimize the MPPT performance, the P&O method and the incremental conductance (IncCond) method were united by Ishaque et al. [19]. Under non-linear loading conditions, the MPPT efficiency of the IncCond method was analyzed and improved by Sivakumar et al. [20]. Except for these conventional MPPT methods, more and more attention to the intelligent control methods has been paid. In Ref. [21], Salam et al. classified these intelligent MPPT methods as the soft computing methods. A comparison between conventional methods and genetic algorithm (GA) was finished by Shaiek et al. [22] under partial shading conditions, the GA technique was used to PV array reconfiguration [23]. A fuzzy method which had the ability of adaptive MPP tracking step size was proposed by Guenounou et al. [4]. A multi-fuzzy logic MPPT method was studied to achieve the global MPP by Rajesh and Mabel [24]. To match the fast changing environments, a neural network method was proposed to track the MPP of PV system by Liu et al. [25]. Under uniform and non-uniform irradiances, a MPPT method based on extremum seeking control was proposed by Heydari-doostabad et al. [26]. In addition, there are some other MPPT methods such as the lagrange method [27]. It is obvious that, on the basis of these existing MPPT methods, almost all PV systems can successfully operate at their own MPPs to avoid the produced power losses, which indicates the reasonableness of linearizing PV cell at the MPP. Furthermore, because the P&O method can be regarded as the representation of the existing MPPT methods and has been widely used in practical application, in this paper, it is selected as the compared object to verify the feasibility and availability of proposed linear models, test the characteristics of three linear model parameters and analyze the MPPT performance of PV system using a proposed model in simulation experiments.

This paper is divided into the following sections: the principle of linear equivalent models of PV cell is analyzed by the algebra and geometry relations of $V-I$ characteristic at the MPP of PV system in Section 2. Two linear equivalent models (Thevenin equivalent model and Norton equivalent model) of PV cell are proposed in Section 3. The model parameters of two linear equivalent models are acquired by finding out the relationships between them and S, T, in Section 4. The feasibility and availability of proposed linear equivalent models are verified, the characteristics of model parameters are tested under varying weather and load conditions, and the MPPT performance of PV system with a proposed cell model is analyzed and compared with P&O method in Section 5. Some discussions are had in Section 6. Finally, some conclusions are drawn in Section 7.

2. Principle of linear equivalent models

2.1. Mathematics basis

The common used models of PV cell mainly include the one-diode model, the two-diode model, the four-parameter model and so on. They can be used widely for different application occasions or different purposes. In this paper, the four-parameter model whose mathematics basis is the one-diode model is selected as the basis of the proposed linear models.

The equivalent circuit of PV cell can be shown by Fig. 1, which is usually called as the one-diode model [9]. According to Fig. 1, the output current-voltage ($V-I$) characteristic of PV cell can be given in Eq. (1) [10].

$$I = I_L - I_0\left[e^{\frac{q(V+IR_s)}{AKT}} - 1\right] - \frac{V+IR_s}{R_{sh}} \quad (1)$$

where V and I represent the output voltage and current of the PV cell, respectively; I_0 is the reverse saturation current of diode; q is the electron charge (1.602×10^{-19} C); A is a dimensionless junction material factor; K is the Boltzmann constant (1.38×10^{-23} J/K); T is

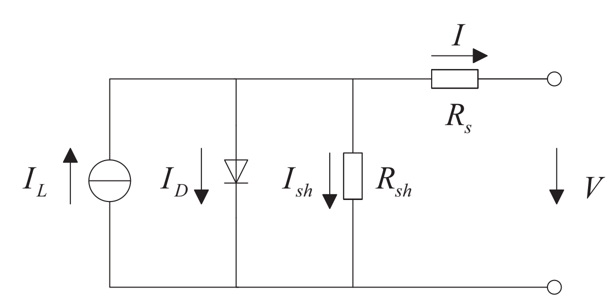

Fig. 1. Equivalent circuit of PV cell.