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Design and construction of photovoltaic simulator based on dual-diode model

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A B S T R A C T

The purpose of this article was to present a photovoltaic simulator that is based on two-diode model. In this simulator, the two-diode model was used for simulation and the performance of photovoltaic cell. The dual-diode model at low-level radiation has fewer errors and is more accurate, and this makes the photovoltaic cells to have fewer errors and more accuracy in the shade. To reduce the computational time, only four parameters were extracted from the model.

To validate the accuracy of the proposed model, three PV modules of different types (multi-crystalline and mono-crystalline) from various manufacturers are tested. The performance of the model was evaluated against the popular single diode models. It was found that the proposed model is superior when subjected to irradiance and temperature variations. In particular, the model matches accurately for all important points of the I–V curves, that is, the peak power, short-circuit current and open circuit voltage. The accuracy of the constructed simulator was evaluated by the real module and the laboratory and simulation results indicated the high accuracy of the simulator.

1. Introduction

Photovoltaic power systems both in high and low capacities, considering the high economic advantages, have become commercial. Government's tax incentives and encouragements for the promotion of clean and sustainable energy have accelerated the rate of photovoltaic power system's growth. This growth is as a result of the crisis and the shortage of energy in the world and the rising cost of fossil fuels. Because of this crisis and the rising cost of fossil fuels, photovoltaic plants due to advantages such as lack of environmental pollution, low cost and low maintenance, have been the center of attention in the energy market (Koran et al., 2010; He et al., 2009; Jike and Shengtie, 2012). To guarantee the optimum use of photovoltaic energy, tracking the maximum power point by the electronic power converters is of high importance. Anyway, for the proper design of MPPT controller, the simulation model should be accurate (Haeberlin et al., 2008; Zhao and Kimball, 2012).

This point is especially important when the maximum power point changes based on the environmental conditions. Particularly, one of the important conditions that should be taken into account is the considerable reduction of photovoltaic power system in the shade.

Photovoltaic inverter tests were conduct to study the maximum power point tracking (MPPT) to control the dynamic behavior of the system and the performance of designed controllers (He et al., 2009; Jike and Shengtie, 2012; Zhao and Kimball, 2012). Implementation of these tests by the real photovoltaic source because of its high cost in high power and also unstable atmospheric conditions (changes in the level of radiation and temperature) is impossible and uneconomical. As a result of this, the necessity of having access to the proper substitution of real photovoltaic source which is economical and has the ability to control the factors that affect photovoltaic source becomes clear. This substitution is known as the photovoltaic simulator source and as a laboratory tool, it has a lot of applications for the photovoltaic researcher and, in fact, it is one of the new challenges in the field of photovoltaic energy. The important point in photovoltaic simulator is the effect of mathematical modeling of photovoltaic cells in the accuracy of simulator. In recent years, for the improvement of accuracy, dual-diode model was suggested by researchers (Mukerjee and Dasgupta, 2007; Li et al., 2009).

Photovoltaic array simulator (PV) can be based on the power and control. For the power part of photovoltaic array simulator, it is possible to use low-power transistors. Although, this method is less complicated and in terms of dynamic response, it is fast, it does have some power limitation and does not respond in high power (Tang et al., 2012). For photovoltaic array simulator, in high power, it is not possible to use low-power transistors. For high-

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power photovoltaic array simulator, the common DC/DC converters should be used; because of dynamic response, this method is slower and more complicated. However, it does not have any power limitation (He et al., 2009; Jike and Shengtie, 2012; Haeberlin et al., 2008; Zhao and Kimball, 2012; Tang et al., 2012).

Authors (Ishaque, 2011) presented the utilization of two-diode model of PV systems. This model is known to have better accuracy at low irradiance levels which allows for more accurate prediction of PV system performance. The accuracy of simulator is verified by applying the model to five PV modules of different types from various manufactures.

Authors (Muhsen et al., 2015) represents a new version of the differential evolution (DE) algorithm, called differential evolution with integrated mutation per iteration (DEIM) to extract the seven parameters of a double-diode PV module model. This algorithm applies the attraction–repulsion concept of an electromagnetism-like algorithm to boost the mutation operation of the conventional DE algorithm. Moreover, a new adaptive strategy was proposed for tune mutation scaling and crossover rate for each generation.

Authors (Ishaque et al., 2011) proposed an improved modeling approach for the two-diode model of photovoltaic (PV) module. The main contribution of this work is the simplification of the current equation, in which only four parameters are required, as compared to six or more in the previously developed two-diode models. Furthermore, the values of the series and parallel resistances are computed using a simple and fast iterative method. To validate the accuracy of the proposed model, six PV modules of different types (multi-crystalline, mono-crystalline and thin-film) from various manufacturers were tested. The performance of the model was evaluated against the popular single diode models.

To guarantee the optimum use of photovoltaic energy, tracking the maximum point by electronic power converters was suggested. Anyway, for proper designing of MPPT controller, simulation should be done accurately. This point is especially important when the power's maximum point of curve changes according to the environmental conditions. Specifically, one of the most important things to consider is the considerable reduction of photovoltaic power system in the shade. The important point is the effect of modeling photovoltaic cell for the accuracy of simulator. To improve the accuracy of the model, dual–diode model (considering R_s and R_p values) was suggested by researchers. However, adding the diode to the model has increased parameters for calculation.

From the preceding discussion, it may be concluded that although the two-diode model is a preferable choice in terms of accuracy, its computational requirement is much more demanding as compared to the single diode models (Gow and Manning, 1999, 1996). This makes it less attractive than the latter. Furthermore, modeling using semiconductor approach as described in Hyvarinen and Karila (2003), Kurobe and Matsunami (2005) is not suitable due to insufficient information from the module manufacturer. In this paper, new simulator based two-diode model was proposed. The accurateness of the model was verified by applying it to three PV modules of different types (multi-crystalline and mono-crystalline) from various manufacturers. The performances of the model were evaluated against the single diode R_s (Walker, 2001) and R_p (Villalva et al., 2009) models. It is worth mentioning that the proposed simulator can be very useful to PV power converter designers and circuit simulator developers who require simple, fast and accurate model for the PV module.

The single-diode model in addition to the shade conditions has a high error, but the dual-diode model as compared to the single-diode model has higher accuracy rate in different conditions. The dual-diode model as compared to the single one is more complicated. The increase in the complexity of mathematical relations causes an increase in the number and duration of computation. As a result, there has been an attempt to reduce the number and duration of computation so that it will not have any effect on the simulator's response time.

The constructed simulator based on dual-diode model was tested in terms of changes in the output load, the radiation level and temperature. The results from the practical and simulative tests indicate that the implemented model in simulation and in practice is in complete conformity with the dual-diode model, and under different load conditions, radiation, temperature, voltage output and simulator current, it conforms to the real one. The error of the constructed simulator under the condition of low radiation is, very low. According to the practical results, the simulator's speed of response under transformation of parameters is acceptable and it guarantees that in photovoltaic inverter test, the analysis of tracking the maximum power point (MPPT), analysis of the system's dynamic behavior and the performance of the designed controllers, the simulator's performance, will be similar to a real photovoltaic array.

2. Modeling the photovoltaic cell based on the dual-diode

The dual-diode model is shown in Fig. 1. The module's output current can be stated as follows:

$$I = I_{PV} - I_{01}\left[\exp\left(\frac{V + I_{RS}}{a_1 V_{T1}}\right) - 1\right] - I_{02}\left[\exp\left(\frac{V + I_{RS}}{a_2 V_{T2}}\right) - 1\right] - \left(\frac{V + I_{RS}}{R_P}\right) \quad (1)$$

In this equation, I_{pv} is the current generated by radiation and I_{01}, I_{02} are respectively, the reverse current saturation of 1 and 2 diodes. Other variables are described as follows:

$$V_{T1,2} = N_s kT/q \quad (2)$$

$V_{T1,2}$ is thermal voltage module consisting of N_s cell that is in a series, q is electric load, k is Boltzmann's constant and T is the connecting temperature of P-N in K. a_1 and a_2 are the ideal constant diodes that respectively show the effect and new combination of the parts. The accurate estimation of other spots for other conditions is other goals of modeling.

Although, by using this model, we can have high accuracy (when compared with the single-diode model), in this model, there is need to calculate seven parameters. For the sake of simplicity, $a_1 = 1$ and $a_2 = 2$ were assumed. These assumptions are always used, but not always accurate.

2.1. Clarifying I_{PV} flow

Photovoltaic flow which is a function of temperature and radiation can be as follows:

$$I_{PV} = (I_{PV-STC} + K_i\Delta T)\frac{G}{G_{STC}} \quad (3)$$

where I_{pv-STC} flow is produced under STC conditions and ($T_{STC} = 25°C$)$\Delta T = T - T_{STC}$. G is the radiation on the solar cell and

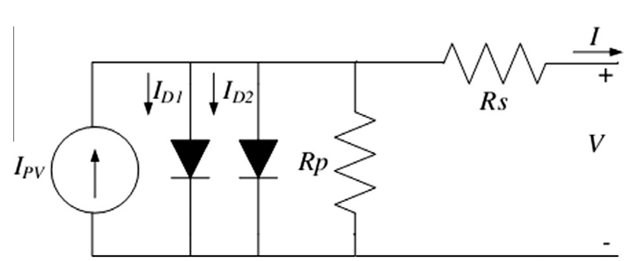

Fig. 1. Dual-diode model.