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A comprehensive review on photovoltaic emulator

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A B S T R A C T

The photovoltaic (PV) emulator is a nonlinear power supply which has similar current-voltage (I-V) characteristic to the PV module. In solar energy generation research, such as the maximum power point tracking (MPPT) and the PV inverter, the actual PV module and the high power controllable light source were used during the experimenting phase. However, this method requires complex experiment setup, is highly inefficient, and can damage the PV module. The PV emulator provides a simpler and more efficient solution compared to the actual PV module and the controllable light source while maintaining similar output produces by the actual PV module. This paper provides a template for the researcher to design the PV emulator according to the requirements established from the tested system. The PV emulator consists of three parts which are the PV model, the control strategy, and the power converter. The PV model produces the I-V characteristic of the PV module. The control strategy determines the operating point of the PV emulator on the I-V characteristics curve and produces the reference signal for the power converter. The power converter follows the reference signal and generates a similar output as the actual PV module.

1. Introduction

A recent study shows the potential of the solar based energy generation using the Photovoltaic (PV) panel to fulfill the world's energy demand. Solar energy is one of the renewable energies that requires little maintenance, has a low operation cost, and does not pollute. Up until 2015, there was a 50 GW increase annually in the global PV energy production, which totaled up to 227 GW of estimated global capacity of the PV energy [1]. This shows a 22% increase in the global energy production from the PV generation based system. Malaysia has the potential for solar based energy generation due to its high and steady irradiance throughout the year [2]. As a result, there was a 245% increase in the PV energy production in Malaysia from 2013 to 2014 [3]. The rise in PV's popularity is due to an increase in awareness of the PV's potential, government programs to promote the use of the renewable energy, and the increase in the market competition of the PV.

One of the components in the PV energy generation system is the maximum power point tracking (MPPT). Since the PV module has nonlinear output, the MPPT ensures the maximum power is extracted from the PV module. In the development stage of the MPPT, the PV module is emitted with the irradiance from the controllable halogen lamp or the light emitting diode (LED) to test the effectiveness of the MPPT [4]. However, the setup for this test bed is complex and temperature manipulation is not flexible. This method also requires a large area for the actual PV module, the light source, and a controllable direct current (DC) or alternating current (AC) source to control the light source. Besides, this method is inefficient since a high power is required by the light source to produce irradiance for the PV module. Another available test bed option for MPPT device testing is the PV emulator.

The PV emulator is a nonlinear power supply capable of producing the current-voltage (I-V) characteristic of the PV module. The PV emulator functions as a power source in the experimental stage of the solar energy generating system to allow repeatable testing conditions. The PV emulator offers a more convenient control of ambient conditions rather than complex irradiance and temperature control to allow faster and more efficient solar energy generation system testing. The PV emulator available in the market varies from a single panel emulation (approximately 300 W) to a PV array emulation (larger than 300 W). However, this type of PV emulator is expensive, ranging from \$ 6385 (Elgar ETS60X14C-PVF) to \$ 21,000 (Magna Power TSD50050240) [5,6]. Therefore, much research related to the PV emulator has been conducted to reduce the overall cost and improve the dynamic response of the PV emulator.

There are several control strategies used for the PV emulator. The direct referencing method is commonly used in the PV emulator due to its simplicity [7–12]. The hybrid-mode controlled method [13–15] and the resistance comparison method [16–18] produce a stable output for the PV emulator at any load condition. The hill climbing method for the PV

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emulator is easily designed since a compensator is not used [19,20]. The analog based method does not have computational delay and the partial shading condition is easily emulated [9,21–24]. Besides the control strategy, the implementation of the PV model is also improved for the PV emulator. The PV model increases the computational delay and results in incorrect output for the PV emulator. To reduce the calculation burden of the PV model in the PV emulator control system, the PV model is simplified [11,12,25–27], changed to the look-up table [28–33], applied with the piecewise linear method [34–37], or trained using the neural network method [12,38]. The power converter is a part of the PV emulator system. The switched-mode power supply (SMPS) is commonly used in the PV emulator and is highly efficient [17,18,33,39,40]. The linear regulator is useful if the output ripple for the PV emulator needs to be removed [13,41–43]. The design of the PV emulator using the programmable power supply is simple since the closed-loop system for the power converter is already included in the system [15,44,45].

Much research has been conducted on the PV emulator. However, there are no specific papers that compile and discuss the techniques and control strategies for the PV emulator. The objectives of this paper are to review the PV emulator system that consists of the PV model, the control strategy, and the power converter. A review of the PV emulator is important to begin research on the PV emulator. This paper is organized as follows, where the next section describes the overview of the PV emulator which consists of three parts namely the PV model, the control strategy, and the power converter system. The next section describes two types of PV models used in the PV emulator application and the PV model implementation method inside the controller. The control strategy discusses the available method, partial shading implementation, and the hardware platform used for the PV emulator. The topology, the continuous current mode, the ripple factor, the small signal analysis, and the PID controller for the power converter system used in the PV emulator application are also discussed.

2. Overview of photovoltaic emulator

There are three parts in the PV emulator system introduced by the researcher, as shown in Fig. 1. The first part of the PV emulator system is the PV model. The function of the PV model is to produce the I-V characteristics of the PV module signal. This signal is used by the closed-loop power converter system to emulate the characteristic of the PV module. The PV model is highly responsible for the accuracy of the PV emulator; however, the PV emulator requires real-time calculations of the PV model to operate properly. Therefore, the PV model used in the PV emulator application must remain simple without compromising the accuracy of the I-V characteristics produced.

The second part of the PV emulator system is the control strategy. The control strategy of the PV emulator is the method used to interface the PV model with the closed-loop power converter system. The control strategy is responsible for finding the operating point of the PV emulator. The control strategy combines the PV model with the closed-loop power converter system to become the PV emulator. A good control strategy should be able to accurately follow the signal produced by the PV model, create a stable PV emulator output, require low processing burden, capable of emulating various types of PV modules without the need to redesign the whole control strategy (adaptability), and does not affect the closed-loop power converter system or the load (independency).

The third part of the PV emulator system is the power converter. The power converter is used to change the I-V characteristic signal produced by the PV model into the I-V characteristic capable of transmitting power. The power converter affects the dynamic performance and the efficiency of the PV emulator. The actual PV module dynamic response is approximately a 10th of a microsecond [46]. Therefore, a good PV emulator needs to have a similar dynamic response to the actual PV module.

3. Photovoltaic model

There are two considerations in the PV model used for the PV emulator. The first consideration is the types of PV models used, of which there are two. The models are the electrical circuit model and the interpolation model, as shown in Fig. 2. The second consideration is the methods used to implement the PV model inside the controller of the PV emulator; there are five of these methods, as shown in Fig. 2, which include direct calculation method, look-up table method, piecewise linear method, neural network method, and curve segmentation method.

3.1. Type of photovoltaic model

3.1.1. Electrical circuit model

The electrical circuit model is the PV modeling represented in the form of an electrical circuit and the PV characteristic equation is derived using the Kirchhoff current law [47]. This model is also known as the analytical model and is commonly used in the PV emulator application. The single diode model and the double diode model are two types of electrical circuit models. The single diode model shown in Fig. 3 is also known as the single diode model with a series and a shunt resistor, the 1D2R model or the five parameter model [17,26,42,48–55]. While the double diode model shown in Fig. 4 is also known as the

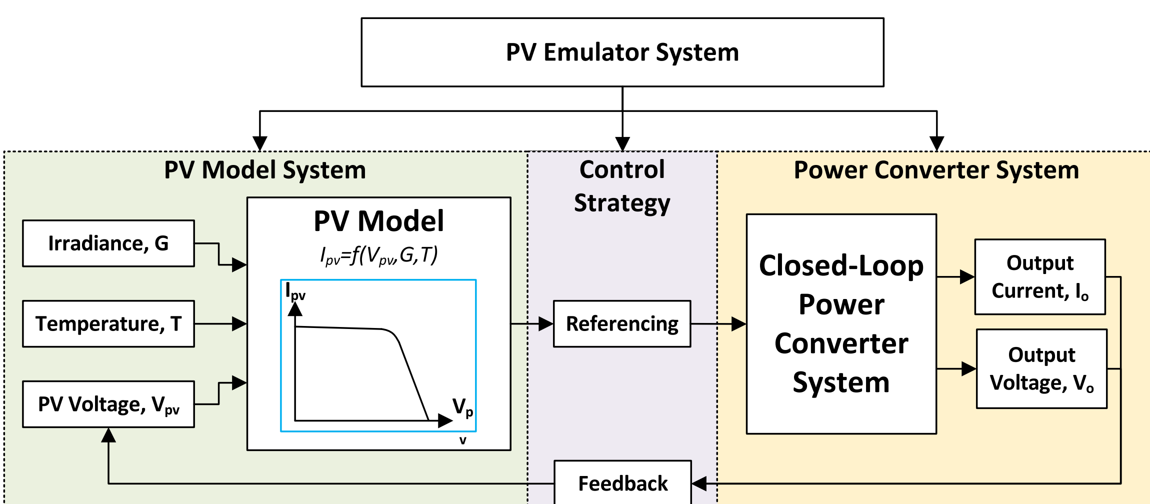

Fig. 1. The three parts of the PV emulator system.