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Dual-mode power regulator for photovoltaic module emulation

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HIGHLIGHTS

- A photovoltaic (PV) module has a dual characteristic as a voltage or a current source.
- We design a dual-mode regulator for PV module emulators.
- We develop a robust control method to perform emulation based on PV module model.
- The proposed PV emulator copes with rapid voltage or current variations.
- We show improved output quality over the entire operating range by real implementation.

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ABSTRACT

Photovoltaic (PV) module emulators, which can provide reproducible and controllable input power profile for a load device corresponding to different ambient conditions for a PV module, can significantly reduce the level of effort and cost for the development and optimization of the PV module, load devices, as well as interfacing power converters. In this paper, we introduce a dual-mode power regulator for the PV emulation. The dual-mode regulator consists of a voltage regulator and a current regulator, connected by two diodes for power hybridization. The circuit switches between the two regulators in order to accurately emulate the electrical output behavior of a PV module under different ambient conditions (e.g., solar irradiance, temperature) and load demands. The proposed regulator circuit provides accurate emulation results over the full operating range of the PV module by complementary use of the two regulators. We develop a robust control method for producing an accurate *I–V* curve with compensation of the loss in the circuit components. We validate the behavior of the proposed circuit and control method by Matlab/Simulink simulations and experiments. The experimental results shows that the PV emulation output is greatly improved with the proposed dual-mode regulator.

1. Introduction

Solar photovoltaic (PV) power is one of the most promising sustainable power sources with distinct advantages [1]: (i) it has no moving parts which would be subject to wear and tear, (ii) it is relatively location independent and environmentally friendly, and (iii) its core technology is experiencing rapid advancement thanks to introduction of semiconductor technologies in the PV cell manufacturing process. However, their power output varies significantly by the ambient conditions such as the solar irradiance level and temperature, and so an elaborate design of power system is needed to efficiently utilize the PV power.

Actual development and deployment of PV modules and solar-powered systems require elaborate experimental setup and experiments of a wide range, and energy efficiency is one of the most important metrics. More precisely, solar-powered systems require holistic optimization on both the PV module side and the load device side, which mandates extensive tunings based on experimental results and measurements.

The electrical output behavior of the PV module is strongly dependent on the ambient conditions, especially to the solar irradiance as shown in Fig. 1. Since the level of PV power generation is strongly dependent on the solar irradiance, it is critical for optimal development and deployment of solar-powered systems. Developing a solar-powered system involves not only development of a PV module, but also deployment of the PV module [2,3], design of associated power sources and storages [4,5], and development of its control system and operation algorithm considering the characteristics of the load device [6,7]. PV module development includes improving energy efficiency of unit PV cells, as well as determining a right design with given unit PV cells. We should carefully determine the unit PV cell type, size, series and parallel connections, and so on. However, it is difficult to achieve

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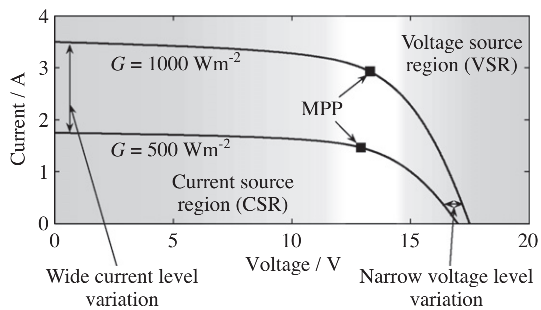

Fig. 1. *I–V* curves at two different irradiance levels. Boundary between the voltage source and current source is not definitive.

the desired design relying solely on standard parameters of PV modules [8]. Furthermore, there are too many combinations of such design parameters, and it is very difficult and highly cost-ineffective to perform experiments with the PV module under the wide range of ambient conditions in order to obtain the corresponding *I–V* characteristics and optimize the whole system including the power delivery circuit and the load device.

Instead, it will be very useful to have a PV emulator that has embedded *I–V* characteristics of the target PV modules and is able to generate the output current and voltage based on the load demand and the ambient conditions. A well-designed power emulator or simulator makes it possible to greatly reduce the amount of time and the cost of developing an optimized system [9]. A system designer can utilize the emulator or simulator to verify the PV module design integrated with the load device. It provides a high degree of freedom for experimenting different designs of a solar-powered system with any ambient condition profiles as desired, which is not possible with real PV modules. A large body of previous research has indeed introduced PV emulators that model various kinds and sizes of PV modules subject to wide-ranging ambient conditions and load demands.

A PV emulator is equipped with an adjustable power regulator, and controls the output of the regulator to accurately reproduce the *I–V* characteristics of a real PV module, which has been subjected to various ambient conditions and demands. A DC–DC converter with a current-limiting power supply can be used to simulate the *I–V* characteristics of a PV module [10], but its accuracy is not high because of the model discrepancy with the actual PV module. A reference diode or a photodiode, and a power amplifier circuit can provide higher emulation accuracy [11–13]. However, the reference diode lacks flexibility in modeling different PV modules because the emulated *I–V* characteristics of the PV module are determined by the material properties and electrical characteristics of the chosen diode. On the other hand, computational model-based PV emulators exhibit a high degree of flexibility to reconstruct an arbitrary *I–V* curve for a PV module corresponding to a desired irradiance level and ambient temperature. The PV module model calculates (predicts) the voltage and current values of the PV module at the desired ambient conditions and load demand. These values are then input to an adjustable power regulator to produce the desired electrical output [14–18]. In this paper, we focus on flexible PV emulators and thus the model-based PV emulation.

2. Motivation

The power-generation behavior of a PV module exhibit dual characteristics, i.e., sometimes the PV module's output is best modeled as a voltage source with a low internal impedance while at other times it is better modeled as a current source with a high internal impedance [19,20]. This distinction naturally gives rise to a *current source region (CSR)* and a *voltage source region (VSR)* for the PV module. When to use which model is answered based on the operating point as depicted in Fig. 1. The PV module typically shows wider output current variation in the CSR depending on the irradiance than the output voltage variation in the VSR. Furthermore, input current control is more prone to saturation than input voltage control because the current at the maximum power point is more close to the maximum output current (short circuit current) than the voltage. Due to this phenomenon, power conditioning techniques for PV modules, including the maximum power point tracking (MPPT) techniques, use a target voltage level as the set point for closed-loop feedback control rather than a current level [19,21]. For the same reason, most conventional PV emulators use only an adjustable voltage regulator to emulate the output behavior of the PV module [11,16,22,23]. They focus on the VSR, therefore, the accuracy of these emulators may be low when the PV module is operating in the CSR. In order to capture the CSR behavior of the PV module, the PV emulator in [13,15] uses a voltage regulator based on a nested-loop control mechanism, composed of an outer voltage control loop as well as an inner current control loop. However, significant current ripples are observed especially in the CSR even though output current filters are used.

Since we do not expect that load devices will always operate in such a way that the PV module remains in the VSR, the PV emulators must be capable of reproducing the real output behavior of the PV modules in its complete current range including the CSR. Even if the PV power management schemes assume operation in the VSR, it is not always possible to avoid entering the CSR. Rapid load variations may increase the current beyond the MPP before the power management scheme reacts, and sudden shading over the PV module may decrease the output and result in shifting to the CSR. For this reason, it is necessary to perform PV power management with explicit consideration on the CSR [24,25] and evaluate its behavior [26] in the CSR. Furthermore, recent research results [27,28] have decisively shown that not only the MPP but also the whole current range should be accurately modeled in order to achieve system-wide optimization of energy efficiency in a solar-powered system.

In this paper, we introduce a new circuit and control method design technique of a model-based dual-mode power regulator for PV emulation and its novel control method. The proposed dual-mode power regulator circuit is composed of an adjustable voltage regulator and an adjustable current regulator, and provides both high flexibility and high accuracy for PV emulation. We develop a robust operation method to seamlessly control the two regulators with compensating the power loss induced in the hybridization circuit. We validate the behavior of the proposed circuit and its control method with Matlab/Simulink simulation and through experiments.

3. PV module *I–V* characteristics

Fig. 2 shows a widely-used single-diode equivalent circuit model of a PV module [20]. Its *I–V* characteristic is given by

$$i_{pv} = i_L - i_d - i_{sh}, \tag{1}$$

where

$$i_L = \frac{G}{G_{\mathrm{STC}}} \cdot i_L(G_{\mathrm{STC}}), \tag{2}$$

$$i_d = i_0(T) \cdot \left(\exp\left(\frac{(v_{pv} + i_{pv} \cdot R_s) \cdot q}{A \cdot N_s \cdot k \cdot T} \right) - 1 \right), \tag{3}$$

$$i_{sh} = \frac{v_{pv} + i_{pv} \cdot R_s}{R_p}. \tag{4}$$