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Programmable energy source emulator for photovoltaic panels considering partial shadow effect

Cheng-Chuan Chen [a], Hong-Chan Chang [a,*], Cheng-Chien Kuo [b], Chien-Chin Lin [c]

[a] Department of Electrical Engineering, National Taiwan University of Science and Technology, 43, Sec. 4, Keelung Rd., Taipei, Taiwan
[b] Department of Electrical Engineering, Saint John's University, 499, Sec. 4, TamKing Rd., Taipei, TamSui 25135, Taiwan
[c] Bestec Power Electronics Co., Ltd., 10F., No.10, Ln. 609, Sec. 5, Chongxin Rd., Sanchong Dist., New Taipei City 241, Taiwan

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ABSTRACT

The aim of this paper is to study and produce a programmable emulator for photovoltaic panels. A uniform solar illumination model, a partially shaded model with two photovoltaic modules in series and a partially shaded model with two photovoltaic modules in parallel are proposed in this paper. Solar illumination and ambient temperature can be set on the emulator to emulate the behavior of a photovoltaic panel and to explore the effect of its being polluted by dust, shaded by clouds or solar oblique incidence. When making the physical models, a digital signal processor is used to calculate the quiescent points of the photovoltaic panels according to the load resistance and characteristics of the photovoltaic panels, and a DC (direct current)/DC buck power converter is adopted to adjust the output of the emulator in accordance with the quiescent points. To reduce the DSP's (digital signal processor) calculation burden, a characteristic curve segmentation method is proposed. This study successfully develops a 300 W/60 V emulator for photovoltaic panels under uniform solar illumination and partially shaded conditions. The load is changed over and over again so as to sketch the *V*–*P* curve and confirm the feasibility of the emulator.

1. Introduction

Both rapid petroleum consumption and the greenhouse effect have prompted many countries to devote considerable resources to the research and development of photovoltaic generation systems; thus, the use of photovoltaic panels as a power source has been the subject of many studies: Since photovoltaic panels are DC (direct current) power sources, some researches study on inverters for connecting AC (alternating current) loads [1–3]. For remote district electrical power supply, stand-alone photovoltaic systems are developed [4,5]. For improving the output efficiency of photovoltaic panels, some innovative studies of maximum power point tracking methods for photovoltaic systems are proposed in Refs. [6–8]. Due to different renewable energy sources could be complementary to each others, some literature focus on hybrid energy systems that can provide more reliable power to customers [9–11]. Also, to integrate storage systems with renewable energy, the studies of energy management strategy for system optimal purpose are proposed in Refs. [12–14]. The requirements for testing and evaluating the performance of photovoltaic panel systems have also increased [15–17]. Sufficient space in which to set up photovoltaic panels is essential for photovoltaic generation system experiments. Also, the experiments are limited by the weather, in that they cannot be repeated under the same ambient conditions. Therefore, many researchers have chosen to set up photovoltaic panels indoors. However, as photovoltaic panels are affected by ambient factors, such as weather conditions and their surface state, for simulating the status of photovoltaic panels under various levels of ambient temperature and solar illumination, an experimental system is required to monitor and control the ambient temperature, as is the installation of an adjustable light source system. This would be both complicated and expensive, and the high power consumption would add to the research costs. To simplify the experimental setting, a DC power supply has been used to replace photovoltaic panels by some researchers [18,19], which was suitable for their research purposes; however, the development of a more practical emulator would be even better.

In general, multiple modules can be connected in series to increase the output voltage and in parallel to increase the output current for expanding the output power capability of a photovoltaic generator. However, when some of the photovoltaic modules are

* Corresponding author. Tel.: +886 2 2737 6677; fax: +886 2 2737 6699.
E-mail addresses: chaung@mail.sju.edu.tw (C.-C. Chen), hcchang@mail.ntust.edu.tw (H.-C. Chang), cckuo@mail.sju.edu.tw (C.-C. Kuo), ksal_lin@bestec.com.tw (C.-C. Lin).

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Nomenclature

D_j	ideal *P–N* junction diode
I_{mp}	current at maximum output power condition (A)
I_{out}	overall output current (A)
i_{ph}	photon-generated current (A)
i_{phj}	the *j*th photon-generated current (A)
i_{pv}	output current of a photovoltaic module (A)
i_{pvc}	critical output current (A)
i_{pvj}	output current of the *j*th photovoltaic module (A)
i_{pvs}	short circuit output current of a photovoltaic module (A)
i_{pvsj}	short circuit output current of the *j*th photovoltaic module (A)
i_{Rj}	forward current that runs through a diode (A)
I_{sc}	short circuit current of a photovoltaic module (A)
i_{tp}	diode's reverse saturation current variations due to changes in temperature (A)
i_{tpj}	the *j*th diode's reverse saturation current variations due to changes in temperature (A)
L	solar illumination (W/m^2)
L_{ref}	reference illumination (W/m^2), here 1 kW/m^2
T	ambient temperature (°C)
T_{ref}	reference temperature (°C), here 25 °C
R_j	incremental resistance of a diode (Ω)
R_L	load resistance (Ω)
R_{Lc}	critical load resistance (Ω)
R_{Lcj}	the *j*th critical load resistance (Ω)
R_s	equivalent series resistance of a photovoltaic module (Ω)
V_{mp}	voltage at maximum output power condition (V)
V_{oc}	open circuit voltage of a photovoltaic module (V)
V_{out}	overall output voltage of photovoltaic modules (V)
v_{pv}	output voltage of a photovoltaic module(V)
v_{pvc}	critical output voltage (V)
v_{pvj}	output voltage of the *j*th photovoltaic module (V)
v_{tp}	diode's forward voltage variations due to changes in temperature (V)
v_{tpj}	the *j*th diode's forward voltage variations due to changes in temperature (V)
α	the temperature coefficients of I_{sc} (%/°C)
β	the temperature coefficients of V_{oc} (mV/°C)

Abbreviations

ADC	analog-to-digital converter
DSP	digital signal processor
PWM	pulse-width modulation
Q-point	quiescent point

polluted by dust, shaded by clouds or solar oblique incidence, the total output power of a photovoltaic generator is greatly reduced. The two peaks phenomenon of output power may appear in an output (voltage–power) *V–P* curve of a photovoltaic generator, which increases the difficulties in maximum power point tracking and then decreases the performance of the overall system. Many studies have presented related system characteristics [20–24]. When actual photovoltaic panels are used for research purposes, establishing an experimental environment becomes even more complicated than for a system established under uniform solar illumination.

When developing a photovoltaic cell power generation system or designing a measurement system to test and evaluate the performance of a photovoltaic cell power system, a standard photovoltaic cell is needed in order to verify the performance of the measurement system. In this case, the set up of a standard photovoltaic cell with a light source can be complicated. To solve the problems mentioned above, this study has proposed an emulator having the characteristics of photovoltaic panels. The emulator would be a substitute source for the standard photovoltaic cell and have the emulation ability for more complex combinations of series and parallel photovoltaic modules to achieve power expansion. The salient features of the emulator would be that it is easy to set up, maintain and is time-saving. More significantly, it could be used as a development tool for measurement systems of photovoltaic panels and photovoltaic power generation systems.

In previous literature [19], according to the maximum power transfer theorem, a variable resistance was used in series with a DC power supply to emulate the (maximum power point) MPP behavior of photovoltaic systems. In Ref. [25], by establishing a database according to the photovoltaic characteristics and searching the database according to the feedback current, a Q-point was quickly obtained. In Ref. [26], according to a mathematical model of photovoltaic module which was embedded in a microcontroller and the feedback current of a DC/DC buck converter, a (voltage–current) *V–I* curve of photovoltaic module was sketched. In Ref. [27], a piecewise linear approach method was proposed to reduce the calculation burden of a microcontroller, so as to choose a low-cost microcontroller. In Ref. [28], a *V–I* curve of photovoltaic module was separated into voltage source region and current source region, according to this opinion, the authors proposed a dual-mode power regulator consisted of a voltage regulator and a current regulator to emulate a photovoltaic module. Also, only the output characteristics under uniform solar illumination were generated in these studies [25–28]. In Ref. [29], the parameters of the equivalent circuits for photovoltaic module were characterized by a new set of matrix equations. In Ref. [30], the DC/DC converter control strategy was deduced by using a comprehensive mathematical model of a photovoltaic module. Both Refs. [29,30], a personal computer based emulator with the characteristics of photovoltaic modules in series under partially shaded conditions was proposed and the photovoltaic model was implemented using Matlab/Simulink. In Ref. [31], a DSP (digital signal processor) based power supply with the characteristics of solar modules in series under partially shaded conditions was proposed, which involved a considerable calculation burden due to the exponential terms of the solar panels' characteristics equations. Also, the studies [29–31] did not consider that the photovoltaic modules were connected in parallel under partially shaded conditions.

Based on the above description, since DSP has superior mathematical computation ability with lower cost, a DSP based emulator with the characteristics of photovoltaic modules in parallel under partially shaded conditions still needs studying. Therefore, in accordance with the conditions of the sunlight incidents upon the photovoltaic panels, a partially shaded model with two photovoltaic modules in parallel including a uniform solar illumination model and a partially shaded model with two photovoltaic modules in series was implemented in this paper. Moreover, a characteristic curve segmentation method was also proposed to reduce the calculation burden of DSP. The purpose of this study was to produce a programmable emulator having the characteristics of photovoltaic panels. The parameters, such as the electrical parameters of the photovoltaic panel, ambient temperature and solar illumination, were set up for the emulator; then, the *V–P* curve of the photovoltaic panel under various setups could be sketched.

To save electrical energy, this study used a switching mode DC/DC power converter to produce an emulator with a maximum