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Reconfigurable emulator for photovoltaic modules under static partial shading conditions

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ABSTRACT

This paper aims to emulate the *IV* characteristics of a multiple-substring photovoltaic (PV) module under nonuniform irradiance levels by taking into account the breakdown voltage of shaded cells, configurations of bypass diode connections, and cell temperatures. A suitable control scheme for the emulator's power stage significantly improves the performance of the emulator's output. As a result, this PV emulator proves to be capable of performing under various operating conditions of the PV module including uniform irradiation and nonuniform partial shading with great accuracy.

1. Introduction

Reproducing the current–voltage (*IV*) characteristics of a PV module under different environmental conditions is challenging and time-consuming in a laboratory set-up (Woyte et al., 2003). Therefore, a PV emulator, which is a programmable power system duplicating the electrical *IV* characteristics of a given PV module at an emulator's output, provides a useful test facility solution for PV applications. Thirty years ago, the first generations of PV emulators were developed by implementing analog circuits (Vachtsevanos and Kalaitzakis, 1987). PV cell and module emulators have been studied since then. The PV emulators are classified into two groups: (1) few watt emulator systems (Wandhare and Agarwal, 2011; Schofield et al., 2011); (2) hundred-to-few kilowatt emulator systems (Martín-Segura et al., 2007; Kadri et al., 2010; Dolan et al., 2011; Abidi et al., 2012; Lu and Nguyen, 2012; Agrawal and Aware, 2012; Kim et al., 2013; Koran et al., 2014; Erkaya et al., 2015; Balato et al., 2016). These two categories also reflect the primary purpose of using the emulator which can be PV cell or PV module/array emulation.

Recent research also raises great interest in the study of PV behavior under partial shading conditions. This implies that the developed PV emulators should be capable of emulating more complicated test cases with appropriate transient responses. The PV module, in general definition, consists of substrings with an equal number of cells. When some of the PV cells are not fully illuminated compared to other cells, the partial shading effect causes mismatch in the PV module. Although bypass diodes connected in parallel to the substrings block high negative voltages across each substring, individual shaded cells in a substring can cause a significant decrease in energy yield and multiple power peaks (Woyte et al., 2003).

The development of partial shading PV emulators has been proposed in recent times in several studies regarding power electronic converters for decentralized PV systems and the question is whether the designed converters can steadily deliver the highest PV power/energy to the output under nonuniform irradiance conditions. These PV emulators emulate partially shaded PV modules with different approaches to produce the *IV* curves. The first approach uses a look-up-table method where a discrete and limited amount of data of *IV* curves in given shading conditions can be found in commercial products such as Chroma (2012). In the second approach, a multi-*IV* circuit magnifies the small *pn* photosensor output by analog technology (Nagayoshi, 2004; Koran et al., 2014) which provides little or no flexibility of PV characteristics and bypass diode configurations. In the third approach, model-based PV emulators at different environmental and shading conditions are taken into consideration (Di Piazza and Vitale, 2010; Kadri et al., 2010; Chroma, 2012; Heredero-Peris et al., 2014).

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These modeling methods, however, show several limitations in either modeling the negative breakdown voltage or/and different configurations of partially shaded substrings. The complexity of the *IV* curves also leads to the deterioration of the output performance in the emulators when partially shaded PV emulation is activated. To mitigate the limitations of previous methods, there is an urgent need to build a PV emulator capable of performing well under partial shading conditions such as in complex urban areas where influential environmental parameters including cell temperature and solar irradiation conditions are separately defined for each PV cell.

The emulator proposed in this paper is designed to tackle such issues. The modeling of a partially shaded PV module involves extracting *IV* characteristics from cell-level parameters such as temperatures, irradiance levels, and breakdown voltage (Díaz-Dorado et al., 2014; Quaschning and Hanitsch, 1996; Patel and Agarwal, 2008). The modeling of PV module substring configurations and bypass diodes under partial shading scenarios are also discussed. For high operation quality, measurement errors and control delays caused by sensors and analog-to-digital interfaces are mitigated by introducing the Kalman filter (KF) approach.

This paper is organized into four sections. In Section 2, the PV modeling and implementation methodology is presented. A mathematical PV model is derived from the solar cell level to the PV module level. Hardware connection diagrams, a real-time measurement technique, and a hybrid control strategy are also presented. Section 3 introduces experimental tests of the emulator performed on an electronic load and a DC demonstration board to assess the emulator's operation. Finally, a summary of our work is presented in Section 4.

2. Methodology

2.1. PV module modeling

As the smallest elements of a PV module, the PV cells directly convert solar irradiation to electricity due to the photovoltaic effect. The power produced by each cell depends on operating points along the *IV* curve, temperature, irradiation, and PV technology. Therefore, the modeling of PV cells is the core element for emulating the whole PV module in this study.

2.1.1. Modeling of a solar cell with consideration of the avalanche breakdown

The proposed equivalent circuit of a PV cell in Fig. 1 refers to a single-diode model and a current source representing the avalanche breakdown behavior, which has been validated for modeling PV cells in literature (Silvestre et al., 2009; Ishaque et al., 2011).

$$I_{cell} = \underbrace{\frac{S}{S_n}\left(I_{ph,0} + K_I\Delta_T\right)}_{I_{ph}} - \underbrace{I_0\left[\exp\left(\frac{V_{cell} + I_{cell}R_s}{\frac{nkT}{q}}\right) - 1\right]}_{I_d} - \underbrace{\frac{V_{cell} + I_{cell}R_s}{R_p}}_{I_{sh}} - \underbrace{a(V_{cell} + I_{cell}R_s)\left(1 - \frac{V_{cell} + I_{cell}R_s}{V_{br}}\right)^{-m}}_{I_{br}} \qquad (1)$$

Eq. (1) describes the *IV* characteristic of a PV cell including the avalanche breakdown. The first three terms, namely the light-generated current I_{ph}, *pn* junction current I_d, and shunt-resistance leakage current I_{sh} express the single-diode model of a PV cell (Vachtsevanos and Kalaitzakis, 1987). The last term, controlled current source I_{br}, is added into the original one-diode model to describe the avalanche breakdown in the case of high reverse-bias voltage (Quaschning and Hanitsch, 1996; Kawamura et al., 2003; Díaz-Dorado et al., 2014).

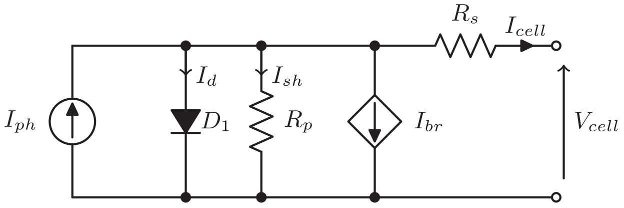

Fig. 1. Model of one-diode PV cell with current source I_{br} generating avalanche breakdown at high negative voltages.

In the case of the PV cell model introduced in (1), $I_{ph,0}$ is the light-generated current at the standardized condition (STC). S/Sn represents the ratio of the cell irradiance level (S) to 1000 W/m^2 that is the STC irradiance levels. $\Delta_T = T - T_{25}$ is the difference between the actual and STC cell temperatures. I_0 denotes the reverse saturation current for an ideal *pn*-junction diode. n is the diode ideality factor. Rs and R_p are respectively the cell series resistance and shunt resistance of a PV cell under identical temperature values. q is the elementary charge. k is the Boltzmann's constant, and T is the cell temperature (in Kelvin).

In the case of diode breakdown at a high negative voltage, V_{br} describes the avalanche breakdown voltage. a represents the correction factor and is often less than $1\,\Omega^{-1}$ (Quaschning and Hanitsch, 1996). The parameter m denotes the avalanche breakdown exponent. These parameters are estimated from the measurement of a PV module (Kawamura et al., 2003).

Given that environmental parameters including S and T can be set by users and the other parameters are defined in the datasheet, the combinations of n, R_s, and R_p have to be estimated to obtain the *IV* characteristics of cells in a PV module.

By applying the fast-convergence method illustrated in Carrero et al. (2011) to estimate PV parameters from the given datasheet, $I_{ph,0}, I_0, R_s, R_p$, and n during environmental conditions are specified. The *IV* characteristic is hence obtained by applying (1) and the sweeping current from zero to the short-circuit current corresponding to the highest irradiance level over a substring, which also defines the negative voltage area of the PV cells.

$$I_{cell} = \mathbf{g}(V_{cell}, S) \qquad (2)$$

For a substring comprising N_s uniformly irradiated cells in series and operating at the same cell temperature T, it is feasible to extend the expression of a single cell to the following substring equations:

$$\left.\begin{aligned} I_{substring} &= I_{cell} \\ V_{substring} &= N_s \times V_{cell} \end{aligned}\right\} \Rightarrow I_{substring} = \mathbf{g}\left(\frac{V_{substring}}{N_s}, S\right) \qquad (3)$$

Modeling *IV* characteristics under uniform irradiation (S) is validated through the datasheet of PV module KC200GT (Kyocera, 2009). Results of the comparison are depicted in Fig. 2. Under high irradiation levels, the obtained *IV* curves fit the experimental ones over all temperature ranges. Under low irradiation levels, although the voltage slightly deviates from the experimental data near the open-circuit voltage area, the relative error of maximum power remains low at 1% as mentioned in Ishaque et al. (2011). In addition, the calculation time of the single-diode model approach is approximately 1.6 times shorter than the calculation time of the two-diode model (Ishaque et al., 2011). Therefore, subjected to multiple PV cell modeling under different environmental conditions, the computational time for estimating typical *IV* characteristics of cells is reduced.

Finally, the characteristics of cells are extrapolated in accordance with the working conditions of cell irradiance levels and temperatures to obtain the *IV* characteristics under given partial shading conditions. The *IV* curve of the module is subsequently