

Model of a photovoltaic panel emulator in MATLAB-Simulink

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Abstract: Being able to behave electrically similar to photovoltaic (PV) panels, PV emulator systems make it possible to perform different PV system tests under various operation conditions. In this paper, a model of a PV panel emulator is presented using the Power System Blockset under MATLAB-Simulink. The simulation of the emulator system is developed for testing a controller prior to a real-time implementation. The model can handle the dependence of all of the parameters in the model with respect to solar radiation and temperature. The simulation results show that the output characteristics of the simulator have good agreement with those of the actual PV panel in various load conditions. Additionally, the simulator has a good dynamic response.

Key words: Circuit based, emulator, modeling, photovoltaic panel

1. Introduction

The renewable energy market has grown rapidly in the last decade. In particular, electricity production by solar energy is promoted in many countries and is considered to be a strategic objective for governments. Increasing interest in solar energy has made photovoltaic (PV) systems a promising alternative to conventional energy sources. For this reason, the demand for appropriate equipment to test PV systems has been on the rise.

The power output of PV systems is directly affected by solar irradiance and temperature. The testing of early solar equipment, such as inverters and maximum power point trackers (MPPTs), was possible under real weather conditions because of the low power of these old systems. However, it is difficult to test modern PV systems that generate hundreds of kilowatts of power due to the space, cost, and weather dependency of the test equipment. Therefore, an emulator circuit, which has similar electrical characteristics to a PV system, is an industry necessity.

The advantages of the PV emulator over the solar panel are summarized as follows:

- The PV emulator requires less space.
- Any atmospheric conditions can be easily simulated.
- Different types of solar cell characteristics can be simulated.
- PV emulators can be used for calibration purposes.
- Being a programmable device, the PV emulator can protect itself under overload or short-circuit conditions, which are normally expected to occur during testing.

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For the reasons mentioned above, many researchers have been trying to develop their own PV emulators. Several methods for PV emulators have been suggested. The PV emulator presented in [1,2] is based on the amplification of a p-n photosensor output voltage by a DC power amplifier. However, this kind of emulator has limited use because of its need for a light-emitting diode driver circuit and a temperature controller for each p-n photosensor. It is also very difficult to simulate partially shaded conditions for different irradiation and temperature values with this system. Moreover, only the p-n photosensors used in the emulator's I-V characteristics can be obtained. Lloyd [3] developed an emulator using a class-A amplifier to amplify the command current or voltage values stored in an EPROM, which correspond to the simulated PV module current-voltage characteristics, but the emulator is not flexible when different PV module types or PV module configurations are simulated.

Additionally, several studies for emulating the I-V characteristics of PV systems have been focused on using different power converter topologies [4-7]. In [5], the authors use a DC/DC full bridge structure of an inverter and high-frequency transformer to provide galvanic isolation. Some emulators consist of a buck-type DC/DC power converter, which is controlled by a field-programmable gate array-based unit using the pulse width modulation (PWM) principle [6], and some emulators use a DC/DC buck converter topology that includes partial shadow conditions and the dynamic behavior of the emulator [7].

During the realization process of an emulator, most researchers first develop the model of the emulator system using different computer simulation platforms, like MATLAB-Simulink [8-10]. The model is then used to specify the system and controller parameters, search the dynamic response, and verify the output of the system with the actual one.

In this paper, a buck-type DC/DC power converter has been established in a MATLAB-Simulink environment using the piecewise linear electrical circuit simulation (PLECS) toolbox. The proposed model allows for the simulation of different PV module types and PV module configurations, and it is also flexible, allowing for changes in the solar irradiation and temperature values.

The rest of the paper is organized as follows: in Section 2, the fundamental properties of a PV panel and its mathematical model are summarized; Section 3 describes the design and control of the DC/DC converter; Section 4 describes the construction of the PV panel emulator model for MATLAB-SimPowerSystems; Section 5 is devoted to the performance simulation of the proposed PV panel emulator; and, finally, Section 6 includes the conclusions.

2. Mathematical model of PV panel

In this paper, we used a well-known one-diode model incorporating the shunt resistance as illustrated in Figure 1. This model offers a good compromise between simplicity and accuracy. Many power electronic designers prefer this model for the simulation of PV devices with power converters [11,12]. Its characteristic equation is given in Eq. (1).

$$I = I_{pv} - I_o \left[\exp \left(\frac{V + R_s I}{V_t A} \right) - 1 \right] - \frac{V + R_s I}{R_p} \quad (1)$$

Here:

I_{pv} = photoelectric current (A)

I_o = diode saturation current (A)

V_t = junction thermal voltage (V)

V = terminal voltage (V)
 R_s = cell series resistance (Ω)
 R_p = cell shunt resistance (Ω)
 A = diode ideality factor

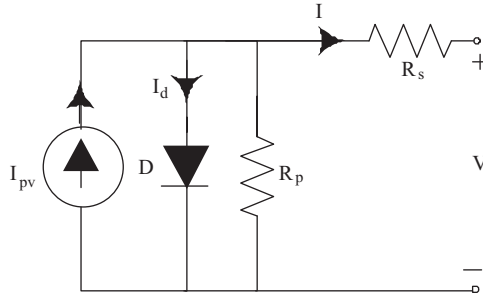


Figure 1. Equivalent circuit of a PV cell.

$V_t = kT/q$; q is the electron charge [1.602×10^{-19} C], where k is the Boltzmann constant [1.38×10^{-23} J/K] and T is the cell temperature (K).

In the above model, the photoelectric current, I_{pv} , comprises terms to handle variations in the radiation and temperature, and the diode saturation current, I_o , comprises a term to handle temperature changes [13]. The above model is completed with the following equations. The photoelectric current is defined as:

$$I_{pv} = \frac{G}{G_n} (I_{scn} + K_i(T - T_n)), \tag{2}$$

where I_{scn} is the short-circuit current at the standard test condition ($T_n = 25$ °C, $G_n = 1000$ W/m² and air mass 1.5) and T and T_n are the actual and nominal temperatures (K), respectively; G (W/m²) is the radiance on the device surface and G_n is the nominal radiance; and K_i is the temperature coefficient of the short-circuit current (A/K).

The dependence of the diode saturation current on the temperature is expressed as follows:

$$I_0 = \frac{I_{scn} + K_i(T - T_n)}{\exp((V_{ocn} + K_v(T - T_n))/AV_t) - 1}, \tag{3}$$

where V_{ocn} is the nominal open-circuit voltage and I_{scn} is the nominal short-circuit current.

It is worth noting that the model described above is referred to as a single-cell model. However, once the model parameters for a single cell are known, it is possible to extend the results to the entire PV panel.

The following equations summarize how a single-cell model can be extended to represent a PV panel:

$$I_{pv,tot} = N_p I_{pv}, \tag{4}$$

$$I_{o,tot} = N_p I_o, \tag{5}$$

$$R_{s,tot} = \frac{N_s}{N_p} R_s, \tag{6}$$

$$R_{p,tot} = \frac{N_s}{N_p} R_p, \tag{7}$$

$$A_{tot} = N_s A, \quad (8)$$

where N_p is the number of parallel cells and N_s is the number of series cells.

Single-cell model equations can be upgraded to represent the PV panel when all of the parameters in Eqs. (4)–(8) are substituted into Eqs. (1)–(3).

3. Control scheme and design of the DC/DC converter

A PV panel emulator system is basically a switching power supply, but the difference is that a steady working point of the PV emulator system is required to run on the I-V characteristic curve of a PV panel so that the actual panel can be replaced by the emulator circuit to conduct an experiment.

The block diagram of the PV emulator system is shown in Figure 2. First, the detection circuit samples load the voltage and current values with the specified sampling period. Next, according to the load current value, the corresponding reference voltage is calculated by the PV panel model block. This block includes the load voltage by a function of the load current, irradiance, and temperature, $V = f(I, G, T)$. This means that the reference load voltage can be obtained by the measured load current, the irradiance, and the temperature. Next, the difference between the reference and the measured values of the load voltage is applied into the proportional-integral (PI) regulator to obtain an appropriate duty cycle. Finally, the PWM generation block provides the switching signal to drive the switch of DC/DC converter.

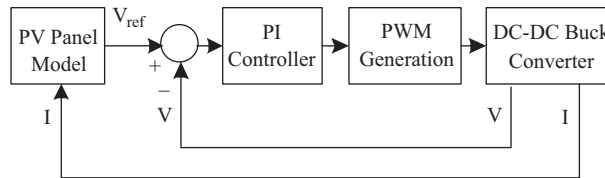


Figure 2. Control schematic diagram of PV panel emulator system.

A DC/DC buck converter is presented to simulate the electrical behavior of the PV panel for the variations in the solar irradiance, temperature, and load conditions. The DC/DC power converter is driven according to the mathematical model of the PV panel. The basic buck converter circuit is shown in Figure 3. The relationship between the input and output voltage of the converter is given in Eq. (9). This equation shows that the output voltage is lower than the input voltage; hence, the duty cycle is always less than 1.

$$V_o = DV_{dc} \quad (9)$$

For the design of the converter output inductor-capacitor (LC) filter, the determination of the value of L and C are not going to be explained in full detail here, because it is out of scope of this paper. The minimum inductance and capacitance values can be determined as in Eqs. (10) and (11), using the following constraints:

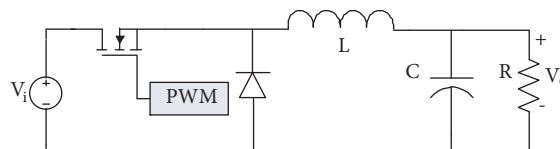


Figure 3. The circuit of a DC/DC buck converter.

- As the converter operates in continuous mode, the current through the inductor should be within a reasonable range for all of the load conditions.
- Maximum ripple on the output voltage should not exceed a few percentages.

$$L \geq \frac{V_{dc}}{\Delta I_L f_s} D(1 - D) \tag{10}$$

$$C \geq \frac{(1 - D)}{8L f_s^2} \left(\frac{V_o}{\Delta V_o} \right) \tag{11}$$

Here, ΔI_L is the limit current between the continuous and discontinuous conduction mode, f_s is the switching frequency, D is the duty cycle, V_o is the output voltage of the converter, and ΔV_o is the maximum allowed voltage variation.

4. Model of PV emulator in MATLAB-Simulink

The architecture of the proposed PV emulator system is schematized in Figure 4. The PV emulator system is developed in a MATLAB-Simulink environment using the PLECS toolbox. In Figure 4, the PV model and the PI controller MATLAB function blocks correspond to MATLAB files.

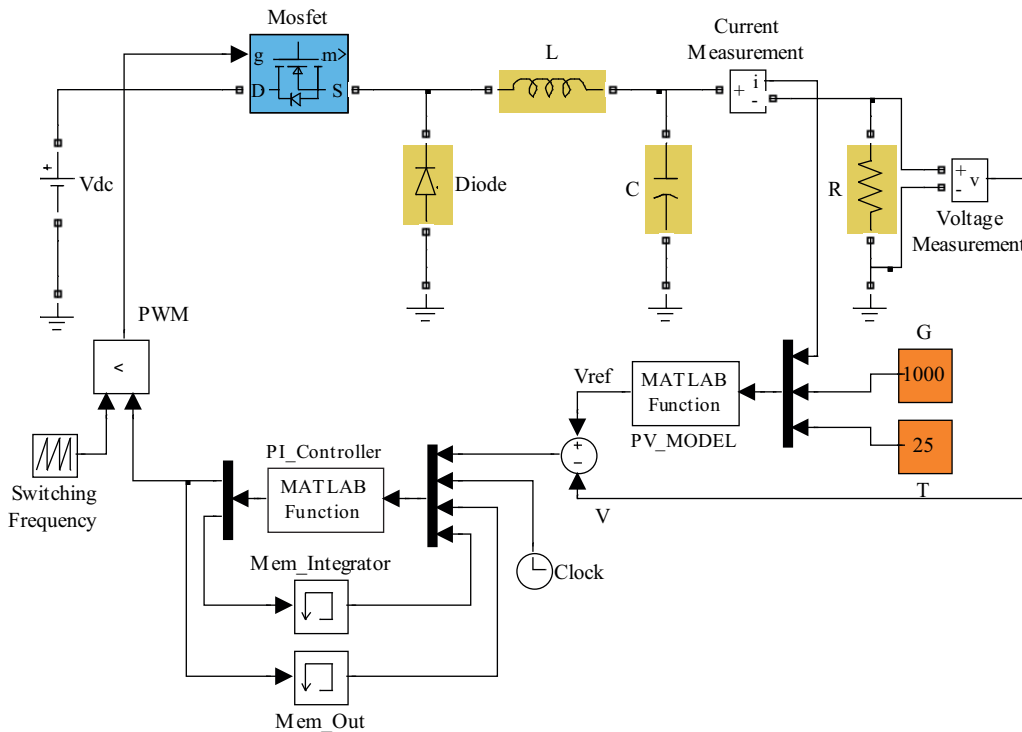


Figure 4. Model of the PV panel emulator in MATLAB-Simulink.

The PV model block calculates the reference voltage according to the I-V behavior of the PV panel. Its inputs are the vectors of the solar irradiance and temperature and the current supplied by the power stage to the load. As mentioned in Section 2, a one-diode model of the PV cell with shunt resistance (5-parameter) has been used. However, Eq. (1) of the solar cell cannot be solved explicitly in general for its output current. For

this reason, numerical methods are required to obtain the solution of the I-V relation of the PV panel. In this study, the Newton–Raphson method is used to calculate the output voltage as a function of the solar irradiance, temperature, and output current.

For the PI controller block, the difference between the reference voltage and the samples of the load voltage provides the input for the PI regulator to obtain an appropriate duty cycle. The integration time-interval can be adjusted to the desired value using the clock signal.

Until now, most researchers have been simulating their own PV emulator system using the transfer function of the DC/DC converter [8,14,15]. However, any modification on the DC/DC converter, such as changing the switching frequency, inductance, and capacitance values, requires the recalculating of the transfer function. On the other hand, the simulation environment of the PV emulator system presented in this paper is very flexible in terms of its design aspects.

In particular, simulation can be carried out to observe the effect on the variations of the solar irradiance, temperature, and load values. Additionally, the sampling period of the voltage and current measurement can be adjusted to the desired values.

5. Simulation results of the emulator system

For the purpose of testing and validating the operating principle of the PV panel emulator, the simulation system based on a DC/DC buck converter was carried out in MATLAB-Simulink. The details of the simulation of the PV panel emulator system are shown in Figure 4. The parameters of the emulated PV panel and the simulation system are shown in the Table.

Table. PV panel and simulation circuit parameters.

The PV panel specifications (1 kW/m ² , 25 °C)		Simulation circuit parameters	
Typical peak power	55 W	Switching frequency	50 kHz
Voltage at peak power	18.5 V	Filter inductance	1.5 mH
Current at peak power	3.5 A	Filter capacitance	25 μF
Short-circuit current	3.85 A	Integral coefficient	240
Open-circuit voltage	23.3 V	Proportional coefficient	0.21

Simulations have been carried out with 2 different scenarios to analyze the performance of the simulation system. In the first scenario given in Figure 5, the load resistance was increased gradually and the dynamic response of the emulator was evaluated. The worst settling time was less than 10 ms and occurred in the final step of the simulation, as shown in Figure 5. Here, the solar irradiation and temperature values were set to 1000 W/m² and 25 °C, respectively.

In the second scenario presented in Figure 6, the dynamic response of the emulator was tested for various solar irradiance and temperature. Here, the load resistance was set to a constant (6 Ω) during each state of the simulation. The irradiation and temperature levels in each case are shown. As can be seen from Figure 6, the response of the PV panel emulator system lasted for less than 10 ms. Note that the maximum ripple on the output voltage and current waveform stayed within the range of a few percentages during the steady-state condition.

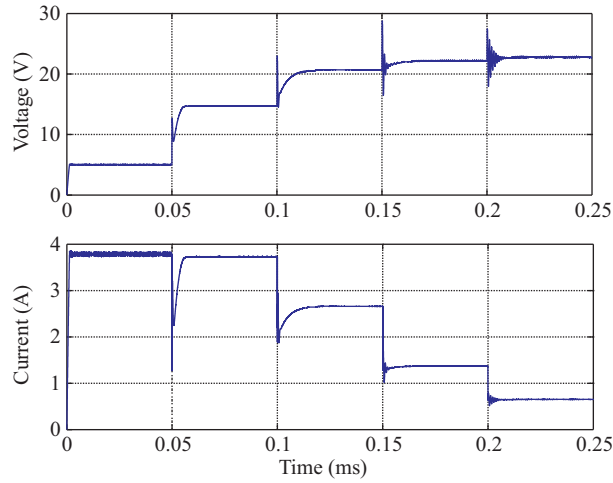


Figure 5. Output characteristics of the PV panel emulator system with load variations.

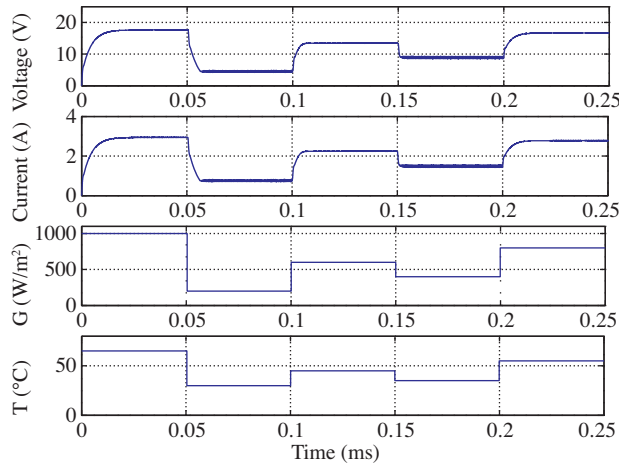


Figure 6. Output characteristics of the PV panel emulator system with irradiation and temperature variations.

6. Conclusion

In this paper, we presented a simulator that can model all of the hardware and software components of an emulator in one MATLAB-based software environment, hence enabling us to design and test emulators prior to their physical implementation. The hardware component of the underlying emulator that we simulated is a buck converter. The software component of the emulator is a 5-parameter model of a PV panel and the related PI controller. Our overall simulation system can produce the electrical behavior of the PV emulator for various solar irradiance, temperature, and load conditions. The performance of the proposed PV emulator model has been tested under dynamic conditions, and satisfactory results have been obtained.

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