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Design and development of a model-based hardware simulator for photovoltaic array

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ABSTRACT

This paper presents a model based hardware simulator to emulate a photovoltaic (PV) array/module for all operating conditions. For making the model accurate the values of manufacturer dependent parameters pertaining to a PV array are extracted from the published data sheet of the array by a curve fitting based extraction technique. The proposed simulator consists of a microcontroller controlled switched mode DC–DC converter. The mathematical model of the PV array is embedded in the controller with provisions for the user to enter the required ambient conditions. A feedback compensator is implemented to achieve fast response and good stability and to minimize the steady-state error. As a test case to design, develop and test for compliance the published data of 115 W solar panel Shell S115 has been used. The prototype is tested for steady-state and transient conditions. The experimental results of the simulator are presented. The results are compared with the cell characteristics available in literature and compliance is confirmed.

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1. Introduction

The world wide, demand for electrical energy is growing fast, demanding the utilization of alternative and renewable energy sources. The increased use of distributed generation calls for the growth of associated power electronics; for example, to maximize the utilization of solar PV panels and to convert the dc power of the panel to suit the loads/grid requirements. For consistent performance of these PV power converters the experiments need to be repeated for every load/grid condition at every possible insolation, i.e. irradiance, G and temperature, T_C. This becomes difficult with a solar PV panel, as it is not practical to repeatedly set the steady-state and transient insolation at all values and as required. To perform intense testing of the PV power converter's functionality, its closed loop control, its performance when subjected to grid disturbances, a real-time hardware infrastructure is essential. Thus the simulator is primarily intended as a power source to the converter in experiments to verify the reliability and repeatability of operation of the converter in steady-state as well as in transient conditions of all possible insolation/grid conditions. Such a hardware simulator has to produce dc outputs effectively as will be given by a PV panel at any operating condition.

Wide varieties of hardware PV simulators have been reported in the literature. In [1,2] the output of a single photo sensor is magnified using linear amplifiers to emulate the PV array. No temperature variation has been considered. The series resistance, the ideality factor and reverse saturation current of cells in an array may be different from that of a single photo sensor that can cause errors in the model. The major drawback of this method is its lower efficiency due to linear amplification. This will be a serious concern for high power simulators.

The simulator in [3], uses a switching power converter with an analog control and matching only the open circuit and short circuit points of the simulator with those of the actual PV panel. Also changes in load conditions have only been considered and the changes in insolation have not been accounted. Using switching power converter, a digital control strategy is adapted in [4–5], in which a Look Up Table (LUT) is used to store the V–I relationship of a PV array for some discrete insolation conditions. The LUT is referred to for the control of the power converter so that the converter output is the same as the values in the table. No provision for accounting the change in insolation is reported in [4]. In [5] only three sets of insolation conditions are used which are manually selected. Variable insolation conditions are not realized. Different types of PV cell models are reported in [6–11], and model based emulators are reported in [12,13]. However [12], did not consider the changes in the ambient conditions while in [13] these were considered, but it is applicable for a particular site. The irradiance is given as an input to get the PV characteristics. The temperature

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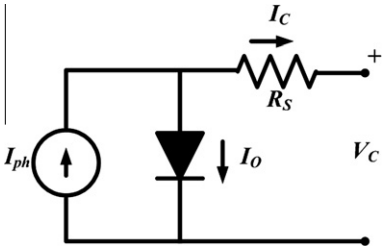

Fig. 1a. Equivalent circuit.

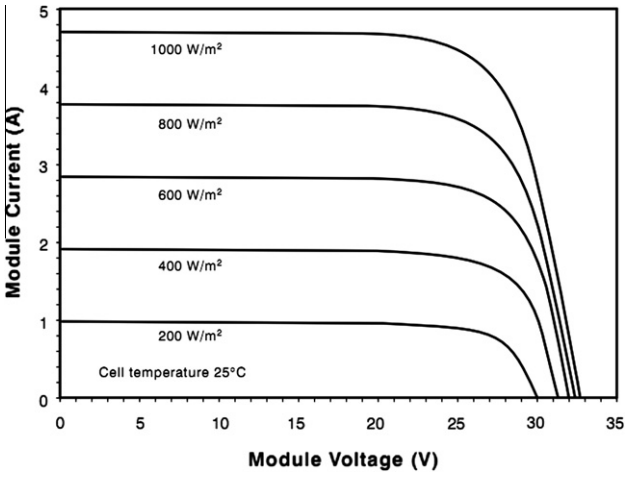

Fig. 1b. *V–I* characteristics of solar PV panel S115l.

is indirectly estimated from a site data. Thus it is dependent on the site data, and that constrains the universal use of the simulator.

This paper presents a model based hardware PV simulator, which emulates the *V–I* characteristics of a typical 115 W Shell solar PV module S115 for any temperature and irradiance conditions. The model parameters are extracted using only the published cell characteristics of the manufacturer. None of the values required for the cell equation has been assumed as has been done often in the literature [14–17], thus the model replicates the commercial PV panel very closely. The emulator uses the model for obtaining the *V–I* relationships, thus no look up tables are used requiring large memories. This enables to obtain the characteristics at any insolation conditions, compared to [3–5] where, emulation at certain discrete insolation is only reported. First the mathematical modeling of a commercial PV array is explained followed by the design specification of the converter used in the simulator. Finally the development of the hardware setup and the experimental results are presented. The simulator can be used for testing of power converters for PV applications where it can replace the actual panel at any desired insolation level as well as for testing of various Maximum Power Point Tracking (MPPT) algorithms.

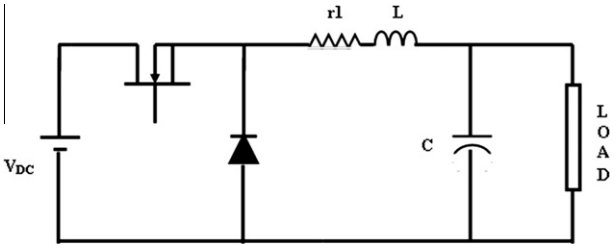

Fig. 3. Power circuit of PV simulator.

2. Mathematical model of PV panel

The equivalent circuit of a solar cell is given in Fig. 1a. The *V–I* characteristics [18] of a solar module (S115) are given in Fig. 1b.

The output voltage of a single solar cell [14] in volts is expressed as

$$V_C = \frac{AkT_C}{e}\ln\left(\frac{I_{ph}+I_O-I_C}{I_O}\right) - R_S I_C \quad (1)$$

where A is diode ideality factor, I_{ph} is photocurrent (A), I_O is reverse saturation current (A), e is electron charge (Q), R_S is series resistance of the cell (Ω), k is Boltzmann's constant, T_C is cell operating temperature in Kelvin, V_C is cell output voltage (V), I_C is cell output current (A).

The values of the manufacture-dependent parameters viz, I_{ph}, I_O, A and R_S, pertaining to a particular PV panel are extracted from the *V–I* characteristics published in the data sheet of that particular PV panel. A curve fitting based extraction technique is adapted in this paper.

The first unknown parameter I_{ph} in (1) is seen to be equal to I_C under short circuit of panel as drop in R_S is too small to make the

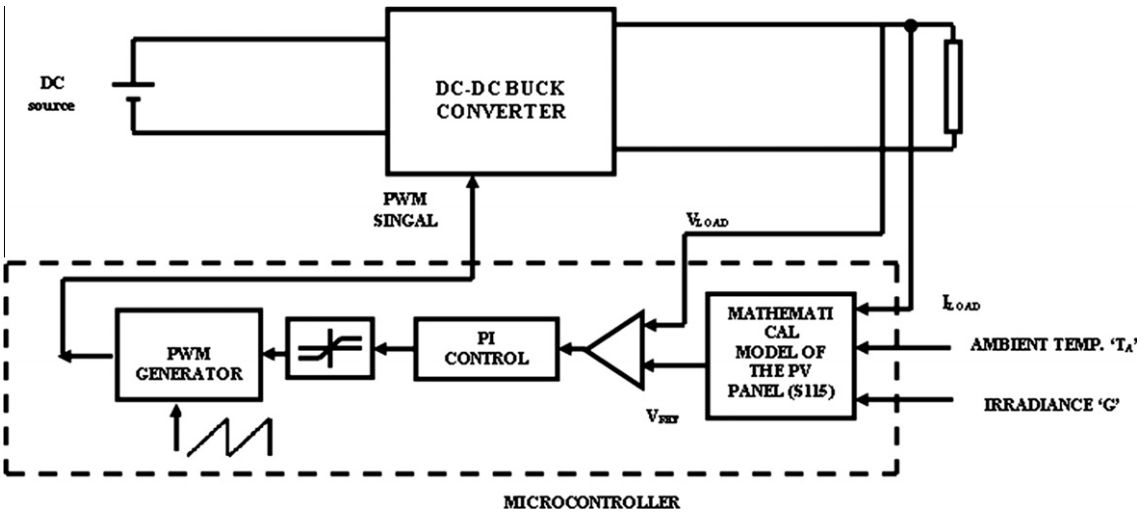

Fig. 2. The proposed hardware PV simulator.

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