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DC-DC Converter for Adaptation of Thin-Film PV Panel I-V Characteristics for Microinverter

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***Abstract*—With increasing uncertainty in the supply of the main energy carriers (gas and oil), as well as the increasing cost of electricity on a European scale, the use of small photovoltaic systems (PV), is gaining more and more interest. The development of power electronic technologies would help the faster implementation of small PV systems in households and in places without an electricity grid. In the present work, the focus is placed on the modeling of a DC-DC converter for connecting a thin-film PV panel to a microinverter. The goal is to integrate such a converter to connect the panel to the microinverter seamlessly. The volt-ampere characteristic of the panel is transformed by the converter so that the PV module voltage matches the input voltage of the microinverter. A simulation model of the system involving thin-film PV panel, DC-DC converter and input stage of the microinverter with MPPT controller was developed in Matlab/Simulink environment. The obtained results show the adequacy of the approach and the flawless operation of the proposed DC-DC converter with a microinverter.**

Keywords—photovoltaic panel, DC-DC converter, microinverter

I. INTRODUCTION

Motivated by ever-increasing global energy needs and greenhouse gas emissions from conventional fossil fuels, renewable energy sources such as solar, wind, geothermal and others are poised to become a significant part of the global energy portfolio. In the new policy scenario, the share of renewable energy in three main energy applications of electricity, heat and transport will grow by 18% in 2035. The use of solar energy has been increasing rapidly in recent years. Governments are implementing many policies and initiatives to introduce renewable energy production and sustainability of energy supplies [1].

Photovoltaic systems with small power are an efficient and sustainable method of generating electricity. Mounted on roofs, facades, sheds or other free spaces, these systems are currently the most cost-effective option for utilizing free areas, reducing electricity costs and sustainable production of electricity, without additional losses from its transmission.

One of the bases of classification of solar inverters is their size and scope of application, where they can be classified as: microinverters, string inverters and central inverters. Microinverters are usually used for individual panels under 500W. As the microinverter controls the power output from a single panel, the MPPT tracking is more efficient, resulting in more energy production by PV installations [2]. With the improvement of power electronic devices, DC-DC converters are increasingly used in photovoltaic systems, as well as for MPPT tracking under different operating conditions [3]. In order to increase the energy yield, the point of maximum power must be continuously monitored, and the PV module operated in this zone. Many MPPT algorithms have been developed during the years. Some of the most effective algorithms that are widely used are the perturbation-observation (P&O) method and the incremental conductance method [4], [5].

Photovoltaic modules from the crystal silicon technology generate a low voltage (usually under 70 V), which is within the input voltage range of microinverters. However, the modules that are produced by the thin-film technology, (such as Cadmium Telluride, Copper Indium Gallium Selenide or Microcrystalline Silicon) have voltages over 100 V, which is serious problem for working with microinverter. This problem is a challenge that needs to be tackled. The authors propose a DC-DC converter for transformation of PV panel I-V characteristics so as it fits the microinverter input requirements.

The paper presents the development of a simulation model of a PV system consisting of thin-film PV panel, specialized DC-DC converter and microinverter input stage with MPPT algorithm.

II. DESCRIPTION AND MODELING OF THE SYSTEM

The main idea of the work is to introduce a DC-DC converter between the PV panel (or array) and the microinverter which will adapt the I-V characteristic of the panel to the inverter input requirements. On Fig. 1 is shown simplified schema of the system with DC-DC converter.

As it is necessary to apply linear transformation of the module voltage and current the relation between input and output voltage of the DC-DC converter must be linear. This condition can be accomplished using a converter operating with fixed duty cycle. But on the other hand, the voltage should remain unchanged for wide range of current variation

Fig. 1. Simplified schema of the system.

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– practically from zero to the maximum PV panel current. This requirement can be satisfied when the converter operates entirely in continuous current mode [6]. Considering these requirements, a full-bridge DC-DC converter with transformer was chosen.

The PV panel voltage should be decreased with a ratio m, calculated from maximal panel voltage V_m and maximal inverter input voltage V_{DCm} [7]:

$$n = \frac{V_m}{V_{DCm}}. \tag{1}$$

The DC-DC converter should transform the PV panel voltage with constant ratio m. Consequently, for each point of the I-V characteristic of the PV panel the converter will produce output voltage:

$$V_{DC} = mV\,. \tag{2}$$

Assuming that the converter is lossless, the output and input power will be equal i.e:

$$P_{DC} = P \qquad \Rightarrow \qquad V_{DC}I_{DC} = VI\,. \tag{3}$$

For the relation between PV current and output converter current we obtain:

$$I_{DC} = mI \quad . \tag{4}$$

A. Model of PV Module

The photovoltaic module model is based on a single diode equivalent circuit of a photovoltaic cell shown in Fig. 2. When the PV cell is illuminated, the diode current I_d is subtracted from the photocurrent I_{pv}:

$$I = I_{pv} - I_d \tag{5}$$

The connection between current and voltage of the PV cell (I-V characteristic) is expressed by [9]:

$$I = I_{ph} - I_0\left(e^{\frac{q(V+IR_S)}{CkT}} - 1\right) \tag{6}$$

where: I_0 is diode saturation current, T – temperature of the cell (K), k – constant of Boltzmann, q – electronic charge, V – voltage across the cell, R_s – series resistor, C – ideality coefficient of diode.

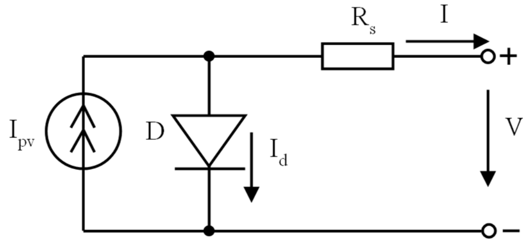

Fig. 2. Equivalent circuit of PV cell.

The current I_{ph} depends on the solar radiation and the cell temperature. For conditions different from Standard Test Conditions (STC) it is defined by the following expression:

$$I_{ph} = \frac{G_a}{G_{STC}}\left(I_{SC0} + k_i(T - T_{STC})\right) \tag{7}$$

where: G_a is solar radiation in cell plane, G_{STC} =1000W/m^2 is solar radiation at STC; I_{SC0} is short-circuit current at STC; T_{STC} =25°C is STC temperature and k_i is thermal coefficient of SC current.

B. Converter Modeling

The DC-DC converter model is developed under assumption that all its components are idealized. Switching times of the transistors and diodes are zero i.e., they are ideal switches with some very small internal resistance. The series resistances of inductors, capacitor and transformer windings are also very small (in the simulation model 1.10^{-4}Ω). Leakage inductances of transformer are neglected.

III. Simulation Model of the System

A simulation model of the system from Fig. 1 is created in Matlab/Simscape. The model is shown in Fig. 3.

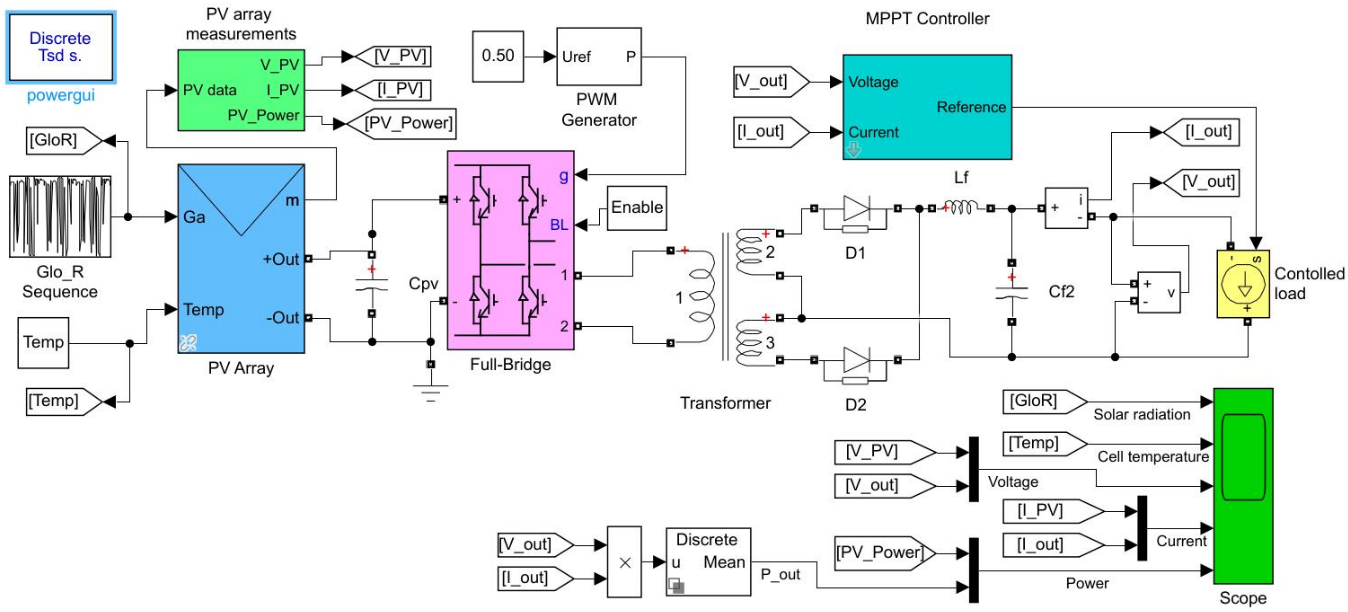

Fig. 3. Simulation model of the PV array, DC-DC converter and controllable load with MPPT in Matlab/Simscape.

A. PV Array, DC-DC Converter, and Microinverter Models

Four thin-film Cadmium Telluride PV panels are used in the simulation model. They are connected in parallel to achieve power of 300W. The resulting parameters of the PV array are:

- Maximum power P_m = 300Wp
- Voltage at maximum power V_{mp} = 69.4V
- Current at maximum power I_{mp} = 4.32A
- Open-circuit voltage V_{OC} = 92V
- Short-circuit current I_{SC} = 4.8A
- Open-circuit voltage temperature coefficient k_v = -0.237 %/°C.

The unknown parameters for the PV panel model are determined by optimization procedure using experimental data [9]:

- Diode saturation current $I_0 = 2.26.10^{-13}$A
- Diode ideality coefficient C = 1.056
- Series resistance R_S =12.3Ω

A microinverter of type Aurora micro-0.30-I-OUTD with following data is chosen to be connected to the PV array via the proposed DC-DC converter:

- Maximum DC input voltage: 65V
- DC voltage for full power at MPP: 30-50V
- Rated output power: 300W.

The chosen DC-DC converter is of full-bridge type with four MOSFET transistors, transformer, center-tap rectifier, and L-C filter - Fig. 3.

The transformer ratio is calculated considering maximum PV array voltage at temperature -10°C and maximum input DC voltage of the inverter [7]. Its value used in simulation model is 2.5.

The transistors are controlled by two pulse trains generated by a PWM generator. The primary transformer voltage is rectangular with magnitude equal to PV voltage V and frequency 25kHz. The duty ratio of control pulses is 50% which results in 100% duty ratio of voltage pulses after rectification. The filter components have following values: inductance Lf is 50.10^{-6}H and capacitor Cf2 is $4.7.10^{-6}$F. The capacitor Cpv (10.10^{-6}F) filters out the high-frequency component of converter current making the PV current as smooth as possible.

B. Microinverter Model

In order to test the possibility of common operation of proposed converter with the microinverter, appropriate simulation model is created. The microinverter is represented as a load to the DC-DC converter. This load consists of controlled current source and Maximum Power Point Tracking (MPPT) controller as shown in Fig. 3.

Incremental conductance (IC) tracking method is chosen for the MPPT controller. This method uses the difference between incremental conductance and instantaneous conductance value of the photovoltaic panel (array). Based on this value, the slope of P-V characteristics is altered [4]. When the PV panel operates at its maximum power point the derivative of the power is zero [5]:

$$\frac{dP}{dV} = 0 \tag{8}$$

The expression (8) is rearranged as follows:

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = \frac{dI}{dV}V + I \tag{9}$$

$$\frac{dI}{dV}V + I = 0 \Rightarrow \frac{dI}{dV} + \frac{I}{V} = 0 \tag{10}$$

The last expression in (10) represents an error that is used for control of the electronic load of the PV panel and searching of the maximum power point of operation. The following cases occur when using incremental conductance algorithm:

- $\frac{dI}{dV} + \frac{I}{V} = 0$ The error is 0 and maximum power point is achieved.
- $\frac{dI}{dV} + \frac{I}{V} > 0$ The error is positive and operating point is dragged towards the left of the P-V curve and current increases.
- $\frac{dI}{dV} + \frac{I}{V} < 0$ The error is negative and operating point is dragged towards the right of the P-V curve and current decreases.

Based on these equations, a simulation model of Incremental Conductance MPPT algorithm is created in Simulink. It is shown in Fig. 4. The two components $\frac{dI}{dV}$, $\frac{I}{V}$ and the error are calculated. The error is accumulated by a discrete integrator which produces a correction to the reference for the load current. The MPPT algorithm runs with a discretization step of 500.10^{-6} s while the entire Simulink model is discretized with step of 1.10^{-6} s.

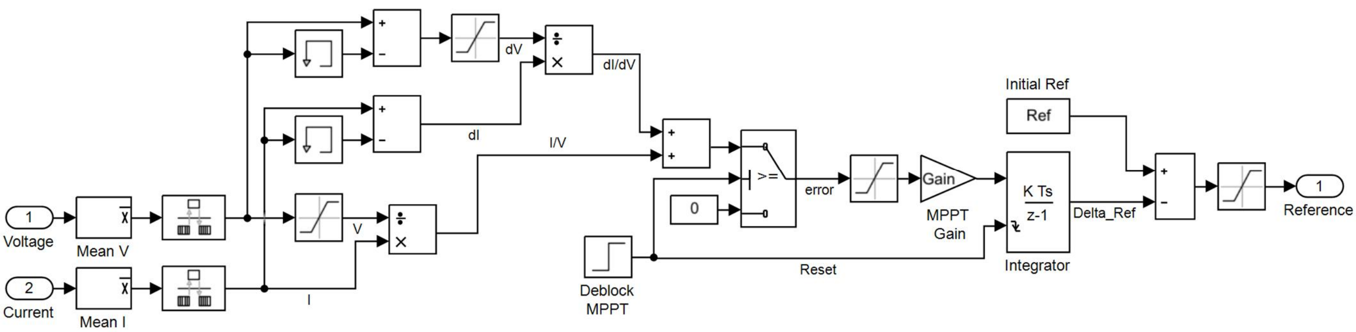

Fig. 4. Simulation model of the Incremental Conductnce MPPT controller.

IV. Simulation Results

Here, are presented main results from computer simulations carried out with the created Simulink model.

First, the static I-V characteristics of the PV array and these at the output of DC-DC converter are shown. These characteristics are calculated by the simulation model when a controlled DC voltage source is connected to the DC-DC converter output. By varying in steps, the output voltage from 1 to 55V, the points of the characteristics are calculated by the simulation model.

In Fig. 5 are shown the obtained I-V characteristics of the PV array and at the output of DC-DC converter when the modules operate at STC - global radiation 1000W/m^2 and cell temperature 25°C. In the same figure, the power variation with the voltage is also shown.

As it can be seen, the I-V characteristic of the PV array is transformed in different characteristic on the converter output. The new characteristic looks like a characteristic of the PV panel but with lower voltage and higher current. The maximum power of the PV array and at the output of converter have a small difference of 3.3W which represents 1.1% difference. This difference is due to the losses in the converter (some resistances still exists as it was explained in the converter modeling) and to the inevitable error of discrete digital solution of differential equations of the model.

To study the influence of the PV panel illumination on the converter behavior, a set of simulations are performed under different values of solar radiation and constant temperature. The results are shown in Fig. 6 where I-V characteristics on the output of the converter are shown and in Fig. 7 where the output power characteristics are drawn.

The results show that the static I-V curves at the output of the proposed converter are with the same form as usual characteristics of PV panels without any distortions. This is also due to the idealization of the converter. Taking into account all the features of the building components, there will be deviations, which, however, will not lead to the impossibility of using the converter for the purpose for which it is intended.

To test the dynamic behavior of the proposed converter and its common operation with the microinverter several simulations under different conditions are performed using the described above (Fig. 3).

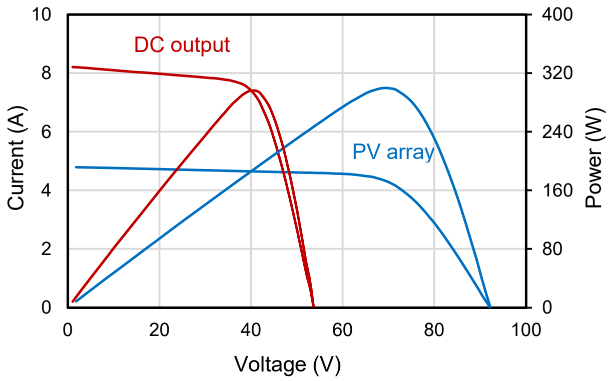

Fig. 5. I-V and power characteristics of PV array (blue) and at the output of DC-DC converter (red) at global radiation 1000W/m^2 and 25°C.

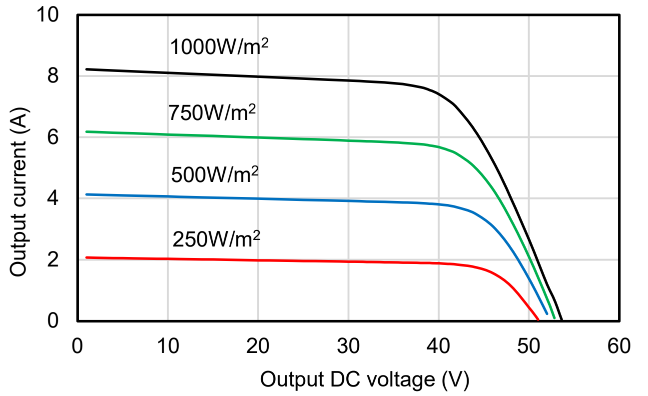

Fig. 6. I-V characteristics at the output of DC-DC converter at solar radiation 250 - 1000W/m^2 and cell temperature 25°C.

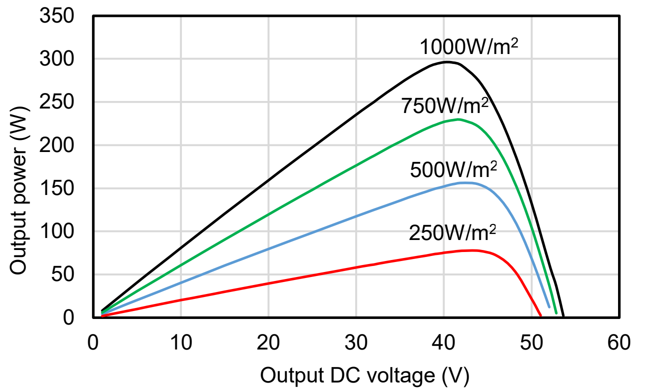

Fig. 7. Power characteristics at the output of DC-DC converter at solar radiation 250 - 1000W/m^2 and cell temperature 25°C.

The tests involve study of the behavior of the system: PV array-DC-DC converter-microinverter under variable solar radiation and PV module temperature. The results demonstrate the dynamic properties of the DC-DC converter and the capability of MPPT algorithm to follow maximum power using the voltage and current at the output of the converter.

First test is done with abrupt changes in solar radiation and cell temperature. The results are shown in Fig. 8. The simulation shows that the dynamic performance of the converter and MPPT controller are very good and they follow without visible lags the changes in solar radiation. The changes in cell temperature are also reflected to the output of the converter by variations in the voltage and power.

Second test is done using real data for solar radiation obtained from test facility described in previous authors' work [8]. The results from this simulation are shown in Fig. 9.

Here, the cell temperature is assumed constant because the capability of the model to follow correctly the temperature changes was proved by the previous test. In this test the time is "compressed" with the aim to save calculation time. Thus, the speed of change of solar radiation is increased but the MPPT algorithm is still able to follow correctly the changes. In both tests (Fig. 8 and Fig. 9), lines of PV power and output power practically coincide because the difference is around 3.3W and cannot be seen in this scale.

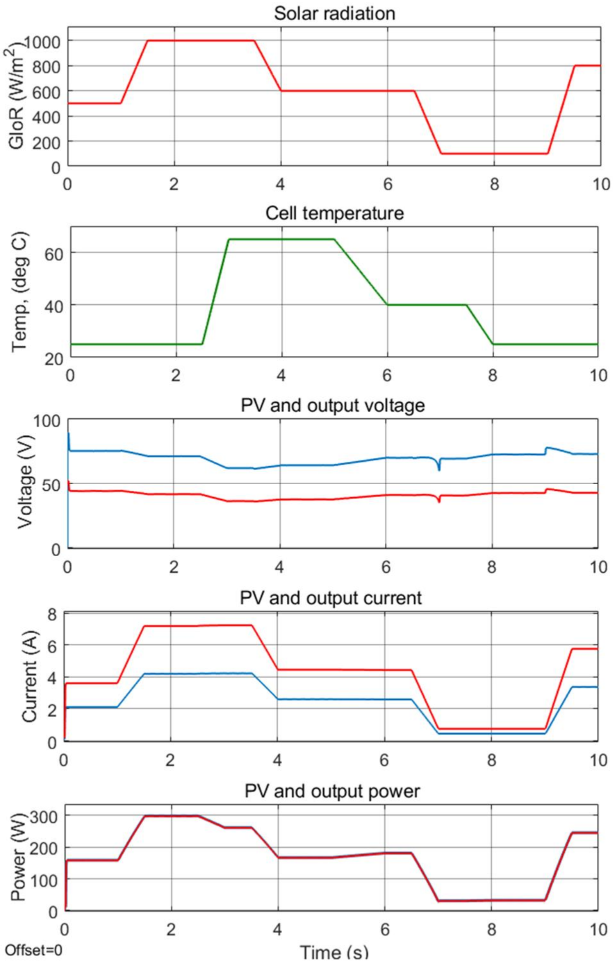

Fig. 8. Rezults from simulation with abrupt changes in solar radiation and cell temperature. PV variables are shown with blue lines, the converter output variables – with red lines.

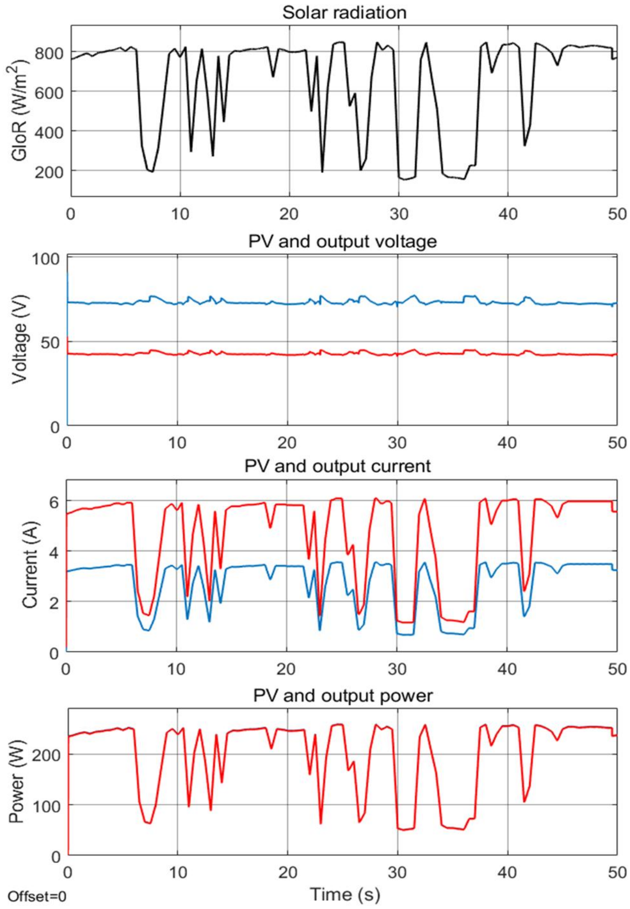

Fig. 9. Results from simulation of the system (PV array-DC-DC converter-load with MPPT) with real data for solar radiation and cell temperature 25°C. PV variables are shown with blue lines, the converter output variables – with red lines.

V. Conclusion

The paper presents a proposed by the authors isolated DC-DC converter which serves as interface between thin-film PV panel (or array) and microinverter. The converter uses full-bridge circuit with transformer, which is necessary for linear transformation of PV voltage and current and is useful for safety of the inverter. The converter mathematical model is developed in state space using instantaneous values. The simulation model is detailed but with idealized components. The simulation model also includes the microinverter input stage with MPPT algorithm. The complete model gives the possibility to study by digital experiments the static characteristics and dynamic behaviour of the whole system under variable solar radiation and cell temperature for relatively long time periods. The calculated I-V characteristics prove that the proposed converter operates as expected and its output characteristics imitate exactly like those of connected PV panel but with different voltage and current and the same power. The possibility of operation with inverter using MPPT algorithm is also demonstrated by simulations with artificial and real sequences of solar radiation data.

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