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Power Injection Control System and Experimental Model based on Manufacturer Characteristic Curves for a Photovoltaic Generation System

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Summary: **This paper attempts to validate the performance of a power injection control block for Photovoltaic Generation Systems (PVGS). This device uses a control module based on detecting the power injected into the supply by the inverter, instead of measuring the power generated by the PVGS. The performance is evaluated using the concept of *Maximum Energy Curve* that takes into account both transient and permanent control performance. The paper presents a basic and simple procedure to obtain a model from the manufacturer characteristic curves of the photovoltaic cells. MATLAB® Simulink® is used as simulation tool to obtain the response of the proposed system to changes in temperature and irradiance.**

Keywords:
Inverter Current Controller (ICC), Inverter Reference Current Generator (ICRG), Maximum Power Point Tracking (MPPT), Photovoltaic Cell (PV Cell), PV Voltage and PV Current, VI characteristic equations

1. INTRODUCTION

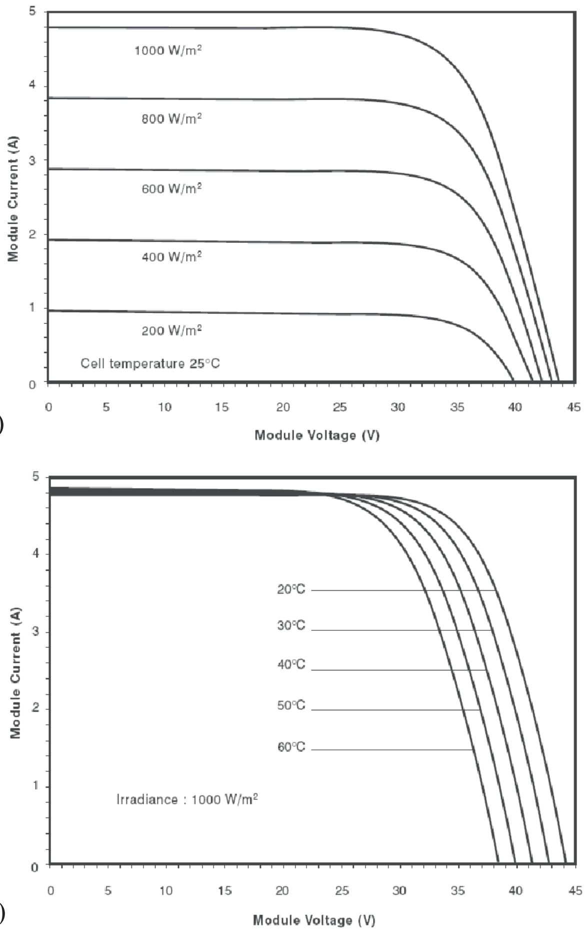
A PVGS consist on various components, each of them complied with one or more specific functions in order to inject the energy produced by the Photovoltaic Cells (PV Cell) into the Electric Power System. One of these components is the module that controls the inverter, which converts the power from DC to AC side. Usually this module contains the Maximum Power Point Tracking (MPPT), the Inverter Reference Current Generator (ICRG) and the Inverter Current Controller (ICC) blocks. In this paper, a performance procedure based on the *Maximum Energy Curve* is presented to evaluate both MPPT and ICRG blocks.

The paper is structured in the following form. First, a PV Cell model is obtained by a basic and simple procedure that starts from the manufacturer characteristic curves [1]. This model must be implemented in MATLAB® Simulink® and it allows simulated changes in temperature and irradiance. MPPT and ICRG are presented on part three of the paper. Finally, on part four, the simulation results are shown and analysed.

2. PV CELL MODEL WITH IRRADIANCE AND TEMPERATURE CHANGES SIMULATION CAPACITY

The aim of this section is to obtain a simple model for the PV Cell from the manufacturers characteristic curves I-V. Usually, the manufacturer provides a set of I-V curves, each of them for a concrete value of irradiance and temperature, Figure 1. Two significant parameters of the PV Cell could be obtained from these curves: open circuit voltage (V_{oc}), that is the voltage supplied by the PV cell when it is in open circuit so the current is zero, and short circuit current (I_{sc}), that is the current supplied by the PV cell when it is in short circuit so the voltage is zero.

Furthermore, the manufacturer provides the voltage (V_{MPP}), current (I_{MPP}) and power (P_{MPP}) of the Maximum Power Point, which depends on the irradiance and temperature conditions, so the result is:



a)
b)

Fig. 1. I-V curves for Shell SP150-P Photovoltaic Solar Module: (a) I-V curve of the solar module at various levels of irradiance, (b) I-V curve of the solar module at various cell Temperatures

$$P_{MPP} = V_{MPP} \cdot I_{MPP} \tag{1}$$

These parameters, as the curves, depend on the temperature and irradiance values. Figure 1 shows these curves for the Shell SP150-P photovoltaic solar module [1] when variations of irradiance, Figure 1a or temperature are produced, Figure 1b.

A model for the PV Cell will be obtained by means of a regression of the manufacturer I-V curves to the proposed mathematical function [2]:

$$i = A\left(1 - Be^{\left(\frac{v-C}{D}\right)}\right) \tag{2}$$

that corresponds to the curve show in Figure 2.

The values of the function coefficients A, B, C and D must be determined. The proposed procedure guarantees that the regression function fulfils the next points, approximately:

1) Open circuit point:

$$i = 0;\; v = V_{OC} \rightarrow C \approx V_{OC} \tag{3}$$

2) Short circuit point:

$$i = I_{SC};\; v = 0;\; exp^{\left(\frac{v-C}{D}\right)} \simeq 0 \rightarrow A \approx I_{SC} \tag{4}$$

B and D will be determined by means of the maximum power point.

3) Maximum power point:

$$I_{MPP} = I_{SC}\left(1 - Be^{\left(\frac{V_{MPP}-V_{OC}}{D}\right)}\right) \tag{5}$$

$$i = I_{MPP};\; v = V_{MPP};\; A \approx I_{SC};\; C \approx V_{OC}$$

And the derivative:

$$\left.\frac{dP}{dV}\right|_{MPP} = \left.\frac{dI}{dV}\right|_{MPP} \cdot V_{MPP} + I_{MPP} = 0 \tag{6}$$

With the equations (5) and (6) are obtained:

$$D = \frac{V_{MPP}}{I_{MPP}}\left(I_{SC} - I_{MPP}\right) \tag{7}$$

$$B = \frac{I_{SC} - I_{MPP}}{I_{SC} \cdot exp^{\left(\frac{-V_{OC}-V_{MPP}}{\tau}\right)}} = \frac{1 - \frac{I_{MPP}}{I_{SC}}}{exp^{\left(\frac{V_{MPP}-V_{OC}}{D}\right)}} \tag{8}$$

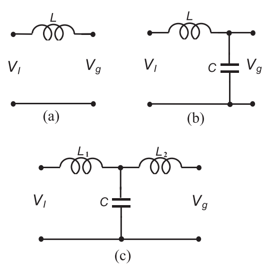


Fig. 2. I-V curves

The previous coefficients have been calculated with reference values of irradiance and temperature. In order to obtain the desired model for the PV cell where the influence of irradiance and temperature changes are taken into account, the values of the I_{SC} and V_{OC} parameters are modified following the next expressions [3, 4]:

$$I_{SC,T} = I_{SC,ref} \cdot \left(\frac{W}{W_{ref}}\right)$$

$$\begin{aligned} V_{OC,T} &= V_{OC,ref} - k_T\left(T - T_{ref}\right) - V_{OC,W} = \\ &= V_{OC,ref} - k_W\left(\frac{W_{ref} - W}{W}\right) \end{aligned} \tag{9}$$

where:

$I_{SC,ref}$	—	Short circuit current at the reference irradiance level and cell temperature (A).
I_{SC}	—	Short circuit current at the actual irradiance level and cell temperature (A).
$V_{OC,ref}$	—	Open circuit voltage at the reference irradiance level and cell temperature (V).
V_{OC}	—	Open circuit voltage at the actual irradiance level and cell temperature (V).
W_{ref}	—	Reference irradiance level (W/m^2).
W	—	Actual irradiance level (W/m^2).
T_{ref}	—	Reference cell temperature (^{o}C).
T	—	Actual cell temperature (^{o}C).
k_T	—	Temperature variation coefficient of V_{OC} (V/^{o}C).
k_w	—	Irradiance variation coefficient of V_{OC} (V/ (W/m^2).

It must be noted that the I_{SC} parameters do not change with the cell temperature, Figure 1b.

2.1. Shell SP150-P Photovoltaic Solar Module MATLAB®/SIMULINK® model.

The proposed PV Cell can be modelled using the set of equations (3–9), Figure 1 and Table I, adopting as reference irradiance level 1000 W/m^2 and as reference cell temperature 25^{o}C. Therefore, the equation values must be:

$$D = 3.0909;\quad B = 1.7442$$

$$A = I_{SC} = 4.8A;\quad C = V_{OC} = 43.4V$$

$$k_W = \frac{V_{OC\left(200W/m^2\right)} - V_{OC\left(1000W/m^2\right)}}{\left(1000 - 200\right)\cdot 1000}\frac{V}{W/m^2} = 0.85\frac{V}{W/m^2}$$

$$k_T = \frac{V_{OC(60^oC)} - V_{OC(25^oC)}}{\left(60 - 25\right)}\frac{V}{^oC} = 0.14\frac{V}{^oC}$$

K_W and K_T from Figure 1b.

The resulting set of curves I-V of the proposed model for various irradiance levels and cell temperatures are shown in Figure 3, where can be observed that they are closed

Table 1. Shell sp150-p Photovoltaic Solar Module Electrical Characteristics at Standard Test Conditions (stc) 25ºC and 1000W/m2.

Electric Characteristics	Data
Open circuit voltage(VOC)	43.4 V
Short circuit current (ISC)	4.8 A
Maximum power point Current (IMPP)	4.4 A
Maximum power point voltage (VMPP)	34 V
Maximum power (PMPP)	150 W

enough to the manufacturer curves, Figure1. These results are sufficiently representative for their use in next sections, so the proposed basic and simple procedure to obtain a model for the PV cell has been validated. Furthermore, the proposed PV model takes into account the changes in irradiance level and cell temperature.

The obtained PV model has been implemented in Simulink® resulting in the block shown in Figure 4, which has three inputs: irradiance level, cell temperature and PV current, and one output: the PV voltage. The mathematical equation implemented into the Simulink® block is the reverse from (2).

3. POWER INJECTION CONTROL SYSTEM (MPPT)

In this section is presented the Power Injection Control System used to extract the power from the PV Cells and to inject it to the Electric Power System. Only the MPPT and the IRCG blocks are described. The ICC is out of the paper scope. The Figure 5 shows a general scheme of the Power Injection Control System.

3.1. MPPT block

The MPPT must extract the maximum available power from the PV cell, and it must be able to execute it for any irradiance level and cell temperature [5].

At the MPP the power is maxima so its derivative is null:

$$\frac{dP_{pv}}{dV_{pv}} = \frac{dI_{pv}}{dV_{pv}} \cdot V_{pv} + I_{pv} = 0 \tag{10}$$

where:

$$P_{pv} = V_{pv} \cdot I_{pv} \tag{11}$$

The MPPT block scheme in Simulink® is shown in Figure 6, where the derivative of power respect to the voltage is tracked to zero by a well-designed Proportional-Integral (PI) controller. It is helped by an adequate Low-Pass Filter (L.P.F). The output of the MPPT block is a PV Cell reference current value.

3.2. IRCG

The IRCG block must obtain the inverter reference current that will be passed to the ICC, so the last control block, the inverter, injects into the Electric Power System a current as close to the reference current as it could be possible.

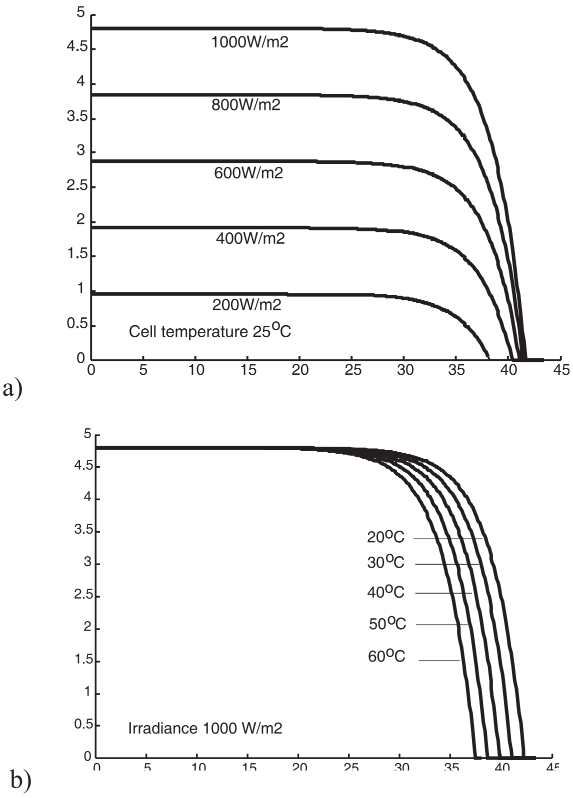


Fig. 3. I–V curves for PV Cell model obtained for the Shell SP150-P photovoltaic solar module: a) I–V curve of the solar module at various levels of irradiance; b) I–V curve of the solar module at various cell Temperatures

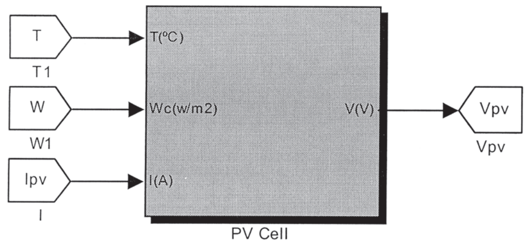


Fig. 4. PV Cell model by Simulink®

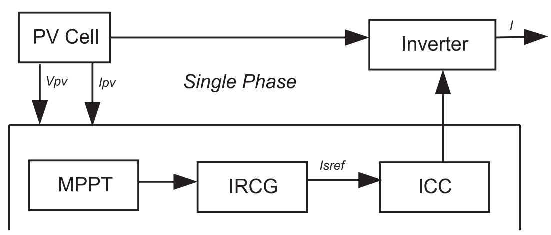


Fig. 5. Power Injection Control System

To obtain the inverter reference current, a Unity Power Factor (UPF) strategy is used. Therefore, the reference current will result from multiply a unitary RMS value sinusoidal wave, u_S, obtained from the Electric Power System by a parameter, k. This parameter coincides with the supplied RMS current value:

$$i_s(t) = k \cdot u_s(t); \quad u_s = \frac{v_s}{V_{s,rms}} \tag{12}$$

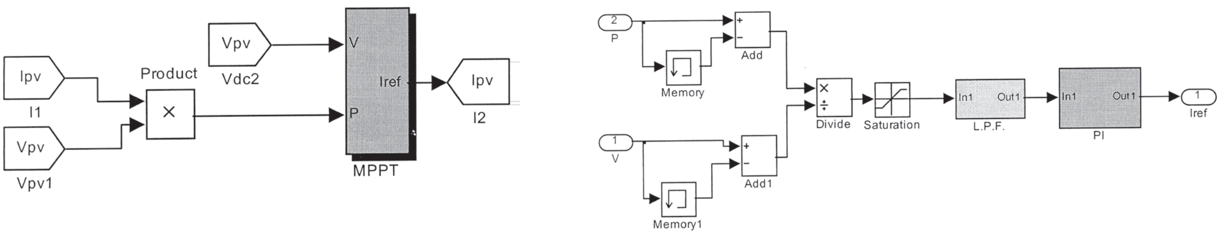


Fig. 6. MPPT block scheme

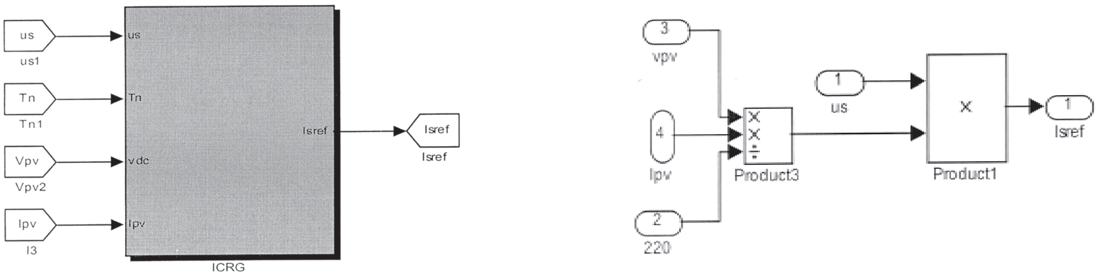


Fig. 7. Block diagram of ICRG

The constant value, *k*, will be obtained from the assumption that the mean active power injected by the inverter (P_s) must be equal to the maximum PV power (P_{pv}) determined previously by the MPPT block:

$$\left.\begin{aligned} P_{pv} &= V_{pv}\cdot I_{pv} \\ P_s &= V_s\cdot I_s = V_S\cdot k \end{aligned}\right\} \rightarrow$$

$$\rightarrow P_S = P_{PV} \rightarrow P_s = V_s\cdot I_s = V_s\cdot k = V_{pv}\cdot I_{pv} \rightarrow \qquad (13)$$

$$\rightarrow k = \frac{V_{pv}\cdot I_{pv}}{V_s}$$

In the proposed control system is assumed that $I_{PV} = I_{PV,ref}$, so the ICC block ,which is not analysed in the present paper, operates correctly. In the next simulated situations only will be needed three variables: PV voltage (V_{pv}), PV current and supply voltage (V_s). In Figure 7 the Simulink® model for the IRCG is shown.

4. PERFORMANCE EVALUATION

The performance of the power injection control systems is developed in this section. The power effectively injected by the proposed system is compared with the Maximum Energy Curve. The Maximum Energy Curve is obtained by an off-line optimization process that calculates the Maximum Power at every instant, considering the irradiance level and the cell temperature at this instant.

The complete Simulink® model [2] for the PV generation system is shown in Figure 8. It includes the PV cell model of section 2.1. the power injection system of section III and other necessary blocks.

The performance of the described system has been evaluated through simulation in four different situations:

4.1. Case A

This simulation corresponds to the system starting up under the Standard Conditions of irradiance (1000 w/m^2) and cell temperature (25^{o}C).

4.2. Case B

Simulation system when irradiance level changes are produced. The irradiance level starts at 1000 W/m^2, changes to 800W/m^2 at 1.0s and comes back to 1000 W/m^2 at 2.5s. The cell temperature is kept constant at 25^{o}C.

4.3. Case C

Simulation system when cell temperature changes are produced. The cell temperature starts at 25^{o}C, changes to 15^{o}C at 1.0s and comes back to 25^{o}C at 2.5s. The irradiance level is kept constant at 1000 W/m^2.

4.4. Case D

Simulation system when irradiance level and cell temperature changes are produced. The irradiance level and cell temperatures starts as 1000 W/m^2 and 25^{o}C respectively. The irradiance level changes to 800 W/m^2 at 1.0s. The cell temperature changes to 15^{o}C at 2.0s and comes back to 25^{o}C at 3.0s. The irradiance comes back to 1000 W/m^2 at 4.0s.

The simulation results are summarized in Figures 9 to 12. These figures show the same information: Mean active power (a), Inverter Reference Current (b), PV voltage (c) and PV current (d). In all graphics, the simulation results (width and strong curves) are plotted together with the ideal curves (dashed lines and light curves) obtained from an off-line process that calculates the magnitudes of the MPP. The closer the curves are, the better will be the performance of the power injection system.

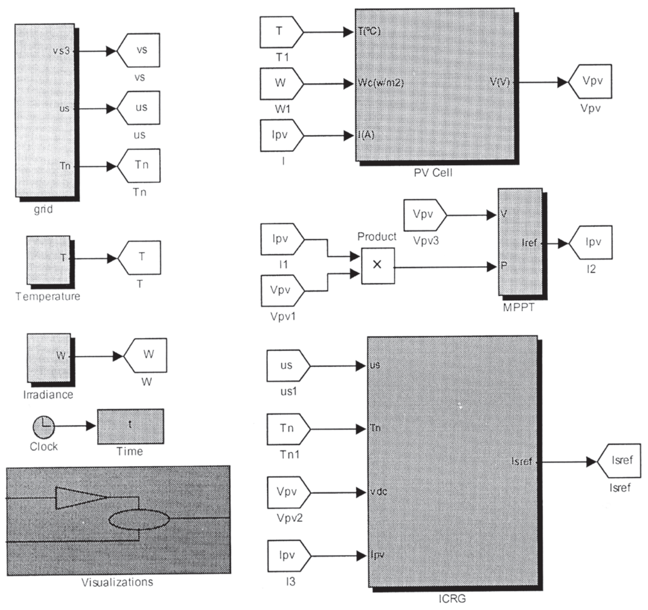


Fig. 8. Power Generation System Simulink® model

In order to evaluate the power injection system performance the first graph (mean active power (a)) must be considered. The zone between the ideal and simulated mean active power is the non-injected energy, that represents the energy that the PV system could have injected into the Electric Power System, but it has not happened due to the limitation of both transient and permanent characteristics of the power injection system.

The simulated mean active power has been calculated from the active power injected by the inverter. This power is a pulsed magnitude, so a Low-Pass Filter has been used to extract the mean value producing a little delay time that can be observed on every figure. It must be noted that the simulated mean active power never can be greater than the ideal one.

5. CONCLUSIONS

The Maximum Energy Curve concept has shown that it may be very useful to evaluate and to compare the generation photovoltaic control system.

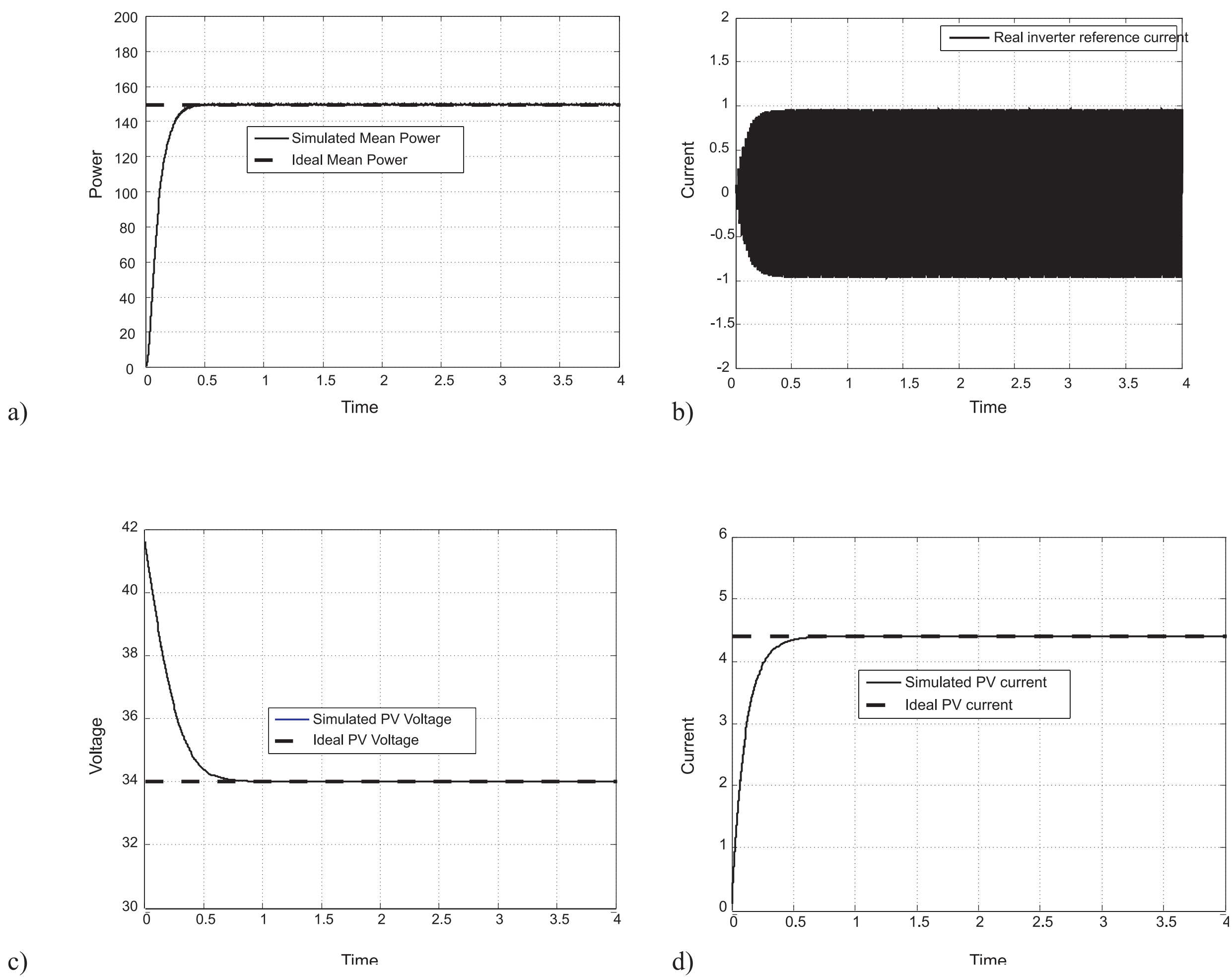


Fig. 9. Simulation results for case A: a) Mean Active Power; b) Inverter Reference Current; c) PV Voltage; d) PV current

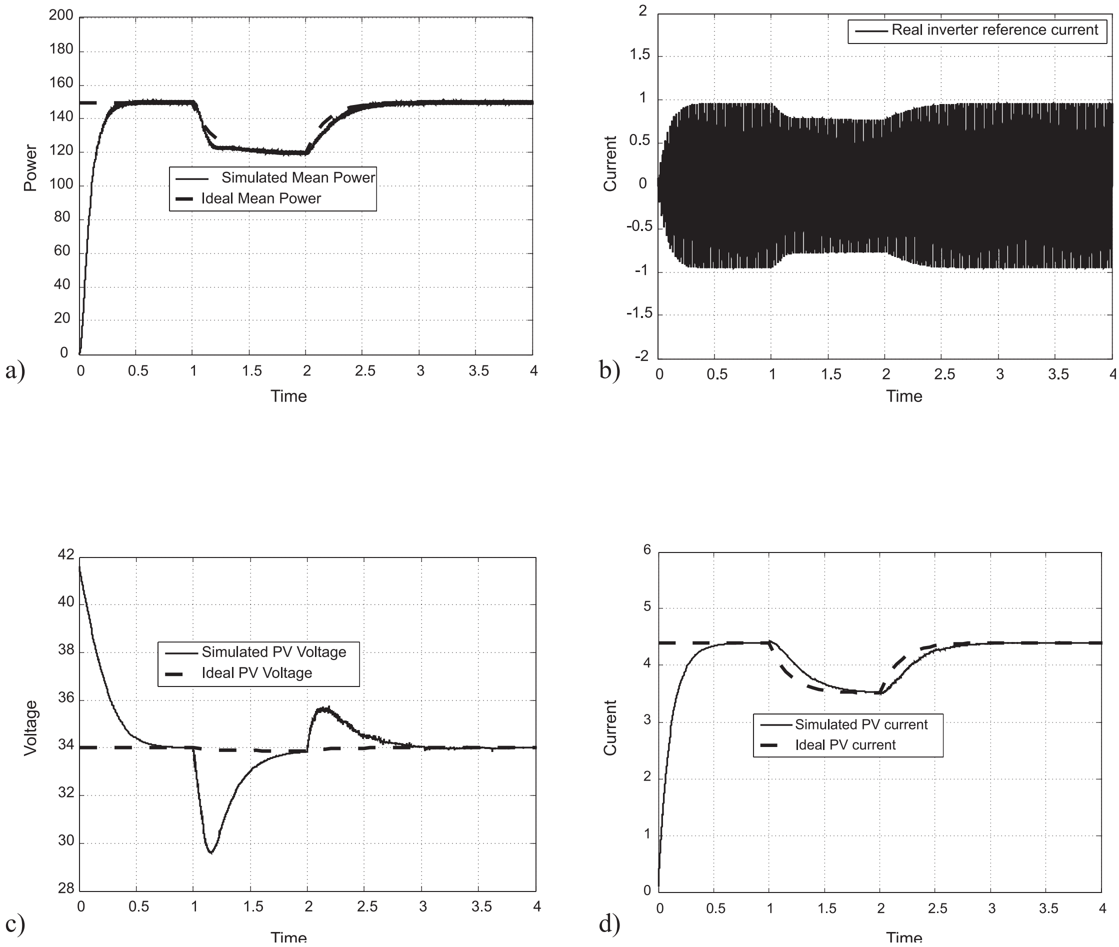


Fig. 10. Simulation results for case B: a) Mean Active Power; b) Inverter Reference Current; c) PV Voltage; d) PV current

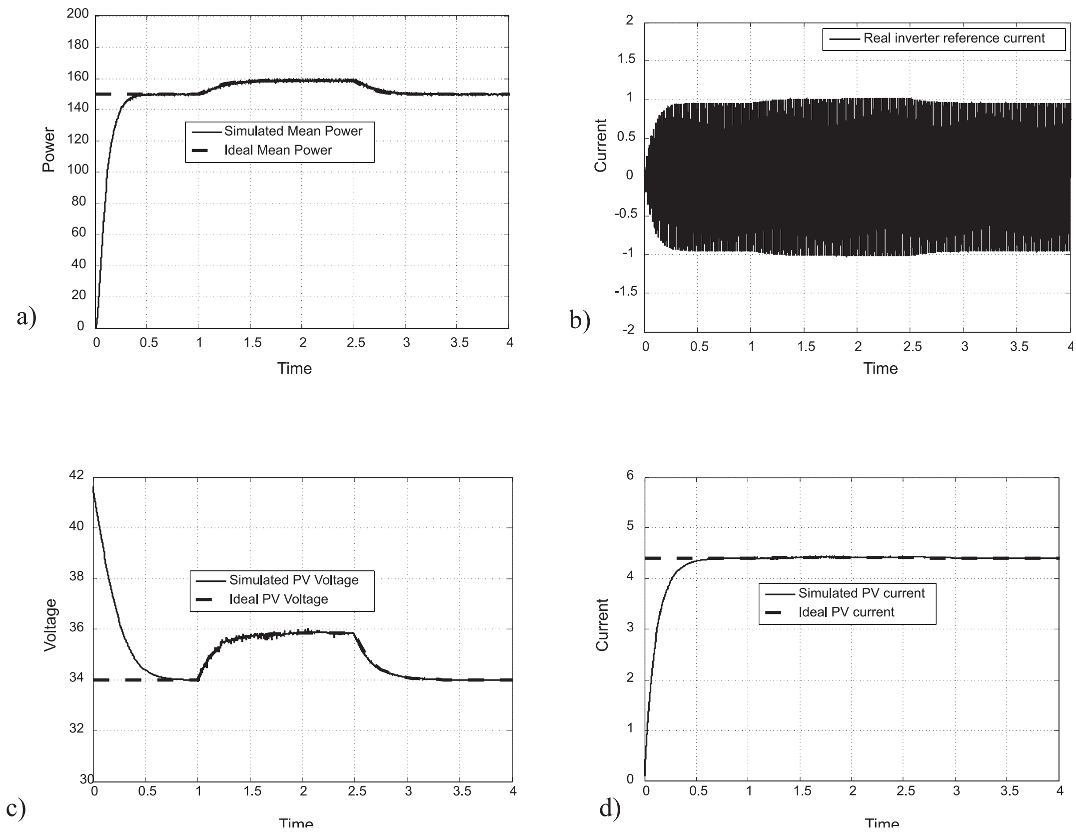


Fig. 11. Simulation results for case C: a) Mean Active Power; b) Inverter Reference Current; c) PV Voltage; d) PV current

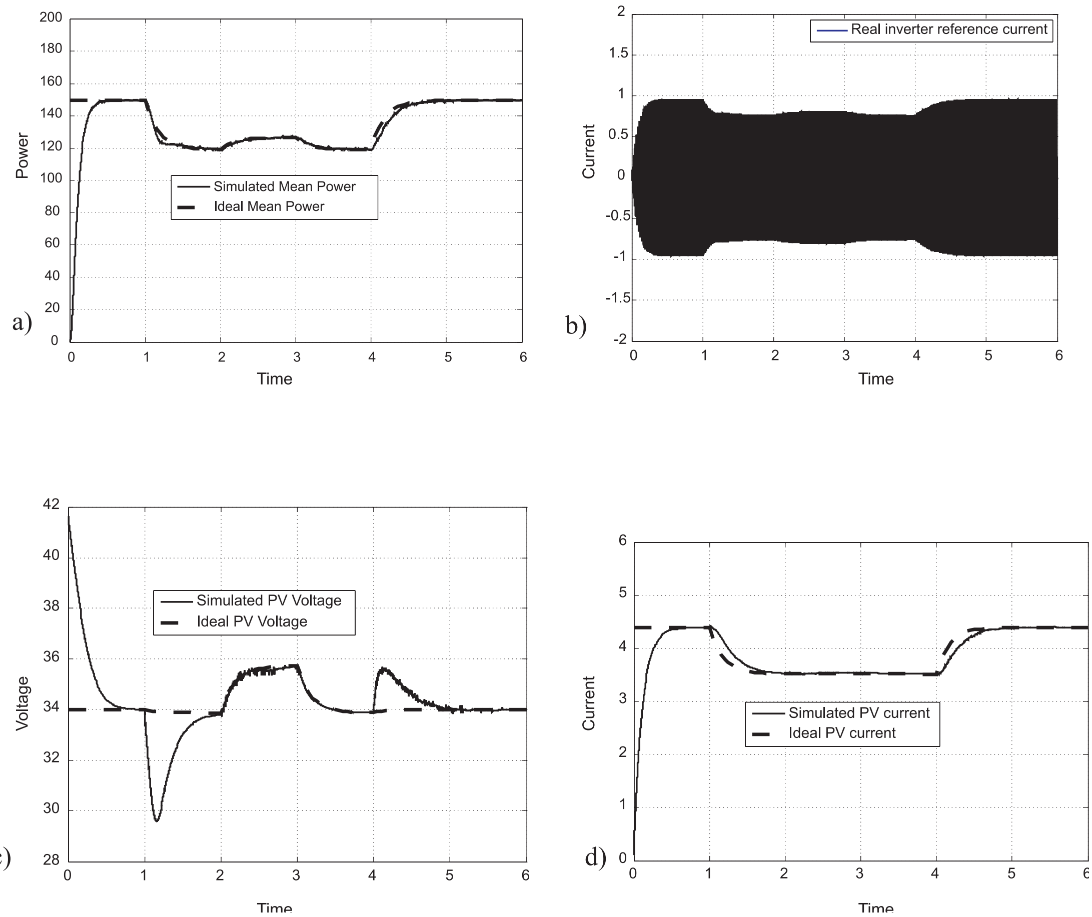


Fig. 12. Simulation results for case D: a) Mean Active Power; b) Inverter Reference Current; c) PV Voltage; d) PV current

The MPPT and IRCG blocks, simples and solids of the power injection, have been shown. These blocks are able to work correctly even in irradiance and temperature change situations, which may be caused by atmospheric cloudiness. The proposed blocks have been simulated and validated comparing their function curves with the ideal ones.

A basic and simple procedure to obtain PV cell models from the manufacturer data has been presented and evaluated. This model is an alternative to the actual ones, easier to use in order to model a real PV cell and to take into account the irradiance levels and cell temperatures, allowing changes during simulation on these magnitudes.

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