Modeling, Simulation and Control of Photovoltaic Power System

MONICA LEBA, EMIL POP, CAMELIA TABACARU-BARBU, PETRE VAMVU
System Control, Applied Informatics and Computer Engineering Department
University of Petrosani
Str.Universitatii, nr.20, 332006, Petrosani
ROMANIA

Abstract: - The main objective of this paper is to determine the Solar Photovoltaic and its appropriate controller mathematical models, to validate them through simulation results in order to practically design such a system. In this paper we consider a Photovoltaic Solar system consisting of the solar radiation, the photovoltaic panel, the power batteries, the DC/AC inverter and the controller. Each part of this system is analyzed, modeled and simulated. At the end of the paper the full system is modeled and simulated. The simulation results are as expected and validate the developed mathematical models.

Key-Words: - Photovoltaic, solar, modeling, simulation, controller

1 Introduction

The direct conversion of solar radiation into electrical power is done using photovoltaic cells. A photovoltaic element can be represented by an equivalent electric diagram as shown in fig.1.

The elements from this diagram are: a current source, a series resistance R_s, a shunt resistance R_{sh}, a diode D and a load resistance R_L. The source produces the current I_L which branches in three currents: I_D through the diode, I_{sh} through R_{sh} and I through R_s and R_L. The current I is the current produced by the cell and can be externally used.

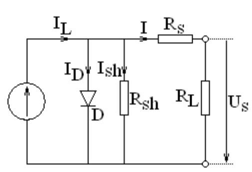

Fig.1. Equivalent diagram of the photovoltaic cell

From fig.1, there can be written the following equations:

$$I_L = I_0 + I_{sh} + I \quad (1)$$

$$I_s = I_0 \cdot (e^{\frac{U_s}{a}} - 1),\ a = \frac{A \cdot k \cdot T}{q} \quad (2)$$

$$U_s = U + R_s \cdot I \quad (3)$$

$$I_{sh} = \frac{U + R_s \cdot I}{R_{sh}} \quad (4)$$

Based on the above equations, we get the relationship between I and U and the cell's power P:

$$I = I_L - I_0 \cdot (e^{\frac{U + R_s \cdot I}{a}} - 1) - \frac{U + R_s \cdot I}{R_{sh}} \quad (5)$$

$$P = U \cdot I \quad (6)$$

The parameters I_L, I_0, R_s and R_{sh} depend on the photovoltaic element type and also on the temperature T. The parameter a is called the thermal potential and depends on the temperature T and on the quality factor A of the diode D.

The other means are: the electron charge q; the Boltzmann constant k; the short-circuit current I_L and the inverse saturation current of the diode I_0.

The relation (5) represents the precise equation of the photovoltaic element, but, in practice, R_s and I_0 are very small and can be neglected and R_{sh} is very big so the term $\frac{U + R_s \cdot I}{R_{sh}}$ is null.

Results the simplified equation of the photovoltaic element:

$$I = I_L - I_0 \cdot e^{\frac{U}{a}} \quad (7)$$

In fig.2.a and b are presented the model and simulation results for the equations (5) and (7) in order to illustrate the good approximation considered.

On the other hand, the means I_L, I_0 and a depend on the temperature that can be determined by measurements on a known photovoltaic element, considering a reference irradiation power $P_{i,ref}$=1000 W/m^2 and a reference temperature T_{ref}=25^{o}C=298^{o}K. In fig.2.d is presented the three-dimensional representation of I=f(U,a).

In the case of constant temperature T and known $I_{L,ref}$ there can be determined the currents $I_{L,i}$ for different irradiations P_i using the relation:

$$I_{L,i} = \frac{P_i}{P_{ref}} \cdot I_{L,ref} = \frac{P_i}{1000} \cdot I_{L,ref} \qquad (8)$$

where: $I_{L,ref} = I_{0,ref} \cdot e^{\frac{U_0}{a_{ref}}}$ (9)

In fig.2.c are presented the characteristics of the photovoltaic element for four different irradiations. In order to generate the maximum power it is necessary to have maximum current without decreasing too much the voltage. For example, at 400 W/m^2, this point is located at 2A and 17V.

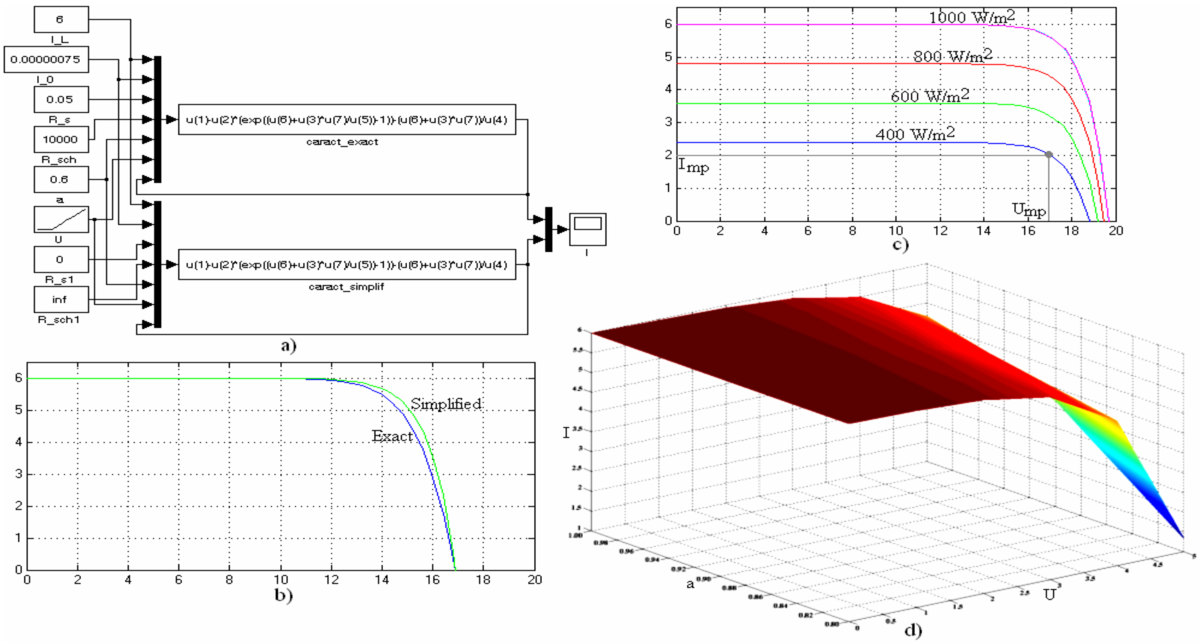

Fig.2. Photovoltaic cell: a) Model; b) Exact and simplified characteristics; c) Characteristics for different irradiations; d) Three dimensional characteristics I=f(U,a)

2 Problem Formulation

In this section we will model and simulate all the components of the photovoltaic power system.

First we will model the solar radiation and panel, then the power batteries, the DC/AC inverter and the controller. In fig.3 is presented the block diagram of the photovoltaic system.

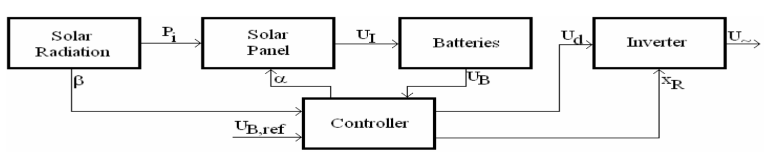

Fig.3. Block diagram of the photovoltaic power system

2.1 Solar Radiation and Photovoltaic Panel Model

First, we will write the mathematical model for the solar radiation.

We'll consider that the solar radiation along a certain hours light day varies by a sine form depending on the solar rows incidence angle β on Earth. In fig.4 is presented the solar radiation model and simulation results considering the maximum irradiation power of 2000 W/m^2 and 10 hours of light on the day.

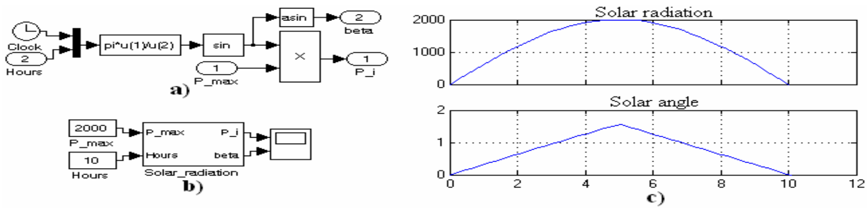

Fig.4. Solar radiation: a) Detail; b) Model; c) Simulation results

Second, we will write the mathematical model for the photovoltaic panel.

In order to write the mathematical model for the photovoltaic solar panel we have to know that the parameters I_L, I_0 and a depend on the solar radiation P_i and the panel temperature T.

We will determine the equations of these parameters reported to the reference values $P_{i,ref}$=1000 W/m^2 and T_{ref}=25°C. In the following relations there are used the known data: ε=1.12 eV (for Si) or ε=1.35 eV (for GaAs); N_s is the cells number from one module multiplied by the modules number in the panel; $\mu_{I,sc}$ is the temperature coefficient for the short circuit current; $\mu_{U,oC}$ is the temperature coefficient for the open circuit voltage; $U_{oC,ref}$ is the open circuit voltage and I_{sc} is the short circuit current.

There can be written the relations:

$$I_{L,ref} = I_{sc} \quad (10)$$

$$a_{ref} = \frac{\mu_{U,oC} \cdot T_{ref} - U_{oC,ref} + \varepsilon \cdot N_s}{\frac{\mu_{I,sc} \cdot T_{ref}}{I_{L,ref}} - 3} \quad (11)$$

$$I_{0,ref} = I_{L,ref} \cdot e^{-\frac{U_{0C,ref}}{a_{ref}}} \quad (12)$$

$$I_L = \frac{P_i}{P_{i,ref}} \cdot \left[I_{L,ref} + \mu_{I,sc} \cdot (T - T_{ref}) \right] \quad (13)$$

$$a = a_{ref} \cdot \frac{T}{T_{ref}} \quad (14)$$

$$I_0 = I_{0,ref} \cdot \left(\frac{T}{T_{ref}} \right)^3 \cdot e^{\frac{\varepsilon \cdot N_s}{a_{ref}} \left(1 - \frac{T_{ref}}{T} \right)} \quad (15)$$

Based on the reference parameters, there are determined $I_{L,ref}$, a_{ref} and $I_{0,ref}$, using the equations (10), (11), (12). Then, based on these values, there are determined I_L, a and I_0. In the end, there is determined I=f(U).

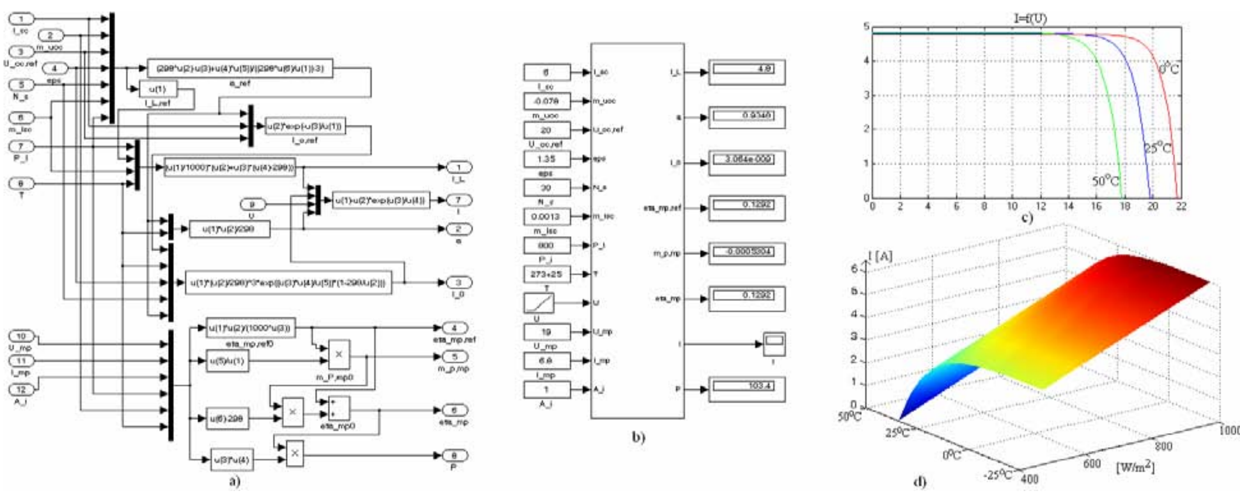

Fig.5. Photovoltaic solar panel: a) Detail; b) Model; c) Simulation results; d) I=f(T,P_i) for U=16V

For a photovoltaic panel in order to be efficient it is mandatory to produce the maximum power. The maximum power is determined by the relation:

$$P_{mp} = U_{mp} \cdot I_{mp} \quad (16)$$

It is important to determine the maximum power reported to the irradiation power P_i[W/m^2]. For a specific surface A_i of the panel, the total power is $P_p=A_i \cdot P_i$. So, the efficiency will be:

$$\eta_{mp} = \frac{U_{mp} \cdot I_{mp}}{A_i \cdot P_i} \quad (17)$$

But, η_{mp} depends on $\eta_{mp,ref}$ and on the panel temperature T. There is known $\mu_{P,mp}$ that is the power temperature coefficient and is determined by the relation:

$$\mu_{P,mp} = \eta_{mp,ref} \cdot \frac{\mu_{U,0C}}{U_{mp}} \quad (18)$$

Results:

$$\eta_{mp} = \eta_{mp,ref} + \mu_{P,mp} \cdot (T - T_{ref}) \quad (19)$$

$$P_{mp} = A_i \cdot P_i \cdot \eta_{mp} \cdot \eta_s \quad (20)$$

These equations fully and precisely model the photovoltaic solar panel. In fig.5 are presented the model and simulation results for the following constant data: ε=1.35; N_s=30; $\mu_{I,sc}$=1.3·10^{-3}; $\mu_{U,oC}$=-0.078; $U_{oC,ref}$=20; I_{sc}=6; P_i=800; U_{mp}=19; I_{mp}=6.8; A_i=1. There were used three temperature values: 0°C; 25°C and 50°C.

2.2 Batteries and Inverter Model

Most of the times, the solar energy produced by the photovoltaic cells is stored in batteries. The batteries have the nominal voltage of 12V, 24V, 48 V or even more. We will model and simulate the batteries based on equivalent diagram from fig.6.

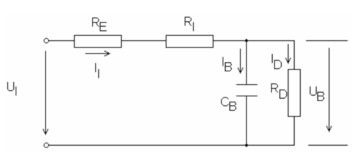

Fig.6. Batteries equivalent diagram

Based on the above diagram there can be written the following equations:

$$I_I = I_B + I_D \quad (21)$$

$$U_I = (R_E + R_I) \cdot I_I + U_B \quad (22)$$

$$C_B \cdot \frac{dU_B}{dt} = I_B \quad (23)$$

$$U_B = R_D \cdot I_D \quad (24)$$

From these equations, result the following differential equations:

$$T_1 \cdot \frac{dU_B}{dt} + U_B = k \cdot U_I \quad (25)$$

$$T_2 \cdot \frac{dU_B}{dt} + U_B = R_D \cdot I_I \quad (26)$$

$$T_1 \cdot \frac{dI_I}{dt} + I_I = k_1 \cdot T_2 \cdot \frac{dU_I}{dt} + k_1 \cdot U_I \quad (27)$$

$$T_2 \cdot \frac{dI_B}{dt} + I_B = T_2 \cdot \frac{dI_I}{dt} \quad (28)$$

$$T_1 \cdot \frac{dI_B}{dt} + I_B = k_1 \cdot T_2 \cdot \frac{dU_I}{dt} \quad (29)$$

where: $k = \frac{R_D}{R_D + R_E + R_I}$; $k_1 = \frac{1}{R_D + R_B + R_I}$;

$T_1 = \frac{R_D \cdot (R_E + R_I)}{R_D + R_E + R_I} \cdot C_B$ and $T_2 = R_D \cdot C_B$.

In fig.7 there are presented the model and simulation results for equations (25), (27) and (28).

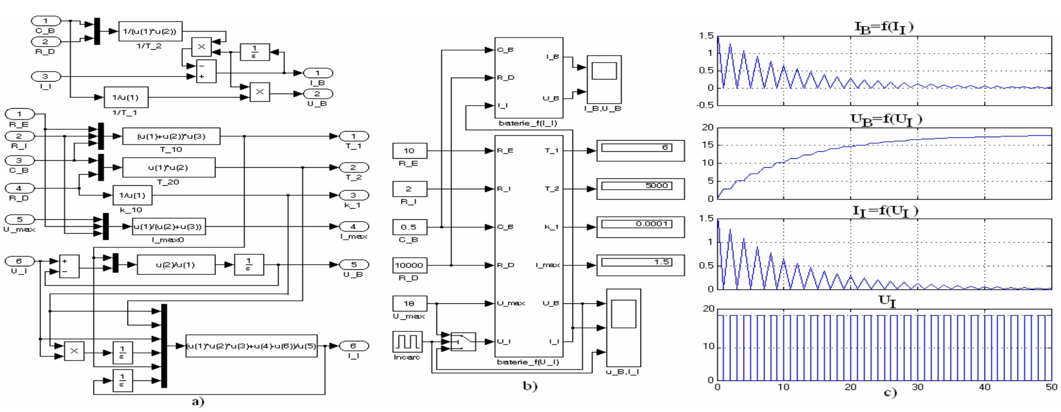

Fig.7. Batteries: a) Detail; b) Model; c) Simulation results for voltage pulse charging case

The inverter uses the batteries voltage to convert it into AC voltage. Usually it is used a Pulse Width Modulation (PWM) inverter. In this way, the voltage is controlled by the modulation index R and the frequency f is kept at a preset value of 50 Hz.

In fig.8 are presented the model and simulation results of such a PWM inverter, for R=1 and U_d=48V.

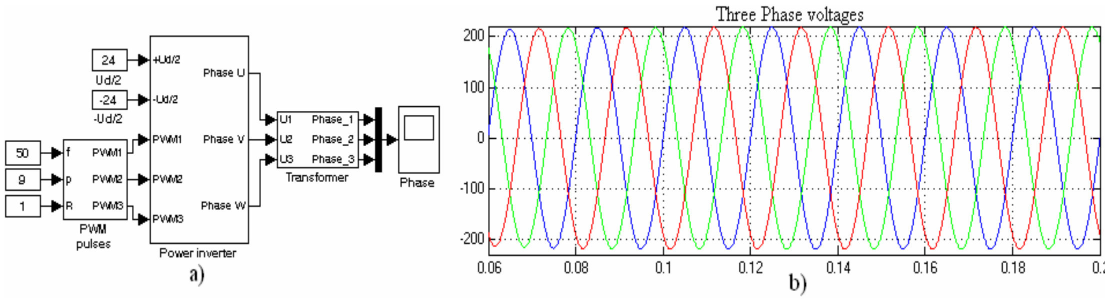

Fig.8. PWM inverter: a) Model; b) Simulation results

3 Problem Solution

In this section we will present the modeling and simulation of the entire photovoltaic power system, consisting of the solar radiation, panels, batteries, DC/AC inverter, together with the dedicated controller. This controller controls the panels pitch angle and the output AC voltage of the inverter.

3.1 Controller Design

First, we will design the controller that has three inputs and three outputs. The inputs are the solar radiation angle β, the batteries reference voltage $U_{B,ref}$ and the batteries charging voltage U_B. The outputs are the panel control angle c_{panel}, the inverter DC input voltage U_d and the inverter modulation index R.

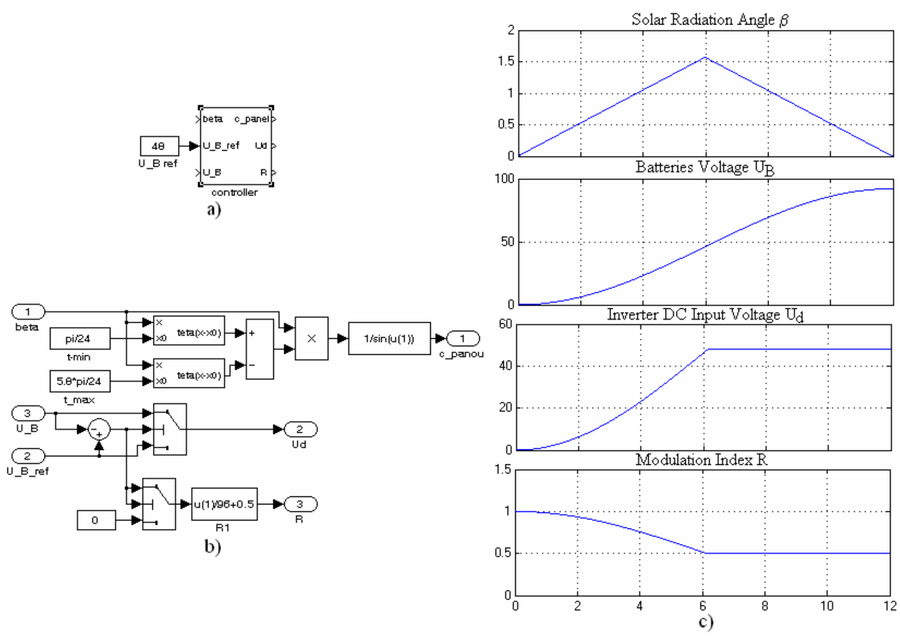

Fig.9. Controller: a) Model; b) Detail; c) Simulation results

In fig.9 are presented the controller model and simulation results for one day (12 hours) of solar radiation and 48V batteries reference voltage.

3.2 Photovoltaic System with Controller

The Photovoltaic Solar System full model was obtained connecting all the elements presented in paragraph 2 and the above controller. In fig.10 are shown the simulation model and results for this system. There were used the following data: I_{sc} = 6 A; $\mu_{U,oC}$ = -0.078; $U_{oC,ref}$ = 20 V; ε = 1.35 eV; N_s = 30; $\mu_{I,sc}$ = 0.0013; P_i = 1000 W/m_2; H = 12 h; T = 323^oK; U_{mp} = 19 V; I_{mp} = 5.8 A; A_i = 1 m^2; $U_{B,ref}$ = 48 V.

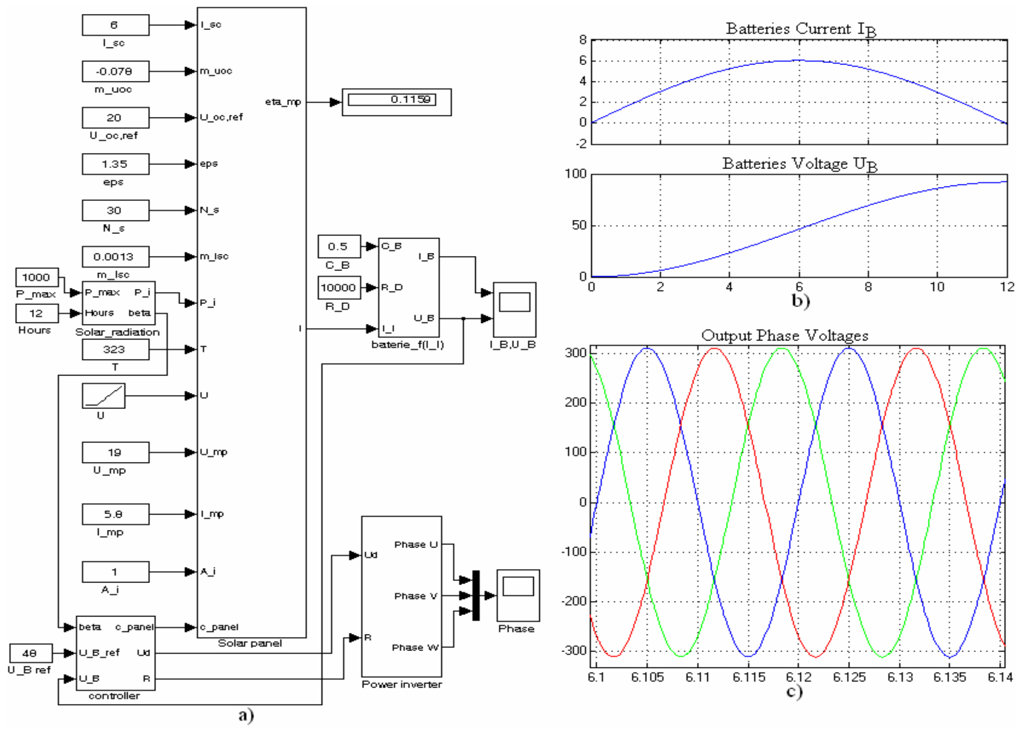

Fig.10. Photovoltaic Solar system: a) Model; b) Simulation results; c) Three Phased Controlled Output Voltage

4 Conclusion

The direct conversion of the solar energy in electrical energy represents the most challenging method of clean energy production. This because the Sun can be considered an unlimited resource and the conversion is achieved in fully static way. The main disadvantage is the low efficiency. Also, the solar radiation has different power among the Earth. In this paper, we have considered a Photovoltaic Solar System, consisting of five elements: the solar radiation, the photovoltaic panel, the power batteries, the DC/AC inverter and the controller. The paper presents a systemic approach on this, starting with the block diagram of each component.

There are modeled and simulated the solar and photovoltaic part (solar radiation, photovoltaic panel) and the electric part (power batteries, DC/AC inverter). Then, there is designed, modeled and simulated the Controller for this system. In the end there are obtained the simulation results for the full system. The Photovoltaic System mathematical model was validated by the simulation results.

The results of this paper prove the correctness of this solution and the developed models can be used in solar systems design applications.

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