Original Research Paper

Efficient FPGA Implementation to Estimate the Maximum Output Power of a Photovoltaic Panel Using Xilinx System Generator

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Abstract: This paper presents an efficient architecture for different mathematical models for optimal design of a photovoltaic system using Xilinx System Generator (XSG). This architecture offers an alternative through a graphical user interface that combines MATLAB/Simulink and XSG and explores important aspects of the experimental implementation. The use of the Xilinx generator for calculating the power output of a photovoltaic system reduces the complexity and structural design and also provides an additional feature for materializing the system.

Keywords: Photovoltaic Panel, Maximum Power Point Tracking, FPGA Implementation, Xilinx System Generator

Introduction

Nowadays, designing an optimized photovoltaic system remains a challenge facing researchers. Indeed, the output power of PV generator is strongly correlated to the temperature, to the light and evidently to the photovoltaic panel ageing. The problem of perfect coupling between the PV generator and the load is not yet fully resolved. In fact, the problem of working at the maximum power point of the PV Generator (PVG) is not practically achieved despite many control algorithms devoted to this task.

There are two approaches for modeling the solar panels. The first requires to perform measurements on the solar panel when installed. This case corresponds to the models developed by Sandia and Cenerge (Chenni *et al*., 2007). The second approach is to focus only on the manufacturer's data (King *et al*., 1998).

Jones and Underwood (2002) proposed another model to calculate the maximum power at the terminals of a solar panel. This model is given as a function of the module temperature. Moreover, it has a logarithmic relationship with the solar radiation absorbed by the solar panel.

Today, the implementation of FPGA-based industrial control systems represents an attractive and efficient alternative to solutions based on software such as microprocessors or Digital Signal Processors (DSP). Qualified by significant performance advantages such as speed, flexibility and integration density, FPGAs have become media effective in various fields of applications of power electronics, industrial control and monitoring of sensors (Bueno *et al*., 2009; López *et al*., 2008; Monmasson and Cirstea, 2007).

In this study, we will at first explore four models to determine the maximum power across a PVG using Xilinx System Generator (XSG) (XI, 2010). A comparison of performance in terms of area and speed will be deeply discussed.

Then, the implementation of these models for the estimation of the power provided by a solar panel on the FPGA target using XSG was dealt with. After collecting the performance of the four models in the Simulink environment, they are then processed through XSG that provides a graphical language with a higher level of development and designs on a FPGA (Bravo *et al*., 2001). Various challenges must be considered when converting designs control implemented in the Simulink environment for the hardware FPGA implementation, such as the length of the words and their appropriate selection to achieve the compensation coefficients.

Calculation of the Output Power

First Approach (Model 1)

The model giving the general relationship for calculating the maximum output power as a function of the temperature of the PV module and the solar radiation is obtained by using experimental measurements. It can

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be widely applied to PV systems with high accuracy. This model was developed and validated experimentally by (Lin, 2004; Lu, 2004; Lu and Yang, 2004).

The maximum generated power is given by the following relationship:

$$P_m = -(a \cdot G + b) \cdot T_c + c \cdot G + d \tag{1}$$

P_m = Maximum output power (W) *a*, *b*, *c* and *d*: Are positive constants which are experimentally determined

T_c = The temperature of the cell, which varies depending on the ambient temperature according to the following linear relationship:

$$T_c = T_a + \left[(NOCT - 20)/800 \right] \tag{2}$$

T_a = Ambient temperature (K)
NOCT = Nominal operating temperature of the solar cell

It is defined as the temperature of the cell, if the module is subjected under certain conditions such as solar illumination (800 W/m^2), the spectral distribution (AM 1.5), ambient temperature (20°C) and the wind speed (> 1 m sec^{-1}), G being the incident solar radiation given in (W/m^2).

Second Approach (Model 2)

The energy produced by a photovoltaic generator is estimated using data from the global irradiation on an inclined plane, ambient temperature and manufacturer's data for the photovoltaic module design used. The power output of the PV generator can be calculated from the following equation (Belhadj *et al.*, 2009):

$$P = \eta \cdot S \cdot N \cdot G \tag{3}$$

η = Instantaneous efficiency
S = Surface of the photovoltaic module
G = The solar irradiation on an inclined plane in (W/m^2)
N = Number of modules constituting the PV field

The instantaneous efficiency is calculated by the following equation (Markvart, 1994; Diaf *et al.*, 2007):

$$\eta = \eta_r \cdot \left(1 - \gamma \left(T_c - T_0 \right) \right) \tag{4}$$

η_r = The reference efficiency of the module in the standard conditions (T = 25°C, G = 1000 W/m^2 and AM 1.5)
γ = The temperature coefficient (K) determined experimentally, it is defined as the change in the module efficiency for a 1°C of the cell temperature

The typical values of this coefficient are between 0.4 and 0.6%/K [13].

The advantage of this model lies in its simplicity and ease of implementation from the specifications given by the manufacturer under standard conditions (Efficiency η reference module and the surface of the panel).

Third Approach (Model 3)

The following model is developed by Borowy *et al.* (1996). The formulas for calculating the optimum point of the voltage and current in arbitrary conditions are given below. This model makes use of the specifications of the PV modules offered by manufacturers, so it provides a very simple way to estimate the power produced by the PV modules (Borowy *et al.*, 1996) which is expressed by the following relationship:

$$P_m = V_m \cdot I_m \tag{5}$$

V_m is the maximum voltage operating point of the PV module in arbitrary conditions, it is determined by the following equation:

$$V_m = V_{mp0} \cdot \left[1 + 0.0539 \cdot ln \left(\frac{G}{G_0} \right) \right] + \beta_0 \cdot \Delta T \tag{6}$$

V_{mp0} = The maximum voltage of the module under standard conditions (V)
β_0 = The coefficient of the voltage as a function of the temperature (V/K)
G_0 = Solar irradiance reference (1000W/m^2)
I_m = The maximum operating current of the PV module in arbitrary conditions. It is determined by the following Equation 14 and 15:

$$I_m = I_{cc0} \left\{ 1 - C_1 \cdot \left[\exp \left(\frac{V_m}{c_2 \cdot V_{cc0}} \right) - 1 \right] \right\} + \Delta I \tag{7}$$

V_{co} = Open circuit voltage of the module (V)
C_1 and C_2 = Parameters which can be calculated by Equation 9 and 10 respectively in terms of characteristics of PV modules:

$$\Delta I = a_0 \cdot \left[\frac{G}{G_0} \right] \cdot \Delta T + \left(\frac{G}{G_0} - 1 \right) \cdot I_{cc0} \tag{8}$$

α_0 = Coefficient of current according to the temperature (A/K)
I_{cc0} = The short circuit current of the module (A), with T = $T_C - T_0$:

$$C_1 = \left(1 - \frac{I_{mp}}{I_{cc}} \right) \cdot \exp \left(- \frac{V_{mp}}{c_2 \cdot V_{c0}} \right) \tag{9}$$

$$P_{NM} = N \cdot M \cdot P_m \tag{10}$$

For a series and parallel M N modules, the maximum power output is determined by:

$$P_{module} = FF \cdot \left(I_{cc} \cdot \frac{G}{G_0} \right) \cdot \left(V_{co0} \cdot \frac{l_n(k_1 G)}{l_n(k_1 G_0)} \cdot \frac{T_0}{T} \right) \qquad (11)$$

Fourth Approach (Model 4)

Jones and Underwood (2002) developed the following practical model which predetermines the maximum output power of a photovoltaic module. It is given by:

$$P_{module} = FF \cdot \left(I_{cc} \cdot \frac{G}{G_0} \right) \cdot \left(V_{co0} \cdot \frac{In(k_1 G)}{In(k_1 G_0)} \cdot \frac{T_0}{T} \right) \qquad (12)$$

k_1 = Constant $k_1 = K/I_0$ (around $10^6 \text{m}^2/\text{W}$)
I_{cc} = The short circuit current (A)
V_{oc} = The open circuit voltage (V)
FF = Form factor, it is determined by the following equation:

$$FF = \frac{P_m}{V_{c0} \times I_{cc}} \qquad (13)$$

Simulation and Comparison of the Output Power using the Different Models

After the presentation of the simplified mathematical models, their simulation becomes easier. To achieve this, the software Matlab/Simulink was used to predetermine

the different characteristics for a BP Solar 340 module which have the following characteristics:

- Efficiency: $\eta = 11.3$ (%)
- Maximum Peak Power Capacity: $P_{max} = 40$ (W)
- Open circuit voltage: $V_{co0} = 21.8$ (V)
- Short-circuit current: $I_{cc0} = 2.5$ (A)
- Voltage Maximum Peak: $V_{mp} = 17.3$ (V)
- Family Crest Maximum current: $I_{mp} = 2.3$ (A)
- Length of the photovoltaic module: $l_{en} = 0.665$ (m)
- Width of the photovoltaic module: $W_{id} = 0.537$ (m)
- Temperature Coefficient (K) for P_{max}: $\gamma = 0.005$ (%/K)
- Temperature Coefficient (K) for I_{cc}: $\alpha = 0.065$ (%/K)
- Temperature Coefficient (K) for V_{co}: $\beta = -80$ (mV/K)

The models predicting the output power of the PV module were implemented under Matlab Simulink environment. The four models are grouped in the same block Simulink as shown in Fig. 1. It contains two inputs (T_a ambient temperature and solar irradiance G), four outputs (power P1 for Model 1, P2 for Model 2, P3 for Model 3 and P4 for model 4).

Simulation Results and Comparison

Simulation results of the models 1, 2, 3 and 4 are presented in Fig. 2 for four irradiance values (300, 500, 700 and 1000 W/m²).
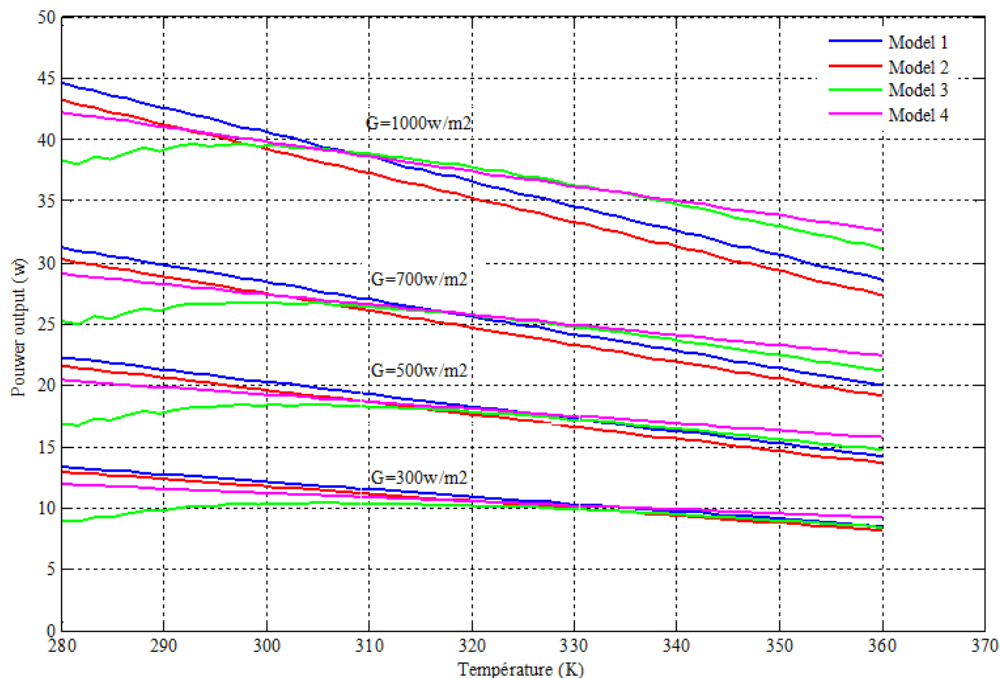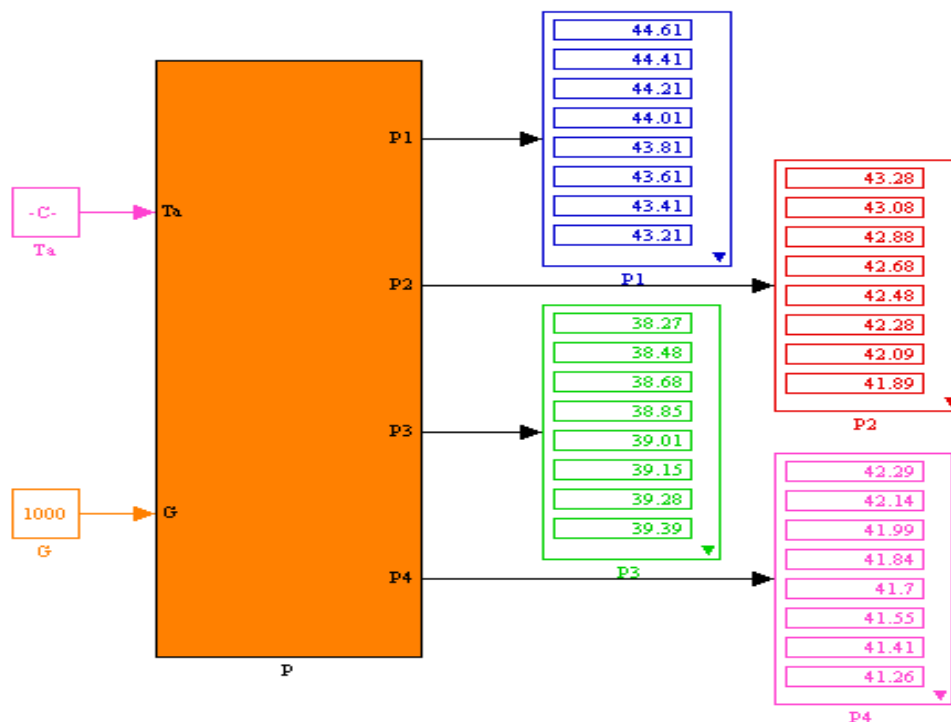

Fig. 1. Simulation block of the different models

Fig. 2. Variation of the maximum power produced by the PV module Vs the temperature for the four models, $G = 300, 500, 700, 1000$ W/m^2

It is seen from the simulation results that there is a proportional change in the output power of the PV module depending on the sunlight. In the same figure, we see that all three models 1, 2 and 4 show a good linear relationship (straight line) between the module temperature and the maximum power produced. Model 4 overestimates the output power for higher temperatures. For model 3, we see that the power delivered by the PV module is maximal for a temperature between 290 and 310°K for all the solar irradiation levels (300, 500, 700 and 1000 W/m^2).

Design Flow Using Xilinx System Generator

As a part of the ISE® Design Suite, Xilinx System Generator offers a series of Simulink blocks for several hardware design that may be implemented on Xilinx FPGAs. It incorporates adders, multipliers, registers, filters, memories and several specific for blocks of particular applications. These blocks can be employed to simulate the hardware system functionality of in the Matlab-Simulink environment (Martín *et al*., 2013). These blocks adapt the Xilinx IP core generators to deliver optimized results for the selected device. The majority of FPGA implementation design steps, including synthesis and place and route, are achieved to generate an FPGA programming file. The main advantage of using Xilinx System Generator for hardware implementation is the option of the hardware

co-simulating using FPGA boards and the Matlab-Simulink interface.

XSG Architecture Adopted for Model 1

XSG Architecture for Model 1 has two inputs (the ambient temperature Ta and the solar radiation intensity *G*), one output (the maximum power output) and a block for calculating the maximum power output. It is composed of two blocks, the block constants and the calculation block of the power produced, the two blocks are shown in Fig. 3 and 4 respectively. In order to reduce the cost of our system, optimization of the used resource must be developed. It will be reached by useful mathematical adaptations and simplifications. The temperature calculating given by Equation 2 is considered as an example. Using NOCT as a constant, Equation 2 becomes:

$$T_c = T_a + 0.375 \tag{14}$$

XSG Architecture Adopted for Model 2

The XSG architecture for model 2 has three inputs (the ambient temperature T_a, the intensity of solar radiation and *G* the number of modules *N*), one output (maximum power output) and a block which computes the produced maximum power. The Block constant and the computed output power are presented in Fig. 5 and 6 respectively.
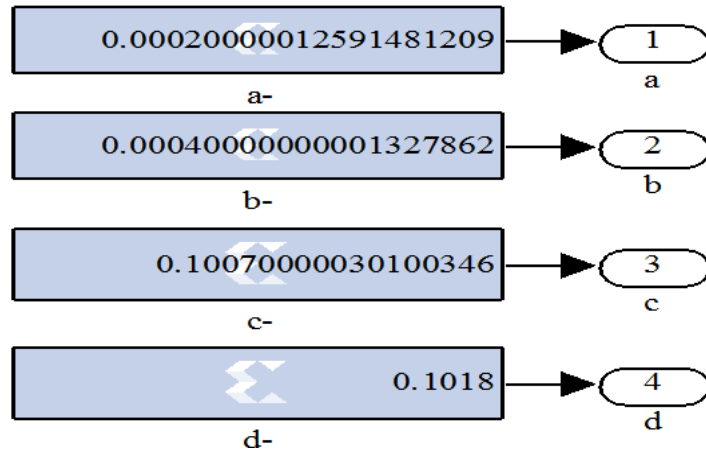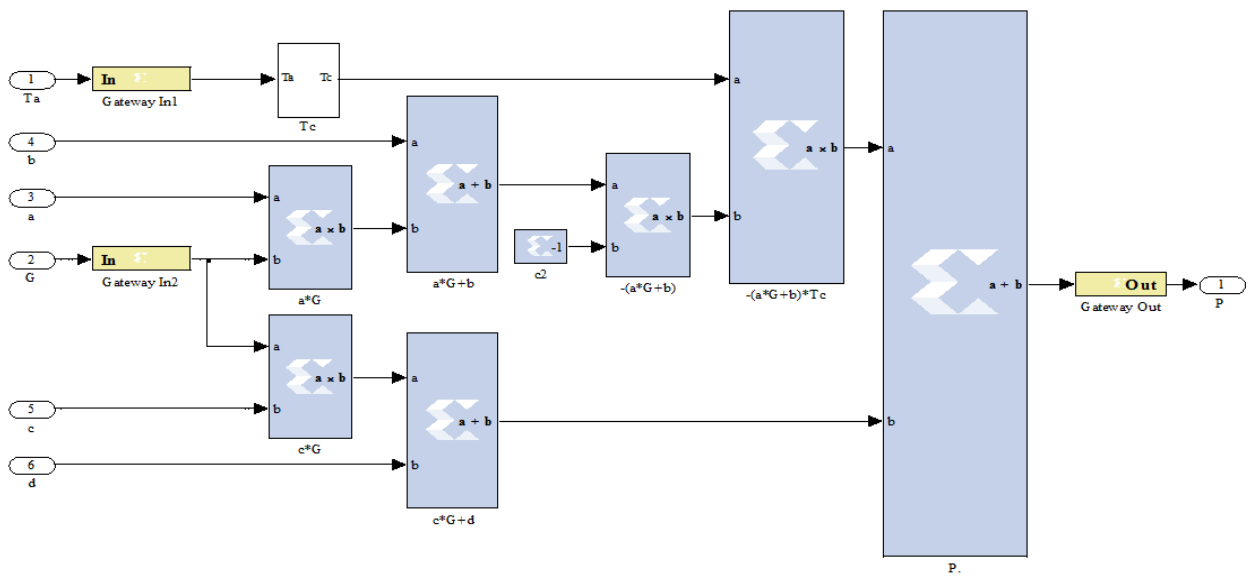
Fig. 3. Block constant model 1

Fig. 4. Implementation of the calculated power output of model 1 through XSG
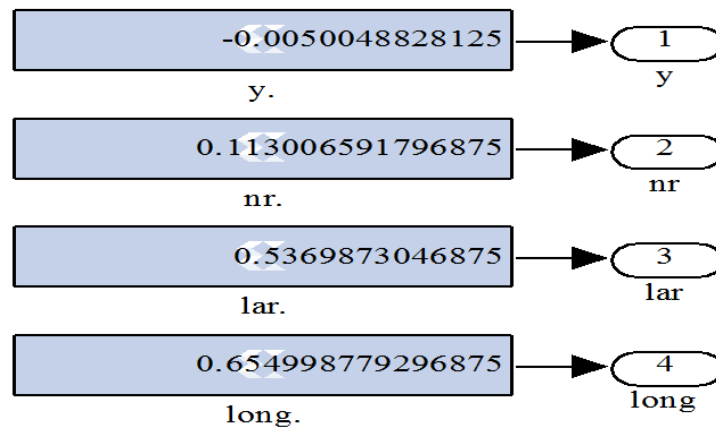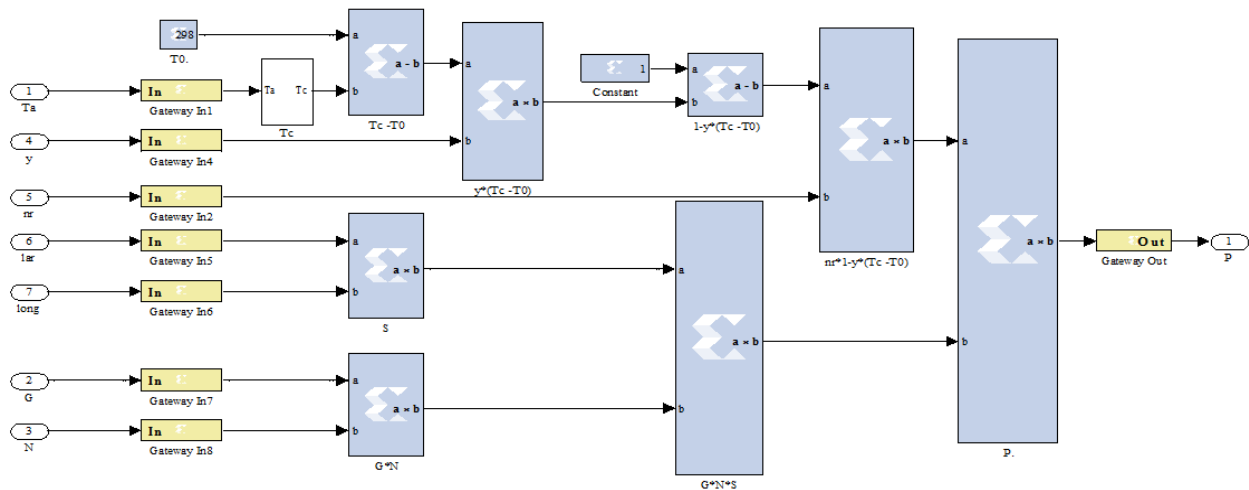

Fig. 5. Block constant model 2

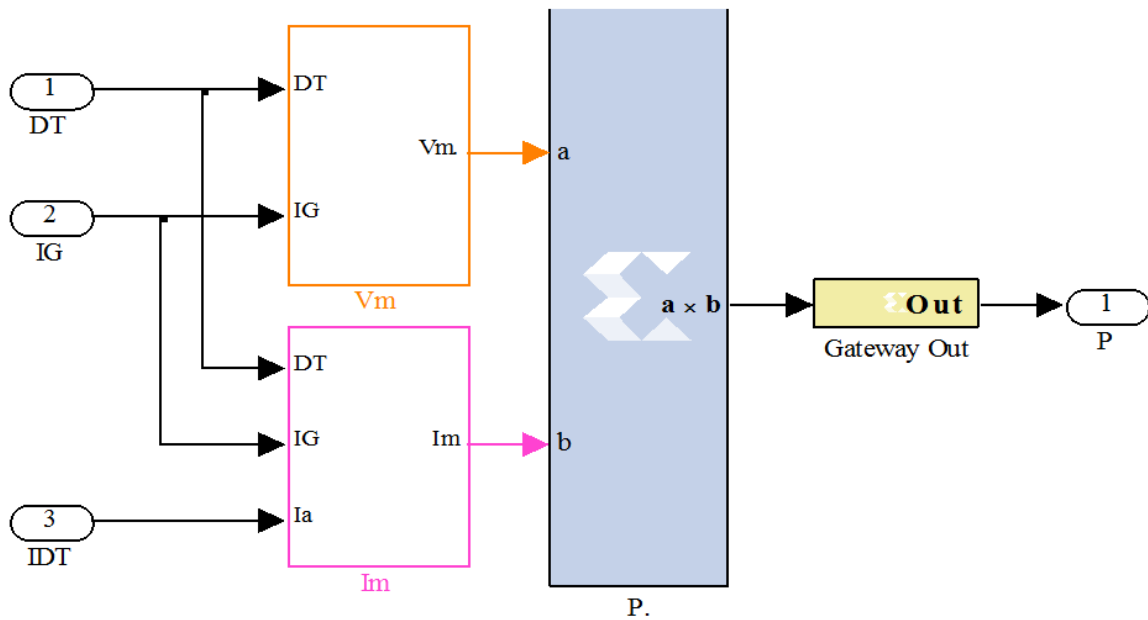Fig. 6. Implementation of the computed output power of model 2 through XSG

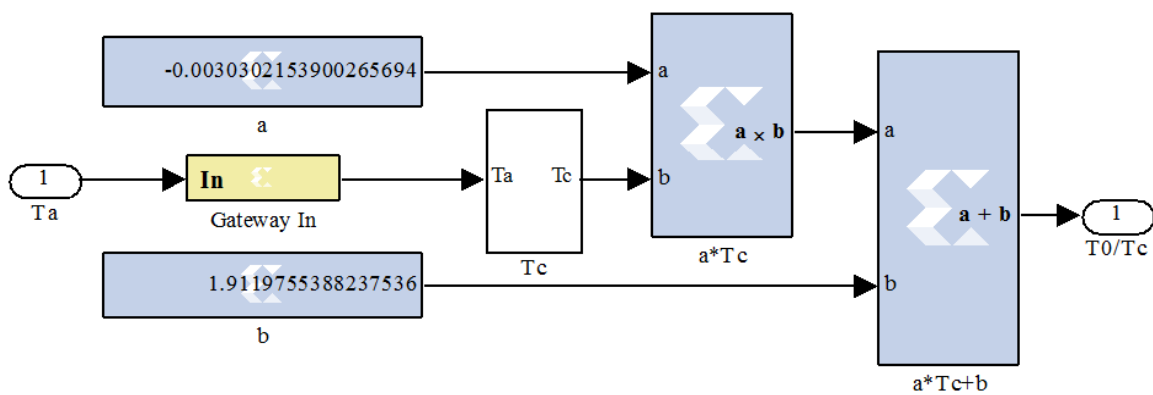Fig. 7. Implementation of the computed output power of model 3 through XSG

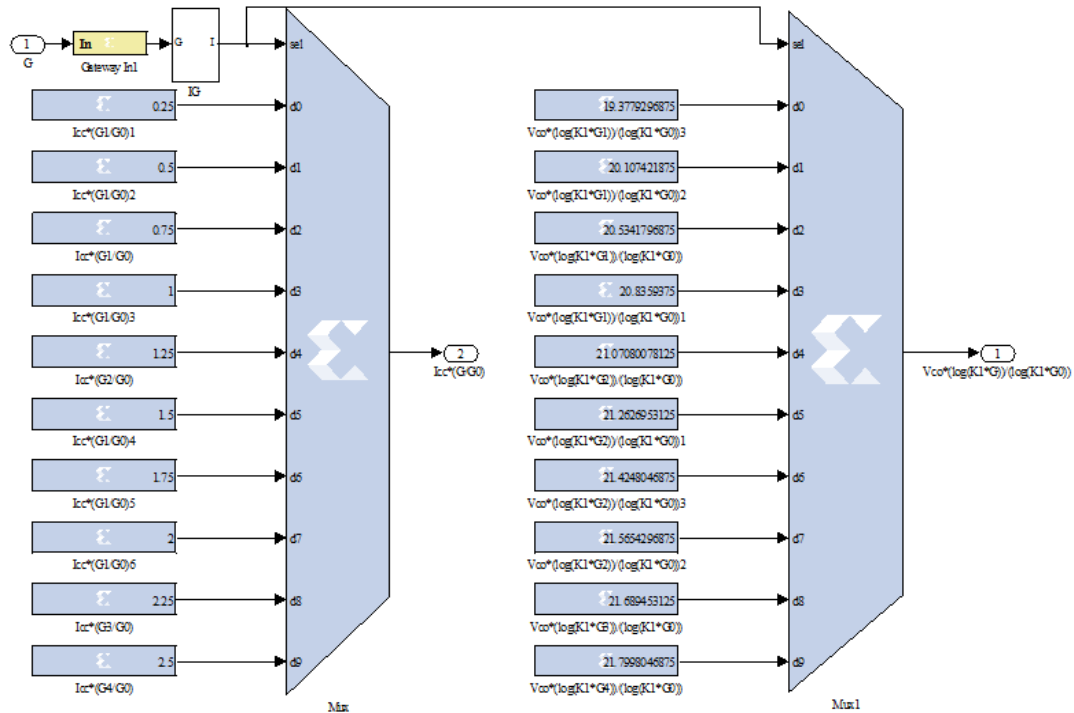Fig. 8. Implementation of ratio T0/Tc of model 4 through XSG

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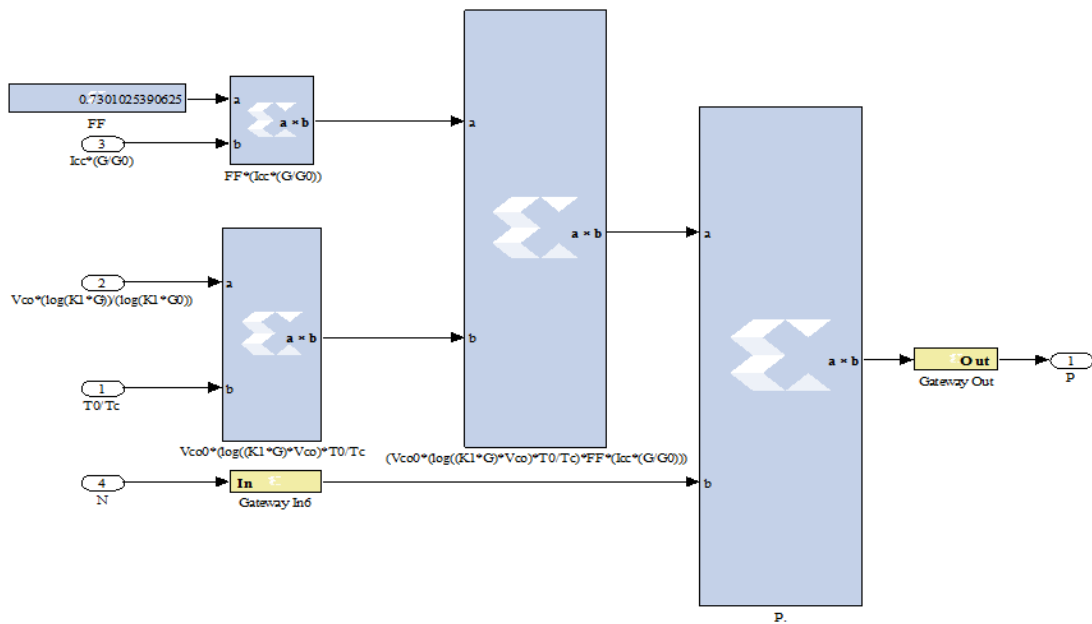
Fig. 9. Voltage implementation of model 4 through XSG

Fig. 10. Implementation of the computed output power of model 4 through XSG

XSG Architecture Adopted for Model 3

The Model 3 XSG architecture is similar to model 2. In this case the computing block of the produced maximum power is composed of three blocks. A block called ΔT for the computed values of ΔT for different values of T_a, a block (IG, IDT) and finally the block P completes the computing of the power. Figure 7 represents the computed output power.

XSG Architecture Adopted for Model 4

The XSG architecture for Model 4 is similar to that of model 2, also in this case the computing block of the produced maximum power is composed of three blocks. Ta,

the intensity of solar radiation G and the number of modules N, one output (the maximum output power) and a block for calculating the maximum power produced. It is composed of two blocks. A block called T_0/T_c which calculates T_0/T_c and reports the different values of temperature T_a and a block V which gives the values to the voltage according to the formula $[V_{oc} \times (\log (K_1 \times G))/\log (K_1 \times G_0))]$ and $[I_{cc} \times (G/G_0)]$ for different values of G. The ratio T_0/T_c and the Voltage implementation through XSG are exposed in Fig. 8 and 9 respectively. The block k finally completes the calculation of the power Fig. 10.

Simulation Results Using Xilinx System Generator

After describing XSG mathematical models of the power produced, several tests were conducted to compare the results obtained in Matlab/Simulink and SXG environments. The curves shown in Fig. 11-14 describe the comparison of the results obtained by XSG and Matlab/Simulink. The generated power of the four models depending on the temperature for different values of insolation G is given.
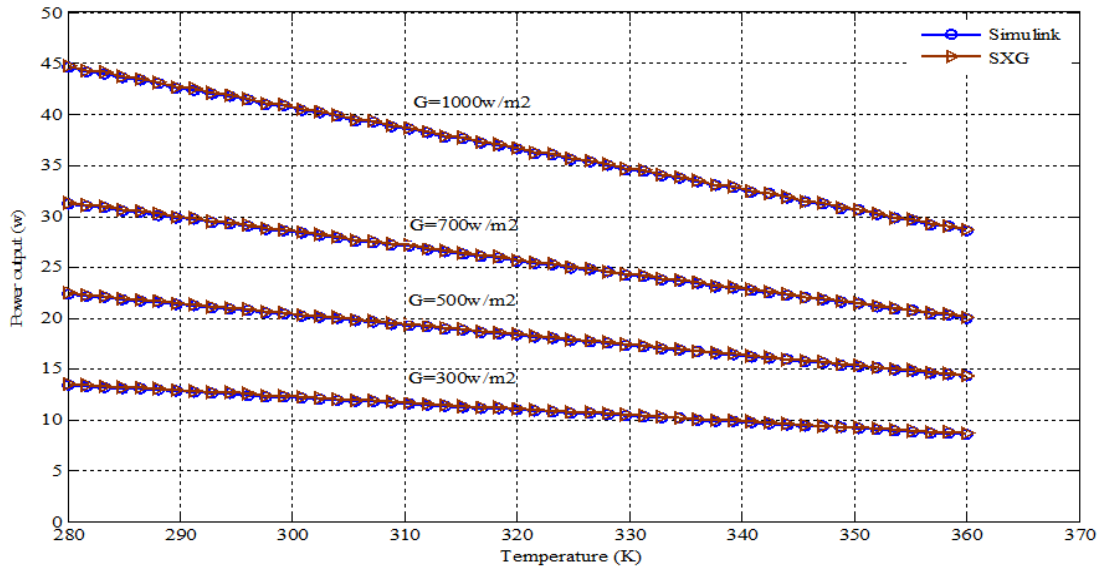

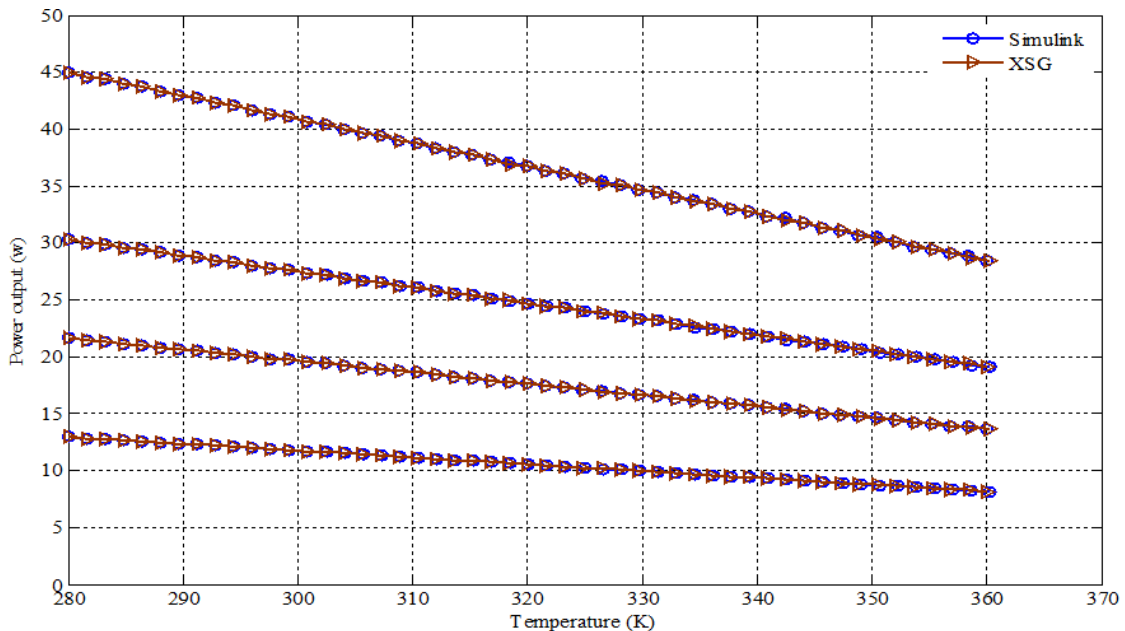Fig. 11. Comparison of the output power with XSG and Matlab/Simulink model 1

Fig. 12. Comparison of the output power with XSG and Matlab/Simulink model 2
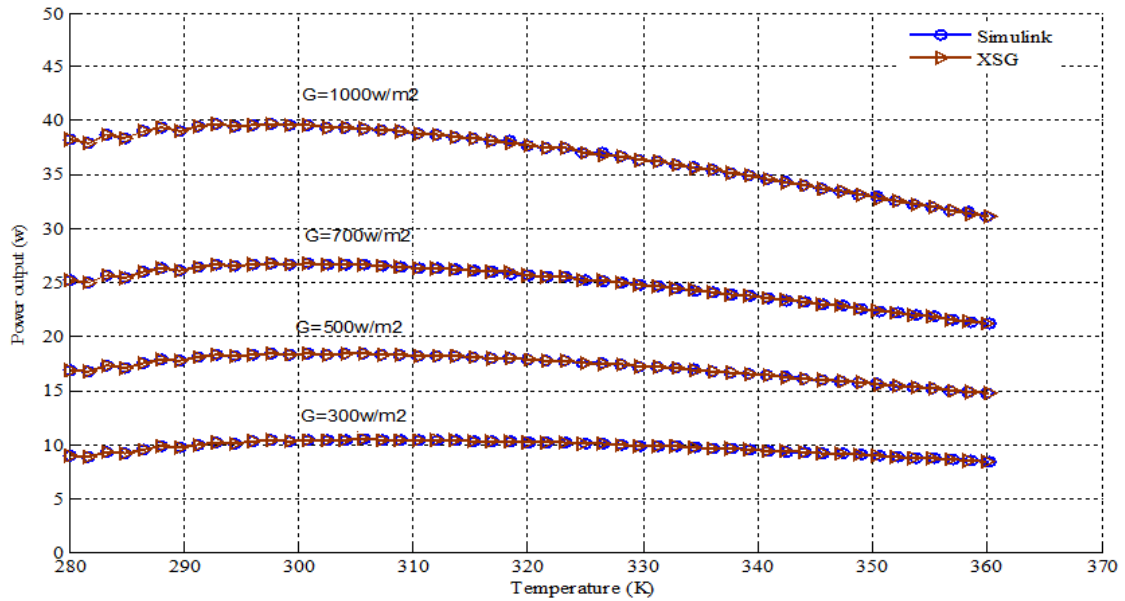
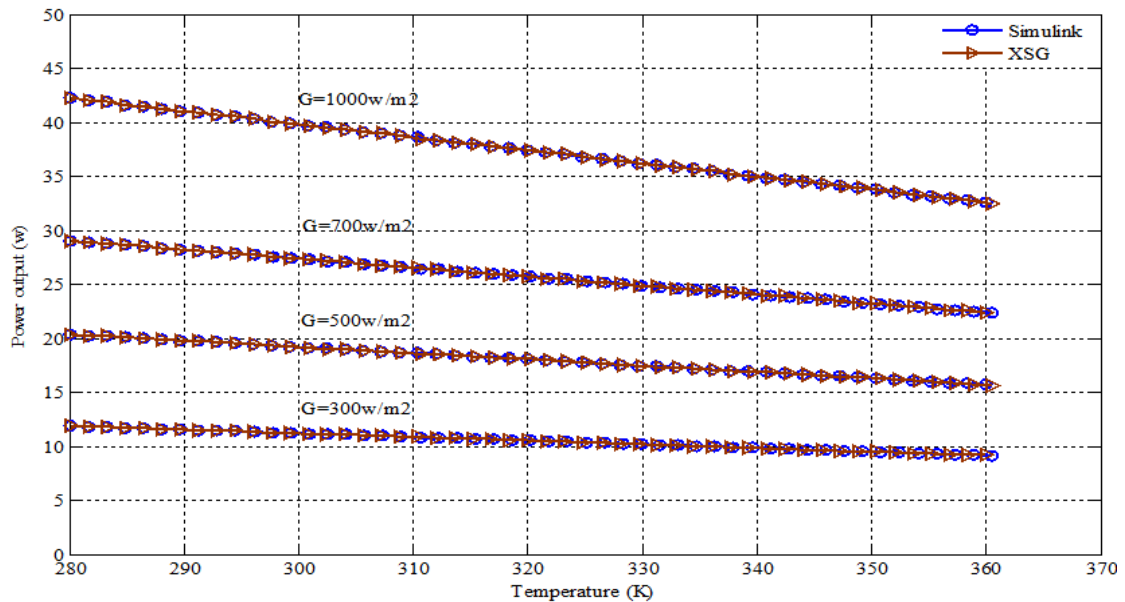Fig. 13. Comparison of the output power with XSG and Matlab/Simulink model 3

Fig. 14. Comparison of the output power with XSG and Matlab/Simulink model 4

Table 1. FPGA Post-Map Resource Estimation Results using Xilinx Virtex-6 VSX315T FPGA device

Models	Device post-map resource estimation results		
	Slices	LUTs	DSP48s
Model 1	1% (87)	1% (339)	1% (16)
Model 2	1% (196)	1% (767)	1% (50)
Model 3	1% (325)	1% (1186)	1% (48)
Model 4	1% (116)	1% (424)	1% (29)

From these results we can see a very good agreement between the results obtained using the two methods. This shows a good performance of the simulation established using XSG which will result on the effectiveness of the architecture implemented. Therefore an implementation on a FPGA becomes easier and very useful.

The results of the Post-Map Resource Estimation of the presented models, using the Xilinx Virtex-6 VSX315T FPGA device, are shown in Table 1. As we can see, the proposed implementations uses less than 1% resource utilisation and furthermore to that, the Model 2 and Model 3 exploit below 0.04% of Virtex-6 DSP slices.

The proposed design demonstrates the performs and confirms the low-cost benefit of exploiting the dynamic

simulation. FPGA-based dynamic and real-time simulation can be used for numerous industrial process for designing photovoltaic panel.

Conclusion

In this study four existing models to predetermine the produced output power by a photovoltaic system are reviewed and their results compared. Moreover, these models are implemented using the Xilinx system generator for an eventual FPGA implementation. This opens ways to real time implementation that provides the flexibility to modify the designed system without changing the hardware. Moreover, concurrent operations, less material, easy modification of the circuit and a relatively low cost rapid prototyping are the other advantages that offers this implementation.

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Author's Contributions

Rezki Tadrist: Organized the study, performed the simulation and the FPGA implementation, in addition to contributed to the results analysis and the writing of the manuscript.

Adnane Hassani: Participated in the results analysis and contributed to the writing of the manuscript.

Mountassar Maamoun: contributed to the FPGA implementation and the writing of the manuscript.

Ali Nesba: Supervised of the study and reviewed the manuscript.

Ethics

The authors have no conflicts of interest in the development and publication of current research.

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