

# Adjustment and Validation of a 25 kW Photovoltaic System Matlab/Simulink Model

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**Abstract**-.Distributed generation is one of the ways forward for the development of renewable energy. Electrical and thermal microgrids are being widely investigated and begin to be implemented. Therefore, if microgrids are developed with careful design and intelligent operation, they could be the solution to the many challenges presented by today's electric network. (Electrical losses in the power grid, power quality and power supply to remote areas, for instance).

Owing to this reason, CENER (National Renewable Energy Centre of Spain) has installed a microgrid (ATENEA) located in the industrial area of Rocafort (Town of Sangüesa, Navarra, Spain). The aim of the facility is the control strategy testing as well as being a test bench for the different generation and storage technologies. Developing a simulation platform where the entire components belonging to the microgrid are modeled is one of the present purposes. Firstly, models have to be elaborated in Matlab-Simulink. Secondly, the measurement executed in the different systems, will help the models in order to be validated. The final goal is that the models could behave in the same way as the systems behave in the reality.

The purpose of this article is developing the model belonging to the photovoltaic system using the software mentioned. The model consists of the following parts: model of photovoltaic panels and maximum power tracking algorithm (MPPT). This article discusses the theoretical basis used for the realization of models, trials for subsequent validation and obtaining system characteristic parameters.

**Keywords** photovoltaic model, Matlab-Simulink, microgrid, simulation platform.

## 1. Introduction

The basic structure of a cell model or solar cell is similar to that of a photodiode, generally of silicon, designed to maximize the absorption of photons from the light and minimize reflection. When it receives an incident light behaves as a current generator whose value increases in inverse function of the amount of light incident upon it. Thus, if the behavior is studied in depth shows that this current generation is expressed as the difference between three currents. The current generated ( $I_L$ ) due to carrier generation in the incident light, the diode current ( $I_d$ ) due to the dark current by carrier recombination which produces the external voltage and the shunt resistance current ( $I_{sh}$ ). In this way, the current generated be expressed as subtraction of them as can be observed in the equivalent circuit model [1, 3, 5]:

$$I = I_L - I_D - I_{sh} \quad (1)$$

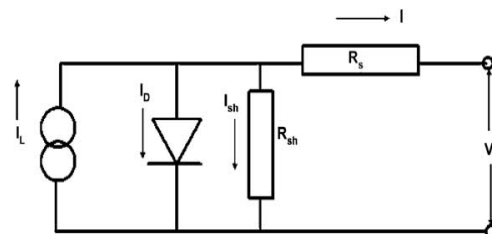


Fig. 1. Equivalent circuit model

The mathematical expression used to represent the equivalent circuit of the photovoltaic device of a diode is the following [1, 2, 3, 5]:

$$I = I_L - I_0 \times \left[ \exp\left(\frac{V + I \times R_s}{a}\right) - 1 \right] - \frac{V + I \times R_s}{R_{sh}} \quad (2)$$

Where:

IL: Generated current or photo-generated current (A).

ID: Diode current (A).

Ish: Shunt Resistance Current or losses outside Current (A)

Io: Diode Reverse saturation current (A)

Rs: Internal series resistance (Ω).

Rsh: Shunt Resistance (Ω).

V: Working Voltage (V).

a: V-I Curve fit parameter (Vt × A) where:

Vt: Thermal voltage that is equal to  $V_t = \frac{q}{n \times k \times T}$

q: electron charge (1.602 × 10<sup>-19</sup> C);

k: is the Boltzman constant, (1.381 × 10<sup>-23</sup> J / K)

n: is the diode ideal factor N=1 (Si);

T: cell temperature (Kelvin)

It can be considered some simplification in the expression presented above. In Ref. [3] the considerations that can be assumed are the following:

$$\exp\left(\frac{V + I \times R_s}{a}\right) \gg 1 \quad (3)$$

$$I_L = I_{sc} \quad (4)$$

Where

Isc= Short-circuit current (A)

Rsh = could be considered infinitive (5)

Owing to simplifications the expression changes into the following one:

$$I_L = I_L - I_o \times \left[ \exp\left(\frac{V + I \times R_s}{a}\right) \right] \quad (6)$$

Moreover, the diode saturation current has the next expression [3]:

$$I_o = I_{sc} \times \left[ \exp\left(\frac{q \times V_{oc}}{n \times K \times T}\right) \right] \quad (7)$$

Where

Voc= Open-circuit voltage (V)

Therefore, if (7) is substituted in (6), the result is:

$$I = I_L - I_{sc} \times \left[ \exp\left(\frac{V_{oc}}{v_t}\right) \right] \times \left[ \exp\left(\frac{V + I \times R_s}{a}\right) \right] \quad (8)$$

$$I_L = I_{sc} - I_{sc} \times \left[ \exp\left(\frac{V - V_{oc} + I_{sc} \times R_s}{a}\right) \right] \quad (9)$$

$$I = I_{sc} \times \left[ 1 - \exp\left(\frac{V - V_{oc} + I_{sc} \times R_s}{a}\right) \right] \quad (10)$$

(10) is the equation that describes the cell behavior [3, 5]. In order to define the photovoltaic model it is necessary to include the number of series modules (Ns) and the number of parallel modules (Np). The figure 2 shows the simplified equivalent circuit [3, 5]:

$$I = I_{sc} \times \left[ 1 - \exp\left(\frac{V - V_{oc} + I_{sc} \times R_s \times N_p}{a \times N_s}\right) \right] \quad (11)$$

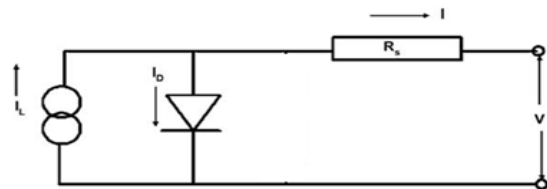


Fig. 2. Simplified Equivalent circuit model

The next step is to define the characteristic parameters of the photovoltaic system under the operating conditions (Working Voltage, Ambient Temperature and Irradiation). [2, 6]

Thus, the short circuit current of a photovoltaic cell is computed based on its linear dependency on the irradiation as the equation number 12 shows [3, 5]

$$I_{sc} = C_1 \times \text{Irradiance} \quad (12)$$

Where C<sub>1</sub> is the linear dependency parameter calculates by [3, 5]

$$C_1 = \frac{I_{sc0}}{\text{Irradiance}_0} \quad (13)$$

Where I<sub>sc0</sub> is the short circuit current at standard condition and the Irradiance<sub>0</sub> is the irradiance at standard condition too.

Secondly, the working temperature of the cells T<sub>cell</sub> depends exclusively on the Irradiance and on the ambient temperature T<sub>amb</sub>, according to the empirical linear relation, as mentioned in [3, 4, 5]:

$$T_{cell} = T_{amb} + C_2 \times \text{Irradiance} \quad (14)$$

It is reasonable to approximate  $C_2 = 0.03 \frac{C_m^2}{W}$  as it is approximated in Ref 3 and 5. Finally, the open circuit voltage of the cell depends on the temperature of the solar cells [3, 5]:

$$V_{oc} = V_{oc0} + C_3 \times (T_{cell} - T_{cell0}) \quad (15)$$

Where  $C_3$  is usually considered [5] to be  $-2.3$  (mV/C).

## 2. Photovoltaic System Definition

### 2.1 Manufacturer sheet data

Suntech Power STP280-24/Vd photovoltaic modules key specifications are listed in Table 1. The most important parameters widely used for describing the cell electrical performance are the open-circuit voltage  $V_{oc}$  and the short-circuit current  $I_{sc}$ .

The system consist of 90 modules of 275 W each one and they are distributed in 6 parallel ( $N_p$ ) chains of 15 ( $N_s$ ) series modules each one. The following table presents the data that must be introduce in the model [8]. The standard test conditions (STC) are: 1000 W/m<sup>2</sup>, 25 °C, AM 1.5

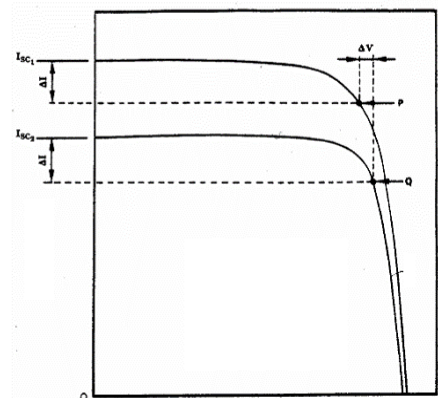
**Table 1.** Suntech Power STP280-24/Vd Characteristics

|  |              |
|--|--------------|
| Typical peak power ( $P_p$ )                     | 25.2 kW      |
| Voltage at peak Power ( $V_{pp}$ )               | 590 V        |
| Current at peak power ( $I_{pp}$ )               | 39 A         |
| Short-circuit current ( $I_{sc}$ )               | 8.26 V       |
| Open-circuit voltage ( $V_{oc}$ )                | 44.7 V       |
| Temperature coefficient of opens-circuit voltage | -0.44 % / °C |
| Temperature coefficient of short-circuit current | -0.33 % / °C |
| Approximate effect of temperature on power       | 0.055 % / °C |
| Nominal Operating cell Temperature (NOCT)        | 45 °C        |

### 2.2 Series Resistance Value

The value of the series resistance,  $R_s$ , is not available in the manufacturer sheet. In [13] a new algorithm for determination of the series resistance is presented. To avoid the development of a new algorithm, this value was obtained by measurements in this paper.

Firstly, curves are plotted with different conditions of irradiance and a similar temperature in two different moments. Secondly, the  $I_{sc}$  values are also calculated.



**Fig. 3.** Internal Series Resistance Calculation

$$R_s = \frac{\Delta V}{I_{sc1} - I_{sc2}} \quad (16)$$

Where

$R_s$ = Series Resistance

$\Delta V$  =Voltage difference between  $V_1$  and  $V_2$

$I_{sc1}$ = Short circuit current (A) number 1

$I_{sc2}$ = Short circuit current (A) number 2

The series resistance was calculated using a software developed by CENER based on IEC\_60891.

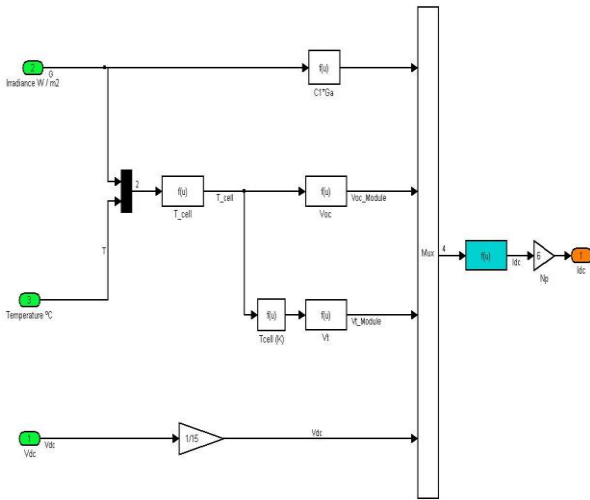
## 3. Model Development and Performance analysis

As a first step a theoretical model is presented. It was built based on the equations described in the introduction section. Taking into account the real measurements it checks that this model does not fit with the real behavior of the installation. So it is necessary debugging the previous model.

### 3.1 Theoretical model and simulation

The theoretical model and the results are shown in the next figures. It can check how the results do not fit with measurements.

Figure 4 shows the simulink theoretical model with its inputs and outputs that represent equation 11.



**Fig. 4.** Theoretical Model.

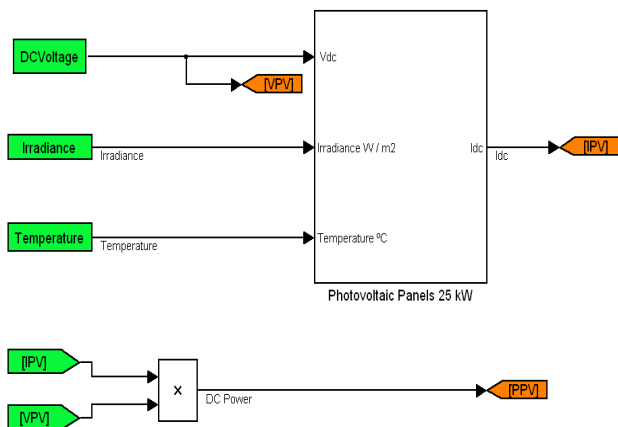
Theoretical model inputs:

- Irradiance (W/m<sup>2</sup>)
- Temperature (°C)
- Voltage (V)

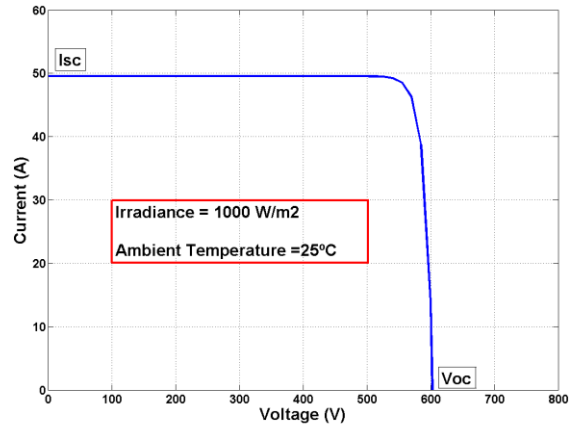
Theoretical model output:

- Output generated current (A)

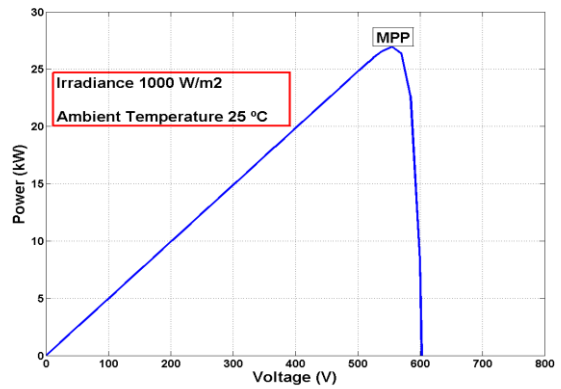
Figure 5 illustrates the whole system as a single Simulink block acting as an interface for its inputs/outputs from/to Matlab's Workspace.



**Fig. 5.** Simulink Theoretical model implementation



**Fig. 6.** I-V Curve Theoretical Model



**Fig. 7.** P-V Curve Theoretical Model

Figures 6 and 7 illustrate the theoretical Current-Voltage curve (I-V curve) and Power-Voltage curve (P-V curve) represented when the irradiance is 1000 (W/m<sup>2</sup>) and the temperature is 25 °C. The simulation of the theoretical model was made with these values (Standard Test Conditions) in order to compare with the manufacturer data.

As it can be observed, the Power-Voltage curve exceeds the maximum power point that the manufacturer considers in the specification sheet. However, the short-circuit current (Isc) and the open-circuit voltage (Voc) match with the manufacturer's sheet values.

In order to validate the models, different tests were conducted in the photovoltaic installation.

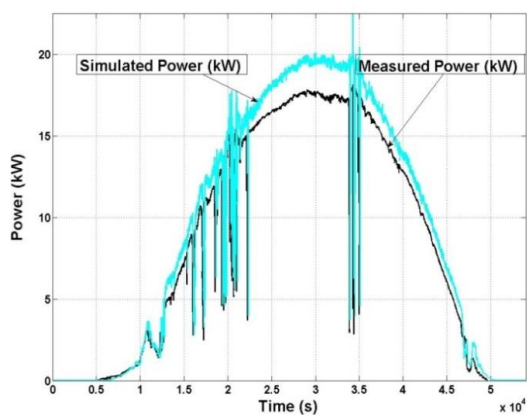
Each tests consisted of one-day data recording. Radiation, temperature, the output current and voltage and the generated power were stored using a recorder for each day.

Thus, both the theoretical model and the following models could be compared with the installation actual data. It is defined as Record 1, Record 2 and Record 3 to dataset randomly selected belonging to a day 1, day 2 and day 3 respectively. Next figures illustrate a sunny day, for

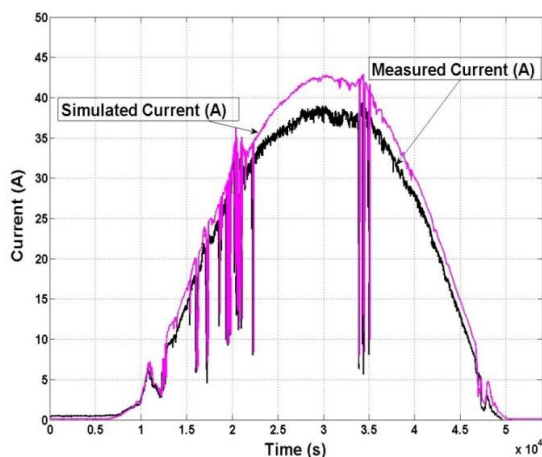
example, Record 1, and Record 3 for a cloudy day. The plotted data represents only daily hours to show radiation hours and not night hours where there is no production.

The comparison between measured power and simulated power is illustrated in Figure 8 and Figure 10 as well as the comparison between measured current and simulated current (Figure 9 and 11).

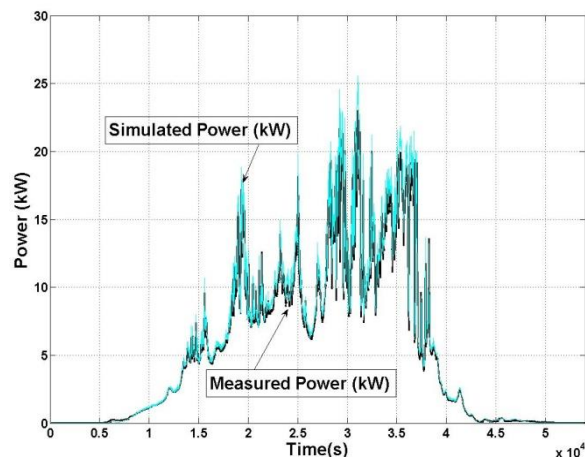
It can be observed a difference between the measure and the simulation. The manufacturer's data were using in this example. The simulation output power current is bigger than the registrations. Through the different tests, it will be noted that the data used in this theoretical model does not correspond exactly with the real behaviour of the installation. This is the reason because the theoretical model does not fit the reality.



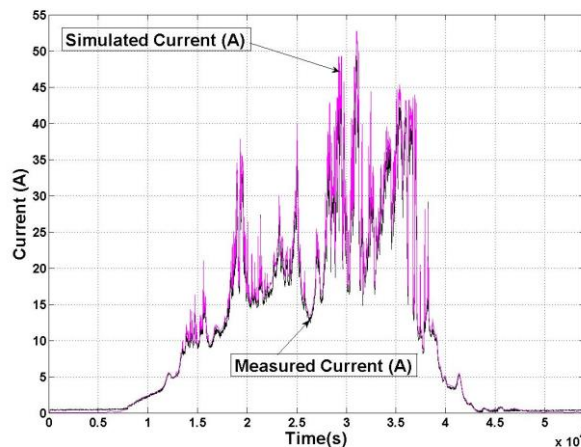
**Fig. 8.** Record 1. Comparison between measured power (kW) and theoretical simulated power (kW)



**Fig. 9.**Record 1. Comparison between measured current (A) and theoretical simulated current (A)



**Fig. 10.** Record 3. Comparison between measured power (kW) and theoretical simulated power (kW).



**Fig. 11.** Record 3. Comparison between measured current (A) and theoretical simulated current (A).

3.2 CENER's model and results

CENER has developed a more accuracy model for its photovoltaic installation.

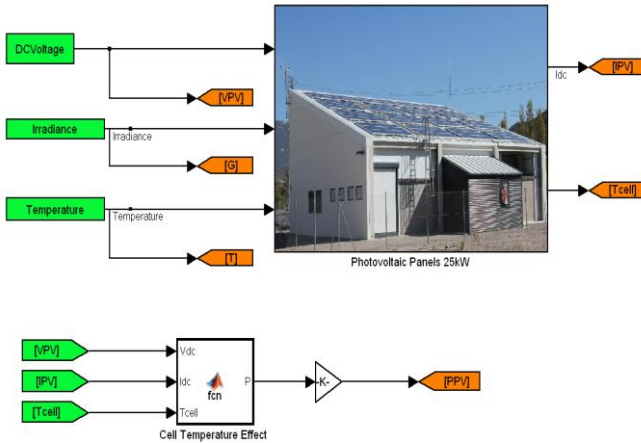


Fig. 12. CENER's model

3.2.1 I-V Curve fit parameter (A)

Figure 13 and 14 illustrates the curve I-V and P-V when the irradiance value is 1000 (W/m<sup>2</sup>) and the ambient temperature is 25 °C. As it is mentioned above, the simulation of the theoretical and CENER's model was made with these values (Standard Test Conditions) in order to compare with the manufacturer data.

It could be observed how the photovoltaic curve in CENER's model does not exceed the maximum power point. Otherwise, the theoretical model is higher than 25 kW. Regarding I-V curve in Figure 14, CENER's model fits the exponential trend better than the theoretical one.

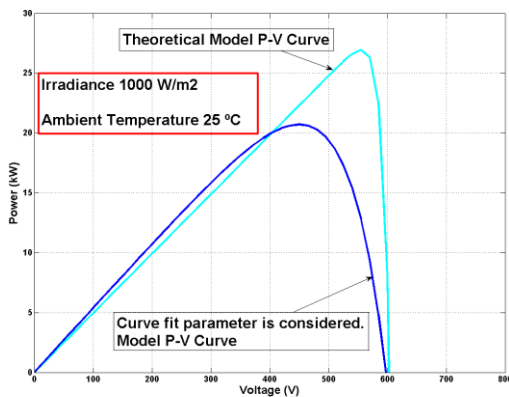


Fig. 13. CENER's versus theoretical P-V curve

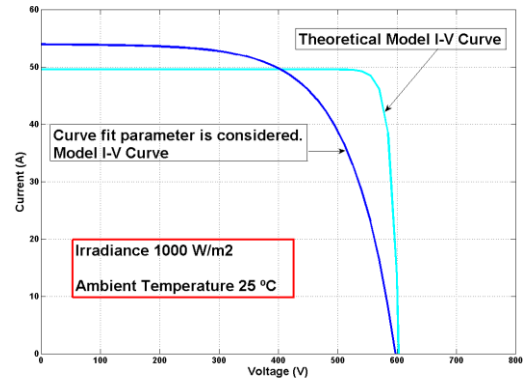


Fig. 14. CENER's versus theoretical I-V curve

3.2.2 Short-circuit current and irradiance relation

The value of C1 is equal to 0.00826 according to (12). Real data shows that if this value is constant the model does not fit the real behaviour. [3]

Instead of the constant C1 is placed a Look up Table \* in the model based on experimental facts (Figure 12).

Thus, the irradiation remains an input which is connected directly with this table. Depending on the irradiation level, a linear relationship (experimentally validated) is obtained. Finally, this relation is multiplied again by radiation and Isc is calculated.

\* The Look up Table is a Simulink Block. The block computes an approximation to a function  $y = f(x)$  given data vectors x and y. To map two inputs to an output, use the Look up Table (2-D) block.

You define the lookup table by specifying:

- Vector of input values as a 1-by-n vector of x data points
- Table data as a 1-by-n vector of y data points

3.2.3 Cell Temperature Effect

In [9] the importance of solar cell/module operating temperature for the electrical performance of silicon based photovoltaic installations is presented.

Both the short circuit current and open circuit voltage are dependent of the PV temperature.

Owing to the temperature increasing, the cell performance worsens. Taking as a reference the values of 25 ° C, the circuit current increases slightly  $15 \times 10^{-6} \frac{A}{cm^2 \times ^\circ C}$  while the open circuit voltage decreases (approximately  $2.3 \frac{mV}{^\circ C}$ ) [4].

This result implies that when the working temperature rises, the PV output power value decreases. Therefore, most cases assume a degradation coefficient ( $\delta$ ) varying between 0.7 and 0.86 % of the total output power when the operating temperatures are above 25 °C. [4]

According to Eq. 14 the cell temperature is:

$$T_{cell} = T_{ambient} + k \times \text{Irradiance} \quad (17)$$

Where  $T_{ambient}$  is given in (°C), Irradiance in (W/m<sup>2</sup>) and  $k$  is a coefficient that depends on the average wind speed, whose values are between 0.2 and  $0.4 \frac{^{\circ}\text{C} \times \text{cm}^2}{\text{mW}}$ .

The output power of the PV panel at a temperature  $T$  could be calculated as follows: [2, 4]

$$P_{out} = P_p - (P_p \times \delta \times \Delta T) \quad (18)$$

Where  $P_{out}$  is the output power (kW) at the working temperature ( $T$ ) measured in °C;  $P_p$  is the panel peak power (kW);  $\delta$  is the degradation coefficient and  $\Delta T$  is the temperature increasing above 25 °C.

Therefore, the cell temperature effect has been considered into the model.

### 3.2.3.1 Cell Temperature Effect Model Results

Considering the cell temperature effect above 25 °C into the model, the output power decreases and becomes more similar to the measured power. If the cell temperature effect above 25 °C is not taken into account, the model simulated power is bigger than the measured one and moves away when the cell temperature is higher as the figure 15 illustrates.

Figure 16 shows the description presented above in the case of Record 1. This model also considers the cell effect temperature in the output current.

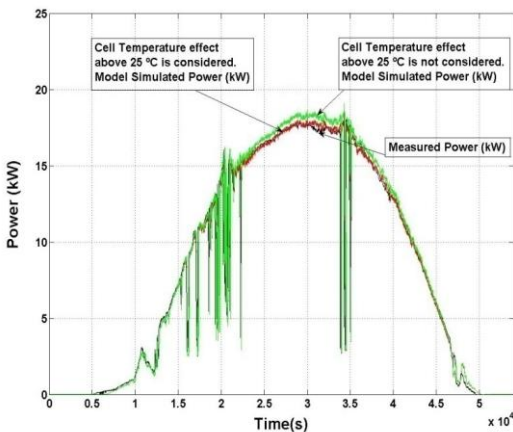


Fig. 15. Record 1. Cell Temperature Effect on Power

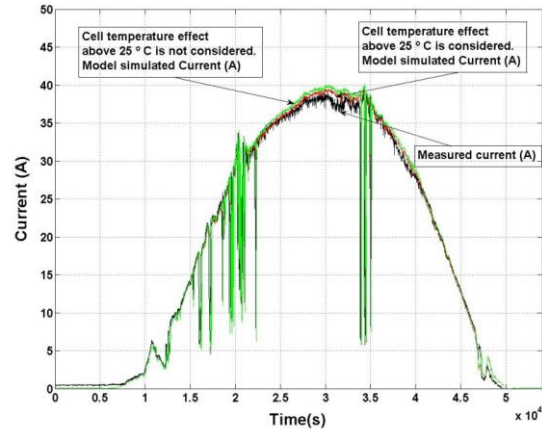


Fig. 16 .Record 1.Cell Temperature Effect on Current

### 3.2.4 Theoretical, CENER's Model and measurement comparison

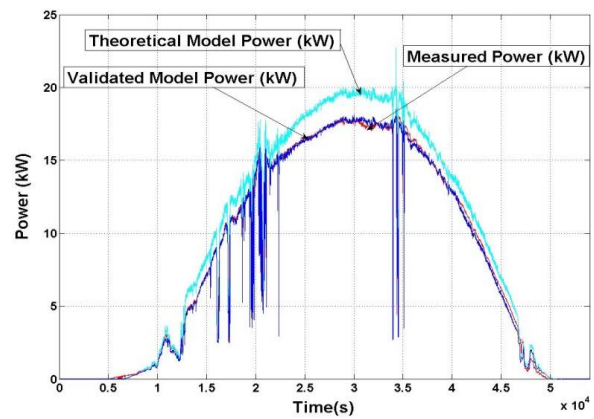


Fig. 17 .Record 1. Measured vs Theoretical vs CENER's model Power (kW)

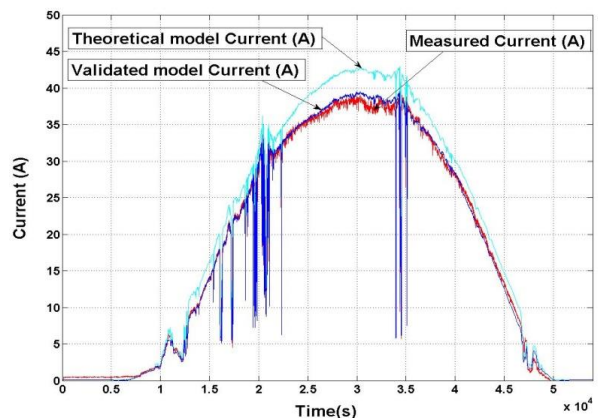
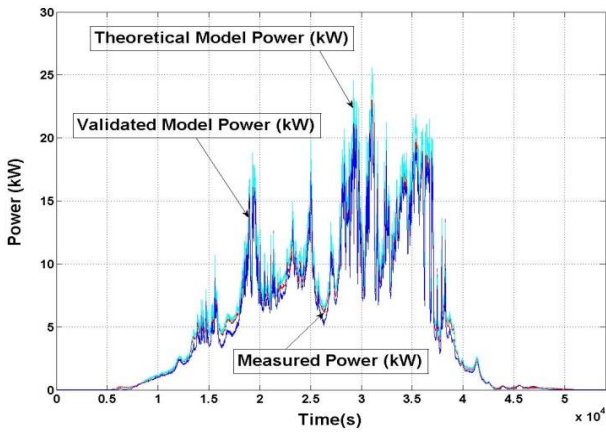
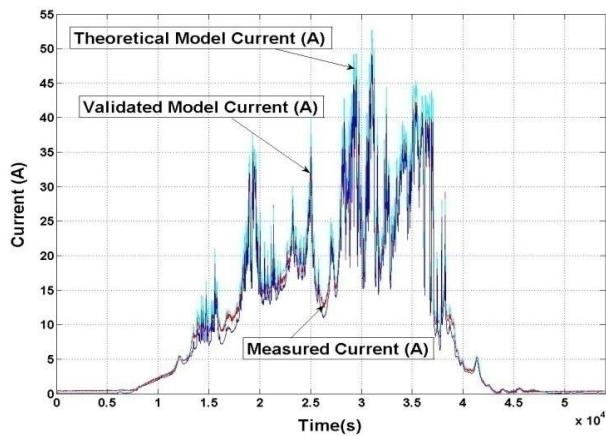


Fig. 18 .Record 1. Measured vs Theoretical vs CENER's model Current (A)



**Fig. 19** .Record 3. Measured vs Theoretical vs CENER’s model Power (kW)



**Fig. 20** .Record 3. Measured vs Theoretical vs CENER’s model Current (A)

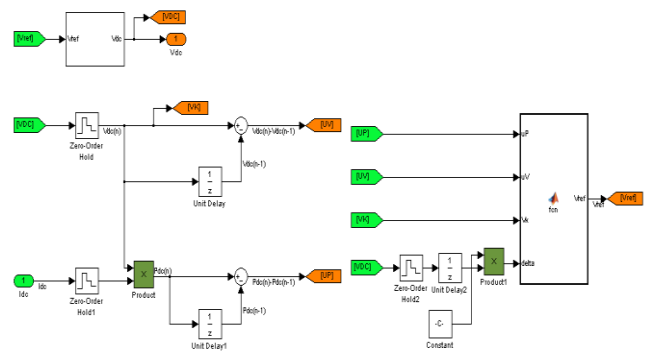
**4. Maximum Power Point Tracking Algorithm (MPPT)**

Due to MPP dependence with the irradiation and temperature, MPPT algorithms are required in order to obtain the maximum power from a solar array.

There are different algorithms to execute the maximum power tracking point. In this model, the Perturb and Observe (P & O) algorithm was selected and implemented [6, 7, 10].

The advantage of this method is its simplicity and low computational needs. The shortcomings are also well-known: Firstly, oscillations around the MPP. Secondly, the algorithm can get lost and track the MPP in the wrong direction during rapidly changing atmospheric conditions.

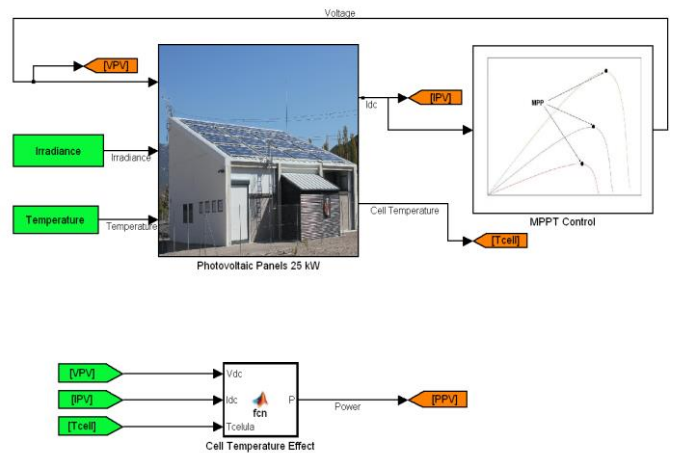
The resulting block diagram MPPT control can be seen in Figure 21 [6]:



**Fig. 21**. Matlab/Simulink Subsystem implementation of MPP algorithm design perturbation and observation (P&O).

*4.1 MPPT implemented model Simulation*

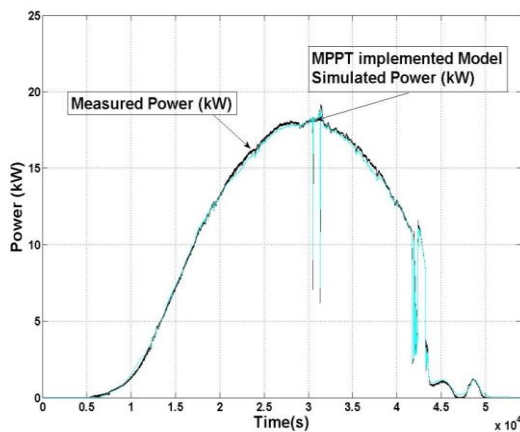
The comparison between the simulation and the measured data is going to be presented when the MPPT algorithm is considered in Matlab-Simulink model.



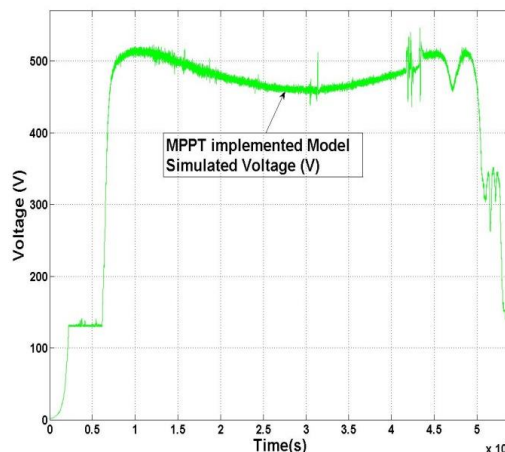
**Fig. 22**.MPPT algorithm Matlab-Simulink CENER’s model



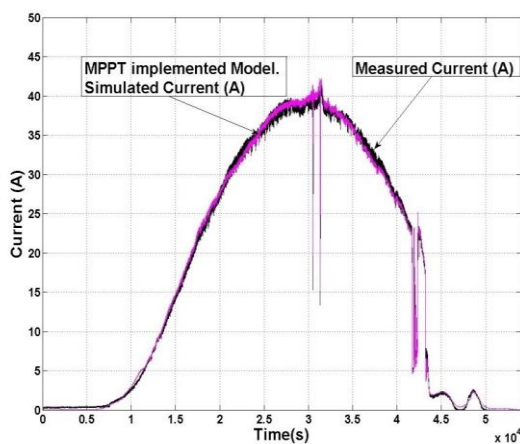
4.2 Results



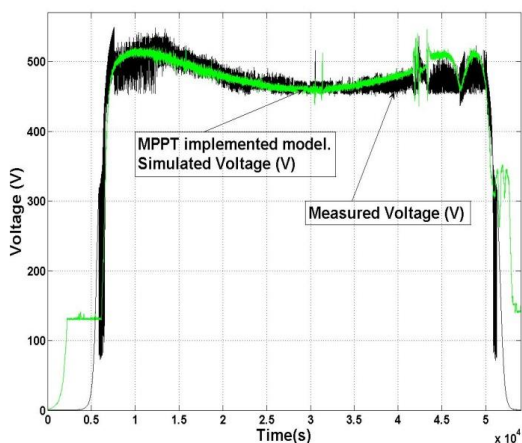
**Fig. 23.**Record 2. Measured vs MPPT implemented model simulated Power (kW)



**Fig. 26.**Record 2. Simulated model voltage (V)



**Fig. 24.**Record 2. Measured vs MPPT implemented model simulated Current (A)



**Fig. 25.** Record 2. Measured vs MPPT implemented model simulated Voltage (V)

As Figure 25 shows, the comparison between the measured voltage and the simulation one across the simulated MPPT algorithm are quite similar. However, there are little differences in the waves forms. This may be due to rapid changes in environmental conditions (temperature and irradiance). This problem appears in the early and the late hours in the day. As a result, the disturbance size is smaller than in the case of measurements. Thus the simulated voltage signal for a whole day, (in this case belonging to the record number 2, as the Figure 2 shows) is a thinner signal in comparison with the measured one.

Despite of the fact, the final result is observed in Figure 23 and 24. The simulation power and the simulated current are practically equal to the measured one. In short, the MPPT implemented model is validated.

5. Conclusions

The model presented allows an accurate prediction of the generation of the PV system for a given radiation and temperature profile for the case analyzed.

The results obtained by CENER's model fits with the real behavior with a maximum error of 2.3%. This fact is due to it is considering many of the parameters that explain the performance of the photovoltaic system. In the checked references these parameters are considering in an individual way.

The first step was to measure those variables that the manufacture does not provide, for example, the series resistance ( $R_s$ ).

As it was explained above the theoretical model does not get I-V and P-V right curves. For this reason, the fit parameter (A) was introduced. As the same as the resistance it was obtained in an experimental way.

Secondly, it has taken into account the effect of the cell temperature, the relationship between radiation and short-circuit current and the maximum power point tracking (MPPT), at the same time, because they have a direct influence in the model.

All of these variables were measured in the microgrid facilities. The temperature of the cell had a negative effect if it increases substantially above of 25 °C. Regarding relation between radiation and short-circuit current it concluded that is not a constant and it is depending on the incident irradiation level on the panels.

Finally, the model includes an MPPT algorithm (based on the perturbation and observation algorithm) to define the voltage reference.

Summarizing, in this paper we present a methodology to develop a PV model that take into account different parameters and it permits obtain a more accurate model.

## 6. References:

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