

Analysis of mismatch and shading effects in a photovoltaic array using different technologies.

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Abstract. In this paper, we analyze the performance of a photovoltaic array implemented in the Universidad Politécnica de Valencia which consists of modules of different technologies and power, connected in series, in order to quantify the energy losses due to mismatch and the effect of the shadows. To do this, the performance of the modules was measured in operation under ambient conditions with field measurement equipment (AMPROBE Solar Analyzer, Solar – 4000), which allows the extrapolation of measures to standard conditions STC. For the data validation, measures under controlled conditions were taken to some modules in the flash test laboratory of the Institute of Energy Technology ITE of Valencia in Spain. Subsequently the array curves measured were validated with a photovoltaic array model developed in MATLAB-Simulink for the same conditions and technologies. The results of this particular array are lost up to 20% of the energy supplied due to the modules mismatch. The study shows the curves and the energy loss due to shadows modules. This result opens scenarios for conceivable modifications to the PV field configurations today, chosen during the design stage and unchangeable during the operating stage; and gives greater importance to the energy loss by mismatch in the PV array.

1. Introduction

In recent years, with oil prices reaching record highs, nuclear plunged into crisis and international commitments to reduce emissions associated with conventional energy were made. Renewable energy has been gaining ground, and is seen to occupy a prominent place in the global generation, especially in the field of electric power. In this context, photovoltaic generation systems have the opportunity to be as much as suitable for their important advantage of being able to produce electrical energy very close to the electric loads. In this way the transmission losses are avoided and it is also possible to satisfy the daily load diagrams' peaks since they supply the maximum power quite in correspondence to the maximum request. The photovoltaic plants, moreover, do not emit pollutant emissions, do not vibrate and, thanks to their modularity, can comply with the morphology of the installation sites and so they present a lower environmental impact with respect to other renewable energy systems [1].

Optimizing the power output of a PV array is a very important task, especially in the novel Smart Grid context, that will rely on real time control and redirection of locally available power to loads [2].

One of the factors that affect the performance of a photovoltaic array is the mismatch. This term indicates the electrical maladjustment among the photovoltaic PV modules of the entire array. The causes of this maladjustment are attributable to the not homogeneous external characteristics of the

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modules, due to the dissymmetric manufacturing, the degradation of the module blooming layer, the manufacturing defects, the possible breaking of the cells, the dirt on the anterior part of the modules, the degradation of the materials used for the cells encapsulating, the unequal radiation of the modules, and the combination of different powers and technologies of modules in the array.

All these factors lead to a reduction of the array performances implying that the generated power of an array is less than the sum of the generated power for the single modules [2].

Several authors have analyzed the effects of using different power photovoltaic modules or mismatches, but using the same photovoltaic technology [3-5]. In this paper, we analyze the performance of a photovoltaic array, which consists of modules of different technologies and power, connected in series, in order to quantify the energy losses due to mismatch and the effect of the shadows.

2. Photovoltaic System

The photovoltaic system of Distributed Resources Laboratory (labDER) of the Universidad Politécnic de Valencia is an array of 11 photovoltaic modules of different technologies, powers and manufacturers as presented in Figure 1:

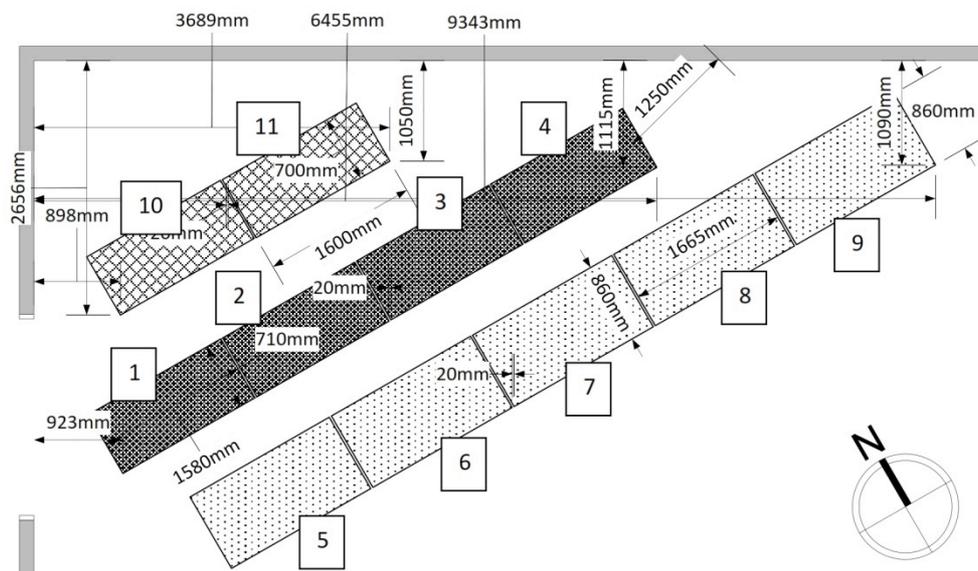


Figure 1. Photovoltaic field arrangement in the LabDER roof

- Modules 1 - 4
Monocrystalline technology, manufacturer WANXIANG – China (180 W)
- Modules 5 - 9
Monocrystalline technology, manufacturer REC – Norway (230 W)
- Modules 10, 11
Polycrystalline technology, manufacturer USL – India (150 W)

The labDER photovoltaic system was studied to analyze the mismatch losses caused by the different panels' power and technologies.

2.1. Measurement System

Using an AMPROBE SOLAR – 4000 (Solar Analyzer) allowed to measure the characteristics of the static system installed in the LabDER roof. The power curves and power losses of each group of panels with the same type were obtained in outdoor conditions. In addition, to obtain the real curves of

panels, the equipment generates the curves corresponding to standard conditions of measurement STC (irradiance of 1000 W/m^2 and temperature of 25°C) like a standard conditions in order to compare that results with other ones.

Every group of panels was measured independently and then the whole photovoltaic system was measured, getting I-V and power curves. In figure 4 it may be observed that I-V curve leans more to the left, indicating a lower efficiency of the USL panels compared to the other references.

The characteristics of the whole system are similar to the power curves of photovoltaic array with mismatch losses [4]. The effect of the low efficiency and power of the USL panels is a little bit remarkable in the power curve of the entire system. The goal of this work is to quantify these losses.

On the other hand, the STC power curve calculated for the solar analyzer is showed up for every array, resulting 658 W for the WANXIANG modules (Figure 2), 1082 W for the REC modules (Figure 3) and 253 W for the USL modules (Figure 4). A total power of 1993 W was expected, however the measured power results in 1585 W (Figure 5), obtaining a significant drop of 20% in the power of the global array.

These losses almost doubled those of the corresponding old and dirty panels [3], so we see that the use of panels of different technologies and manufacturers has much bigger influence.

- Measurement 1, Modules 1, 2, 3 y 4.

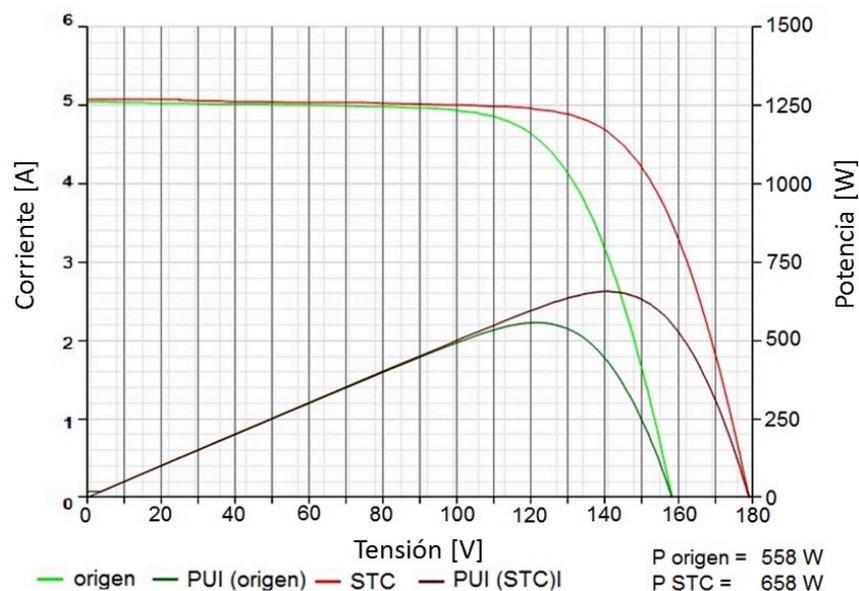


Figure 2. Curve I-V and P-V of WANXIANG panels

- Measurement 2, Modules 5, 6, 7, 8 y 9.

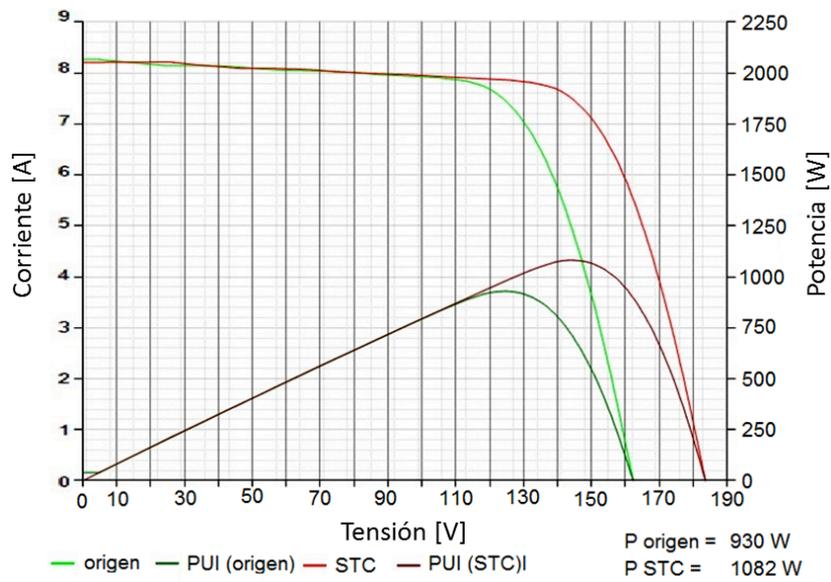


Figure 3. Curve I-V and P-V of REC panels

- Measurement 3, Modules 10 y 11.

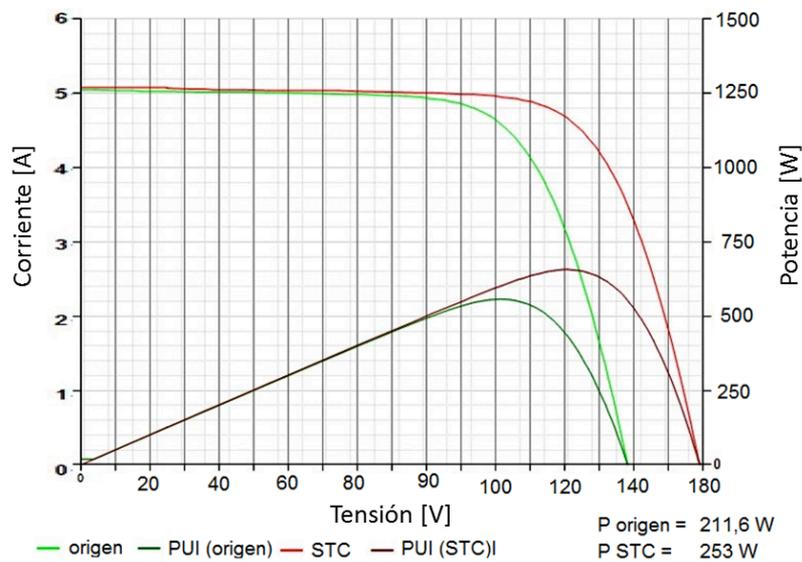


Figure 4. Curve I-V and P-V of USL panels

- Measurement 4, Total photovoltaic array

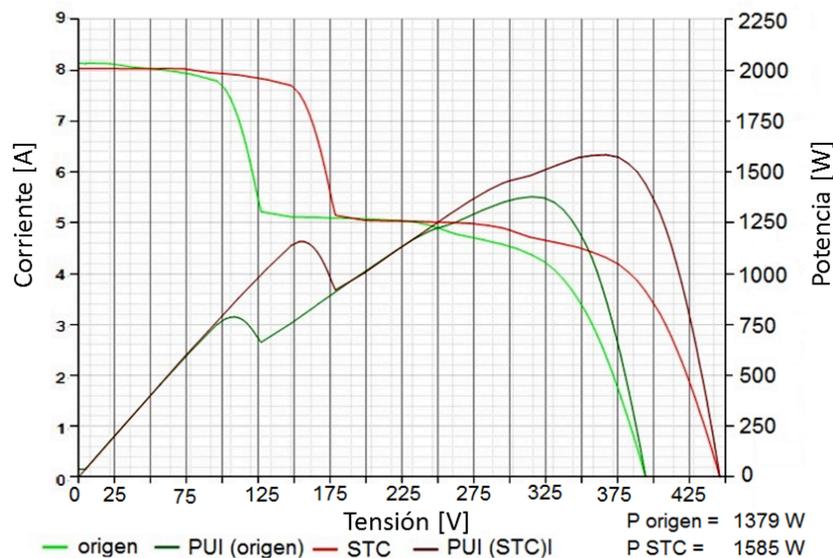


Figure 5. Curve I-V and P-V of total array

3. Verification of data reliability

As a part of the methodology of this study, an important item is the verification of the data provided by the field equipment AMPROBE SOLAR – 4000, because of the controversy that exists on the veracity of the data of in situ measurements. The results provided by the equipment AMPROBE are compared to those measured in the laboratory test of the photovoltaic panels, by means the “flash test”, with this test, output values of V-I are measured in controlled irradiation and temperature conditions, obtaining the characteristic photovoltaic module curve. This test was made in the Institute of Electrical Technology ITE, this research center has the equipment, to obtain the electrical characteristics of the photovoltaic panels with a latest technology solar simulator, class A according to the standards IEC 60904-9, IEC 60904-1, and IEC 60891.

A test panel (Solar Plus – 40 W Module) was measured with both techniques (flash test simulator and field equipment), in order to evaluate if the results are correct. The measurement in the flash test (Figure 6) was 43,7W VS 41,81W obtained with the field equipment (Figure 7). The comparison gives an error of 4%, being according with similar studies published in the literature, which reports errors in the range of 3% - 4% when a field equipment is compared to the flash report [5].

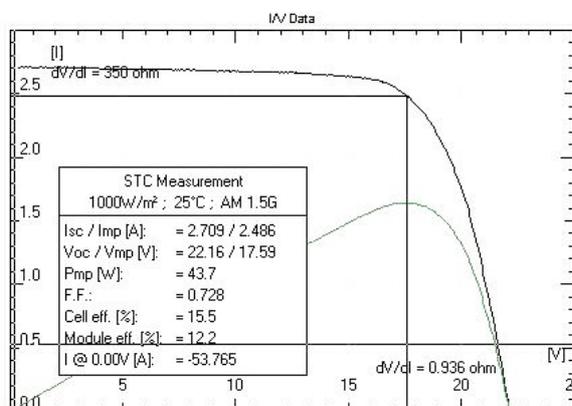


Figure 6. Curve I-V and P-V of flash report.

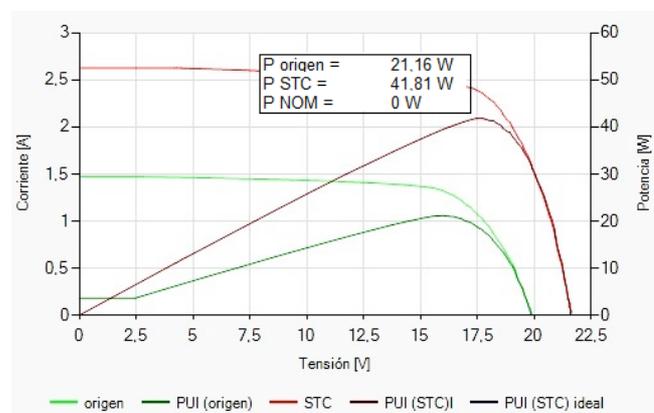


Figure 7. Curve I-V and P-V of Amprobe Solar.

Besides the used method to prove the veracity of field equipment with one of laboratory, there are other comparison methods as presented in [6].

4. Behavioral Validation

An important factor for ensuring the possibility of a power loss caused by the mismatch of about 20%, is to prove that this loss would not exist without mismatch. To validate the array's behavior without mismatch, the LabDER photovoltaic generator was modelled, with the different types of modules connected in series.

The MATLAB-Simulink model is formed by 3 arrays (2*USL, 4*Wanxiang, 5*REC) connected in series, a load resistance and an electrical measurement equipment.

Every array models different type of modules and consists of a function block (Fcn), a controlled voltage source and conditional blocks (If, If Action Subsystem) as presented in Figure 8

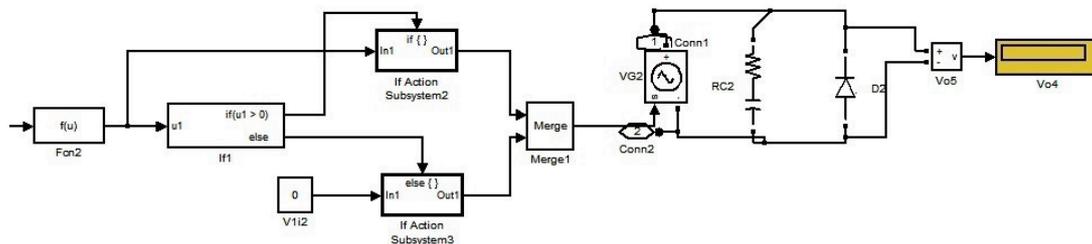


Figure 8. Simulink block model of a photovoltaic array of panels from the same manufacturer.

Instead of the typical $I - V$ relation of the photovoltaic module, the function (Fcn) calculates the inverse function and gives a voltage dependent of the current panel and its characteristics, according to the next expression:

$$V_1(I_0) := N_{MS1} N_S \cdot V_t \cdot \ln\left(1 - \frac{I_0}{I_{SC1}}\right) + N_{MS1} \cdot V_{OC1} - I_{SC1} \cdot R_s \quad (1)$$

The expression of the Fn1 Simulink block is:

$$u(7) * u(4) * u(5) * \log(1 - (u(3)/u(2))) + u(7) * u(1) - u(2) * u(6) \quad (2)$$

where:

$u(1)$ = In1= Voc: Module Open Circuit

$u(2)$ = In2= Isc: Module Short Circuit Current

$u(3)$ = In3= Module output current

$u(4)$ = $N_S = 72$: Number of cells of the module

$u(5)$ = $V_t = 26e-3$: Thermal Voltage

$u(6)$ = R_s : Module Series Resistance

$u(7)$ = In4: Number of same type modules connected in series

Block Fcn output is a numerical value representing the voltage produced by the array formed by modules in series of the same type. In order to convert it into an electrical quantity, is applied to the control input of the controlled voltage generator.

The 3 blocks are connected in series and the output is applied to a resistive load. The current is the same in all the blocks and the output voltage is the sum of the voltages generated by each block. The characteristics curves I-V and P-V of the photovoltaic system are obtained varying the input current and measuring the load voltage and power.

Conditional blocks (If, If Action Subsystem) in order to avoid simulation error, producing no voltage if the current through a block is bigger than the short-circuit current. This fact happens by mismatch effect in systems with different types of modules, as in the present study; when a type of module produces a current bigger than the short-circuit current of another type, the bypass diodes connected in parallel with the less current module would drive, and the voltage through them would be almost zero. Figures 9 and 10 shows a power loss of about 20%.

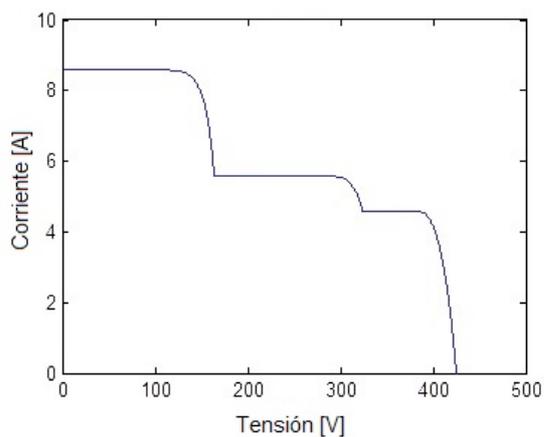


Figure 9. Curve I-V of Model Simulink.

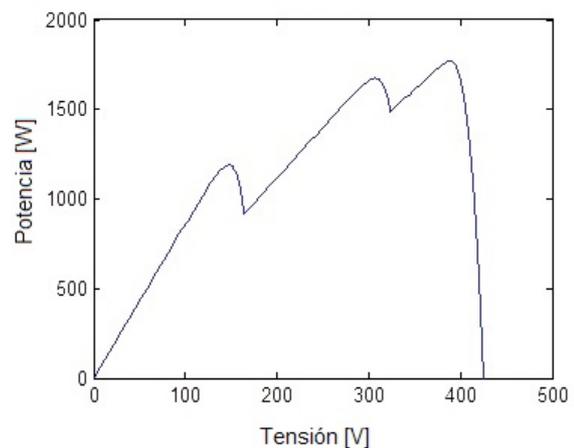


Figure 10. Curve P-V of Model Simulink.

This result agrees with the experimental measures, because without mismatch effect the system would produce a total power of about 1900 W.

The model could be modified to look for the optimum configuration, but these studies have already been reported in [1].

5. Shading Effects

The study of shading effects is important to foresee the working point of a system in case of shading. When a module or a part of it is shaded some of its cells become reverse biased, acting as loads instead of generators. If the system is not appropriately protected, hot-spot problem can arise and, in severe cases, the system can be irreversibly damaged [7]. In this section the losses caused by shadings in a photovoltaic module are analyzed, using a monocrystalline panel Solar Plus of 40 W. The process consists in shading a cell of the panel and measuring the characteristic curves before and after the shading effect. In addition pictures with a thermographic camera were taken, measuring temperatures in different points of the panel and relating the panel power loss and the temperature increase. The shading effect was made evident in the thermographic camera capture using a black paper with an emissivity = 1.

After shading a cell during several seconds the shade was removed, the results are shown in Figure 11, where is remarkable the heating of the shaded cell about to 55°C, also and a smaller heating of the next 3 chains of cells, caused by the change of the operating point of the shaded cell, that changes the behavior as a generator, to load.

Figure 12 shows the characteristic curves of the panel before and after the shading. Power loss is significantly high, the module reduces the power from 40,33 W to 3,935 W, almost a 90 % of power loss caused by the shading effects. These curves agree with the behavior of a shaded panel [8] but with a much bigger loss, even after several minutes a bigger heating in the nearby cells of the shaded cell is observed, that can causes the module damage. These results suggest future studies and advances in shading effects, because power losses are in the range of (40% - 90%), causing big cost in the photovoltaic field, considering is still an expensive technology.

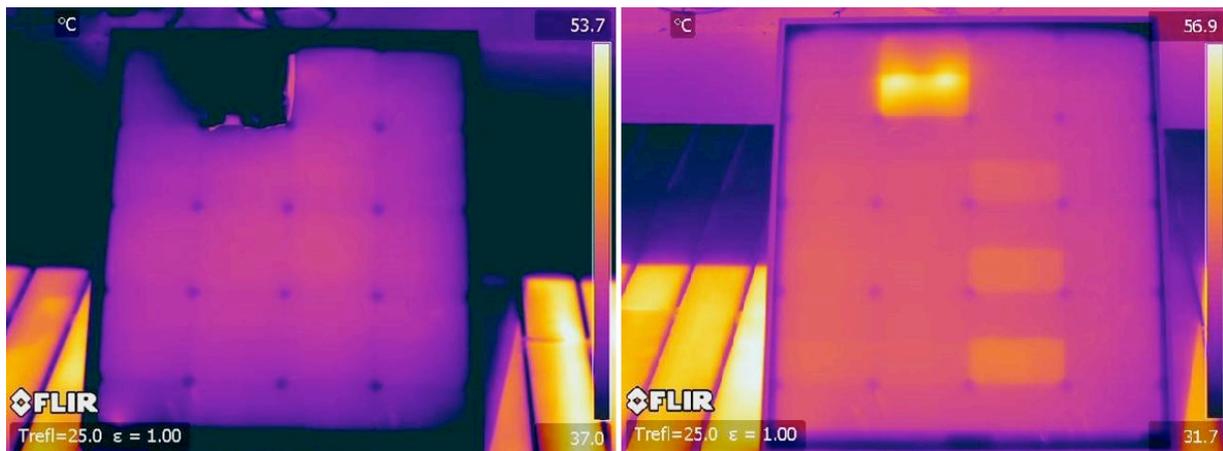


Figure 11. Effect of a shaded cell in a photovoltaic panel heating different cells.

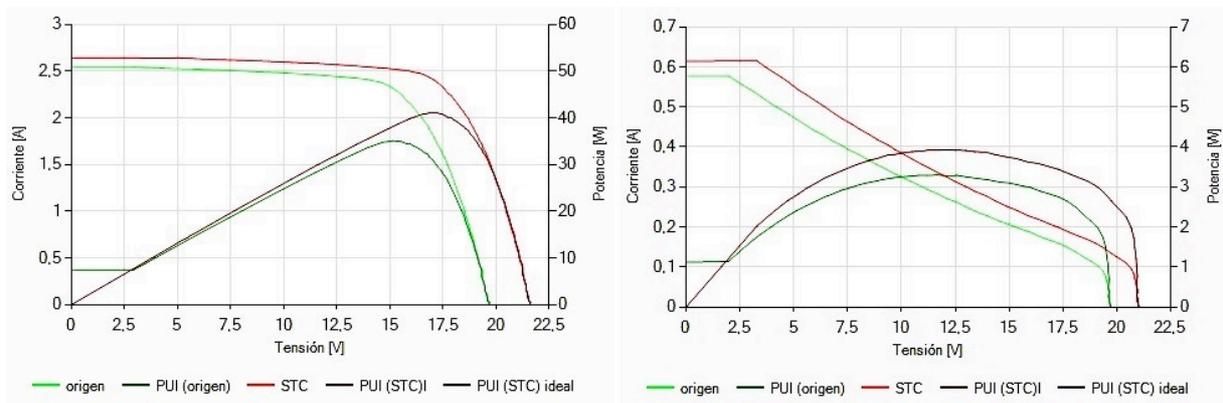


Figure 12. Power loss after shading a cell.

6. Conclusions

- The study shows an absolute error of 4% between the measuring with a field equipment vs laboratory measurements, an acceptable error in the engineering estimation area.
- Reference researches about mismatch losses in series connected arrays report bigger losses caused by ageing and dirt, however the present study prove that mismatch losses increase in array with different technologies.
- The MATLAB-Simulink model presented is compared to real operating curves of a photovoltaic array and successfully validate.
- This study proves that a photovoltaic panel can loss up to 90% of power by shading a unique cell. This shading causes heating in the shaded cell and in other cells because it becomes a load in the module.

7. References

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