

# CONCENTRATING PHOTOVOLTAIC MULTI-JUNCTION (CPVM) MODULE ELECTRICAL LAYOUT OPTIMISATION BY A NEW THEORETICAL AND EXPERIMENTAL “MISMATCH” ANALYSIS INCLUDING SERIES RESISTANCE EFFECTS.

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## ABSTRACT

A new theoretical and experimental ‘current mismatch’ analysis of CPVM modules, including series resistance effects, is proposed. It allows predicting the I-V curve and the maximum power point of the module, considering its series resistance value and a given mismatch condition, for all the possible circuitual module topologies having a fixed number of Multi-junction (MJ) solar cells. The optimum module circuitual layout can be determined considering the mismatched cells number, the mismatch distribution in the module, the current mismatch percent value related to each cell, the module series resistance value and the resistance value of cables connecting the module to the inverter.

The new theoretical approach is validated on a 144 MJ solar cells Point-Focus module, of which, in order to experimentally simulate the mismatched conditions, some cells are on purpose blinded and the module experimental I-V curve detected. The experimental curves are successfully compared with the theoretical ones predicted by the modeling application.

On the base of the theoretical mismatch analysis for modules consisting of only-one string with series-connected receivers, an original algorithm is developed to identify the current receiver’s mismatch starting from any experimentally detected I-V curve, also for curves presenting many current steps.

## INTRODUCTION

Modeling outdoor photovoltaic behavior of CPV Multi-junction module with reference to the electro-optical mismatches and series resistance effects is necessary for its electrical lay-out optimization. So far, the scientific literature is lacking of theoretical and experimental analysis on this subject. On the other hand, the presence of soiling effects, optic defective parts, cell non uniform behaviour owing to solar tracker misalignment, introduce current mismatch among the solar cells penalizing the module photovoltaic performances [see for example 1,2 on soiling effect]. Therefore, it is of importance to study the different possible module electrical layout configurations that can make the CPV module more “robust” to mismatch condition.

The presented analysis will be shown useful for:

- Simulating mismatch operating conditions for all the possible circuitual module topology, e.g. considering

a different number of cell per receiver, number of series-connected receivers and number of strings;

- Predicting the I-V curve and maximum power point of the module considering a given mismatch condition, its series resistance value and the resistance value of cables connecting the module to the inverter;
- Determining the best module circuit layout in relation to the number of mismatched cells, the mismatch distribution in the module and the mismatch percent value presented by each cell;
- Identifying the module receivers mismatch values starting from the experimental I-V curve of the module.

The outdoor modeling of a CPVM module uses three main terms that are defined as follows:

- *receiver* (consisting of a number M of parallel-connected MJ solar cells),
- *string* (consisting of a number N of series-connected MJ solar receivers)
- *module* (consisting of a number L of parallel-connected strings).

The outdoor modeling of a CPVM module needs as input parameters the 3 numbers L, M and N.

## OUTDOOR CPV MJ MODULE MODELLING

The mismatch analysis of a CPVM module is developed starting from some assumptions on the CPVM module equivalent circuit. In each sub-cell, making part of a multi-junction solar cell, the generation–recombination current in the depletion layer is neglected, since it is assumed that the high concentration of solar light produces enough carriers to saturate the energy level of the defects. The cell shunt resistance effects are neglected as well, since they are usually technology-dependent and, in case of concentrating modules, they can be hidden by more relevant mismatch problems. It can be shown that, under the above assumptions, a CPV multi-junction solar cell is formally equivalent to a single-junction solar cell which is characterized by the three equivalent parameters:  $I_{0eq\_c}$ , the equivalent inverse saturation current,  $n_{eq\_c}$ , the equivalent ideality factor and  $R_{seq\_c}$ , the cell series resistance [3]. In outdoor condition, if no spectral mismatch between the three sub-cells is considered, a

single photovoltaic current  $I_{ph\_c}$  value is associated to each MJ cell. The modeling of a **CPV receiver** is then considered. The CPV receiver can be shown equivalent to a single-junction solar cell characterized by 4 equivalent parameters: the equivalent inverse saturation current  $I_{0eq\_r} = M \cdot I_{0eq\_c}$ , the equivalent ideality factor

$n_{eq\_r} = n_{eq\_c}$ , the equivalent receiver series resistance

$R_{seq\_r} = \frac{R_{seq\_c}}{M}$ , the equivalent receiver photovoltaic

current  $I_{ph\_r} = \sum_{i=1}^M I_{ph\_ci}$ , where  $I_{ph\_ci}$  are the values

of the photovoltaic currents produced in each MJ cell of the receiver. Each receiver has a by-pass diode that allows, in case of current mismatch among receivers, the protection of the receiver from inverse polarization and, in some cases, to recover partially the string electrical power. The modeling of a string, is successively considered. It is clear, from the previous assumptions, that the electrical photovoltaic behavior of the CPV string can be simulated in a conventional way, with a simplified equivalent electrical circuit just determined by a number of *equivalent single junction series connected solar cells*, each one having a by pass diode. The connecting cables are taken in count introducing their resistance  $R_c$ .

If the receivers are sorted in function of their photovoltaic current value, from the highest one to the lowest one, the following equation describes the I-V curve of the string:

$$V_{st}(I) = \sum_{i=1}^N \left( \sum_{z=1}^i \frac{KT}{q} n_{eq\_r} \ln \left( 1 + \frac{I_{ph\_rz} - I}{I_{0eq\_r}} \right) \right) - (NR_{seq\_r} + R_c)I + \quad (1)$$

Voltage contribution of the  $i$ - active receivers

$$- \sum_{z=i+1}^N \frac{KT}{q} n_{by} \ln \left( 1 + \frac{I - I_{ph\_rz}}{I_{0by}} \right) \cdot w_i(I)$$

Voltage drop on the by pass diodes of the  $N-i$  passive receivers

where:

$$- w_i = \begin{cases} 1 & \text{if } I_{ph\_r(i+1)} < I \leq I_{ph\_r(i)} \\ 0 & \text{for all others } I \text{ values} \end{cases}$$

-  $n_{by}$  = ideality factor of the bypass diode;

-  $I_{0by}$  = reverse saturation current of the by-pass diode;

-  $I$  = current load

Starting from the maximum value of the photovoltaic current, all the receivers that can produce a  $I_{ph\_r} > I$  give their voltage contributions and such voltage values are summed, while the other receivers are inverse-polarized

and the voltage drop associated to their by pass diode must be subtracted. Finally, the I-V curve of the CPV module, defined as  $L$  parallel-connected strings, could be traced by adding the string currents at each voltage value. The typical mismatch quantities are defined by the following terms:

- the **j-Cell mismatch**:

$$M_{cj} = \frac{I_{ph\_c\_max} - I_{ph\_cj}}{I_{ph\_c\_max}} \quad \text{with } j=1,2,\dots,(N \times M) \times L. \quad (2)$$

$I_{ph\_c\_max}$  = maximum cell photovoltaic current;

$I_{ph\_cj}$  = photocurrent of the  $j$ -cell.

- the **i-Receiver Mismatch** (within each string):

$$M_{ri} = \frac{I_{ph\_r\_max} - I_{ph\_ri}}{I_{ph\_r\_max}} \quad \text{with } i=1,2,\dots,N. \quad (3)$$

$I_{ph\_r\_max}$  = maximum receiver photocurrent;

$I_{ph\_ri}$  = photocurrent of the  $i$ -receiver.

If the cells of the receiver present the same mismatch  $M_{ci} = M_c$  then:

$$M_{ri} = M_c \cdot \frac{j}{M} \quad (4)$$

where  $j$  is the number of mismatched cells within the receiver.

- **Module power loss**:  $LP\% = 100 \frac{P_{max} - P_{meas}}{P_{max}}$  (5)

where  $P_{max}$  is the maximum power with no mismatch

and  $P_{meas}$  is the measured module power

- **Mismatch receiver order  $k$** , with  $k=1\dots N$ . The receivers mismatches are sorted, with the  $k$  index decreasing, in function of their current mismatch value: the receiver with  $k=1$ , **Mr(1)**, has the highest current mismatch value, while the receiver with  $k=N-1$  has the lower current mismatch value. The receiver with  $k=N$  is considered without mismatch.

The described modeling brings out the following general theoretical results:

- 1) The I-V curve of a string presents a maximum number of "current steps" equal to the number of the mismatched receivers (owing to the presence of the by pass diode in each receiver). The I-V curve can present a number of mismatched receivers higher than the number of current steps.
- 2) While the P-V curve of a string with mismatched receivers but without by-pass diode presents a single *canonical power peak* (P0), **power extra-peaks** are found in the P-V curve of a module having

mismatched receivers and by-pass diodes. The maximum number of “power extra-peaks” is equal to the number of the mismatched receivers, however, the P-V curve can present a number of power extra peaks lower than the number of mismatched receivers. The power extra peak of  $k$ -order is indicated by  $P_k$ .

- 3) The value of voltages corresponding to the power extra-peaks decreases with the mismatch order.
- 4) The value of power peak of  $k$ -order,  $P_k$ , is only a decreasing function of the receivers mismatch values with higher mismatched order:  $P_k = f(m(k+1), \dots, m(n-1))$
- 5) A **critical receiver mismatch** value  $Mrcr$  can be defined. When  $Mr(1) > Mrcr$  it exists a power extra-peak whose value is higher than the canonical power peak:  $P_k > P_0$ . In general the critical receiver mismatch is function of the module (N, M) electrical layout configuration and of the number of mismatched receivers. If  $Mr(1) > Mrcr$  the by pass diode allows to partially recover the string electrical power, while if  $Mr(1) < Mrcr$ , the by pass diode is not effective in recovering the electrical power. Therefore, the (N, M) electrical layout configurations which correspond to a lower value of  $Mrcr$  are more effective in recovering the module electrical power.
- 6) When there is only one receiver that presents a current mismatch, a **critical receiver fundamental mismatch**  $MrcF$  exists which is only function of the (M, N) electrical layout configuration, and it is the lowest possible critical mismatch for a given layout configuration. The critical receiver fundamental mismatch value decreases with the increasing number of series connected receivers (N).
- 7) If there are several receivers presenting a current mismatch, the following relationship holds:  $M_{rcF} < M_{rcr} < M_{rcF} + (t-1)/N$ , where  $t$  is the number of mismatched receivers. In case the  $t$  receivers present the same mismatch value, the following relationship holds:  $M_{rcr} = M_{rcF} + (t-1)/N$

The figure 1 shows an example of a I-V curve of a simulated CPVM module, presenting extra power peaks, due to 2 mismatched receivers.

In order to investigate the mismatch effects, two possible mismatched cells distributions are considered:

- a) *uniform* (mismatched cells are distributed among different receivers minimizing the number of mismatched cell in each receiver), this case can simulate, for example, a soling effect due to dust or pollution effect distributed almost uniformly on the module surface;
- b) *not-uniform* (mismatched cells are ordered maximizing the number of mismatched cells in a single receivers, that is, the mismatched cells are grouped to fill one by one the receivers), this case can simulate, for example, a soling effect due to the accumulation of dust concentrated on some part of the module surface.

In fig.2 the critical mismatch in function of the number of mismatched receivers, for different module layout configurations is depicted. Module layout configurations

considering a higher number of series connected cells present a lower value of the critical mismatch, therefore these configuration are more effective in recovering the module electrical power.

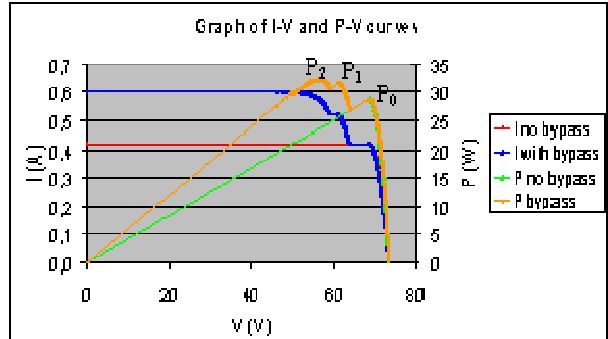


Figure 1. I-V and P-V curves in the case of 2 mismatched receivers in a module consisting of one string, with 18 receivers, each one having 8 parallel connected MJ cells.

A mismatch analysis has been applied to a (16 x 9) module layout configuration considering a not-uniform mismatch distribution. In this example, an increasing mismatch value is applied to each receiver, by increasing the number of mismatched cells, till to consider all the cells of the receiver in mismatched condition. The critical mismatch, reported as a red line in figure 3, starts from the value of 14%, related to the critical receiver fundamental mismatch,  $MrcF$ , when only one receiver is mismatched; it increases by increasing the number of mismatched cells, according to the relationship reported at point 7). The graph of fig.2 shows that, if the number of mismatched cells is in the range (3-54), where  $Mr(1) > Mrcr$  (pale blue colored zone), the power is recovered.

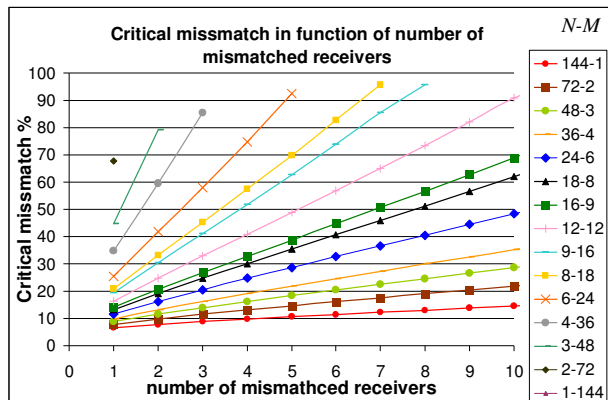
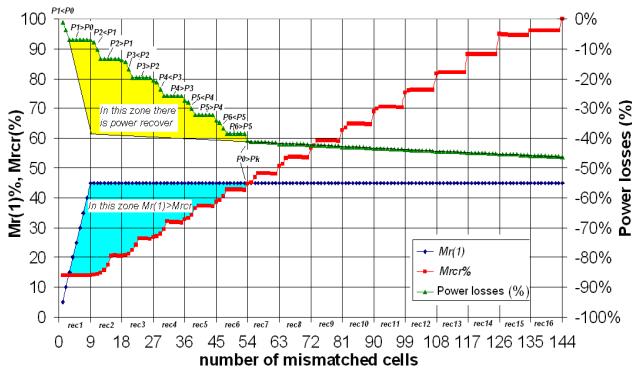


Figure 2. Critical mismatch values in function to the number of mismatched receivers for different electrical module layout configurations.

The yellow colored zone represents the power that it's possible to recover because of the presence of the by pass diode, according to the comments reported at point 5). The left and bottom edges of the yellow zone

represents the module power loss that the module would experience if working at the canonical peak P0 without bypass diode.



**Figure 3. Power losses, first-order receiver mismatch and critical mismatch in the case of 16-9 module layout electrical configuration, considering  $M_c=45\%$ , in function of the number of mismatched cells and not uniform mismatch distribution.**

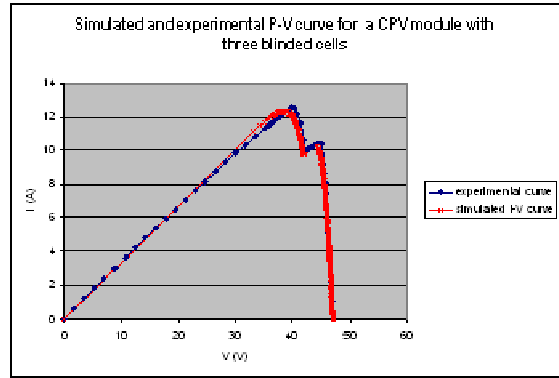
When only one receiver is mismatched, an extra peak P1 exists and its value does not depend on the value of the receiver mismatch, while the canonical power peak P0 does, and it decreases by increasing the mismatch value, according to what claimed in point 4). As P0 decreases, it can become lower than P1, and so the module power becomes constant being controlled by the extra peak P1, which does not depend on the mismatch value.

It's worthwhile to note that P1 becomes greater than P0 exactly when  $Mr(1)$  becomes greater than  $Mrcr$ , according to the consideration reported at point 5). When a second receiver is mismatched, a second power extra peak appears, whose value is lower than P1 and the max module power (P1) decreases as far as the relationship  $P2 < P1$  holds. In this case, while P2 does not depend on the mismatch value  $M(2)$ , P1 does, and its value decreases with the increasing mismatch value till P1 becomes lower than P2, so that the power loss becomes again constant. Therefore, by increasing the number of mismatched receivers, the number of extra power peaks increases and the module power decreases following a "staircase" behavior. The first order mismatch increases till all the parallel-connected cell of the receiver become mismatched. Then its value becomes constant and equal to the cell mismatch value (blue line constant). When the number of mismatched cells is greater than 54 (7 mismatched receivers),  $Mr(1)$  becomes greater than  $Mrcr$  therefore canonical peak P0 comes back to be the highest power peak and there is no power recovering.

### MODELLING VALIDATION

The new theoretical approach is validated on a SolarTec Int. module made of a single string, with a total of 144 cells that are assembled in 16 series-connected receivers, each one having 9 parallel-connected cells. In order to experimentally control the mismatched condition 3 cells of

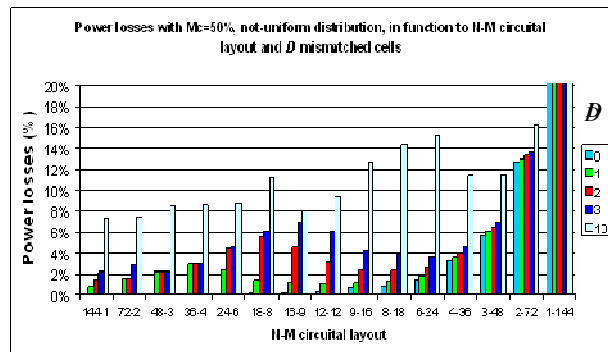
the module are on purpose blinded and the module experimental P-V curve detected. The results of the comparison between the theoretical and experimental P-V curves are reported in figure 4. Since in the 16-9 layout configuration the foreseen receiver critical mismatch is 14%, the introduced receiver mismatch of 33% (calculated with eq.8) is higher than the critical one and, as expected, the extra power peak P1 has a higher value than P0.



**Figure 4. Simulated and experimental P-V curve of a SolarTec CPV module (16-9 configuration), having blinded 3 solar cells (receiver mismatch of 33%) in the same receiver (non uniform mismatch distribution).**

### EVALUATION OF THE BEST ELECTRICAL MODULE LAYOUT

In figure 5, 6 and 7 the power losses are evaluated in function of the possible module layout (N,M, L) configurations and mismatch cell number  $D$ . In the simulations reported in figure 5, the following parameters are used:  $R_{seq\_c} = 0.17\Omega$  and  $R_c = 0.1\Omega$ . In the case of non-uniform mismatch distribution, with a cell mismatch value of 50%, it can be argued that, regardless the number of cells in mismatch condition, the module layout configurations with more cells connected in series is more robust to mismatch losses.



**Figure 5 CPV Module power losses in relation to the electrical layout with not-uniform mismatch distribution.**

With a low number of mismatched cells (1,2, and 3) the

power losses increase with the number of parallel-connected cells, reaching a maximum power drop around the 16-9 configuration and reaching a second minimum power losses with the configuration 6-24, since, having more cells connected in parallel on the same receiver, the incidence of mismatch condition on few cells is less important. In some cases (for example, 48-3 and 36-4) by increasing the number of mismatched cells (1,2,3) the power losses do not change because the critical mismatch is already overcome. In case of uniform mismatch distribution (figure 6), with a cell mismatch value of 50%, it can be argued that the 'balanced' module layout configurations, (with roughly equal numbers of cells connected in series and in parallel) are in most cases more robust to mismatch losses. A more detailed analysis shows this conclusion holds with a cell mismatch value less than 75%.

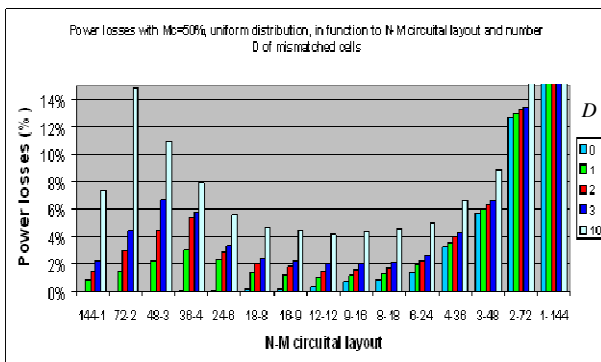


Figure 6 CPV Module power losses in relation to the electrical layout, with uniform mismatch distribution.

Note that in both figures the case '0 mismatched cells' shows the power losses that are due to Joule effect that increase for the parallel configurations (high current).

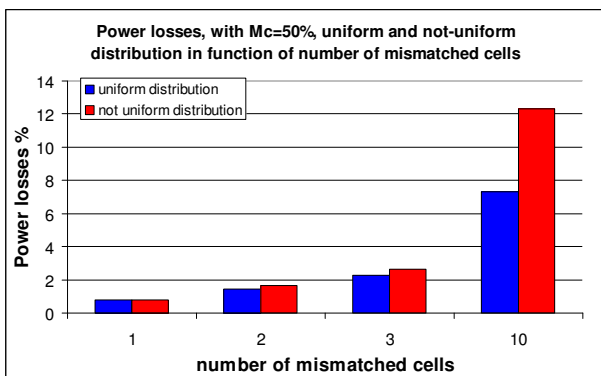


Figure 7 CPV Module power losses in relation to the number of mismatched cells, with uniform and not uniform mismatch distribution, in a module consisting of 2 strings having 72 series-connected cells.

A module with two strings having 72 series connected cells is more robust to mismatch losses than a single string module having series connected receivers (each

one having parallel connected solar cells) when a limited number of mismatched cells are considered. On the contrary, when, for example, 10 cells are in mismatch condition, with a cell mismatch value of 50%, the power losses are above 12% in case of not uniform mismatch condition in contrast with 8% power losses of the (16-9) module layout considered in fig. 5.

### MODULE AND RECEIVER MISMATCH IDENTIFICATION PROCEDURE

An original procedure is developed to identify the module receivers mismatches starting from any experimentally detected I-V curve, also for curves presenting many current steps. The identification procedure is based on an iterative fitting algorithm which compares the experimental I-V curve with a mock curve (calculated with equation (1)) where  $I_{ph\_rz}$  are related to an assumed receivers mismatch condition. At each iteration the receivers mismatch values are varied (and consequently also the  $I_{ph\_rz}$  values) until the mock up curve becomes the best fit of the experimental one.

The procedure requires a previous determination of the following parameters [3]:

- the cell junction temperature  $T_{jm}$  that is associated to the outdoor experimental detected I-V curve;
- the equivalent module series resistance  $R_s$ ;
- the equivalent cell ideality factor  $neq$ ;
- the equivalent inverse saturation current  $I_{0eq}$  at a well-known indoor junction temperature value  $T_{j0}$ .

Since any module I-V curve is strongly dependent on the junction temperature, a good experimental curve fitting can be obtained only if the mock curve is calculated at the same junction temperature at which the experimental curve is detected. In order to compare mock and experimental curves at the same junction temperature, the experimental I-V curve has been shifted from the cell junction temperature  $T_{jm}$  measured in outdoor condition to the cell junction temperature  $T_{j0}$ , where the  $I_{0eq}$  has been calculated [see 3]. The mismatch identifying algorithm uses the fit-error quantity  $err$  that is defined as the sum of the absolute values of the differences between the experimental curve points voltage values and the mock curve ones at the same current value. It's worthwhile to point out that the algorithm, after identifying the first (lowest) order mismatch  $Mr(1)$ , identifies the highest ( $N-1$ ) order mismatch and then it proceeds from the high order to the low order (from  $N-2$  to 2).

The mismatch identifying algorithm is described in the following steps:

1. The Mock curve and the fit-error  $err$  are calculated in the case of no mismatch ( $Mr(1)=Mr(2)=...Mr(N-1) = 0$ ) conditions.

2.  $Mr(1)$  is increased by  $\Delta_m$  maintaining null the other mismatches:  
 $Mr(1)^* = Mr(1) + \Delta_m ; Mr(2) = \dots Mr(N) = 0$ .
3. The mock curve and fit-error  $err$  are recalculated by using the new  $Mr(1)$  value.
4. If  $err$  value is less than the previous one (it means the fitting improves by  $Mr(1)$  increasing), steps 2,3,4 are repeated. If  $err$  value is greater than the previous one it means that the right value of  $Mr(1)$  is the previous one.
5. The best value  $Mr(1)^*$  is assigned to all other mismatches:  $Mr(2)=Mr(3)=\dots=Mr(N-1)=Mr(1)^*$ .
6. The mock curve and fit-error  $err$  are recalculated by using the all new mismatch values.
7.  $Mr(N-1)$  is then decreased by an amount  $\Delta_m$  :  
 $Mr(N-1)^* = Mr(N-1) - \Delta_m$   
 maintaining the lower-order mismatches values to the previous identified value  $Mr(1)^*$ .
8. The mock curve and fit-error  $err$  are recalculated by using the new  $Mr(N-1)^*$  value.
9. If  $err$  value is less than the previous one (it means the fitting improves by  $Mr(N-1)$  decreasing), steps 7,8,9 are repeated. If  $err$  value is greater than the previous one it means that the right value of  $Mr(N-1)$  is the previous one.
10. Steps 7,8,9 must be repeated to identify in sequence each value  $Mr(N-2)$ ,  $Mr(N-3)$ ,... $Mr(2)$ , substituting in these steps the index value  $(N-1)$  by the  $(N-2)$ ,  $(N-3)$  ...  $(2)$  quantities.

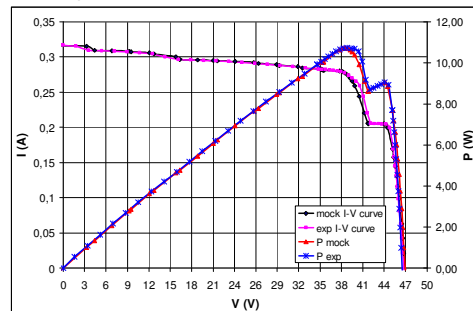
As test-case, the mismatch identification procedure has been applied to a (16 x 9) SolarTec module, using one of its experimental mismatched I-V curves determined when the solar tracker was misaligned. The figure 8 shows that, after mismatch identifying algorithm is performed, the I-V and P-V identified curves are very similar to the experimental ones. The identified receivers mismatches  $Mr(1)$ ... $Mr(15)$  are:

$Mr(1)$	$Mr(2)$	$Mr(3)$	$Mr(4)$	$Mr(5)$	$Mr(6)$	$Mr(7)$	$Mr(8)$
35%	12%	10%	10%	9%	8%	7%	7%
$Mr(9)$	$Mr(10)$	$Mr(11)$	$Mr(12)$	$Mr(13)$	$Mr(14)$	$Mr(15)$	
6%	4%	3%	3%	2%	1%	0%	

### SUMMARY AND CONCLUSION

Considering different electrical module layout, we have investigated the effect on the module photovoltaic performances of two possible mismatched cells distributions (uniform and not-uniform). The work allows optimising the module electrical layout to minimise the power losses, and make the module more robust to the different mismatch causes (soiling effect, tracker misalignment, etc.). The modelling of the mismatched losses takes into account also the series resistance effects to allow a more complete approach of the module electrical layout optimisation. The presence of power extra peaks in the case of CPV mismatched receivers rises new

questions on the utilisation of suitable inverters to minimise the power losses.



**Figure 8 Experimental and identified (I-V), (P-V) curves of a SolarTec module, with 16 x 9 layout.**

The new modelling gives a deep understating of the mismatch effects, allowing predicting the I-V curve of mismatched CPV module and also identifying from the experimental module I-V curve the mismatch values of its receivers. For a definitive selection of the optimal module layout configuration a statistic on the more probable level of mismatch is necessary. It is worthwhile to point out that for a complete optimum module layout configuration, the module producer must also take into account the module voltage temperature dependence which is stronger for a larger number of a series connected cells and receivers.

### ACKNOWLEDGEMENT

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