Forecasting photovoltaic array power production subject to mismatch losses

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Abstract

The development of photovoltaic (PV) energy throughout the world this last decade has brought to light the presence of module mismatch losses in most PV applications. Such power losses, mainly occasioned by partial shading of arrays and differences in PV modules, can be reduced by changing module interconnections of a solar array. This paper presents a novel method to forecast existing PV array production in diverse environmental conditions. In this approach, field measurement data is used to identify module parameters once and for all. The proposed method simulates PV arrays with adaptable module interconnection schemes in order to reduce mismatch losses. The model has been validated by experimental results taken on a 2.2 kWp plant, with three different interconnection schemes, which show reliable power production forecast precision in both partially shaded and normal operating conditions. Field measurements show interest in using alternative plant configurations in PV systems for decreasing module mismatch losses.

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Keywords: Photovoltaic array modelling; Mismatch losses; Interconnection scheme

1. Introduction

The growing number of PV installations throughout the world these last decades has exposed differences between expected power production forecasts and field experience of photovoltaic arrays. These power losses, more commonly referred to as mismatch losses, can be defined as the difference between the sum of the maximum power of each module of an array and the maximum power of the entire plant. In the case of partial shading of an array, the losses are not proportional to the shaded area, but increase non-linearly (Rauschenbauch, 1971; Nguyen et al., 2008). Prior work on the mismatch effect has shown to be responsible for losses up to 10% of the total generated power (Choudier et al., 2009). A second effect of module mismatch is the presence of multiple peaks in the power-voltage characteristic of the PV plant. The appearance of such local maximums can mislead some maximum power point tracking (MPPT) algorithms, especially perturb and observe or incremental conductance methods, which may fail to extract the most power from a solar array (Patel et al., 2008; Petrone et al., 2007).

Mainly two causes provoke module mismatch: dispersion of electrical properties and non-uniformity PV cell illumination composing the array (Choudier et al., 2009; Gautam et al., 2002; Kaushika et al., 2003, 2007; Meyer et al., 2004; van der Borg et al., 2003). Indeed, electrical properties of the solar cells may vary due to manufacturer’s tolerances or degradation processes. Anti-reflection coating degradation, encapsulating material discoloration, light-induced degradation (also known as the Staebler-Wronski
effect (Meyer et al., 2004), hot-spots, and cell structure degradation (such as cracked cells) all participate in the transformation of solar cell electrical properties. Regarding heterogeneous cell illumination, there are two main causes: partial shading of the array and diversity of tilt angles. Generally, solar plants are consists of PV modules which are at the same tilt angle. Yet in certain Building-Integrated PV (BIPV) applications Benemann et al., 1996; Omer et al., 2003; Fernadez-Infantes et al., 2006; Drif et al., 2008, for example modules on roof and wall of a building are connected to a same inverter, the variety of tilt angles in a same array could occasion severe module mismatching. Moreover, PV plants can be subject to partial shading occasioned by nearby trees, antennas, chimneys, passing clouds, or nearby houses that cover a portion of a BIPV plant during the day. In solar tracking plants, shadows of one tracker can appear over modules of another during morning and evening hours. In utility-sized plants, nearby overhead power lines and transmission towers can bring moving shadows across a portion of the plant during the day. In other words, partial shading of solar arrays affects a great variety of PV systems.

Many solutions for reducing mismatch losses have been proposed by modifying array interconnections or adding power converters. Quasi-random cell organization (Feldman et al., 1981) and plant oriented irradiance equalization (Velasco et al., 2005), intend to distribute the impact of shadows as uniformly as possible by reorganizing cell/module connections in strings. Another proposed method is by using alternative array interconnection topologies such as total-crossed tied (TCT) and bridge-link (BL) configurations, which use series–parallelising of modules, either statically (Gautam et al., 2002; Kaushika et al., 2003, 2007; Karatepe et al., 2007) or dynamically (Nguyen et al., 2008). Connection schemes of series-parallel (SP), TCT and BL topologies are shown in Fig. 1. Investigations on adding power conversion units have also been studied for module mismatch reduction such as replacing centralized inverter topologies by string, multi-string, or AC-module technologies (Kjaer et al., 2005). Other solutions proposed using cascaded DC–DC converters in PV plants (Bratcu et al., 2009; Shimizu et al., 2003; Roman et al., 2008) have also been considered for independently extracting maximum power of modules.

This paper deals with solar array modelling using recent photovoltaic module modelling techniques applied to crystalline silicon modules in order to predict power production in existing PV plants. Furthermore, reduction of mismatch losses by changing interconnection schemes of modules in solar generators is addressed. Finally, this paper presents results on novel field tests conducted on a 2.2 kWp plant with several interconnection schemes concurring with model predictions.

### 2. PV module modelling using the Lambert W-function

The one-diode model is commonly used for modelling modules of crystalline silicon technology. The equivalent electric circuit comprises a current source, two resistors, and a single-diode, as shown in Fig. 2. The one-diode model contains five parameters which describe the PV module properties: $I_{ph}$, $I_{o}$, $R_{s}$ (caused by resistances in solder bonds, emitter and base regions, cell metallization, cell-interconnect bus bars and resistances in junction-box terminals) (Meyer et al., 2004), $R_{sh}$ (representing the leakage currents through the solar cell or on cell edges due to crystal damage or impurities near the junction), and $V_{i}$ (depending on module technology and cell organization). The voltage–current relationship that can be deduced using the equivalent circuit results in a transcendental equation (Patel et al., 2008; Kaushika et al., 2007; Joyce et al., 2001; Kawamura et al., 2003) presented in Eq. (1) [PV module current–voltage relation using one-diode model]:

$$I = I_{ph} - I_{o} \cdot \left( \frac{e^{\frac{V + R_{sh} \cdot I}{V_{oc}}} - 1}{e^{\frac{V + R_{sh} \cdot I}{V_{oc}}} - 1} \right) - \frac{V + R_{sh} \cdot I}{R_{sh}}$$

with

$$V_{t} = \frac{N_{s} \cdot a \cdot k_{b} \cdot T}{q}$$

### Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIPV</td>
<td>Building-Integrated photovoltaics</td>
</tr>
<tr>
<td>BL</td>
<td>bridge-link array configuration</td>
</tr>
<tr>
<td>TCT</td>
<td>total-cross tied array configuration</td>
</tr>
<tr>
<td>SP</td>
<td>series–parallel array configuration</td>
</tr>
<tr>
<td>$I_{ph}$</td>
<td>light-induced current</td>
</tr>
<tr>
<td>$I_{o}$</td>
<td>reverse saturation current of the p–n junction</td>
</tr>
<tr>
<td>$R_{s}$</td>
<td>series resistance</td>
</tr>
<tr>
<td>$R_{sh}$</td>
<td>shunt resistance</td>
</tr>
<tr>
<td>$V_{t}$</td>
<td>thermal voltage</td>
</tr>
<tr>
<td>$T$</td>
<td>module temperature</td>
</tr>
<tr>
<td>$a$</td>
<td>diode ideality factor</td>
</tr>
<tr>
<td>$N_{s}$</td>
<td>number of cells in series</td>
</tr>
<tr>
<td>$k_{b}$</td>
<td>Boltzmann constant (1.381e−23 J K−1)</td>
</tr>
<tr>
<td>$q$</td>
<td>fundamental electric charge (1.6e−19 C)</td>
</tr>
<tr>
<td>$I_{sc}$</td>
<td>short-circuit current</td>
</tr>
<tr>
<td>$V_{oc}$</td>
<td>open-circuit voltage</td>
</tr>
<tr>
<td>$G_{i}$</td>
<td>irradiance at environmental condition $i$</td>
</tr>
<tr>
<td>$T_{i}$</td>
<td>module temperature at environmental condition $i$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>short-circuit current correction factor for temperature</td>
</tr>
<tr>
<td>$\beta$</td>
<td>open-circuit voltage correction factor for temperature</td>
</tr>
<tr>
<td>$\delta$</td>
<td>open-circuit voltage correction factor for irradiance</td>
</tr>
<tr>
<td>$N$</td>
<td>length of input voltage vector</td>
</tr>
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</table>
In recent years, interest in using the Lambert W-function, frequently referred to as $W(z)$, for photovoltaic cell models (Petrone et al., 2007; Jain et al., 2006; Ding et al., 2008) has proven to be convenient by directly expressing current as an exact analytical expression of voltage, as shown in Eq. (2) [PV module current–voltage relation using Lambert W-function]:

$$I = \frac{V}{R_s} \left[ \frac{R_s \cdot (I_{ph} + I_o)}{V_i \cdot (R_s + R_{sh})} - W \left( \frac{I_o \cdot R_s \cdot R_{sh} \cdot e^{\frac{V_i - V}{V_i \cdot R_s \cdot R_{sh}}} - V}{V_i \cdot R_s \cdot R_{sh}} \right) \right]$$

The previous expression can be simplified by using the common approximation that the series resistance is negligible with respect to the shunt resistance value ($R_s \ll R_{sh}$), as shown in Eq. (3) [Current–voltage relation with approximation]:

$$I = \frac{V}{R_s} \left[ \frac{R_s \cdot (I_{ph} + I_o)}{V_i} - W \left( \frac{I_o \cdot e^{\frac{V_i - V}{V_i \cdot R_s \cdot R_{sh}}} - V}{V_i \cdot R_s} \right) \right]$$

This model has two main advantages: expressing module current as explicit function of module voltage and accelerated simulation time. Prior research using this model has lacked to emphasize the rapid simulation time of current–voltage values compared with the traditional calculation using the transcendental equation. The Lambert W-function and embedded Newton–Raphson method have been used in MATLAB for module characterization. The developed programs determine the current vector corresponding to an input voltage vector and module parameters. The proposed model uses the series expansion of the Lambert W-function to calculate the numerical current values whereas the Newton–Raphson iteratively determines the corresponding current that verifies Eq. (1). Calculation time resulting from both iterative method and direct calculation are shown in Table 1. Results show that the Lambert W-method solves much faster (approximately 1000 times) which can considerably reduce simulation time in complex calculations.

Furthermore, the proposed model has been used to extract the five characteristic parameters of modules by using the least-square fitting method. Curve-fitting results using the explicit function show high concordance between model and field measurements, as will be seen afterwards.

### 3. PV array modelling with alternative interconnection schemes

PV array production forecasting has brought interest through recent years accompanying the expansion of pho-
tovoltaic systems. Previous papers have proposed matrix models for simulating PV arrays in series–parallel configuration with various environmental conditions (Patel et al., 2008; Kaushika et al., 2003; Kawamura et al., 2003). This method has proven to be convenient of use for implementation and verification of simulations results. The proposed model also uses a matrix approach to solve a PV array problem. The principle is to use either module voltages or currents as unknowns (in our case voltages are chosen for better numerical precision) to determine an unknown vector $X$. Electrical relations describing the PV array are transcribed into mathematical equations and put in matrix format $F$. The solution is obtained once the residual of the product $F \times X$ is sufficiently small. In this paper, the modelling of alternative connection schemes is presented. Custom interconnection schemes may be simulated by dynamically modifying the PV array electrical model matrix $F$. The values of module voltage and current can therefore be determined with given incoming solar irradiance $G$ and module temperature $T$, DC plant voltage as well as other parameters shown in Fig. 3.

3.1. The traditional series–parallel topology

In a PV array composed of $M$ modules per string with $N$ strings, that is to say an array comprising $M \cdot N$ modules, we can identify $(M - 1) \cdot N$ nodes and $(M - 1) \cdot (N - 1)$ possible interconnections of modules, as shown in Fig. 3. The most common topology for PV arrays is series–parallel, where $M$ modules are connected in series, and $N$ strings of $M$ modules are connected in parallel.

The equations describing the electric behaviour of the PV array can be classified into three groups: current laws, voltage laws and DC bus voltage law.

The current laws describe current flow through the array of PV modules using Kirchhoff’s current laws at the nodes of the array. In the case of the SP topology, the current flowing through two consecutive modules in a same string is equal, as shown in Eq. (4) [Expression of current laws for series–parallel array]:

$$\forall i \in [1, M - 1], \quad \forall j \in [1, N], \quad f(V_{i+1,j}) - f(V_{i,j}) = 0$$  

(4)

The DC bus voltage law expresses the voltage that the string is submitted to at the entry point of the inverter, the DC bus voltage. In order to determine the plant current for each DC bus voltage value, the operating point of the plant current–voltage characteristic is calculated for a DC bus voltage $V_{DCbus}$. By choosing to submit the first string voltage to DC bus voltage we obtain Eq. (5) [Expression of DC bus voltage law for series–parallel array]:

$$\sum_{i=1}^{M} V_{i,1} - V_{DCbus} = 0$$  

(5)

Finally, the voltage laws describe the voltage equalities that lie between single modules or strings of modules connected in parallel. In the case of the SP topology, $(N - 1)$ strings of $M$ modules are connected to the first string in parallel, bringing supplementary Eq. (6) [Expression of voltage laws for series–parallel array]:

$$\forall j \in [2, N], \quad \sum_{i=1}^{M} V_{i,1} - \sum_{i=1}^{M} V_{i,j} = 0$$  

(6)

By using the previous $M \cdot N$ equations, the $M \cdot N$ rank non-linear system can be solved. This is done by determining the solution to the matrix equation $F \times X = 0$, where $F$ is a square matrix of dimension $M \cdot N \times M \cdot N$ and $X$ is the voltage vector of length $M \cdot N$. The iterative Newton–Raphson method is applied to solve the equation system using the $F$ matrix and its associated jacobian matrix. The process is initialized by supposing that each module in the array have the same voltage value $V_{DCbus}/M$.

3.2. Alternative module interconnection schemes

Prior research has shown interest in modifying module interconnection schemes for reducing mismatch losses.

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**Fig. 3.** Operational diagram of the PV array forecast model.
Alternative topologies have been proposed such as the TCT and BL configurations which have improved global PV array efficiency by reducing mismatch losses. In previous papers (Kaushika et al., 2003, 2007), simulations were carried out for each topology with a dedicated set of equations in order to forecast PV power production. This paper proposes a simulation model for a PV array where electric equations are automatically modified in order to simulate a custom interconnection scheme, that is to say one single algorithm for various configurations.

As stated previously, in an array of $M \times N$ modules there are $(M - 1) \times (N - 1)$ possible module interconnections. The interconnection matrix $ConMat$, describes the interconnections in an array, by using the null value if the connection is not established, and one in the corresponding cell if modules are interconnected. For example, in the case of the SP topology, the corresponding interconnection matrix is a null matrix of dimension $(M - 1) \times (N - 1)$.

When a module is interconnected with another, that is to say a parallel connection is established, a current law is replaced with a voltage law, thus conserving the total number of equations in the system. Indeed, if nodes $N_{i,j}$ and $N_{i,j+1}$ are connected, as shown in Fig. 3, the two current laws describing current flow between modules $M_{i-1,j}$ and $M_{i,j}$ and modules $M_{i-1,j+1}$ and $M_{i,j+1}$ are fused into a new current law shown in Eq. (7) [Expression of current law fusion equation for $ConMat_{i,j}$ connection]:

\[
\begin{align*}
&f(V_{i-1,j}) - f(V_{i,j}) = 0 \\
&f(V_{i-1,j+1}) - f(V_{i,j+1}) = 0 \\
\Rightarrow & f(V_{i-1,j}) - f(V_{i,j}) + f(V_{i-1,j+1}) - f(V_{i,j+1}) = 0
\end{align*}
\]

(7)

Furthermore, the node connection generates an additional voltage equation, since interconnected modules have the same voltage. In the previous case, the additional equation ties the sum of voltages of modules in the same string prior to modules $M_{i-1,j}$ and $M_{i-1,j+1}$, as shown in Eq. (8) [Additional voltage law due to $ConMat_{i,j}$ connection]:

\[
\sum_{k=1}^{i-1} V_{k,j} - \sum_{k=1}^{i-1} V_{k,j+1} = 0
\]

(8)

Hence, by using and interpreting the interconnection matrix to modify the PV array electrical property matrix $F$, the user can simulate any PV array interconnection scheme.

The shade scenario on the solar array is taken into account by applying a shade factor, with values taken between 0 (for totally shaded modules) and 1 (for non-shaded modules), to the irradiance received by the modules. This simplified model of the effect of shade does not take into account the temperature drop due to shading. Shade factors for each model are grouped into the shade matrix $S$ thus giving the shade scenario for the entire solar array.

4. Module parameter translation method to desired environmental conditions

Module current–voltage characteristics depend on environmental conditions such as irradiance and module temperature. Current–voltage curve translation is based on the calculation of the short circuit current ($I_{sc}$) and open-circuit voltage ($V_{oc}$) at desired environmental conditions ($G_2, T_2$) from a measured $I-V$ curve taken at ($G_1, T_1$). Translation equations have been investigated throughout the past (Blaesser et al., 1988; Anderson, 1996; Marion, 2002; Hermann et al., 1996; Tsuno et al., 2005), demonstrating linear variation of short circuit current with irradiance and variation of open-circuit voltage with temperature, as shown in Eq. (9), these translation equations use temperature and irradiance correction factors $\alpha$, $\beta$ and $\delta$ (Marion, 2002). The translation method can be adapted to other PV module technologies by using suitable correction factor values [Translation equation for module current ($I$) and voltage ($V$) from conditions ($G_1, T_1$) to ($G_2, T_2$)].

\[
\begin{align*}
I(G_2, T_2) &= I(G_1, T_1) \cdot \frac{G_2}{G_1} \cdot \left[1 + \alpha(T_2 - T_1)\right] \\
V(G_2, T_2) &= V(G_1, T_1) \cdot \left[1 + \beta(T_2 - T_1)\right] \cdot \left[1 + \delta \cdot \ln \left(\frac{G_2}{G_1}\right)\right]
\end{align*}
\]

(9)

In order to describe the influence of environmental conditions on the five parameters used in the one-diode model, the translation method was applied to Eq. (1) and by parameter identification, translation formulas were deduced, as shown in Fig. 4. The parameter translation equations can be applied to any crystalline silicon or other technology that uses the single-diode equivalent circuit as a model. The novel parameter translation method uses the correction factor calculation method proposed by Marion (2002). Module parameters have previously been identified from a reference curve and then translated using previously determined correction factors for Isotón I-106 modules ($\alpha = -0.009 \, {^\circ}{C}^{-1}, \beta = -0.0028 \, {^\circ}{C}^{-1}, \delta = -0.0039$), results are shown in Fig. 4. The parameter translation method conserves the precision used by the chosen translation model, in our case the Marion method. The translation of $I-V$ curves by parameter extraction has two benefits: flexibility in translation models and observation of parameter evolution with environmental conditions.

5. Case study: influence of modifying topologies in partial shaded installations

In order to validate the simulation model, measurements have been carried out on a 2.2 kWp rooftop installation, consisting of 20 Isotón I-106 modules, part of the UNIVER project at Jaén University in Spain (Drif et al., 2007) as can be seen in Fig. 5. Originally, the plant was grid-connected and made up of two strings of 10 modules to fit inverter specifications. In order to see the influence of mod-

ule interconnections, the plant has been reconfigured into four strings of five series-connected modules. Furthermore, modifications on the installation have been made in order to rapidly change the module interconnection scheme. To do so, a connection box has been designed to centralize module terminals into a unique location, facilitating plant topology changes in a short time span (less than 15 min) in order to keep similar environmental conditions during measurements.

The experimental procedure consisted in successively measuring the current–voltage characteristic of three topologies (SP, TCT and BL) followed by the I–V characteristic recording of each module within the array. This procedure was carried out in both non-shaded and partially shaded conditions.

Fig. 4. I–V curve translation method using measurements taken at environmental conditions \((G_1, T_1)\) for prediction of I–V characteristic at \((G_2, T_2)\) conditions.

![Fig. 4. I–V curve translation method using measurements taken at environmental conditions \((G_1, T_1)\) for prediction of I–V characteristic at \((G_2, T_2)\) conditions.](image)

![Simulated I-V characteristic at \((G_2, T_2)\) environmental conditions](image)

![Measured I-V characteristic at \((G_2, T_2)\) environmental conditions](image)

![5 parameter extraction \(I_{ph}, R_p, R_{sh}, I_{oc}, V_{oc}\) at \((G_2, T_2)\)](image)

\[
\begin{align*}
I_p(G_2, T_2) &= \frac{G_2}{G_1} \left[ \frac{1}{1+\alpha(T_1-T_2)} \right] I_p(G_1, T_1) \\
V_{oc}(G_2, T_2) &= \left[ 1 + \delta \ln \left( \frac{G_2}{G_1} \right) \right] V_{oc}(G_1, T_1) \\
R_s(G_2, T_2) &= \frac{R_s(G_1, T_1)}{1 + \alpha(T_1-T_2)} \\
R_{sh}(G_2, T_2) &= \frac{R_{sh}(G_1, T_1)}{1 + \alpha(T_1-T_2)} \\
I_{ph}(G_2, T_2) &= \frac{G_2}{G_1} \left[ \frac{1}{1+\alpha(T_1-T_2)} \right] I_{ph}(G_1, T_1)
\end{align*}
\]

Fig. 5. PV plant and connection box used during measurement campaign.
scenarios in order to forecast the plant power production using the proposed method. Static partial shade was performed by covering two modules with bubble wrap film, as shown in Fig. 5b, which decreased incoming irradiance by 40 percent. All of the experimental work was carried on the rooftop installation using a calibrated solar cell, a module temperature sensor and a PVPM 2540C curve tracer. In addition, environmental conditions varied slightly during the measurement campaign with values of incoming solar irradiance ranging between 600 and 660 \text{ W m}^{-2} and module temperatures from 32 °C to 35 °C. Module parameters were extracted separately from the measured $I$–$V$ characteristics and translated to the experimental environmental conditions. Finally, plant production forecast was carried out using the proposed method and compared to experimental data.

5.1. Normally operating PV array results

In normal operating conditions, photovoltaic plants are not subject to partial shade and therefore have a power-voltage characteristic containing only one maximum peak. Experimental results, presented in Fig. 6, show that in homogeneous irradiance conditions all three topologies have similar power-voltage characteristics. Furthermore, TCT and BL topologies have slightly higher maximum power ratings than the series-parallel topology at same environmental conditions. However, in such conditions the power gain remains negligible: +0.2% maximum power increase with respect to the SP topology, considering the measurement apparatus error.

The production forecast method was then applied using the earlier mentioned steps: parameter extraction of individual modules, parameter translation to plant measurement conditions, and plant $I$–$V$ curve construction. Maximum power points of the predicted and experimental curves are presented Table 2. Simulation results fit closely to experimental results throughout the curve, yet some dispersion in maximum power remains due to errors in module $I$–$V$ curve parameters extraction and environmental condition translations. It should be noticed that simulation results always over-estimate maximum power. However, simulation errors are satisfactory remaining between 1% and 2% of experimental maximum power.

<table>
<thead>
<tr>
<th></th>
<th>SP</th>
<th>TCT</th>
<th>BL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>1087.5</td>
<td>1089.9</td>
<td>1090.2</td>
</tr>
<tr>
<td>Simulation</td>
<td>1103.4</td>
<td>1103.8</td>
<td>1104.2</td>
</tr>
<tr>
<td>Simulation error (%)</td>
<td>1.46</td>
<td>1.28</td>
<td>1.28</td>
</tr>
</tbody>
</table>

5.2. Partially shaded PV array results

In partially shaded conditions photovoltaic plants, $I$–$V$ curves present two main properties: maximum power reduction and appearance of multiple power peaks. The first effect is a consequence of lower incoming solar power onto the array. The appearance of multiple peaks is due to module mismatch, which may be accentuated by bypass diode operation. The multi-peak effect is visible on the experimental results, presented in Fig. 7, in case of partial shading of an array. Although all three topologies show inflexion points on their current–voltage characteristics, both TCT and BL arrays have smoother curves consequently lessening the multi-peak effect. Furthermore, measurements show an increase of roughly 4% and 2.5% in maximum power for the TCT and BL interconnection schemes. In other words, the PV array is able to produce 4% more power than the SP topology by simply modifying the array interconnections of the plant into a TCT configuration. PV plant owners can therefore expect higher

Fig. 6. Experimental values of non-shaded 2.2 kWp plant.

Fig. 7. Experimental values of partially shaded 2.2 kWp plant.
energy production yields leading to higher return on investment rates.

Simulation results confirm the plant’s $I-V$ curve evolution, with maximum power brought by the TCT topology followed by the BL topology, as can be seen in Table 3. Simulation errors are slightly higher than previous simulations but remain well under the 5% threshold. In the partial shading case, additional errors in the bypass diode model can explain higher error levels. Another phenomenon validating the simulation model is the reduction of the multi-peak phenomena which is more pronounced in the simulation model than in experimental measurements.

The use of alternative module interconnection schemes have shown increase in power production during shaded conditions by using simulation tools validated experimentally. The experimental power increase in alternative schemes is directly linked to mismatch losses considering that the use of the connection box reduces significantly the additional cable losses.

### 5.3. Analysis of mismatch losses

The proposed PV array forecasting algorithm has been used to determine mismatches in the experimental results. To do so, the module $I-V$ characteristics have been translated to the $I-V$ plant curve conditions environmental conditions for each topology SP, TCT and BL. Then, the maximum power of each module has been calculated and summed in order to determine the maximal available array power at given environmental conditions. The difference between the maximal available power and the maximum measured power for each topology in both non-shaded and partially shaded conditions was then calculated. Results shown in Fig. 8, present the mismatch losses, expressed in percent with reference to the maximal available power of the array.

The TCT configuration shows the least mismatch losses in partially shaded conditions, whereas the BL configuration has the least mismatch losses in non-shaded conditions. It should be noticed that in traditionally configured arrays, the calculated mismatch losses for the 20 module plant represent a 19 W loss, that is to say a 1.71% power loss in this case. Whereas in the BL configuration, mismatch losses in non-shaded conditions add up to 11 W. Module connection modifications are expected to bring higher power increase ratios in more severe mismatch cases such as different shade scenarios with higher solar irradiance values.

### 6. Conclusion

A method for forecasting existing photovoltaic plants’ power production has been proposed and validated by experimental measurements in both shaded and non-shaded conditions. The PV module model uses the Lambert W-function enabling a direct tie between current and voltage of modules which significantly reduces calculation time. Furthermore, various interconnection schemes of modules can be simulated thanks to the automatically generated electrical relations which describe solar array operation. This paper also addresses PV module parameter identification and novel parameter translation to desired environmental conditions, which are necessary for comparing expected power production with changing irradiance and temperature levels. Moreover, new experimental work on alternative array configurations shows that modifying the module interconnection scheme inside a PV plant can raise maximum power output by up to 4%, especially in partially shaded conditions, with respect to traditional module interconnection schemes. Further simulation results should be carried out to see if TCT and BL topologies can have a greater impact in different scenarios.

Control strategies for dynamically modifying array interconnections, thanks to automated DC switches inside a connection box, could help optimize PV array power output in degraded mode operation. Such control strategies could consist in real-time control of PV plants given the rapid simulation times using the Lambert W-function model when applicable. The PV forecast method could also be used for determining the optimal interconnection schemes with given shade scenarios for maximizing power production of PV plants submitted to recurrent partial shading as can be found in previously discussed PV applications.

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