Improving the prediction of photovoltaic power production in urban environments

A. Trejos, C.A. Ramos-Paja, and A.J. Saavedra-Montes

***Abstract*—This paper proposes an improved model to estimate the power and energy production from photovoltaic installations under dynamic shading conditions typical of urban environments. The impact of dynamic shades on the power production is analyzed, illustrating the large errors introduced by classical prediction approaches. Moreover, a procedure to model the shades profile in any environment is described and illustrated. Finally, an experimental irradiance profile is used to evaluate the performance of the proposed model in contrast with the classical approach, obtaining satisfactory results.**

***Index Terms*— Mismatching conditions, photovoltaic generator, power and energy prediction, shade modeling.**

I. Introduction

PHOTOVOLTAIC (PV) power systems are a renewable option to replace fossil fuels in both stationary and mobile applications. Moreover, PV generators are a suitable power source for isolated consumers due to the reduced maintenance required and the absence of combustible, which contrast with the high requirement of diesel generators or fuel cells. Such advantages of PV systems make them an attractive alternative for distributed generation systems and for its integration in the power grids [1, 2].

The increasing popularity of PV systems has also generated the development of building integrated photovoltaic (BIPV) covering roof surfaces with optimal solar exposure [3, 4], this to take profit of the space available in rooftops and parking lots. But such urban PV systems have generated new challenges related with the dimensioning of the installation, the cost analysis and the planning of the power delivery to the grid [5]. To address such problems the designers require to accurately predict the power that will be generated by the system. Such information allows to calculate the number of modules required to fulfill the consumer load profiles, it also allows to estimate the return-of-investment time in which the installation cost will be recovered, and it also provides the information required to schedule the appropriate instant to inject the power to the grid.

Urban environments introduce multiple source of shading over the PV modules difficult to overcome, e.g. Fig. 1 shows the shading generated by posts, near installations, trees, etc. Such shades generate a mismatching effect over the PV arrays that strongly degrade the power produced [6] in a non-linear way, which makes difficult to estimate the generator power profile. This topic was addressed in [3], where an evaluation of the solar potential of several shapes of two storey houses is presented. The main objective of such paper is to assess the advantage and disadvantages associated with different shapes in contrast with the reference rectangular shape. In the paper the authors make evident that shading produced by building rooftop topologies affect the electricity generation. Even when the authors develop simulations to calculate the energy per square meter, but a shading model that allows predicting the PV power profile is not presented.

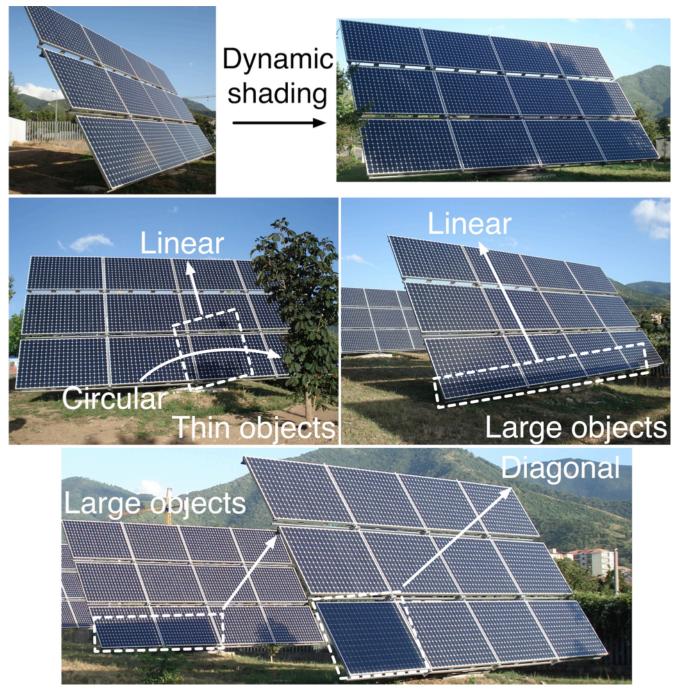

Fig. 1. Shading conditions caused by thin and large objects: the dynamic shade profile generates different operating conditions to the array.

In addition, the shades over the modules change dynamically during the day, increasing even more the complexity of the power prediction. Such an aspect has been addressed by neglecting the shading effect or by averaging the shading profile [7]. In that paper, five algebraic methods are used to predict the behavior of PV generators under natural sunlight. The results show that the performance may be

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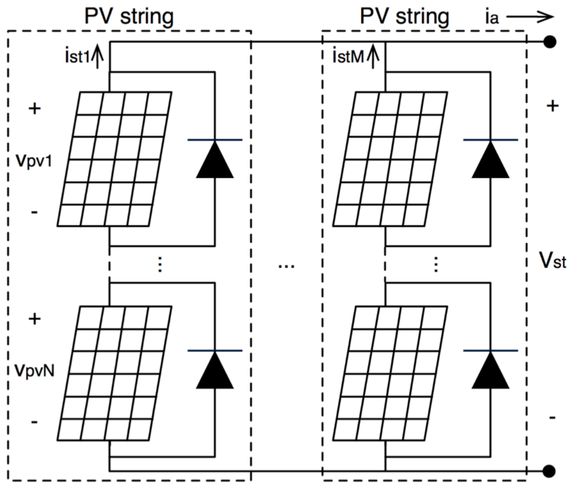

Fig. 2. PV array in series-parallel structure.

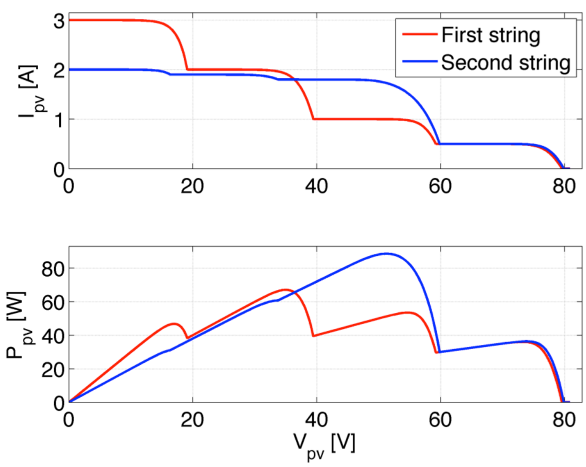

Fig. 3. Shade effect on the electrical characteristics of two PV strings.

described with sufficient accuracy using two methods, but only taking into account incident global irradiance, and module temperature. If the PV modules are not electrically characterized in Standard Test Conditions (STC) poor results may be achieved regardless the selected prediction method. In any case, those methods do not take into account the different shading effect on each module and the dynamic change of the shades. Therefore, despite it improves the energy prediction, significant errors are still generated since the wide variation of the shades is not taken into account.

This paper proposes a novel modeling approach able to predict the PV power profile in presence of dynamic shading conditions. The proposed solution significantly reduces the prediction errors in comparison with classical approaches by taken into account the effective irradiance profile for each module without any averaging process. The paper is organized as follows: Section II discusses the mismatching effect to identify the aspects that must be modeled in order to improve the power prediction under shading. Then, Section III describes an array model able to calculate the PV power from the static values of the effective irradiances in each module. Section IV introduces the improved prediction model accounting for the dynamic changes of the shades that affect each module. Such section also evaluates the model performance in comparison with the classical approach using an experimental irradiance profile. Finally, conclusions close de paper.

II. The Mismatching Effect

The mismatching effect is caused by difference between the operation conditions of PV modules that compose an array. It is important to note that the mismatching conditions are also generated by the difference between the modules parameters, dust, heat sources, etc. But the largest sources of mismatching conditions are shades generated by objects near to the PV installation. In addition, since the sun position changes, the shape of the shade changes dynamically, producing variable mismatching conditions to the PV array. The top of Fig. 1 shows a PV module completely irradiated and another one almost completely shaded, which creates a wide difference in the operating conditions of a PV array. The same figure also shows multiple shades generated by thin and large objects. The sun translation causes that such objects project predictable shades profiles, which in the case of thin objects could be linear or circular. In the case of large objects, the shade moves across the array in linear or diagonal directions. Therefore, the shading profile at the beginning of the day may be very different to the one affecting the array in other time of the day.

Fig. 2 shows the structure of a typical PV array in series-parallel configuration [6]: the array is formed by parallel-connected strings, which in turns are made of the series-connection of PV modules. The number N of modules in series depends on the voltage required at the array terminals, while the number M of strings in parallel is defined to meet the load power requirements. In such a system, the short-circuit current of each module depends on its particular irradiance and parameters. Hence, if a shade is covering (partially or totally) a module, its current could be lower than the one imposed to the string by the other highly irradiated modules. In such a case, the current in excess over the maximum module current, i.e. short-circuit current, must to flow through the associated bypass diode, which imposes null voltage to the module, avoiding the module power production. But, in any case, the bypass diode is required to protect the array from damages caused by hot-spots [8].

In strings with one or more active bypass diodes, the current vs. voltage (I-V) and power vs. voltage (P-V) curves exhibit multiple Maximum Power Points (MPP) as depicted in Fig. 3. In such an example, the strings are formed by identical PV modules but with different shading conditions, therefore at the same daytime both strings produces different power curves.

On the light of such a condition, it is evident that classical array models as the one reported in [7], which consider uniform conditions on all the modules, introduce significant errors in the power estimation of shaded arrays. Therefore, the following section presents the array model adopted in this paper, which considers different operating condition for each module, to simulate shaded arrays.

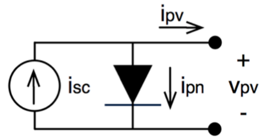

Fig. 4. Equivalent circuit of a PV module.

III. PV POWER UNDER MISMATCHING CONDITIONS

As illustrated above, the power produce by a PV array significantly changes on shading conditions due to the activation of bypass diodes, which forces some modules to produce null power. In the following, a mathematical model to calculate the PV power in shading conditions, introduced in [9], is described.

A. The PV module model

The electrical behavior of a PV module is described by means of a current source modeling the photo-induced current and a diode modeling the P-N junction of the module. Fig. 4 shows the module equivalent circuit, where the following equations describe its electrical characteristics [9]:

$$i_{pv} = i_{sc} - i_{pn} \, , \, i_{pn} = A \cdot \exp\left(B \cdot v_{pv}\right) \tag{1}$$

$$i_{sc} = i_{STC} \cdot \frac{G_{pv}}{G_{STC}} \left(1 + \alpha_i \cdot \left(T_{pv} - T_{STC}\right)\right) \tag{2}$$

$$B = \frac{B_{STC}}{1 + \alpha_v \cdot \left(T_{pv} - T_{STC}\right)} \tag{3}$$

$$B_{STC} = \frac{\ln\left(1 - \left(i_{mpp} / i_{STC}\right)\right)}{v_{mpp} - v_{ocSTC}} \tag{4}$$

$$A = i_{STC} \cdot \exp\left(-B_{STC} \cdot v_{ocSTC}\right) \tag{5}$$

In such expressions, i_{pv} and v_{pv} are the current and voltage of the PV module, respectively. The parameters A, B, and i_{sc} are usually calculated from the datasheet information for a given irradiance (G_{pv}) and temperature (T_{pv}) using (2)-(5), where i_{STC} and v_{ocSTC} are the short-circuit current and open-circuit voltage in Standard Test Conditions (STC), respectively. T_{STC} and G_{STC} are the module temperature and irradiance in STC, respectively; while B_{STC} corresponds to B evaluated in STC. i_{mpp} and v_{mpp} are the current and voltage of the PV module at the MPP for the evaluated irradiance and temperature conditions; and αi and α v are the current and voltage temperature coefficients.

B. The bypass diodes activation

The analysis of the bypass diodes activation is performed string-by-string. Such a procedure does not introduce errors since the activation of a bypass diode depends on the currents of the associated PV module and string exclusively.

It is important to detect the string voltages at which the bypass diodes become active, named inflection voltages: voltages lower than the inflection voltages force the associated modules to operate in short-circuit condition, therefore they do not contribute to both the string voltage and power.

Since strings are formed with PV modules connected in series, the physical position of a module in a string has no impact on the string current. Therefore, without loss of generality, the calculation of the inflection points considers the modules placed in descendent order of i_{sc}, hence $i_{sc,j} \geq i_{sc,k}$ with $j < k$. From such a condition, the bypass diode k (associated to module k) becomes active for (6), where an inflection point occurs. In (6), the current of both modules is the same and equal to the current of module k with null voltage.

$$i_j = i_k \quad , \quad v_k = 0 \tag{6}$$

From (1) and (6), the inflection voltage is given by the voltage of the module j ($v_{o,j,k}$) in (7).

$$A_j \cdot \exp\left(B_j \cdot v_{o,j,k}\right) = i_{sc,j} - i_{sc,k} + A_k \tag{7}$$

But, if the string has more than two modules in series, $v_{o,j,k}$ represents the contribution of the module j to the minimum string voltage that turn-off the bypass diode of module k ($v_{o,k}$). Hence, $v_{o,k}$ is calculated as the sum of the inflection points voltages of the modules with i_{sc} greater than $i_{sc,k}$ (modules from 1 to k-1). In general, the contribution of the module m to the inflection voltage associated to the module k (with $m < k$) is obtained from the solution of $v_{o,m,k}$ in (8), and the value of $v_{o,k}$ is calculated from (9).

$$i_{sc,m} - A_m \cdot \exp\left(B_m \cdot v_{o,m,k}\right) = i_{sc,k} - A_k \tag{8}$$

$$v_{o,k} = \sum_{m=1}^{k-1} v_{o,m,k} \tag{9}$$

From (6) and (7) it is evident that, at maximum, there exists N-1 inflection points, with N being the number of modules in the string. Moreover, since all the modules are considered in descending order of i_{sc}, if the bypass diode k becomes active all the bypass diodes for k+1…N are also active; hence the associated modules are not producing voltage and power.

C. The PV power calculation

The string current i_{st} imposed by an array voltage v_{st} is calculated from (1) using any module voltage. Such module voltages are obtained by taking into account that the string current is the same in all the modules, which defines the following non-linear system:

$$i_{st} = i_1 = i_2 \cdots = i_k = \cdots i_{N_{am}} \tag{10}$$

$$\sum_{k=1}^{N_{am}} v_{pv,k} = v_{st} \tag{11}$$

The non-linear system in (10)-(11) has $N_{am} + 1$ non-linear equations, where N_{am} stands for the number of active modules, i.e. modules with inactive bypass diode. Moreover, such a system can be solved by means of classical approaches like the Newton-Raphson method, or by means of modern approaches like the fsolve() function of Matlab. But in both cases the search domain of the $v_{pv,k}$ solutions is constrained by the inflection points: the string current is limited by the currents of the inflection points that surrounds the string voltage. Therefore, if the operation voltage of the string is placed between the inflection points k and k+1, i.e. $v_{o,k} < v_{st} < v_{o,k+1}$, the string current i_{st} is also placed within $i_{o,k} < i_{st} < i_{o,k+1}$ with $i_{o,k}$ and $i_{o,k+1}$ being the inflection points currents. Such a characteristic speed-up the string current calculation since the zone where the solution occurs is known.

Finally, since the PV array is formed by several strings in parallel, the array current i_a is calculated by adding all the

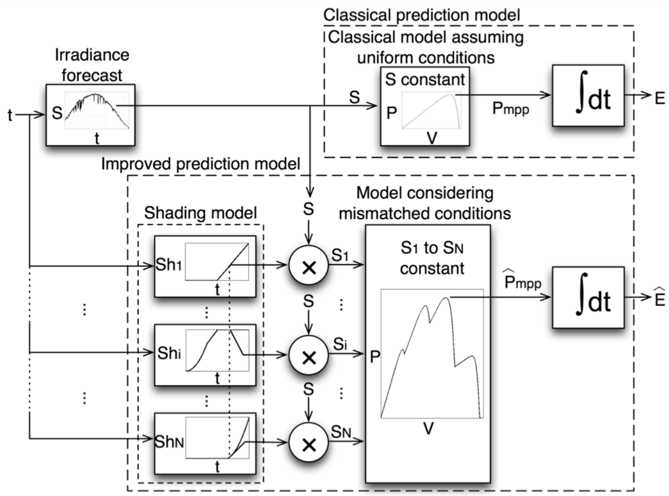

Fig. 5. Prediction structures to estimate PV power profile and energy.

string currents. Then, the array power is obtained from the array current and voltage for the given irradiance condition.

It must be pointed out that this model allows to calculate the array power for different irradiance conditions in each module. But a proper model to introduce urban shading profiles that affect individual modules, producing dynamic shading conditions, is required. Such a topic is addressed in the following section.

IV. Improved Prediction Model

The classical prediction model [7] used to estimate the power and energy profiles in a PV installation is depicted in the top of Fig. 5. In such a structure, all the modules are assumed uniformly irradiated, hence simple expressions based on (1) but scaling the voltage and current in agreement with N and M, are used to calculate the array power for a given irradiance condition. Such a model is feed by an irradiance forecast to evaluate the PV installation in a specific place. Then, the MPP power P_{mpp} for each irradiance condition is registered to provide a power profile, which eventually is integrated to predict the energy production.

For PV arrays without mismatching, the classical model is accurate enough since the P_{mpp} is correctly predicted. The black trace in Fig. 6 corresponds to the power curve of a four-modules string predicted with the classical model, where the P_{mpp} is highlighted. When shading across the modules occurs, the classical model addresses such a condition by reducing the modules uniform irradiance to an average irradiance value in the array. Such an approach is illustrated by the grey trace in Fig. 6, which represents the new power curve and the P_{mpp} predicted for an average irradiance condition generated by a shading profile. Finally, the green trace in Fig. 6 presents a more precise power curve obtained using the model described in Section III, which takes into account the irradiance condition in each module. Such a trace put in evidence the large errors introduced in the power estimation by the classical model in both non-shading and average-shading approaches. Hence, such an error is integrated to produce a large error in the predicted energy production.

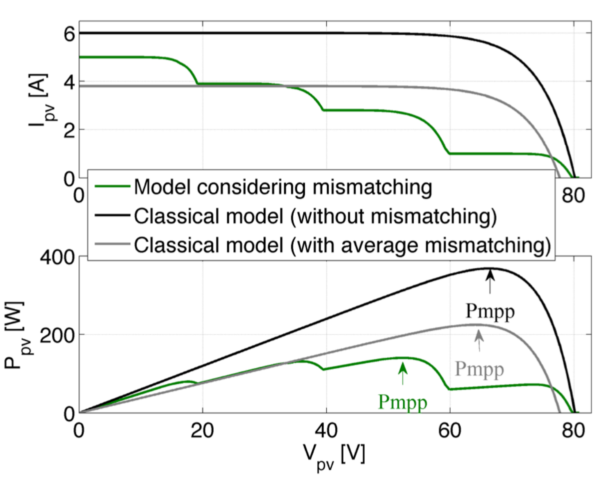

Fig. 6. Electrical characteristics predicted under mismatching conditions.

On the light of the previous analyses, and taking into account that the sun translation changes the shading shape in a particular place along the day, the improved prediction model illustrated at the bottom of Fig. 5 is proposed. Such a novel structure considers dynamic shading conditions for each module, which affect the effective irradiance in each module. Then, the environmental irradiance value provided by the forecast is modified in agreement with the shading profile to generate the irradiance vector $[S_1, \ldots S_i, \ldots S_N]$ to feed the model described in Section III. Then, the MPP power for each irradiance condition forms the power profile to predict the energy production.

A. Shading model

To provide an improved prediction of the power profile, the proposed model includes a first layer to model the dynamic change of the shades. To generate such shading models it is required to acquire data from the place to evaluate, where two options are considered: PV arrays already installed or suitable places for new PV installations. In both cases, the effective irradiance available in the position of each module must be registered along the day. Such a procedure could be done at any moment meanwhile the irradiance forecast for the place is available.

In the case of an array already installed, each PV module must be short-circuited to register the dynamic profile of the short-circuit current using an amperemeter (A). The lower the time intervals used to register the current, the higher the resolution of the shading model. In the case of suitable places for new PV installations, one or several modules could be used to register the short-circuit currents generated in the positions where the modules will be installed.

Then, the effective irradiances for the modules are calculated from (2) using both the measurements and STC short-circuit currents, and using both the forecast and STC temperatures. Fig. 7 illustrates the measurement architecture: the short-circuited module(s) M_{test} is used to register the effective irradiance profiles $S_{test,i}(t)$ along the day. Then, using such profiles and the forecast irradiance profile S(t), the shading profile $Sh_i(t)$ for each module is calculated as in (12).

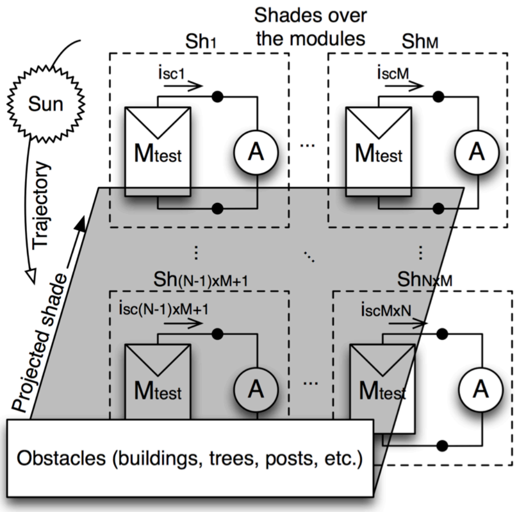

Fig. 7. Shade measurement architecture.

$$Sh_i(t) = \frac{S_{test,i}(t)}{S(t)} \quad (12)$$

To illustrate the shading profiles, Fig. 8 shows a simulation considering a PV array composed by two parallel strings with three modules each, where the shading profile begins at 8:24 in the left-bottom corner of the array. The shade flows towards the top-right corner of the array, it covering the six modules at 16:00. The simulation shows that the bottom-left module is completely shaded at 12:00, while the top-right module is not shaded almost all the time. Fig. 8 also illustrates the non-linearity of the shading profiles, as well as the difference among the patterns in each module.

B. *Model performance evaluation*

To illustrate the performance of the proposed prediction model, an experimental irradiance profile, taken in the south of Italy in a summer day, was used to estimate the power production of a PV using both the classical and the improved approaches. The improved prediction model considers the shading profiles given in Fig. 8, while the classical model was considered with an average shading among such profiles.

The predicted power profiles obtained in Fig. 9 put in evidence the overestimation made by the classical approach with respect to the proposed solution. In such an example, the classical model overestimates in 23 % the energy produced by the array under the forecast irradiance and shading profiles. Therefore, the proposed solution permits to accurately design a PV installation, and provides precise data to plan the energy delivery to the consumer or to the grid.

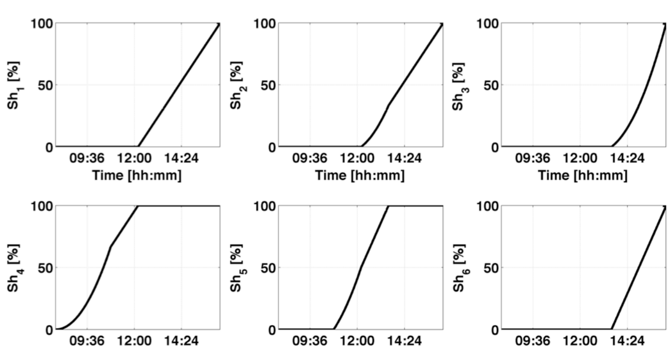

Fig. 8. Shading profiles of the affected PV modules.

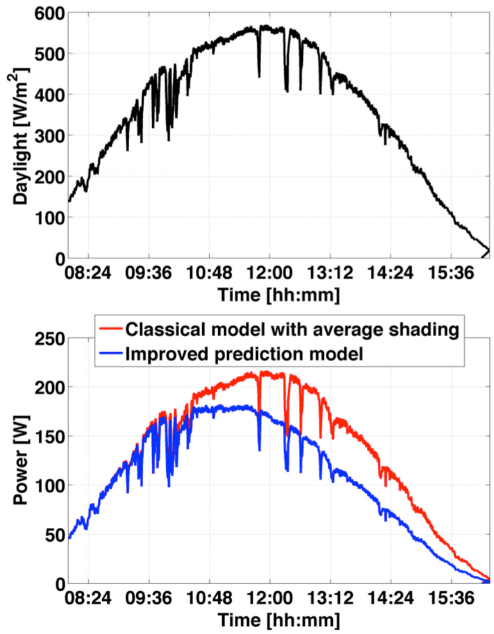

Fig. 9. Forecast irradiance and predicted array powers.

V. Conclusions

An improved model to estimate the power and energy production from photovoltaic installations under dynamic shading conditions was proposed. The approach is based on the modeling of the dynamic profile exhibited by shades affecting the irradiance reaching the PV modules. Such a solution improves significantly the power prediction accuracy in contrast with classical approaches reported in literature. In the example used to validate the model, the classical approach over-estimates the energy production in 23 %. Therefore, the proposed model supports the installation designers and grid planning engineers by giving an accurate estimation of the power production: the former ones profit from an accurate return-of-investment calculation and well-sized equipment design, which permits to evaluate the economical and technical viability of an installation. The later ones profit from the accurate power estimation to avoid unexpected power drops that trigger undesired and costly contingency plans.

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References

[1] G. Brinkman, P. Denholm, E. Drury, R. Margolis, M. Mowers, “Toward a solar-powered grid”, *IEEE power & energy magazine*, vol. 9, pp. 24-32, 2011.

[2] T. Perpétuo, S. Seleme Jr., S. Rocha, “Efficiency optimization in stand-alone photovoltaic pumping system”, *Renewable Energy*, vol. 41, pp. 220-226, 2012.

[3] C. Hachem, A. Athienitis, P. Fazio, "Parametric investigation of geometric form effects on solar potential of housing units", *Solar Energy*, vol. 85, pp. 1864-1877, 2011.

[4] J. Yoon, J. Song, S. Lee, "Practical application of building integrated photovoltaic (BIPV) system using transparent amorphous silicon thin-film PV module", *Solar Energy*, vol. 85, pp. 723-733, 2011.

[5] F. Katiraei, J.R. Agüero, "Solar PV Integration Challenges", *IEEE power & energy magazine*, vol. 9, pp. 24-32, 2011.

[6] M.L. Orozco-Gutierrez, J.M. Ramirez-Scarpetta, G. Spagnuolo, and C.A. Ramos-Paja, "A technique for mismatched PV array simulation," *Renewable Energy*, vol. 55, pp. 417-427, 2013.

[7] M. Fuentes, G. Nofuentes, J. Aguilera, D.L. Talavera, M. Castro, "Application and validation of algebraic methods to predict the behaviour of crystalline silicon PV modules in Mediterranean climates", *Solar Energy*, vol. 81, pp. 1396-1408, 2007.

[8] S. Silvestre, A. Boronat, A. Chouder, "Study of bypass diodes configuration on PV modules", *Applied Energy*, vol. 86, pp. 1632-1640, 2009.

[9] G. Petrone, C.A. Ramos-Paja, "Modeling of photovoltaic fields in mismatched conditions for energy yield evaluations", *Electric Power Systems Research*, vol. 81, pp. 1003-1013, 2011.