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Estimating the produced power by photovoltaic installations in shaded environments

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Abstract
A model to improve the estimation of the power and energy from photovoltaic installations under dynamic shading conditions is proposed in this paper. The model considers the shaded profile in each photovoltaic module and the temperature profile to update the model parameters of each photovoltaic module. The impact of dynamic shades on the power production is analyzed, illustrating the large errors introduced by classical prediction approaches, which consider non-shading at all or average shading. Moreover, a procedure to model the shades profile in any environment is described and illustrated. Finally, experimental irradiance and environment temperature profiles are used to evaluate the performance of the proposed model in contrast with the classical approaches. The results illustrate that the classical approaches overestimate the power produced by the photovoltaic array, in contrast with the power produced by the proposed model.

Keywords: mismatching conditions; photovoltaic generator; power and energy prediction; shade modeling.

Estimación de la potencia producida por instalaciones fotovoltaicas en entornos sombreados

Resumen
En este artículo se propone un modelo para mejorar la estimación de la potencia y energía de instalaciones fotovoltaicas bajo condiciones de sombreado dinámicas. El modelo considera el perfil de sombreado en cada módulo fotovoltaico y el perfil de temperatura para actualizar los parámetros del modelo de cada módulo. El impacto de las sombras dinámicas en la producción de potencia es analizado, ilustrando grandes errores introducidos por las aproximaciones de predicción clásicas, las cuales o no consideran sombreado alguno o consideran un sombreado promedio. Más aún, se describe y se ilustra un procedimiento para modelar el perfil de sombras en cualquier ambiente. Finalmente, perfiles experimentales de radiación y temperatura ambiente son utilizados para evaluar el desempeño del modelo propuesto en contraste con las aproximaciones clásicas. Los resultados muestran que las aproximaciones clásicas sobreestiman la potencia producida por el arreglo fotovoltaico, en contraste con la potencia producida por el modelo propuesto.

Palabras clave: condiciones irregulares; generador fotovoltaico; predicción de potencia y energía; modelado de sombra.

1. Introduction

Nowadays, the photovoltaic (PV) electricity generation is a cost competitive, clean and widely used option to produce electrical energy. PV power plants are suitable power sources for isolated and grid connected consumers. The main advantages of those systems are the reduced maintenance required, which contrast with the high requirement of diesel generators and fuel cells. Therefore, PV generators are an alternative for distributed generation systems and for their integration in power grids [1, 2].

An application of the PV systems is the building integrated photovoltaic covering roof surfaces with optimal solar exposure [3, 4], this is to make use of the space available on rooftops and parking lots. Such urban PV systems have generated new challenges in the sizing of the installation, the cost analysis and the planning of the power produced [5]. To address such problems the designers require to accurately predict the power that will be generated by the system. Such prediction allows the number of modules required to fulfill the consumer load profiles to be calculated, it also allows the return-of-investment time in which the installation cost will be recovered to be estimated, and it also provides the information required to schedule the appropriate instant to inject the power to the grid.

Urban environments introduce multiple sources of shading over the PV modules that are difficult to overcome, e.g. Fig. 1 shows the shading generated by a building over a set of PV modules for different times of the day. Such shades generate a mismatching effect over the PV arrays that strongly degrade the power produced [6] in a non-linear way, which is a challenge to estimate the generator power profile accurately. This topic was addressed in [3], where models of PV arrays considering different temperatures and irradiance levels are proposed. The objective of such a paper is to develop power peak prediction schemes to identify the most efficient configuration under partial shading conditions. The authors propose an electrical model where the surrounding temperature and the solar irradiance are included in the parameter values, however such average methods could over or under estimate the power produced by the PV modules, and therefore give false information in order to invest, plan or operate the system.

In addition, the shades over the modules change dynamically during the day, increasing the complexity of the power prediction. Such an aspect has been addressed by neglecting the shading effect or by averaging the shading profile [3, 7]. In [7], five algebraic methods are used to predict the behavior of PV generators under natural sunlight. The results show that the performance may be 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 of the selected prediction method. In [3], although different shading for each module is considered, the dynamic shading produced during a regular day is neglected. In any case, those methods do not take into account the different shading effect on each module and/or the dynamic change of the shades. Therefore, despite the fact that it improves the energy prediction, errors are still generated since the wide variation of the shades is not taken into account.

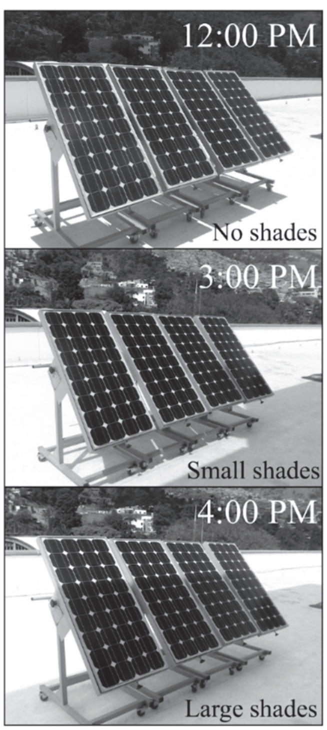

Figure 1. PV array in series-parallel structure.
Source: The Authors

In this paper a novel modeling approach able to predict the PV power profile in presence of dynamic shading conditions is proposed. Such a solution reduces the prediction errors in comparison with classical approaches by considering the effective irradiance profile for each module without any averaging process.

This paper is organized as follows: the mismatching effect to identify the aspects that must be modeled in order to improve the power prediction under shading is discussed in Section 2. Then, an array model able to calculate the PV power from the static values of the effective irradiances in each module is described in Section 3. In Section 4 the improved prediction model accounting for the dynamic changes of the shades that affect each module is introduced. Such a section also evaluates the model performance in comparison with the classical approach using an experimental irradiance profile. Finally, conclusions close the paper.

2. The mismatching effect and the bypass diodes

The mismatching effect is caused by difference between the operation conditions of PV modules that compose an array. Also, the mismatching conditions are generated by the difference between the module 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 relative sun position changes, the shape of the shade changes dynamically, producing variable mismatching conditions to the PV array. Because the sun translation is predictable, the shade profiles are also predictable, 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 will be different to the one affecting the array at another 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 turn are made of the series-connection of PV modules.

The number N of modules in a 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 a module, partially

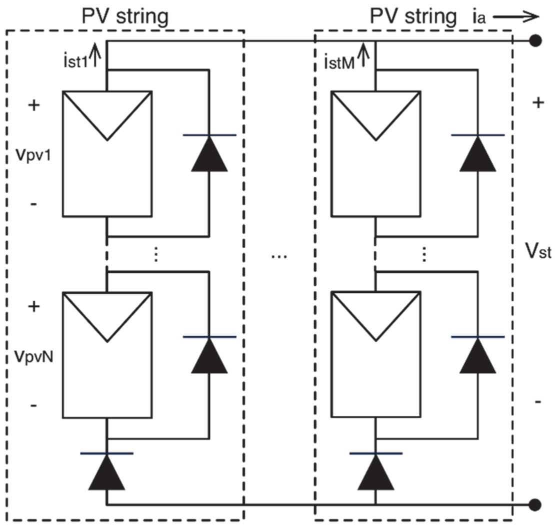

Figure 2. PV array in series-parallel structure
Source: The Authors

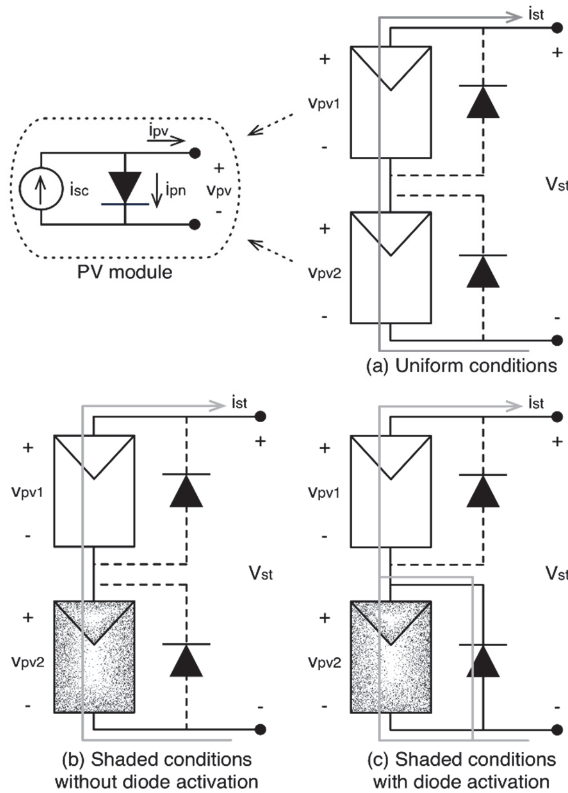

Figure 3. Bypass diodes activation.
Source: The Authors

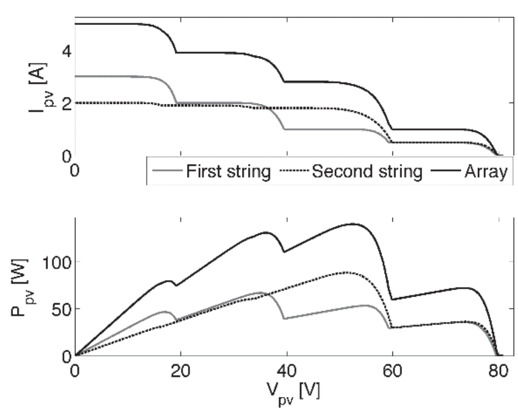

Figure 4. Shade effect on a PV array formed by two strings.
Source: [Authors]

or totally, its current could be lower than the one imposed to the string by other modules more irradiated. In such a case the PV cells associated to that module experiment with negative voltages and a fast increasing current which may cause hot spots and the destruction of the cells [8]. To avoid such negative effects, bypass diodes are connected in anti-parallel to the module, in this way the current in excess, flows through the bypass diode. Fig. 3 shows the possible cases that must be analyzed in a PV string taking into account the bypass diode operation. In Fig. 3(a) two modules are series-connected under uniform operating conditions, in this case the bypass diodes remain inactive. In Fig. 3(b) the same modules are now under irregular conditions since one of the modules is partially shaded, however the current of the string is lower than the short circuit current of the shaded module, in this case the bypass diode associated to it remains inactive. Finally in Fig. 3(c) the same modules are again under irregular conditions, but in this case the bypass diode associated to the shaded module becomes active since the current of the string is higher than the short circuit current of the shaded module [10,11].

When a bypass diode becomes active, it limits the negative voltage of the cells by imposing a value around 0.4 V to 0.7 V, which reduces the power losses and protects the cells in the module [3,12,13]. A common approach is to consider that the module associated to an active bypass diode becomes short circuited. Without loss of generality, this approach is used in this work to improve the speed calculation.

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. 4. In such an example, the strings are formed by identical PV modules but with different shading conditions, therefore at the same daytime both strings produce different power curves. On the light of such a condition, it is evident that considering uniform conditions on all the modules, introduce errors in the power estimation of shaded arrays, such an approach is reported in [7]. Therefore, the following section presents the array model adopted in this paper, which considers different operating conditions for each module, to simulate shaded arrays.

3. PV power under shading conditions

In the following, a mathematical model to calculate the PV power in shading conditions, which was introduced in [9], is described.

3.1. The PV module model

The electrical behavior of a PV module is described by a current source modeling the photo-induced current and a diode modeling the P-N junction of the module. Fig. 3a shows the module equivalent circuit, where the following equations describe its electrical characteristics [9]:

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

$$T_{pv} = T_{amb} + \frac{NOCT - 20}{800} S_{pv} \quad (2)$$

$$i_{sc} = i_{STC} \cdot \frac{S_{pv}}{S_{STC}} \left(1 + \alpha_i \cdot \left(T_{pv} - T_{STC}\right)\right) \quad (3)$$

$$B = \frac{B_{STC}}{1 + \alpha_v \cdot \left(T_{pv} - T_{STC}\right)} \quad (4)$$

$$B_{STC} = \frac{\ln\left(1 - \left(i_{mpp} / i_{STC}\right)\right)}{v_{mpp} - v_{ocSTC}} \quad (5)$$

$$A = i_{STC} \cdot \exp\left(- B_{STC} \cdot v_{ocSTC}\right) \quad (6)$$

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 (S_{pv}) and temperature (T_{pv}) which in turn depends on the ambient temperature (T_{amb}) and the Nominal Operating Cell Temperature (NOCT) expressed in °C and commonly approached to 48°C [14]. i_{STC} and v_{ocSTC} are the short-circuit current and open-circuit voltage in Standard Test Conditions (STC), respectively. T_{STC} and S_{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 α_i and α_v are the current and voltage temperature coefficients.

3.1. 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 consider 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 (7), where an inflection point occurs. In (7), the current of both modules is the same and equal to the current of module k with null voltage.

$$i_j = i_k, v_k = 0 \quad (7)$$

From (1) and (7), the inflection voltage is given by the voltage of the module j ($v_{o,j,k}$) in (8).

$$A_j \cdot \exp\left(B_j \cdot v_{o,j,k}\right) = i_{sc,j} - i_{sc.k} + A_k \quad (8)$$

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 point 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 (9), and the value of $v_{o,k}$ is calculated from (10).

$$i_{sc,m} - A_m \cdot \exp\left(B_m \cdot v_{o,m,k}\right) = i_{sc,k} - A_k \quad (9)$$

$$v_{o,k} = \sum_{m=1}^{k-1} v_{o,m,k} \quad (10)$$

From (7) and (8) 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.

3.2. 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 knowing that the string current is the same in all the modules, which defines the following non-linear system:

$$i_{sc,t} = i_1 = i_2 ... = i_k = ... i_{N_{am}} \quad (11)$$

$$\sum_{k=1}^{N_{am}} v_{pv,k} = v_{st} \quad (12)$$

The non-linear system in (11)-(12) 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. However 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 surround 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 point currents. Such a characteristic speeds-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 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 the array power for different irradiance conditions in each module to be calculated. But a proper model to introduce profiles that affect individual modules, producing dynamic shading conditions, is required. Such a topic is addressed in the following section.

4. Improved prediction model

The classical prediction model used to estimate the power and energy profiles in a PV installation are depicted in the top of Fig. 5. In such a structure, the modules are assumed uniformly irradiated, hence expressions based on (1) but scaling the voltage and current in agreement with N and M, are used to calculate the array power for an irradiance condition. Such a model is fed 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 gray trace in the bottom of Fig. 6 corresponds to the power curve of a four-modules string predicted with the classical model. 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 dotted 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 black 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.

In 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 affects 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 $[S_1, \dots S_i, \dots S_N]$ to feed the model described in Section 3. A forecast of temperature was also considered to recalculate

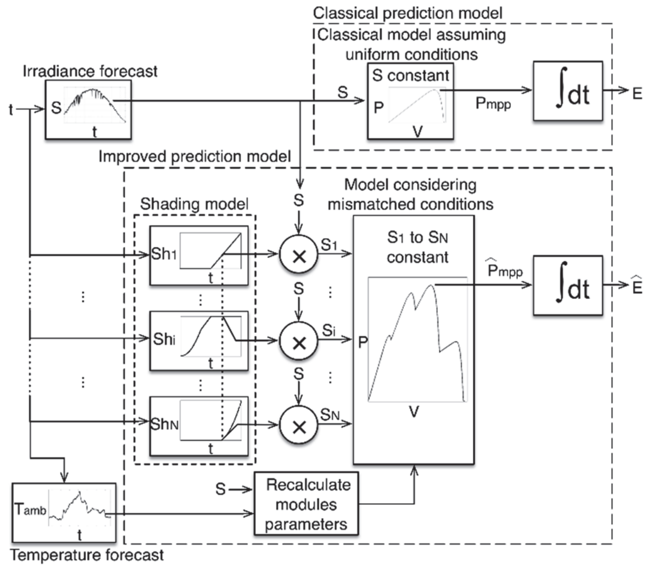

Figure 5. Prediction structures to estimate PV power profile and energy.
Source: The Authors

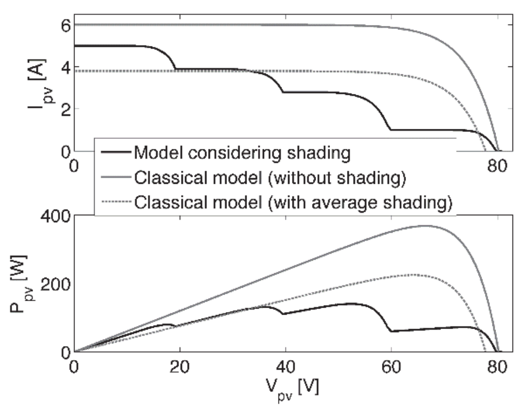

Figure 6. Electrical characteristics predicted under shading conditions.
Source: The Authors

the PV module parameters for each irradiance condition which also improve the accuracy of the prediction model. In this way, the MPP power for each irradiance condition forms the power profile to predict the energy production.

4.1. *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, data from the place to evaluate is required. 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 while 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 (3) 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 modules are 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 (13).

$$Sh_i(t) = \frac{S_{test,j}(t)}{S(t)} \quad (13)$$

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. These shading profiles were taken on a winter day in southern Italy, where the angle of the sun allows the projection of the shadows.

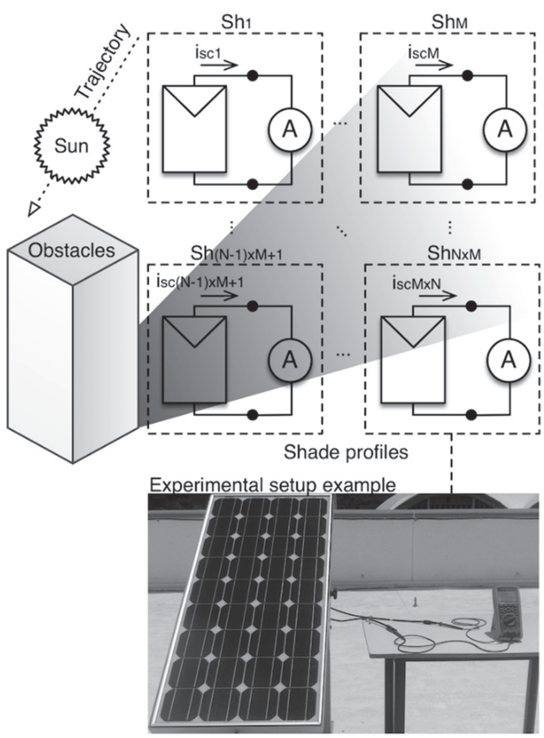

Figure 7. Shade measurement architecture.
Source: The Authors

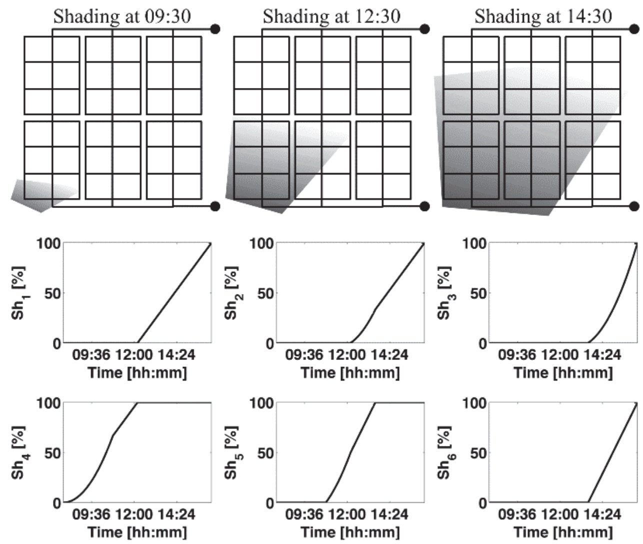

Figure 8. Shading profiles of the affected PV modules.
Source: The Authors

4.2. *Model performance evaluation*

To illustrate the performance of the proposed prediction model, an experimental irradiance profile, taken in the south of Italy on 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 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 by 23% the energy produced by the array under the forecast irradiance and shading profiles. Therefore, the proposed solution allows a PV installation to be accurately designed, and provides precise information to plan the energy delivery to the consumer or to the grid.

5. 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 an evaluation of the economic and technical viability of an installation.

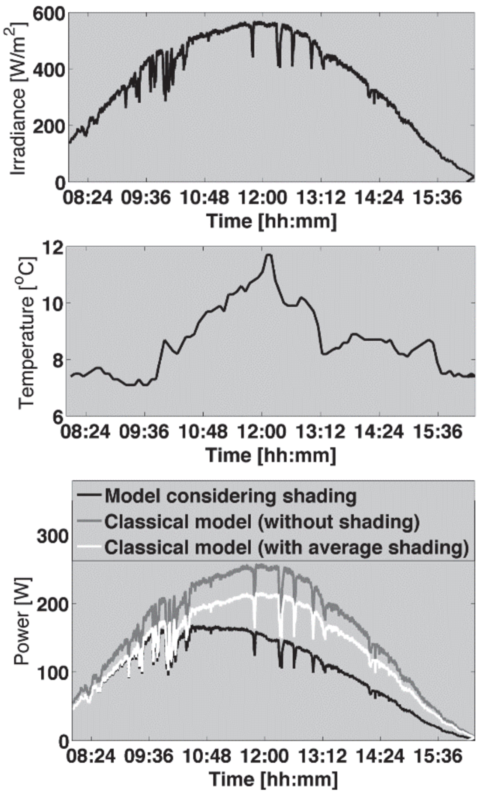

Figure 9. Predicted array powers for winter irradiance and temperature forecast.
Source: The Authors

The later ones profit from the accurate power estimation to avoid unexpected power drops that trigger undesired and costly contingency plans.

Acknowledgements

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