Energy Conversion and Management 150 (2017) 433–450

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

# A method to estimate the energy production of photovoltaic trackers under shading conditions

Eloy Díaz-Dorado, José Cidrás, Camilo Carrillo*

University of Vigo, Spain

ARTICLE INFO

*Keywords:*
Photovoltaic systems
Photovoltaic cells
Partial shading
Ground cover ratio
Planning

ABSTRACT

Energy produced by a photovoltaic park mainly depends on solar irradiance. However in order to estimate the energy production, it must be taken into account the technology of PV-modules, their layout and the electrical connection between them. Furthermore, the energy losses, especially those related to non-uniform distribution of irradiance must be considered. In this context, in a PV-park it is specially important losses related to shadows between trackers. These must be properly estimated to propose different configurations or to evaluate the efficiency of the installation.

In this context, this article presents a methodology to evaluate the energy production of a PV-park where PV-trackers are modeled from their simplest elements to the PV-array. The energy calculation includes losses; therefore, shadows are analyzed and included as irregular distributions of irradiance along the tracker plane. The presented method allows for the analysis of different design criteria: PV-cells and PV-modules arrangement, PV-cell electrical connections inside a module and electrical connections between PV-modules, tracker layout on the ground and tracker dimensions.

Furthermore, the proposed method allows evaluation of the annual energy generation and the losses due to the trackers' shadows, accounting for the irradiance and the temperature.

## 1. Introduction

One usual matter of concern in the analysis of photovoltaic (PV) installations is the estimation of the energy produced under different working conditions, e.g. those far from the rated ones. In this context, one of the most complex situations that is usually found is the estimation of the energy produced when a PV park has no uniform irradiance on its elements. This is a typical situation, and the matter of this paper, in parks formed by sun trackers where partial shading between trackers is quite common.

To accurately analyze the effects of partial shading in PV installations, a detailed model is necessary that takes into account their simplest elements, cells and diodes, and the different electrical connections between them forming panels, strings and, finally, arrays [1,2]. This kind of modeling is usually referred as "cell to array" approach [1] and it is typically implemented in commercially available circuit simulations packages [3–5] or even in specific software for PV systems [6,7]. However, the use of commercial software could limit its use, e.g., for planning purposes and energy assessment.

Shading effects of partial shading on the electrical behavior of PV systems have been analyzed by several authors [1,8–12]. Nevertheless, most of them cannot be used to accurately obtain the energy yield for a PV array with an arbitrary configuration. Usually, the PV-array analysis is done by using different kinds of simplifications. For example, in [13] several simplifications on PV-cell and PV-module models, e.g. the reverse biasing of PV-cells is not considered, have been used to obtain the P-V curve for a partially shaded PV-array. Another kind of simplification consists in restricting the type of shadow to be analyzed [10,11,14–17]. For example, in [15] the MPP values are obtained for long strings and parallel-connected short strings under partial shading conditions. Nevertheless, only complete series of cells with a bypass diode are considered to be shaded. Finally, several authors propose empirical expression to obtain power losses without modeling the PV-array in detail, e.g. in [18].

Regarding field layout of trackers, Refs. [7,19] present the first works dedicated to the minimization of energy losses in PV-tracker parks considering the layout as an input for the optimizations process. In those papers, two examples are used to compare the results of square and hexagonal ground layouts although several simplifications on radiation [19] or granularity of analysis [7] are applied. Most papers related to these ones, [10,16,20–23], put their efforts in modeling shadow geometry for different kind of trackers or field geometries but uses simplifications to obtain the energy losses without considering, for example, the different electrical configurations of PV elements. In [10], a metaheuristic method

---

* Corresponding author.

*E-mail addresses:* ediaz@uvigo.es (E. Díaz-Dorado), jcidras@uvigo.es (J. Cidrás), carrillo@uvigo.es (C. Carrillo).

http://dx.doi.org/10.1016/j.enconman.2017.08.022
Received 7 February 2017; Received in revised form 15 July 2017; Accepted 7 August 2017

## Nomenclature

| | |
|---|---|
| $a$ | fraction of ohmic current in avalanche breakdown |
| $d$ | distance between two trackers |
| $D$ | width of the module |
| $E_{sunny,\alpha\gamma}$ | annual energy production of a PV-tracker under sunny weather conditions for sun position (α, γ) |
| $E_{cloudy,\alpha\gamma}$ | annual energy production of a PV-tracker under cloudy weather conditions for sun position (α, γ) |
| $E_{annual}$ | annual electrical energy produced by a PV-tracker |
| $G$ | global irradiance |
| $G_b$ | beam irradiance |
| $G_d$ | diffuse irradiance |
| $G_r$ | reflected irradiance |
| $h$ | height of the tracker |
| $H_{sunny,\alpha\gamma}$ | irradiation on a tracker under sunny weather conditions for each sun azimuth α and elevation γ when no shading is considered |
| $H_{cloudy,\alpha\gamma}$ | irradiation on a tracker under cloudy weather conditions for each sun azimuth α and elevation γ when no shading is considered |
| $I$ | current |
| $I_{sc0}$ | short circuit current |
| $K_b$ | Boltzmann constant |
| $K_I$ | temperature coefficient of short circuit current |
| $K_P$ | temperature coefficient of MPP power |
| $K_V$ | temperature coefficient of open circuit voltage |
| $l$ | width of the shaded area |
| $L$ | width of the module |
| $L_{annual}$ | annual energy losses |
| $m$ | avalanche breakdown exponent |
| $n$ | ideality factor of cell |
| $n_s$ | number of PV-modules in each PV-string |
| $n_p$ | number of PV-strings in each PV-array |
| $n_f$ | number of rows in a PV-string |
| $n_c$ | number of columns in a PV-string |
| $P^{MPP}_{cell,G}$ | cell MPP power with irradiance $G$ |
| $P^{MPP}_{array,G}$ | array MPP power with irradiance $G$ |
| $P^{MPP}_{array,xy}$ | array MPP power with shaded area ($x$, $y$) |
| $q$ | elementary charge |
| $r_G$ | relationship between indirect and global irradiance |
| $R_s$ | series resistance of PV-cell |
| $R_{sh}$ | shunt resistance of PV-cell |
| $u_0$ | abscissa of the projection of the center of one tracker on another |
| $V$ | voltage |
| $S$ | complete area of the cast shadow on a PV-tracker |
| $s$ | surface area of a PV-cell |
| $T$ | temperature |
| $T_m$ | annual mean temperature |
| $T_n$ | nominal temperature |
| $V_{array,xy}$ | array MPP voltage with shaded area ($x$, $y$) |
| $V_{br}$ | junction breakdown voltage |
| $V_{oc0}$ | open circuit voltage |
| $v_0$ | ordinate of the projection of the center of one tracker on another |
| $w$ | width of the tracker |
| $x$ | horizontal size of the shaded area |
| $y$ | vertical size of the shaded area |

### *Greek letters*

| | |
|---|---|
| $\alpha$ | azimuth angle of the sun position |
| $\alpha_0$ | relative azimuth between two trackers |
| $\phi$ | azimuth angle of normal vector of a plane |
| $\theta$ | elevation angle of normal vector of a plane |
| $\theta_0$ | fixed elevation angle of normal vector of a single-axis tracker |
| $\gamma$ | elevation angle of the sun position |
| $\delta$ | height of the shaded area |
| $\Delta t_{\text{sunny},\alpha\gamma}$ | annual period of time under sunny weather conditions with sun azimuth α and elevation γ |
| $\Delta t_{\text{cloudy},\alpha\gamma}$ | annual period of time under cloudy weather conditions with sun azimuth α and elevation γ |
| $\xi$ | rectangular shaded area ratio for a PV-module |
| $\eta_{xy}$ | efficiency coefficients of the tracker with shaded area ($x$, $y$) |
| $\eta_{\alpha\gamma}$ | efficiency coefficients of the tracker for sun position (α, γ) |
| $\rho_g$ | albedo or ground reflectance |
| $\sigma_i$ | shading coefficient |

### *Subscripts*

| | |
|---|---|
| *b* | beam or normal |
| *cloudy* | under cloudy weather conditions |
| *d* | diffuse |
| *h* | on horizontal plane |
| *n* | on normal plane |
| *r* | reflected |
| *sunny* | under sunny weather conditions |
| *xy* | of sizes $x$ and $y$ |
| αγ | azimuth angle α and elevation angle γ of sun position |
| γθ | azimuth angle γ and elevation angle θ of tracker |

is presented based on evolutionary strategies that are used to obtain the best location of each tracker on a terrain of irregular shape; where it has been taken into account the energy losses caused by shadows from nearby obstacles and between PV-trackers. In [21], results are presented for simulations of the energy yield of flat panels for different locations and tracking strategies as a function of the ground cover ratio, but certain limitations on shadows are applied. In any case, some interesting results for design purposes are shown, such as the optimal position of solar trackers on the ground depending on land availability or the energy gains of each tracking strategy. Similarly, in [22], the energy production for different tracking strategies in a PV park is analyzed, although the layout of PV-modules on the tracker and their electrical connections are not taken into account in the optimization process.

One of the aspects to be analyzed in PV-parks is the geometry of the shadows cast between trackers. Although there are several software packages [6,24] that help to obtain those shadows, in order to easily integrate the results in the energy yield calculation, a trigonometric approach that considers one-axis and two-axis trackers has been used in the proposed method [16,20,25]. After analyzing the equations related to shadow geometry, it has been demonstrated in this paper that its shape is rectangular which makes easier the shadows modeling.

As a resume, the proposed method allows an accurate estimation of the production of a PV-park by considering the following aspects, which are only partially taken into account by the different methods previously commented: PV technology, a high order model for PV-cell including reverse biasing, cell-to-array modeling, shadow geometry, tracker layout (module layout and electrical connections), field layout and annual irradiance. The proposed method allows the calculation the complete P-V curve in a PV system with rectangular shadows. These values, along with a solar energy chart, allow the energy assessment of a PV-park (see Fig. 1).

Finally, it must be considered that the cell to array modeling requires the developing of the entire electric circuit of a PV-tracker so, it