

On the Dependence between the Step Orientation and the Received Direct Solar Radiation of a PV Panel. Part II: The Step Pseudo-Equatorial Orientation

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Abstract. This second part of the paper approaches a problem that is referring to the energetic efficiency maximization of a tracked PV panel, which consists in maximizing the received solar radiation and minimizing the driving energy. The objective is to optimize the “received direct solar radiation” – “number of daytime tracking steps” correlation for a *pseudo-equatorially* tracked PV panel (Fig. 1). The solution presented is a graphical one and an analytical model will be developed in the future.

Key words

PV panel, incidence angle, direct solar radiation, pseudo-equatorial tracker, steps' orientation.

1. Introduction

The main objective of this second part of the paper is to determine the influence of several steps' orientation on the received direct solar radiation.

In order to achieve this objective, firstly the expressions for the unit vectors of the sunray and of the normal to a *pseudo-equatorial** tracked PV (Fig. 1.) panel are needed.

Secondly, with the help of the unit vectors, the expressions of the incidence angle and the received direct solar radiation can be determined, for the considered tracker type.

Thirdly and lastly, the paper presents nomographic charts (Fig. 2 and 3) for a pseudo-equatorial tracker, generated with numerical simulations, which allow the graphical establishment of the parameters that help optimize the correlation between daytime (active) steps' number and the direct received solar radiation.

In the end, the paper also states the resulted conclusions derived from the numerical simulations and graphical optimizations, which together with the analytical models are very useful in the mathematical optimization of the step orientation program for a *pseudo-equatorial* tracker, taking into account real geographical data.

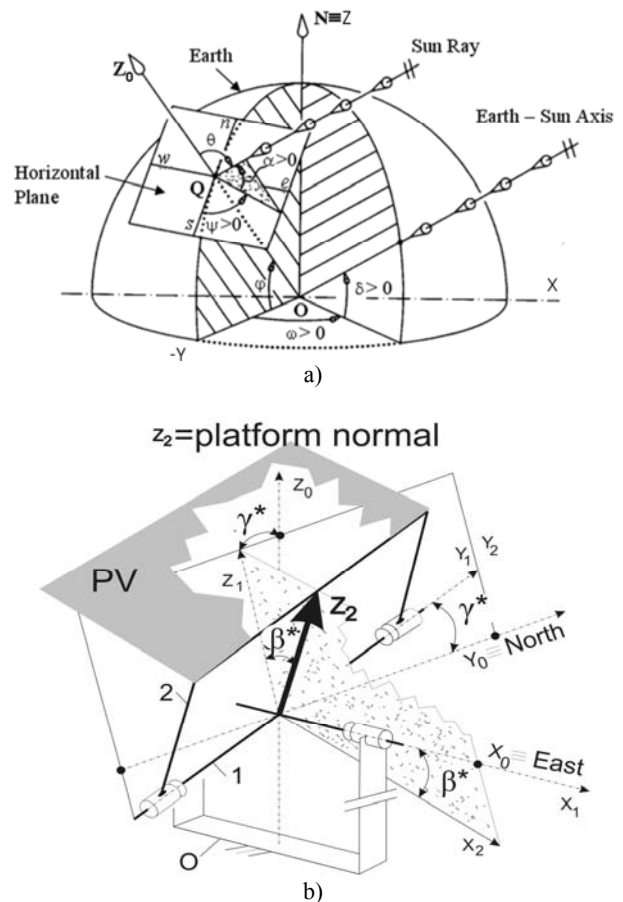


Fig. 1. The sun-ray angles and geometrical scheme of the *pseudo-equatorial* tracker, where $\beta^* \approx \omega^*$ and $\gamma^* \approx (\varphi - \delta)$

* The frequently used *pseudo-equatorial* tracker is derived from the less used *equatorial* tracker (ω , $\varphi - \delta$, Fig.1,a) by the inverting the order of the rotation axes.

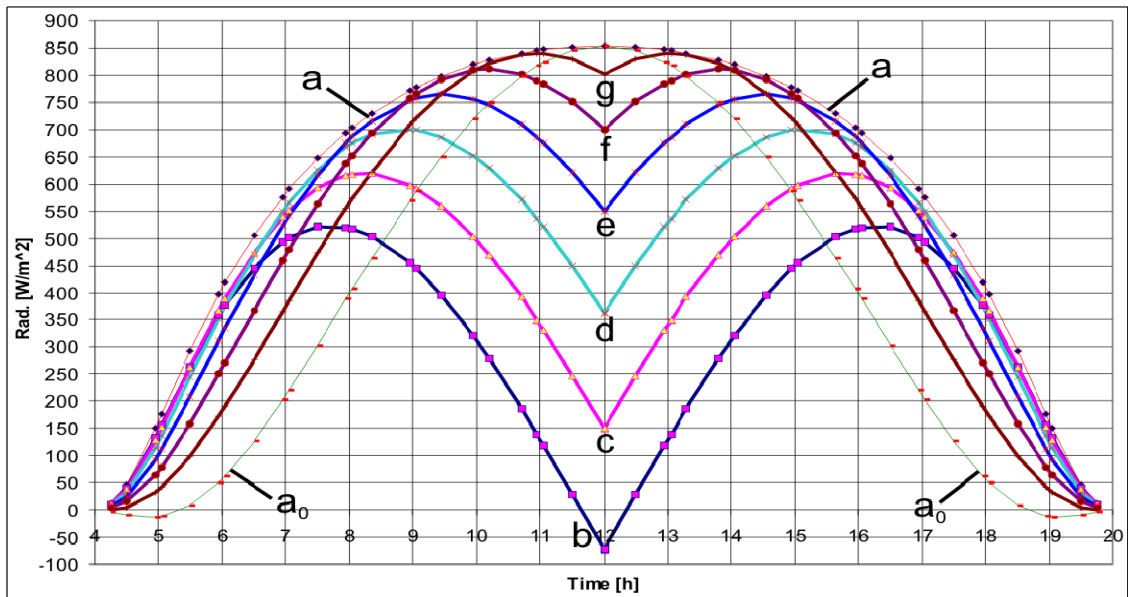


Fig. 2. Nomographic chart with variations of the received direct solar radiation during the Summer Solstice ($\delta = +22,5^\circ$):
 a – total available; a_0 – for a tilted fixed panel ($\omega^* = 0^\circ$); b – for panel with $\omega^* = \pm 95^\circ$;
 c – for $\omega^* = \pm 80^\circ$; d – for $\omega^* = \pm 65^\circ$; e – for $\omega^* = \pm 50^\circ$; f – for $\omega^* = \pm 35^\circ$; g – for $\omega^* = \pm 20^\circ$.

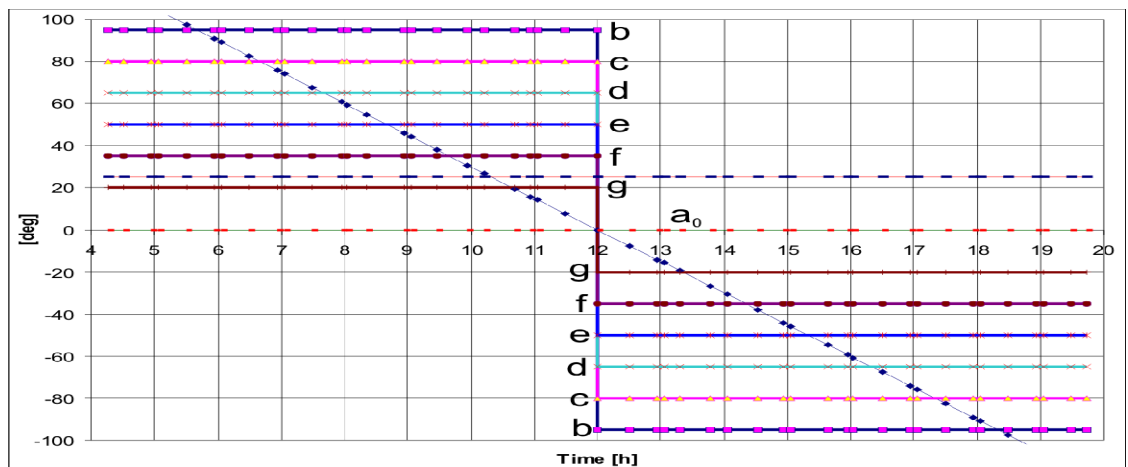


Fig.3. Nomographic charts with variations of hour angles during the Summer Solstice ($\delta = +22,5^\circ$): a_0 – for $\omega^* = 0^\circ$ (tilted fixed PV panel), b – for panel with $\omega^* = \pm 95^\circ$, c – for $\omega^* = \pm 80^\circ$, d – for $\omega^* = \pm 65^\circ$, e – for $\omega^* = \pm 50^\circ$, f – for $\omega^* = \pm 35^\circ$, g – for $\omega^* = \pm 20^\circ$.

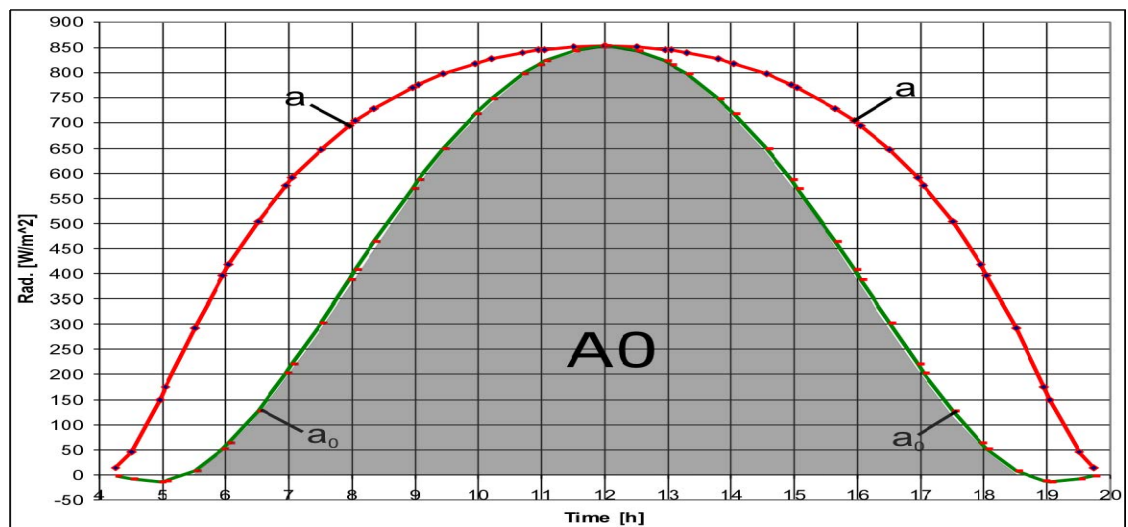


Fig. 4. Variations of the solar direct radiation during the Summer Solstice for:
 a - available radiation, a_0 – for $\omega^* = \pm 0^\circ$ (0 tracking steps = a tilted fixed PV panel)

2. Modeling

In order to be able to track the PV panel one has to know the exact direction of the sun ray. This data can be obtained by using one of the two available systems in which the sun's path can be depicted: the *equatorial* (global) system and the *azimuthal* (local) system. The angles used in the first system are (s. Fig. 1.a): declination (δ) and hour angle (ω), while those used in the second one are (see Fig. 2 and 4): altitude (α) and azimuth angle (ψ).

Because of energetic and economical reasons, the angular displacements of the tracked PV solar panel are made discontinuously (in steps), so the tracker's angles have discrete variations. In order to distinguish them from the sun-ray angles (which have continuous variations: ω , δ ; and γ , β) in the below correlations the tracker's angles are marked with asterisk: ω^* , δ^* and γ^* , β^* (see Fig. 1.b); so, the sizes γ^* and β^* (effectuated by a *pseudo-equatorial* tracker) approximate the variations of the sizes γ and β (effectuated by the sun-ray). Obviously, when the tracker makes the angular displacements continuously, then: $\gamma^* = \gamma$ and $\beta^* = \beta$.

By means of these angles, further on there are modeled: 2.1 the *unit vectors* for the sun-ray and for the normal to the panel, 2.2 the *incidence angle* and 2.3 the *direct solar radiation* that falls on the PV panel.

2.1. *The unit vectors* for the sun-ray and for the normal to the panel are modeled using Fig. 1.(a,b):

$$[\bar{e}_{sr}]_{xyz} = \begin{bmatrix} \cos \delta \cdot \sin \omega \\ -\cos \delta \cdot \cos \omega \\ \sin \delta \end{bmatrix}; \quad (1)$$

$$[\bar{e}_{PV}]_{xyz} = \begin{bmatrix} \sin \omega^* \\ -\sin(\varphi - \delta) \cdot \cos \omega^* \\ \cos(\varphi - \delta) \cdot \cos \omega^* \end{bmatrix}; \quad (2)$$

2.2. *The incidence angle*, depicted as the angle between the sunray and the normal to the PV panel, results as the "dot product" of the previous two unit vectors:

$$\cos \nu = \cos \beta \cos \beta^* \cos(\gamma - \gamma^*) + \sin \beta \sin \beta^* \quad (3)$$

2.3. *The direct solar radiation* R_d [W/m²] depends on the hour and day by the following expression [3]:

$$R_d = 1367 \cdot [1 + 0,0334 \cos(0,9856^\circ \cdot N - 2,72^\circ)] e^{-\frac{T_R}{0,9+9,4 \sin \alpha}} \quad (4)$$

where N – number of the day, α – altitude from relation (4) and T_R – a factor whose values can be found in [3].

The part of the *whole direct radiation* R_d that falls on the panel, named *panel received direct radiation*, is given by relation (the *Lambert's cosine law*):

$$R_{dr} = R_d \cdot \cos \nu; \quad (5)$$

Because $R_d \neq \text{constant}$ the efficiency optimization of the tracker demands an incidence angle variation which maximizes the size R_{dr} .

3. Problem statement and its graphical solving

We divided the optimal step orientation problem in two sub-problems:

a) the maximization of the received direct solar radiation, by optimizing the correlation between *active steps' number* and *received direct solar radiation*;

b) the minimization of the consumed energy needed for powering of the electrical actuators.

The actual paper resolves only the first sub-problem, presenting a graphical solution for maximizing the received direct solar radiation.

The following nomographic charts, representing numerical exemplifications, have as input data: summer solstice (21st June, day number=172), latitude $\varphi=45^\circ\text{N}$, tracker angle $\gamma^*=25^\circ$ (see Fig.1), and radiation loss coefficient $Tr=4,2$ [3].

Based on this input data, in Fig. 2. ... 9 a set of diagrams is presented, corresponding to the following discrete variation of the hour angle: $\omega^*=[\pm 95^\circ, \pm 80^\circ, \pm 65^\circ, \pm 50^\circ, \pm 35^\circ, \pm 20^\circ, 0^\circ]$. This set of diagrams allows us to graphically optimize the *daytime (active) steps' number* – *received direct solar radiation* correlation, using 0, 1, 2, 3 or 4 steps.

In Fig. 4, 5, 6, 7, 8 the relative weight of the successive 4 steps referring to the direct received solar radiation is illustrated for a *pseudo-equatorial* tracked PV panel against a fixed and tilted one. The main idea that results from all these figures is that in the case of *even* steps' number the radiation gain is during the noon, whereas for *odd* steps' number the gain is achieved during the morning and afternoon.

If the PV panel remains fixed (0 tracking steps) at $\omega^*=0^\circ$ (see Fig. 2 and 4), the PV panel receives an energy corresponding to the $A0$ area (Fig. 4), under the line a_0 .

When the pseudo-equatorial tracker makes a single step (1, see Fig. 2 and 5) at noon, the panel receives energy corresponding to the $A1$ area (Fig. 5), under the line f ($\omega^*=\pm 35^\circ$). So, unlike the previous case, the first step brings up a received energy gain corresponding to the area $A1-A0$ (see Fig. 4 and 5).

If the pseudo-equatorial tracker makes two steps (1 and 2, see Fig. 2 and 6), the panel receives energy corresponding to the $A2 + B2$ area (Fig.6), which is maximum for the line e ($\omega^*=\pm 50^\circ$) intersected with line a_0 ($\omega^*=0^\circ$). So, unlike the case from Fig. 5, the two tracking steps 1 and 2 (Fig. 6) bring up a received energy gain corresponding to the $B2$ area.

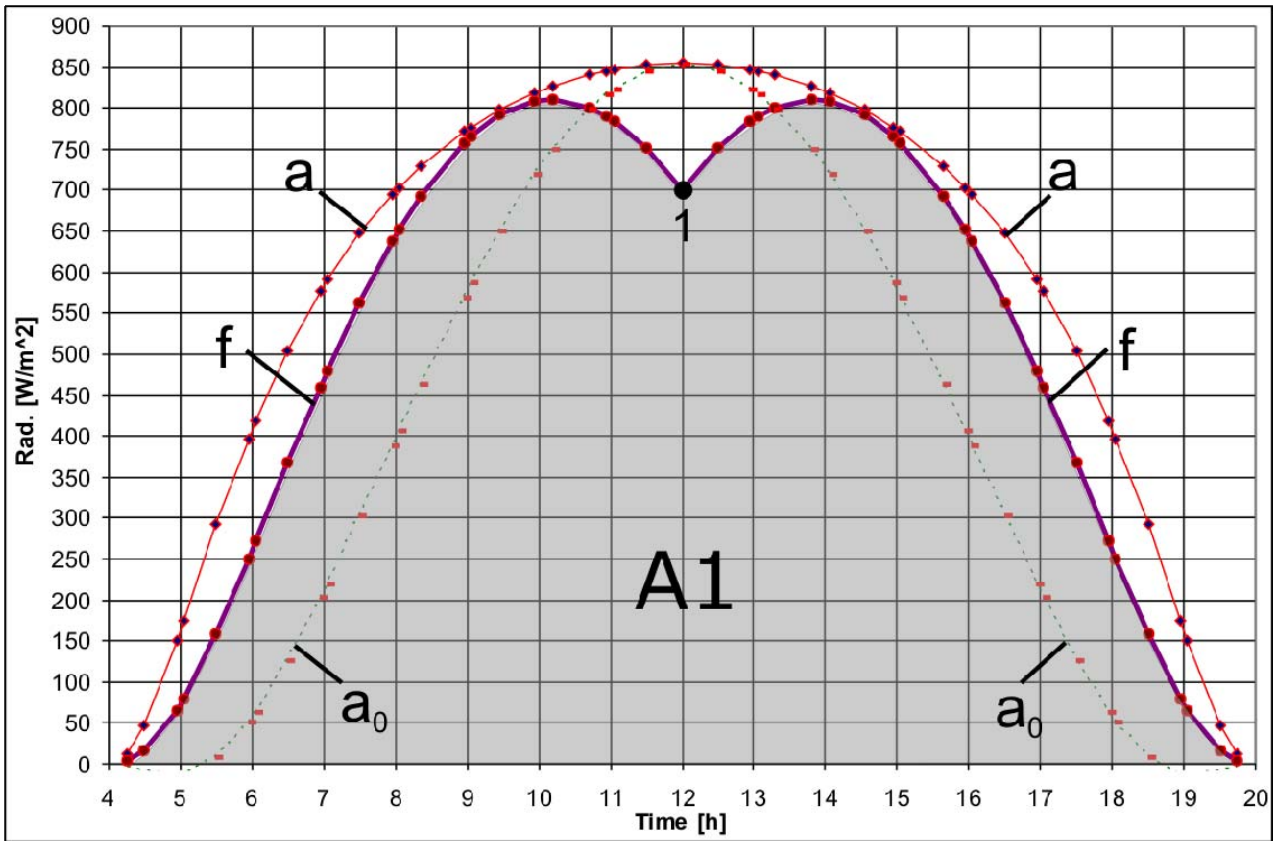


Fig. 5. Summer solstice variations of the received direct solar radiation of a pseudo-equatorial tracked PV panel, for one tracking step (1): a - available radiation, a_0 - for a tilted and fixed PV panel, f - for a PV panel with $\omega^* = \pm 35^\circ$.

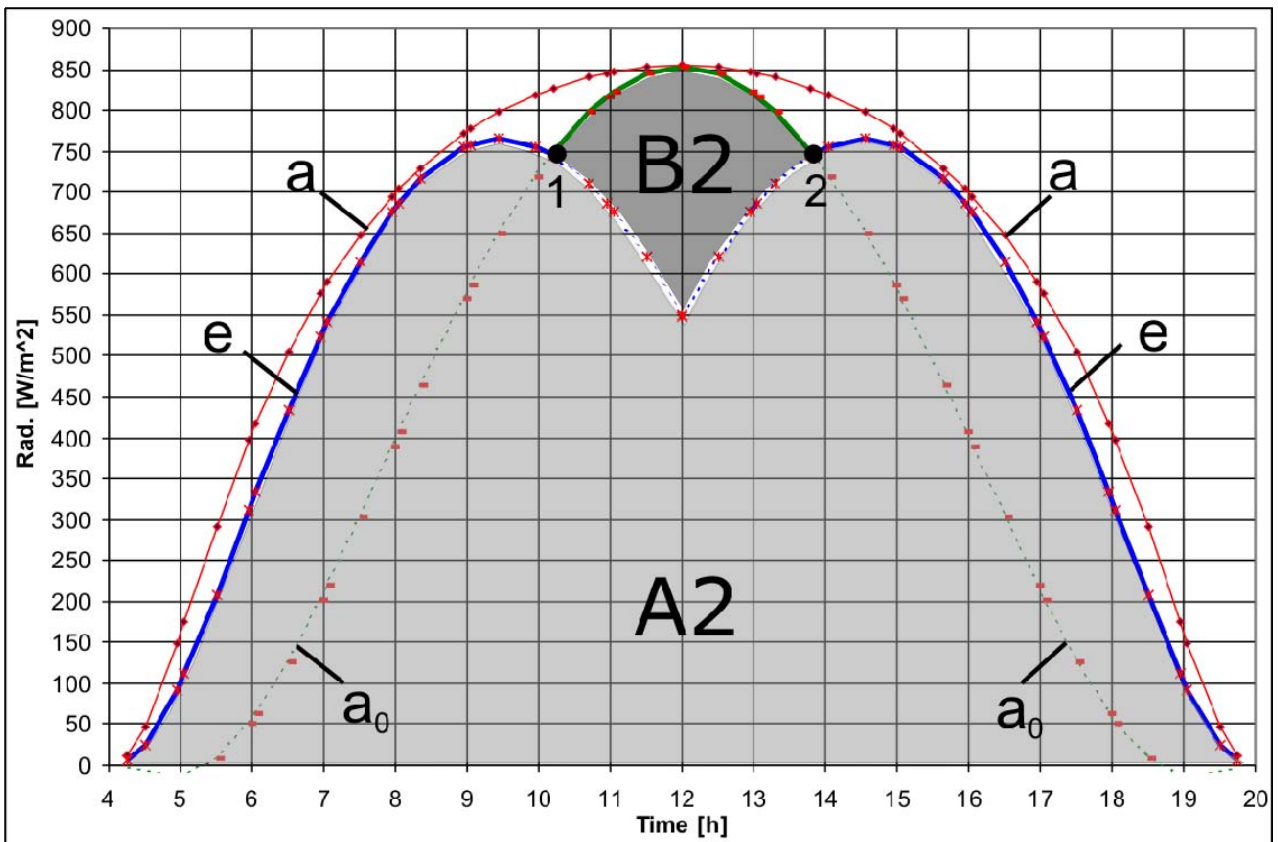


Fig. 6. Summer solstice variations of the received direct solar radiation of a pseudo-equatorial tracked PV panel, for two tracking steps (1 and 2): a - available radiation, a_0 - for a tilted and fixed PV panel, e- for a PV panel with $\omega^* = \pm 50^\circ$.

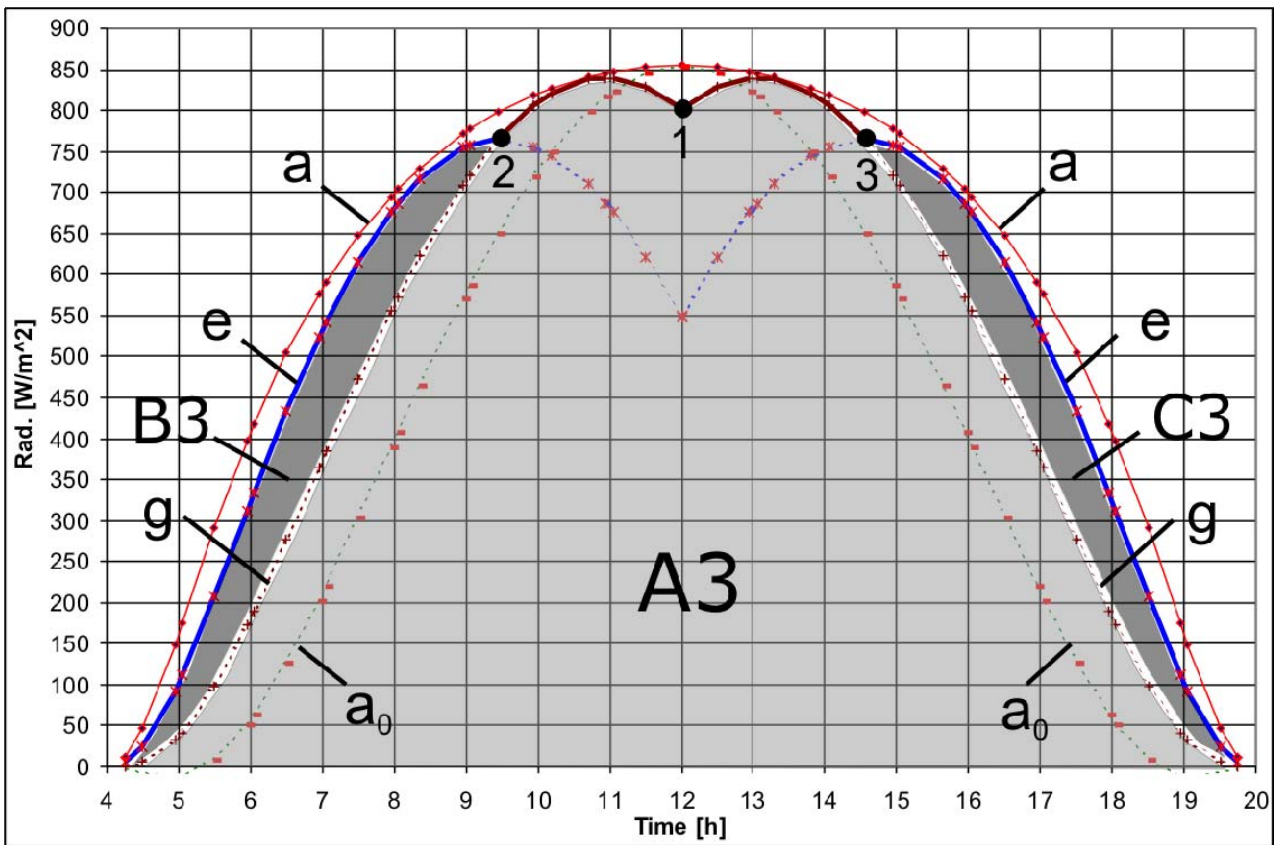


Fig. 7. Summer solstice variations of the received direct solar radiation of a pseudo-equatorial tracked PV panel, for three tracking steps (1, 2 and 3): a - available radiation, a_0 - for a tilted and fixed PV panel, e- for a PV panel with $\omega^* = \pm 50^\circ$ and g - for $\omega^* = \pm 20^\circ$.

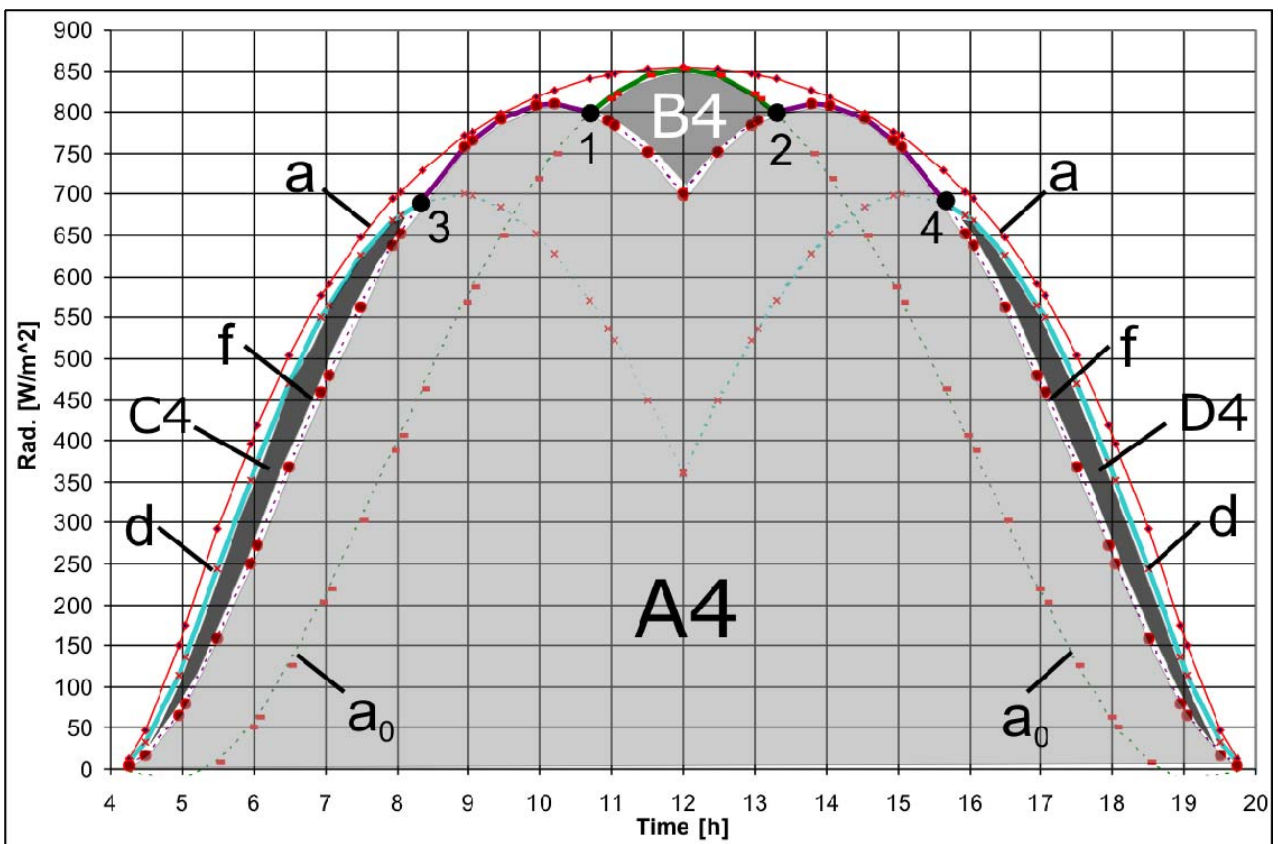


Fig. 8. Summer solstice variations of the received direct solar radiation of a pseudo-equatorial tracked PV panel, for four tracking steps (1, 2, 3 and 4): a - available radiation, a_0 - for a tilted and fixed PV panel, d - for a PV panel with $\omega^* = \pm 65^\circ$ and f - for $\omega^* = \pm 35^\circ$.

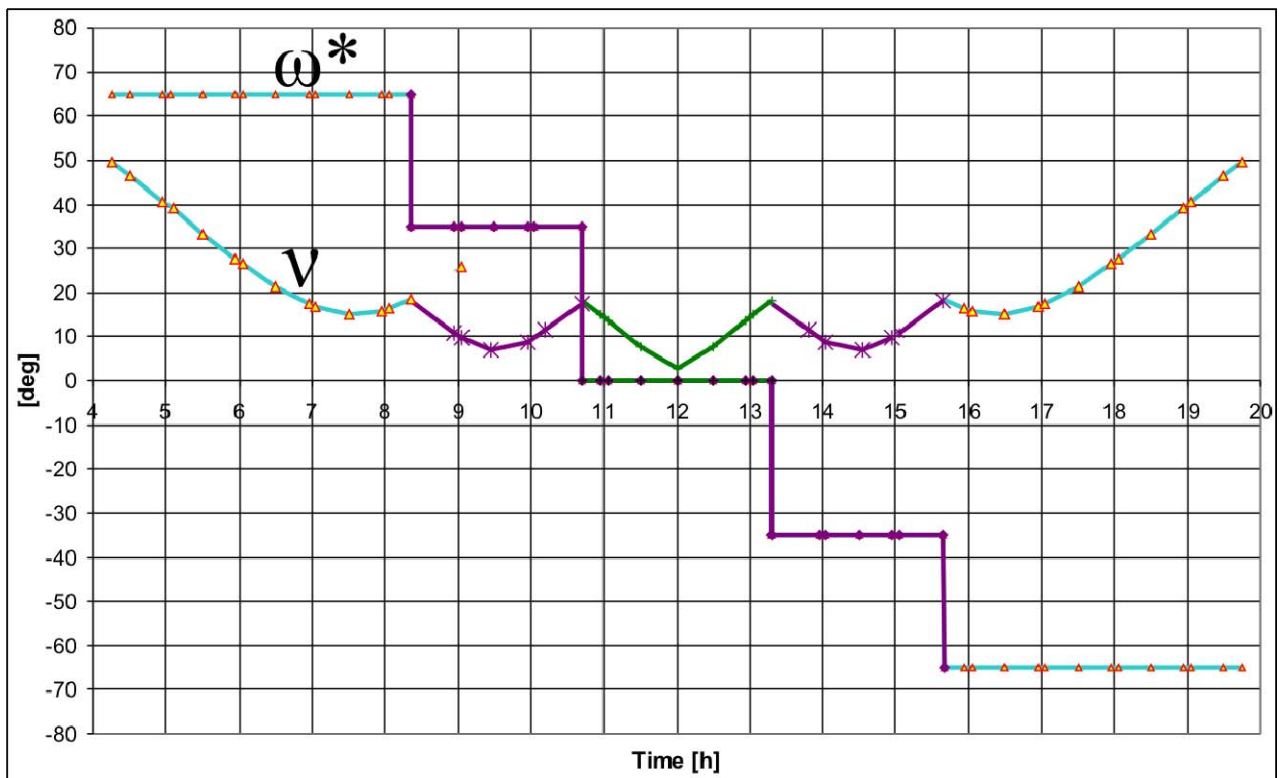


Fig. 9. Summer solstice variations of the incidence angle and of the orientation angles for a pseudo-equatorial tracked PV panel, for 4 tracking steps

When the pseudo-equatorial tracker makes three steps (1, 2 and 3, see Fig. 2 and 7), the panel receives energy corresponding to the $A3+B3+C3$ area (Fig. 7), which is maximum for the lines e ($\omega^*=\pm 50^\circ$) intersected with line g ($\omega^*=\pm 20^\circ$) from Fig. 2. So, unlike the case from Fig. 6, the tracking steps 1, 2 and 3 (Fig. 7) bring up a received energy gain corresponding to the $[(A3+B3+C3)-(A2+B2)]$ area.

If the pseudo-equatorial tracker makes four steps (1, 2, 3 and 4, see Fig. 3 and 8), the panel receives energy corresponding to the $A4+B4+C4+D4$ area (Fig. 8), which is maximum for the lines d ($\omega_d^*=\pm 65^\circ$) intersected with f ($\omega_f^*=\pm 35^\circ$) and a_0 ($\omega^*=0^\circ$) from Fig. 2. So, unlike the case from Fig. 7, the tracking steps 1, 2, 3 and 4 (Fig. 8) bring up a received energy gain corresponding to the $[(A4+B4+C4+D4)-(A3+B3+C3)]$ area. The variation of the incidence angle (v) and of the hour – angle (ω^*), for the case of the tracking with 4 steps (Fig. 8), is presented in Fig. 9.

This cases show that the first steps bring up the maximum energy, while the last steps bring up the minimum energy; so, the optimal steps' number is that in which the energy brought by last step is more than the driving energy of this step.

4. Conclusios

The main conclusions that can be stated taking into account the previous radiation diagrams are:

- the received radiation gain, brought by every step decreases with its order number;

- the optimal steps' number is the one, for that the energetic gain can be compared with the energetic consumption of the actuators;
- considering the previous conclusion, it results that the choosing of the minimum number of steps, respectively of the optimum orientation program depends on the energetic performances of the actuators used for tracking;
- in the design of the tracking program it is necessary to model the optimization for a big enough number of steps, determining so the best values of the (ω_j and $(\phi-\delta)_j$) parameters, which assure the maximum energy for each considered step;
- the analytical development of this aspect, using the MatLab software, will be presented in a future paper.

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