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ON THE DEPENDENCE OF THE RECEIVED DIRECT SOLAR RADIATION ON THE PV PSEUDO-EQUATORIAL TRACKING STEPS' NUMBER

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Abstract: 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*[1] tracked PV panel (Fig. 1). The paper contains a graphical explanation, of the solutions obtained by numerical simulations based on an analytical model developed by authors.

1. INTRODUCTION

The main objective of this paper is to determine the influence of several tracking steps on the direct solar radiation, which falls perpendicularly (normally) on a PV panel with pseudo-equatorial tracking; this component of the direct solar radiation is named *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 tracking type.

Thirdly and lastly, the paper presents nomographic charts (Fig. 2 and 3), generated with numerical simulations based on an analytical model developed by the authors for a pseudo-equatorial tracking, which allow a simplified graphical presentation 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, which together with the analytical models are very useful in the mathematical optimization of the step orientation program for a *pseudo-equatorial* tracking, considering also the real geographical data.

2. MODELING

In order to be able to track the PV panel, the exact direction of the sunray is to be known [1, 3, 4 and 5]. For the pseudo-equatorial tracker, this data can be obtained by using the *equatorial* (global) system. The angles used in this system are (Fig. 1a): declination (δ) and hour angle (ω).

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 discreet variations. In order to distinguish them from the sunray 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^* (Fig. 1d); so, the sizes γ^* and β^* (and their angular

[1] The frequently used *pseudo-equatorial* tracker is derived from the less used *equatorial* tracker (ω, φ-δ, Fig.1,a) by the inverting the order of the rotation axes.

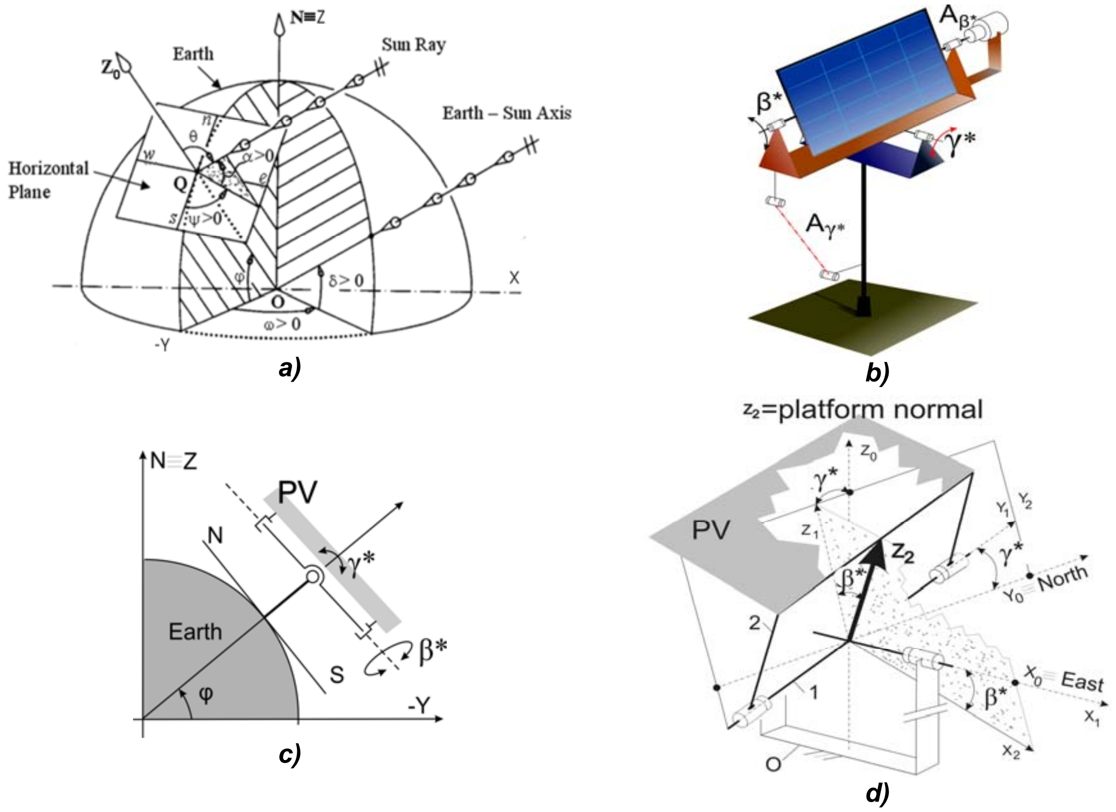

Fig. 1. a) Sunray angles; b) Axes and actuators of the pseudo-equatorial tracker; c) Relative positions of the pseudo-equatorial tracker towards Earth; d) The calculus scheme of the pseudo-equatorial tracker, where β* ≈ ω*, γ* ≈ (φ- δ) and φ is latitude.

stroke made by a *pseudo-equatorial* tracker) approximate the variations of the sizes γ and β (described by the sunray). Obviously, when the tracker makes the angular displacements continuously, then: $\gamma^*=\gamma$ and $\beta^*=\beta$.

Using these angles, further on there are modelled: the *unit vectors* for the sunray and for the normal to the panel, the *incidence angle* and the *direct solar radiation* that falls perpendicularly on the PV panel.

The sunray and the panel normal *unit vectors* are modelled using Fig. 1 [1; 5]:

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

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

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 [1; 5]:

$$\cos\nu = \cos\beta\cos\beta^*\cos(\gamma-\gamma^*)+\sin\beta\sin\beta^*; \tag{3}$$

The direct solar radiation R_d [W/m^2] depends on the hour and day by the following expression [3]:

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

where N – number of the day, α – altitude [1; 5] and T_R – a loss factor whose values can be found in [3].

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

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

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

3. PROBLEM STATEMENT AND ITS SOLVING

The step tracking problem was divided in two parts:

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 driving energy needed for powering of the electrical actuators.

The actual paper resolves only the first sub-problem, presenting a graphical explanation of the solutions which maximize the panel received direct solar radiation. The following nomographic charts, representing numerical exemplifications, have as input data: summer solstice (21st June, day number N=172), latitude φ=45°N, tracker angle γ*=25º (Fig. 1), and radiation loss coefficient T_R=4.2 [3].

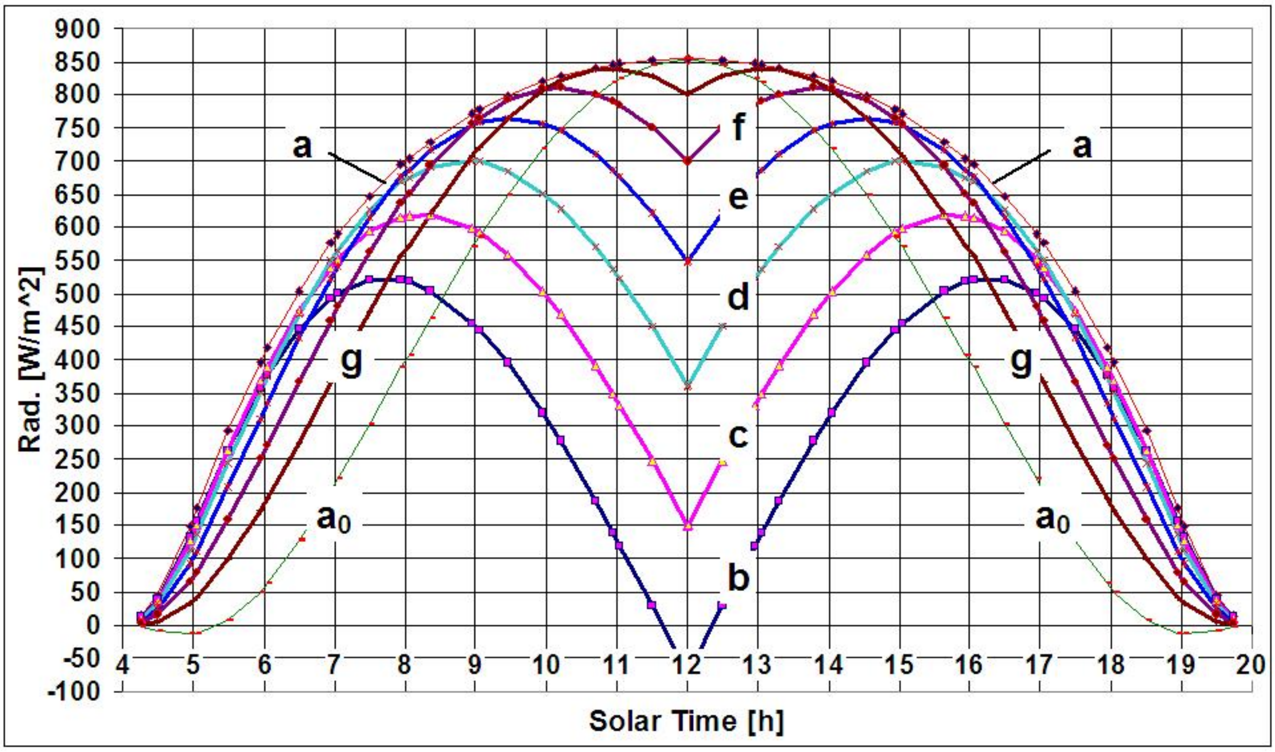

Fig. 2. Variations of the received direct solar radiation durring the Summer Solstice:
a – total available; a_0 – for a tilted and fixed panel (β*= 0)º ; b –for panel with β*=±95º;
c –for β*=±80º ; d –for β*=±65º ; e –for β*=±50º ; f –for β*=±35º; g –for β* =±20º.

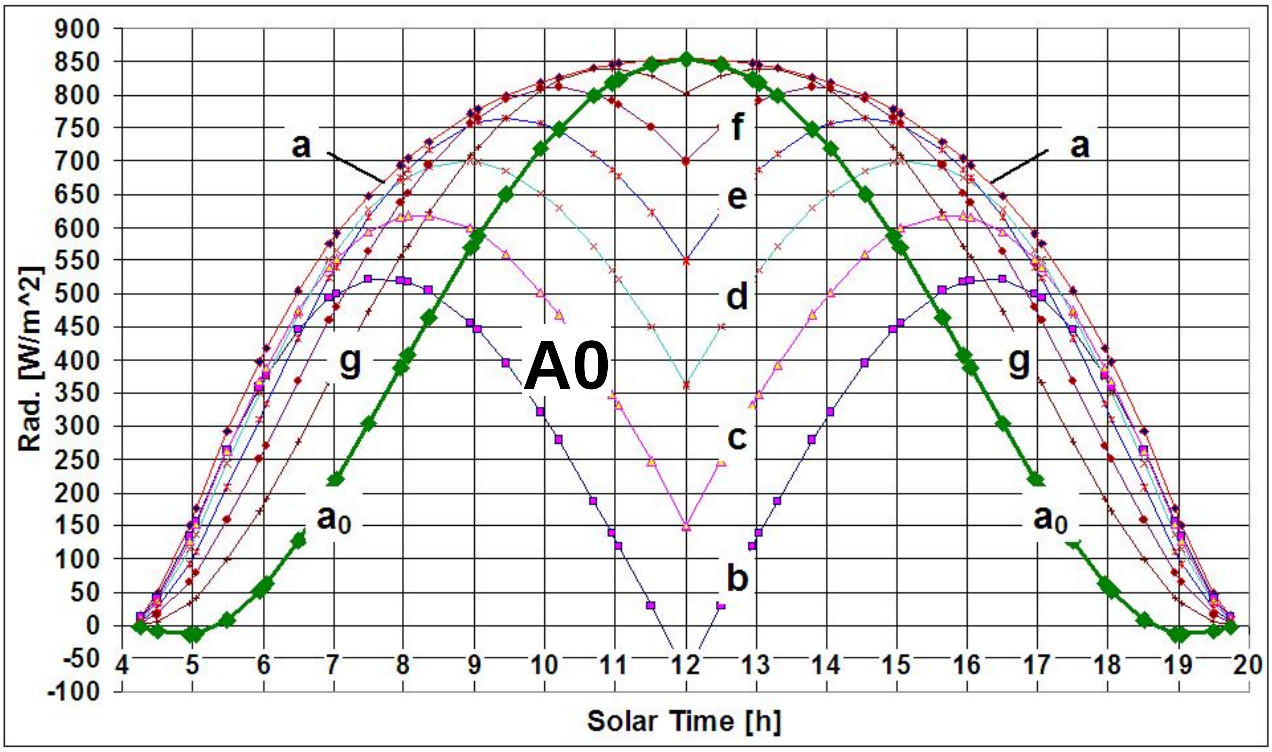

Fig. 3. Variations of the solar direct radiation durring the Summer Solstice for: a - available radiation, a_0 –for β* =±0º (0 tracking steps = a tilted and fixed PV panel).

Based on this input data, in the Fig. 2, …, 7 a set of diagrams is presented, corresponding to the following discrete variation: β*=[±95º, ±80º, ±65º, ±50º, ±35º, ±20º, 0º]. This set of diagrams allows us to optimize the *daytime (active) steps' number – received direct solar radiation* correlation, using as yet 0, 1, 2, 4 or 6 steps.

In Fig. 3, …, 7 the relative weight of 0, 1, 2, 4 and 6 steps referring to the direct received solar radiation is illustrated for a *pseudo-equatorial* tracked PV panel compared to a fixed and tilted panel; the main idea that results from here is that in the case of *even* steps' number the radiation gain is achieved especially during the noon, whereas for *odd* steps' number the gain is achieved especially during the morning and afternoon.

If the PV panel is fixed (0 tracking steps) at β*=0º (Fig. 2 and 3), the PV panel receives an energy corresponding to the A0 area, under the line a_0 (Fig. 3).

When the pseudo-equatorial tracker makes one step (the point 1 from Fig. 4) at noon, the panel receives energy corresponding to the A1 area, under the bolded line *f* (β*=±35º). So, unlike the previous case, the first step brings up a received energy gain corresponding to the area A1-A0 (Fig. 3 and 4).

If the pseudo-equatorial tracker makes 2 steps (points 1 and 2 from Fig. 5), the panel receives energy corresponding to the *A*2 area, which is maximum for the bolded line *e* (ω*=±50º) intersected with the bolded line a_0 (ω*=0º). Compared to the previous case, the two tracking steps bring up a received energy gain corresponding to the A2-A1 area.

When the pseudo-equatorial tracker makes four steps (the points 1, 2, 3, 4 from Fig. 6), the panel receives energy corresponding to the A4 area, which is maximum for the bold curve obtained from the intersection of the curves: d (β*=±65º), f (β*=±35º) and a_0 (β*=0º) from Fig. 2. So, unlike the case from Fig. 5, the tracking steps 1, 2, 3 and 4 (Fig. 6) bring up a received energy gain corresponding to the (A4-A2) area.

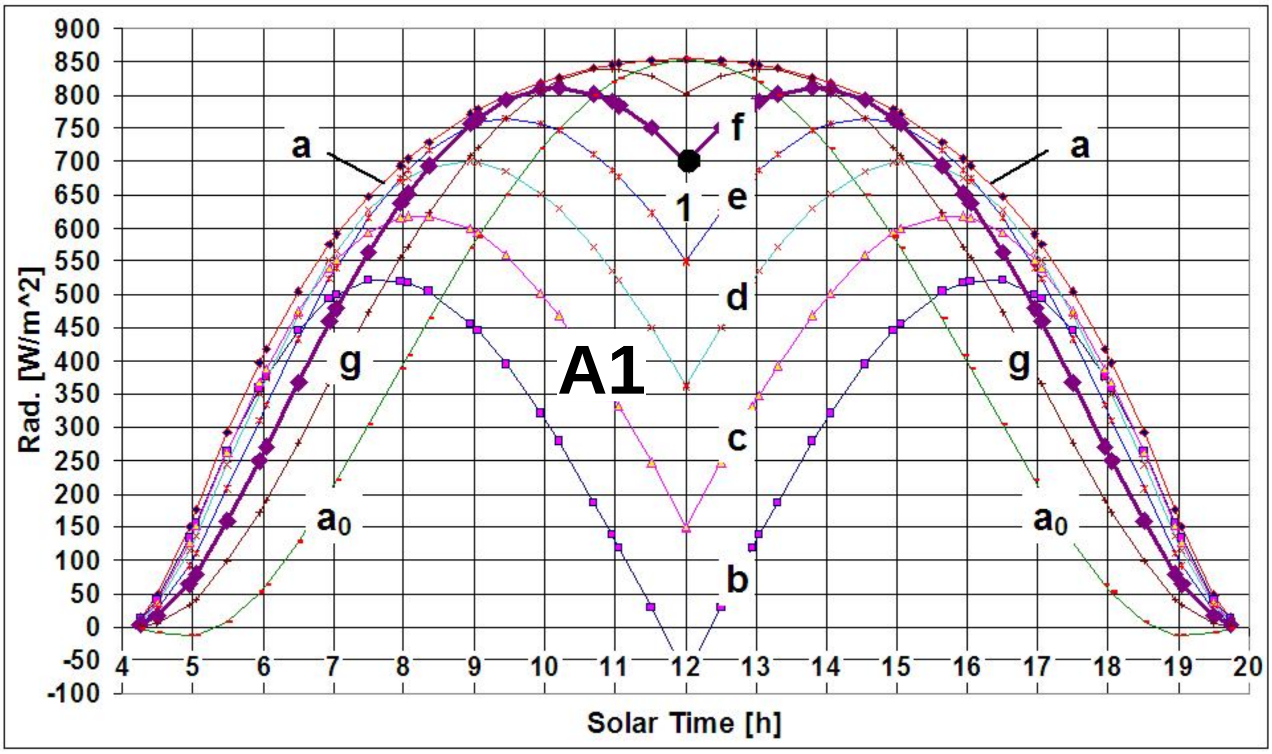

Fig. 4. One tracking step case (1): a - available radiation, a_0 – for a tilted and fixed PV panel, f - for a PV panel with β=±35º.*

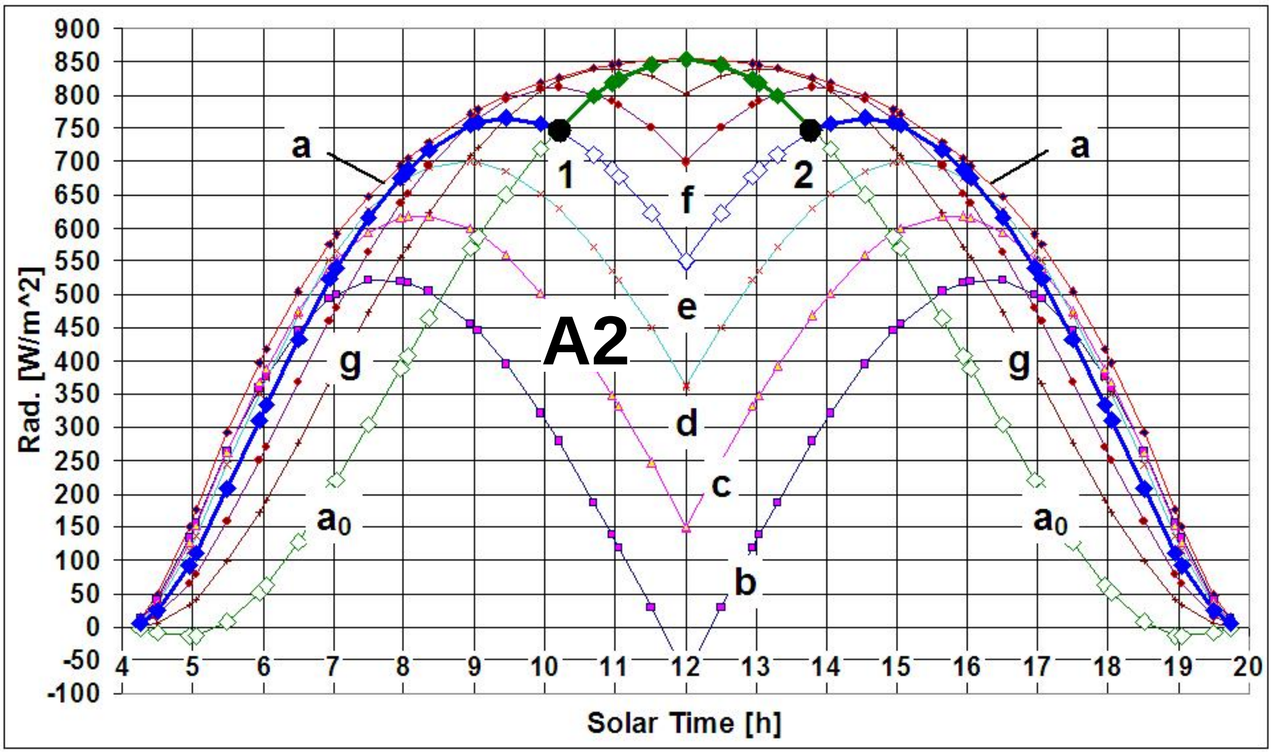

Fig. 5. Two steps' case (1 and 2): a - available radiation, a_0 - for a tilted and fixed PV panel, e- for a PV panel with β=±50º*

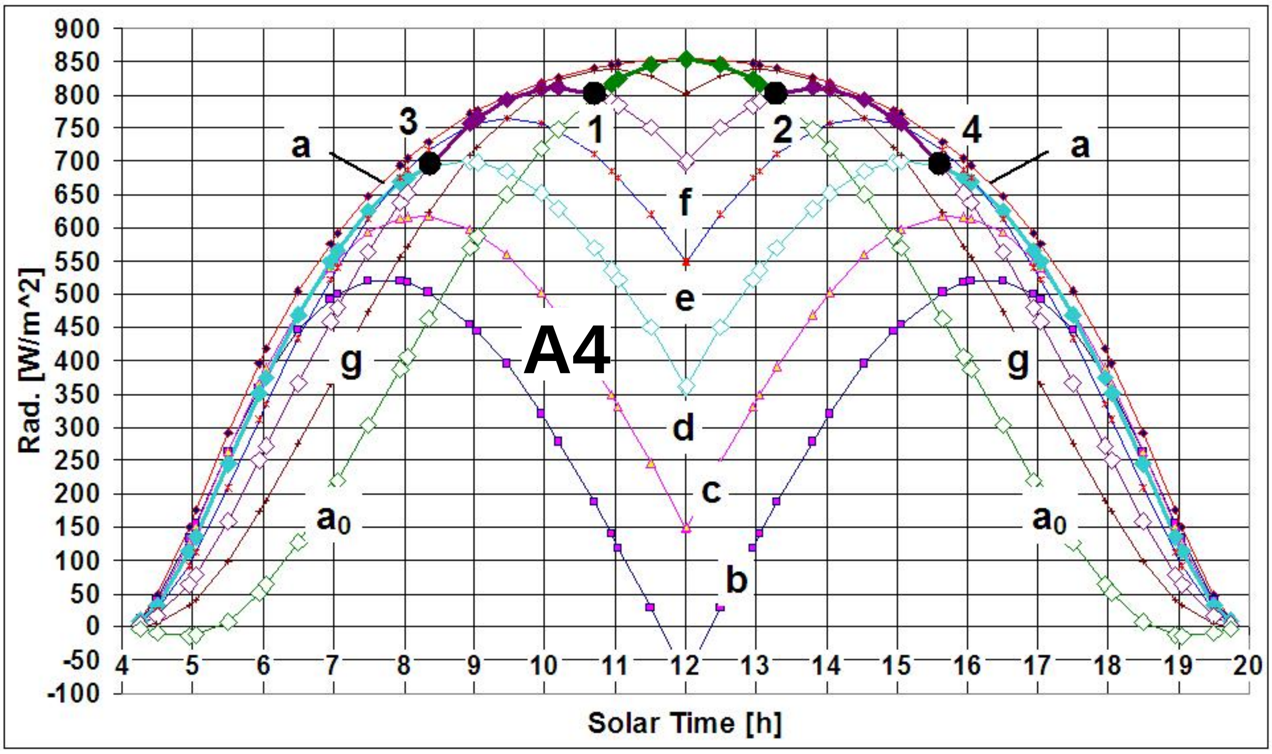

Fig. 6. Four steps' case (1, 2, 3 and 4): a - available radiation, a_0 - for a tilted and fixed PV panel, d –for β=±65º ; f –for β*=±35º.*

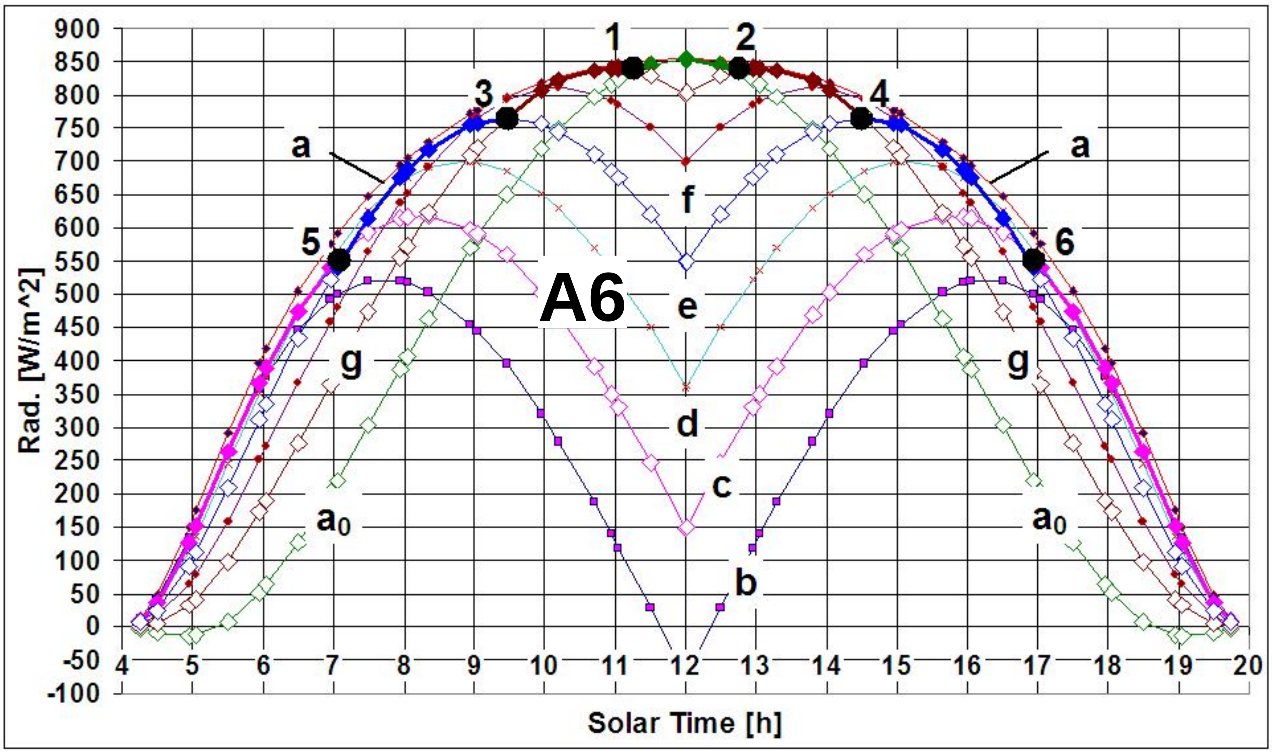

Fig. 7. Six steps' case (1, 2, … , 6): a - available radiation, a_0 - for a tilted and fixed PV panel, c –for β=±80º ; e –for β*=±50º ; g –for β*=±20º.*

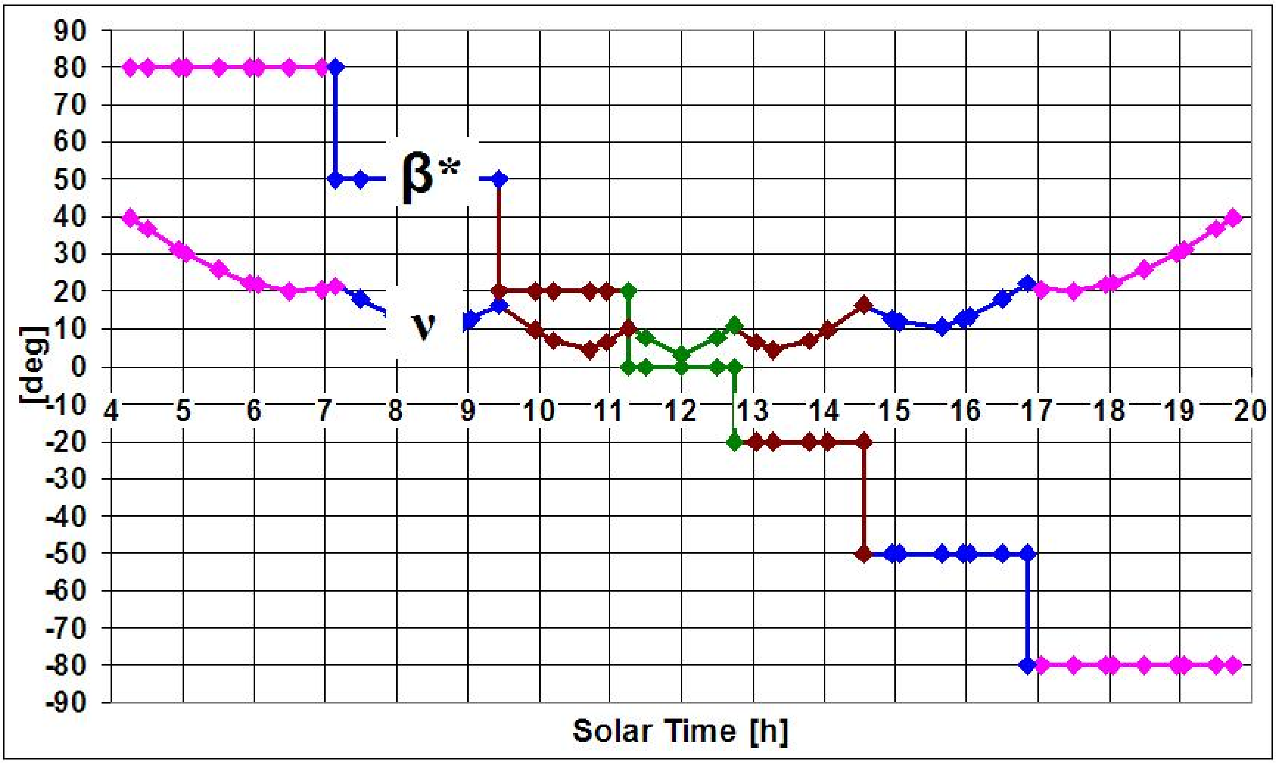

Fig. 8. Variations of the incidence angle and of the panel orientation angles for a pseudo-equatorial tracked PV panel corresponding to Fig. 7.

If the pseudo-equatorial tracker makes six steps (the points 1, 2, 3, 4 , 5 and 6 from Fig. 7), the panel receives energy corresponding to the A6 area, which is maximum for the bold curve obtained from the intersection of the curves: c (β*=±80º), e (β*=±50º), g (β*=±20º) and a_0 (β*=0º) from Fig. 2. Compared to the previous case, the tracking steps 1, 2, 3 … 6 bring up a received energy gain corresponding to the (A6-A4) area.

The variation of the incidence angle (v) and of the angle β*≈ω*, for the case of the tracking with 6 steps (Fig. 7), is presented in Fig. 8.

These 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 for which the energy brought by the last step is higher than the driving energy necessary for this step.

4. CONCLUSIONS

From the previous analysis, the following main conclusions can be stated:

a) the optimal number of steps is that, for which the energetic gain is higher than the energetic consumption of the actuators;

b) the received radiation gain, brought by each step decreases with its order number;

c) from the previous conclusions it results that the choosing of the minimum number of steps, including the optimum orientation programs, depends on the energetic performances of the actuators used for tracking;

d) in the design of the optimal tracking program it is necessary to model the programs for a big enough number of steps, so the best values of the (β* and γ*) parameters can be determined;

e) on the basis of the daily steps' number optimizations, the yearly orientation program can be developed.

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