Geometric Modelling of Low Concentrating Photovoltaic System

IONEL LAURENTIU ALBOTEANU
Department of Electromechanics, Environment and Industrial Informatics
University of Craiova
107, Decebal Bvd., 200440, Craiova
ROMANIA
lalboteanu@em.ucv.ro; http://www.em.ucv.ro

Abstract: - The paper presents aspect to increasing energy production of photovoltaic systems by concentrating solar radiation and orientation of photovoltaic modules. To focus sunlight on photovoltaic surface and increasing thus the energy absorbed, the concentration solar photovoltaic systems used either optical elements retractable (usually Fresnel lens) or reflective elements (usually mirrors). The photovoltaic concentrating system aims to reduce expenses regarding photovoltaic surface and replace it with optical materials. Geometric design issues are presented for these systems adapted to the conditions of a certain geographical location. The paper started with modeling of specific angles of photovoltaic panel and ends with a prototype of low concentrating photovoltaic system (LCPV). The simulation results show that the additional length decreases with the angle formed between the mirror and photovoltaic module x, and increases with the incidence angle h, meaning with the duration of the orientation step. Also, the concentration ratio increases with the increase of angle x. In order do not overweight the supporting structure of the LCPV system there have been utilized materials with light weight.

Key-Words: - photovoltaic (PV), tracking system, low concentrating photovoltaic, modelling, design, geometry

1 Introduction

In recent years, applications that use PV systems are a continuously growing. The current trend is to optimizing these systems by ensuring functionality with maximum efficiency [20].

This paper is the starting work of a study that aims to address meaningfully the issues of increasing efficiency of the photovoltaic systems by utilization of solar radiation concentrator elements, as well as of reducing of costly photovoltaic surface.

Ideally, a PV panel should follow the sun so that the sun rays fall perpendicular to its surface, thus maximizing solar energy capture and thus we obtain the maximum output power. The tracking systems using controlled mechanisms that allow maximization of direct normal radiation received on PV panel [16].

The idea of concentrating solar radiation to generate electricity photovoltaic appeared almost simultaneously with photovoltaic science.

Operating principle of concentrating photovoltaic systems is based on using optics materials to focus sunlight on a photovoltaic surface, thus increasing the amount of energy captured and converted. To focus sunlight on photovoltaic surface and increasing thus the energy potential, the concentrating solar PV systems use either optical elements retractable (usually Fresnel lens) or reflective elements (usually mirrors) [12].

In the literature there are three types of solar concentrators: high, medium or low concentration [15]. This classification depends on the concentration ratio, defined as the ratio of the amount of radiation incident on the photovoltaic module and the amount of radiation available. In the paper is approached low concentrating photovoltaic system (LCPV).

2 Modeling of specific angles for photovoltaic panel

It is known that the Earth behaves a complete rotation in a year, around the Sun in an elliptical orbit and a complete rotation around its own axis during 24 hours. Earth's rotation axis has a fixed direction in space and inclined angle $\delta_0 = 23.5^o$ to the perpendicular plane of the orbit (Fig. 1).

The angle between the direction to the Sun and the equatorial plane, δ is named declination and varies during the year from 23.5^o, at the moment of the summer solstice (June 21) to -23.5^o, at the winter solstice (December 21st).

On 21 March, respectively - September 21 declination $\delta = 0$ and the length of day and night are equal.

Declination can be calculated with the Copper formula [16]:

$$\delta = 23{,}45 \cdot \sin\left(360^{o}\,\frac{284+n}{365}\right) \qquad (1)$$

where n - is the number of days in a year, the first day considering January 1.

Using monthly average of 'n' values is calculated declination of Earth during a year, and the resulting graph is represented in Figure 2.

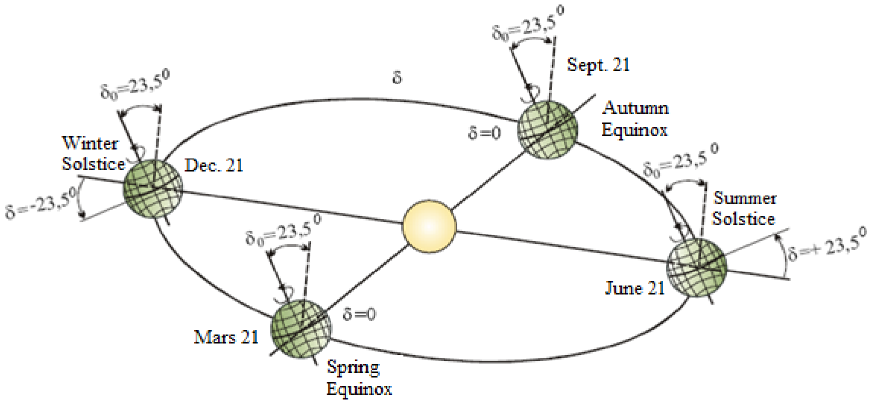


Fig. 1. Earth's orbit and the angle of declination, [8]

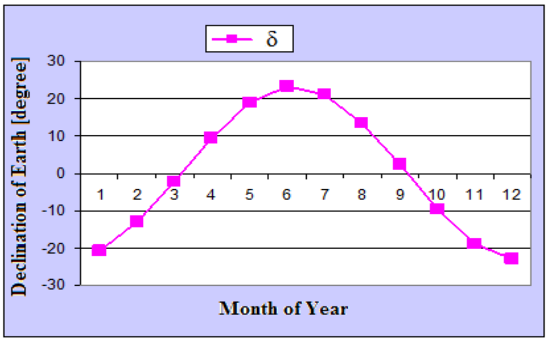


Fig. 2. Annual graphical evolution of declination angle of the Earth

Geometric relations between an arbitrarily oriented plane to the horizontal and direct sunlight that falls on the plan at any point of time, the position of the sun to this plan can be described in terms of several angles [6], [19].

Latitude, φ - angle measured from the equator to the point of interest on the earth's surface, is considered positive for the northern hemisphere and negative - to the south.

The inclination angle of plane β - the angle between the plane and the horizontal surface; $0 \le \beta \le 180$, (Fig. 3). For normal solar installations, maximum angle does not exceed 90°.

Azimuthally angle, γ - the angle between the projection on the horizontal plane perpendicular to the surface of the plan and the local meridian (Fig. 3); equal to zero for that plan south facing; negative - to east, positive - to west; $-180 \le \gamma \le 180$.

Solar azimuthally angle, $\gamma_{s,}$ - the angle between the south and the projection on the horizontal direct radiation (sunlight) (Fig. 3 b); angles measured from south east direction are negative, the measured westward - positive.

The angle of elevation of the sun, αs, - the angle between the horizon and the sun line linking point of interest, or the incident solar beam at the point of interest (Fig. 3).

Zenith angle, θ_z, - the angle between the vertical and the line connecting the sun and the point of interest, or αs complementary angle (Fig. 3).

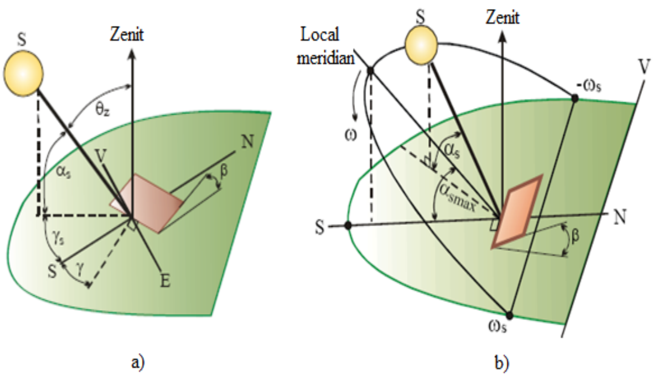


Fig. 3. Explanation regarding to sun’s angles [8]

Hour angle, ω, - determines the position of the sun in the sky at a given moment. Equals zero when crossing the local meridian sun, ie when midday positive and negative east - west (Fig. 3 b). Accordingly, ωs corresponds to the angle of sunrise, and (-ωs), the angle of the sun dusk.

It is obvious that in an hour the sun across the sky at an angle equal to 15°, and his position at any time T is determined by the expression:

$$\omega = 15 \cdot (12 - T) \tag{2}$$

If you know the angles δ, φ and ω, then easily determine the position of the sun in the sky for the point of interest for any time, any day, using the expressions [8]:

$$\sin\alpha_s = \sin\delta\sin\varphi + \cos\delta\cos\varphi\cos\omega = \cos\theta_z$$

$$\cos\gamma_s = \frac{\sin\alpha_s\sin\varphi - \sin\delta}{\cos\alpha_s\cos\varphi} \quad (3), (4)$$

In equation (3) by imposing the condition, calculate east respectively west angle hourly of the sun from the relationship:

$$\omega_s = \pm\cos^{-1}(-\tan\varphi\cdot\tan\delta) \tag{5}$$

For every day of the year in (4) with declination δ previously determined from (1) for a time T is determined the hour angle ω and knowing the latitude φ is determined the sun elevation angle αs.

In Figure 4 is presented photovoltaic panel, P directed to the South. Surface of panel P is inclined to the horizontal with β angle.

Solar radiation on the PV panel will be highest when the afternoon when the sun elevation angle, αs is the maximum distance and sunlight will be minimal time and angle ω = 0. This situation will occur where direct radiation is perpendicular to the surface of the PV panel, P.

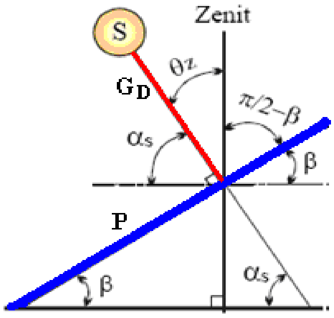


Fig. 4. Direct solar radiation on an inclined plane in midday: ω=0; γ=o; [8]

Figure 4 shows that θz = β, and angle of the panel on S-N direction (elevation), from the horizontal plane is determined by the relationship:

$$\cos\theta_z = \sin\delta\sin\varphi + \cos\delta\cos\varphi = \cos(\varphi - \delta) \quad (6)$$

with:

$$\beta = \varphi - \delta \tag{7}$$

Based on present relationships above, customizing for city of Craiova was obtained graphical representation of specific angles describing the position of the sun in the sky.

In Figure 5 is presented simulation results for the angular system at equinoxes. The same graphs that describing the angular system is shown in Figure 6, for summer solstice and, for the winter solstice in Figure 7.

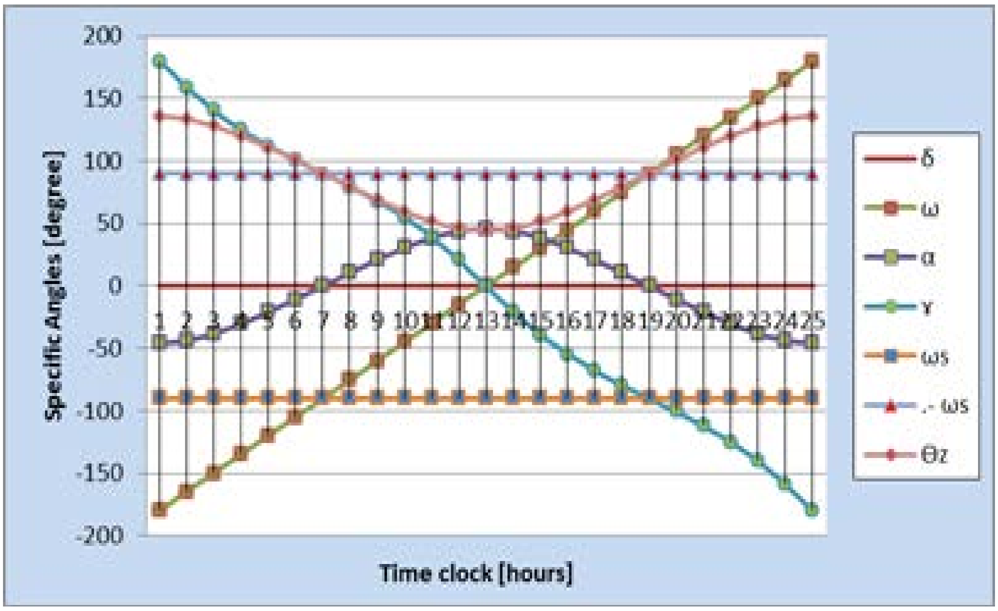


Fig. 5. Simulation results of angular sistem at equinox (21 Mar., 21 Sept.), for Craiova City

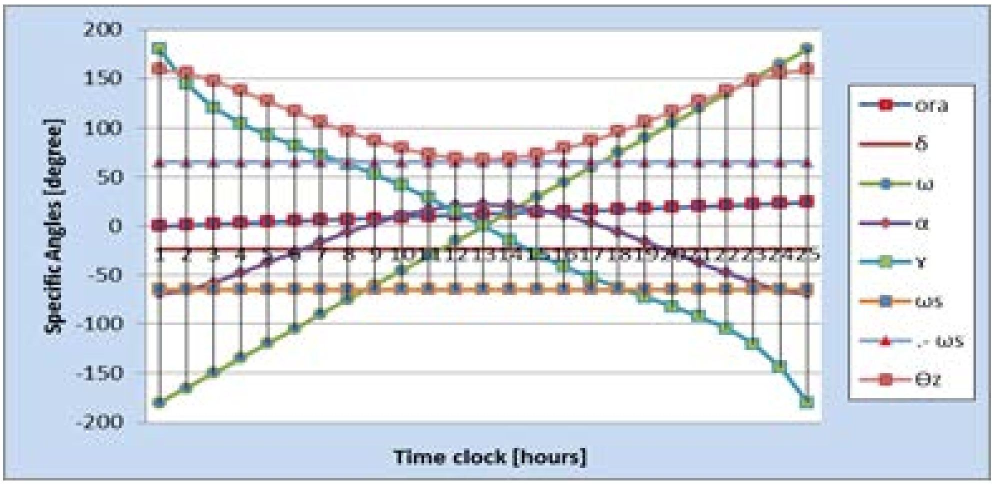


Fig. 6. Simulation results of angular sistem at summer solstice (21 June), for Craiova City

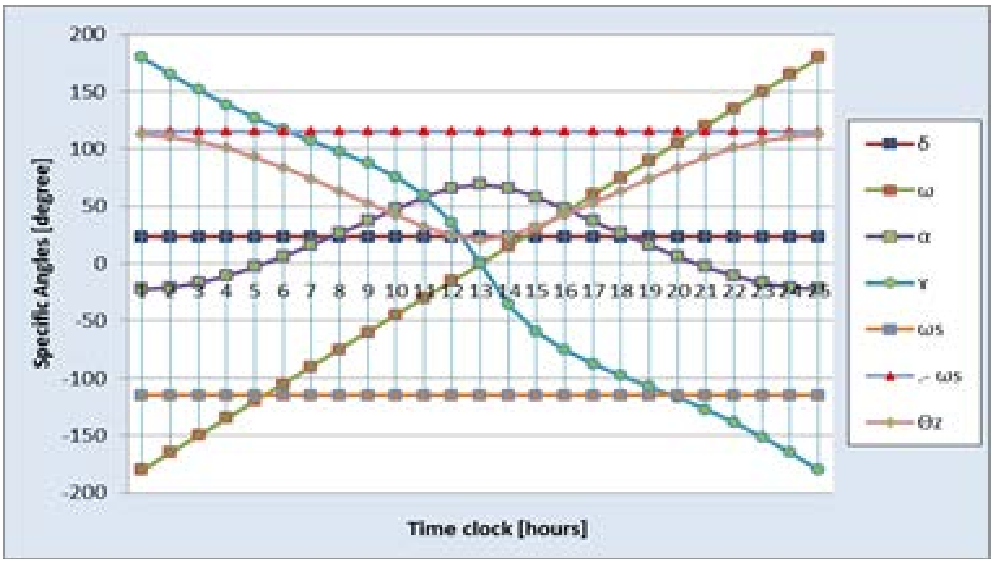


Fig. 7. Simulation results of angular sistem at winter solstice (21 Dec.), for Craiova City

Analysing the graphs resulted from the simulation of angular system customized for location Craiova, in all three cases, we can say that:

- sun altitude or elevation angle (α_s) shows maximum values at midday 48^o at the equinoxes, 68o at summer solstice and 25^o at winter solstice;
- sunset hour angle is 98^o at equinox, at summer solstice is 110^o and 60^o at winter solstice;
- sunrise hour angle is symmetric with the sunset hour angle having the same values but with a negative sign;
- azimuth angle presents positive in the first half of the day dropping to zero during the midday, then afternoon is symmetrical values from the first half of the day;
- hour angle shows negative peaks in the morning and will then drop to zero during the midday and afternoon shows symmetrical values of in the morning.

3 Modelling of tracking system for photovoltaic panel

Electricity production of a PV system depends largely on solar radiation absorbed by the photovoltaic panels. As the sun changes with the seasons and over a day, the amount of radiation available for the conversion process depends on the panel tracking.

Since PV modules have a relatively low yield (up to 30% in laboratory conditions) the aim is to optimize their energy [9], [14].

A method of optimizing available solar energy conversion with real possibilities of implementation is the use of tracking systems. Literature shows that the uses of tracking systems increase from 20% to 40% the amount of energy produced by converting [9].

In practice are two kinds of tracking systems: single axis and double axes tracking systems (Fig.8). In the case where the two orientation axes 3 types of systems can be distinguished, depending on how the axes are placed and how the two movements are entered into the system [9]: the azimuthally systems (Fig. 8 c), the equatorial systems (Fig. 8 d) and the pseudo-equatorial systems (Fig. 8 e).

In this paper was considered the pseudo-equatorial system.

In order to determine the energy absorbed by the PV panel it must be modelled and simulated the tracking system. Modelling and simulation was performed for double axes tracking system.

The relations (4) and (7) describe the position of the PV panel at any time of the year so that sunlight falling perpendicular to it. For location Craiova was resulted both graphs presented in Figures 9 and 10 that describe the two angles corresponding to the PV panel for first four months of the year.

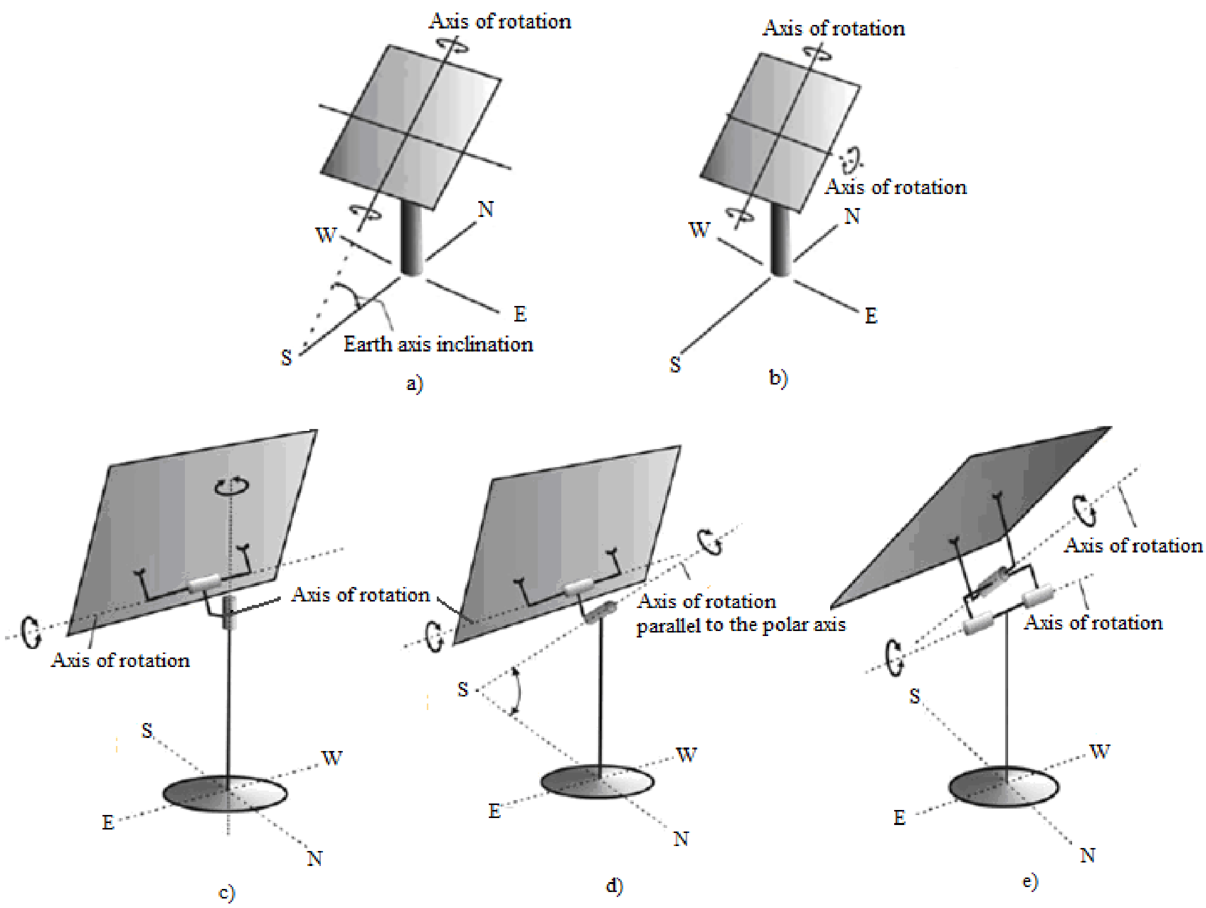


Fig. 8. Tracking systems of PV panel: a) single axis, b) double axe, c) azimuthally, d) equatorial, e) pseudo-equatorial [9]

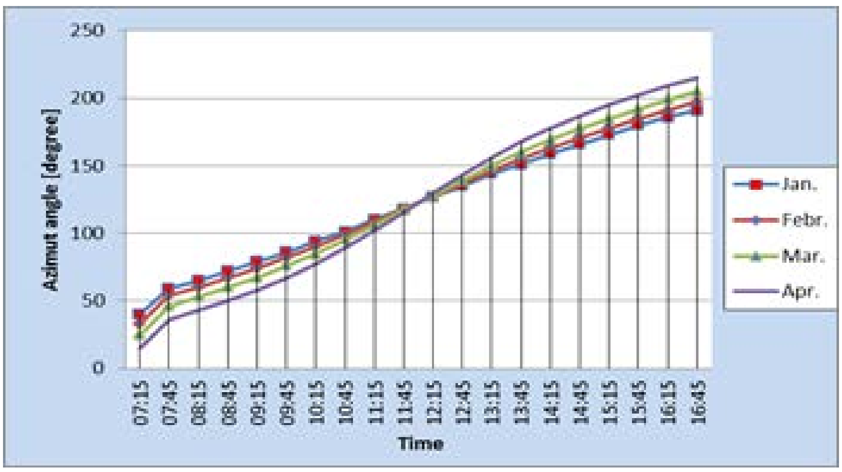


Fig. 9. Azimuth angle of photovoltaic panel

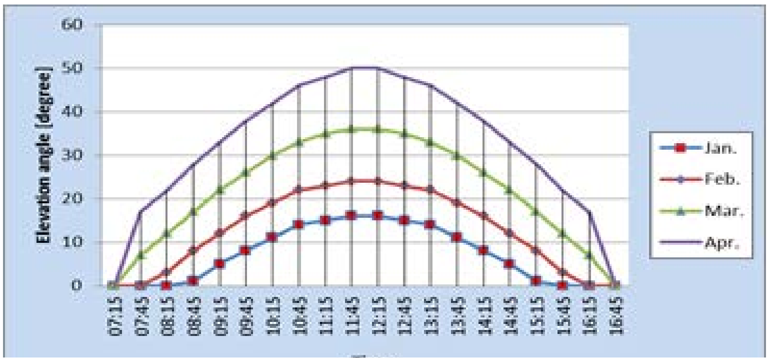


Fig. 10. Elevation angle of photovoltaic panel

4 Modelling of the low concentrating system for the photovoltaic panel (LCPV)

If we ignore tracking, the analysed low concentration photovoltaic system (LCPV) contains: a photovoltaic module and two mirrors arranged symmetrically on large sides of photovoltaic module.

The LCPV system can work in two possible cases [12]: a) when the reflected light from each mirror covers the whole PV module surface, and b) when only half of the surface is covered by light from each mirror. The case a) is analysed in this paper.

Proper functioning of this low concentration photovoltaic system depends by, in particular, the following two requirements [13]:

a) PV module must be completely crossed by direct radiation (excluded initially the effect of shading and diffuse radiation is neglect);

b) PV module must be completely swept for the direct radiation reflected by mirrors.

To identify the geometric parameters that define the system LCPV in Figure 11 is represented the geometric diagram describing sweeping photovoltaic module by direct and the reflected radiation during a step of tracking: in the Figure 11 the red rays represent the start of the step, the rays mid of step is black and the blue is end-of-step rays.

To describe the geometry of the LCPV system considered, were introduced the following parameters [13] (Fig. 11):

- x – angle formed between the mirror and photovoltaic module - constant parameter;
- h - maximum incidence angle formed by the PV normal surface and sun's ray;
- k - ratio of the (Lm) width mirrors and (Lp) PV module width;
- c1, c2– PV module with coefficients swept rays reflected by the mirrors;
- k_l – longitudinal deflection coefficient, defined as ratio of the additional length mirror (necessary to compensate for reflected sunlight deviation caused by deviations elevation to elevation solar PV module) and PV module width.

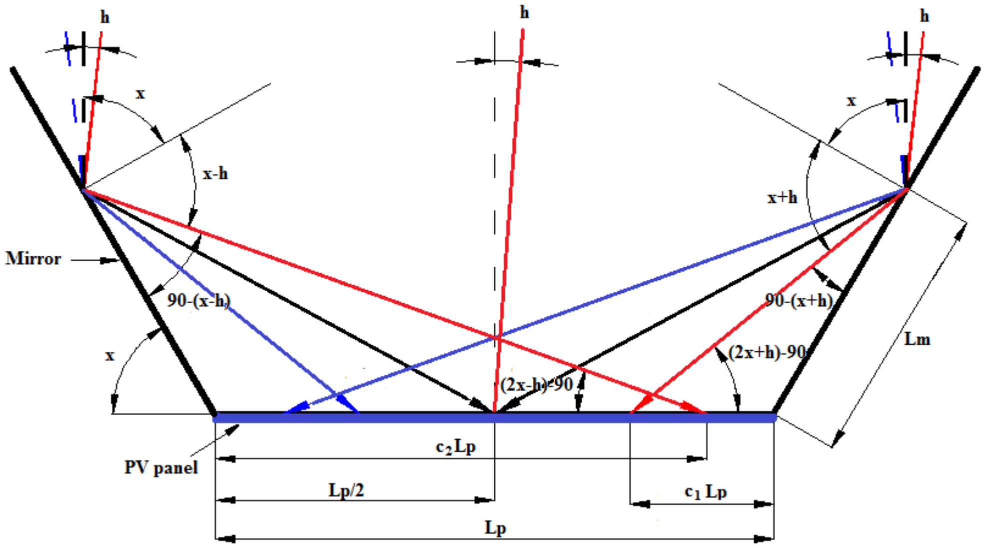


Fig. 11. Scheme for geometric modeling of LCVP system

Sweeping the entire surface of the PV module is determined by the median rays (black colour line Fig. 11), which designates the middle of a tracking step; as a result, the ratio k can be modelled analytically by applying sine theorem in the triangles formed by the Lp and Lm sides with the median rays.

$$k = \frac{L_m}{L_p} = \frac{-\cos(2 \cdot x)}{\cos(x)} \tag{8}$$

By means of the analytical expression obtained In Figure 12 is shown k reports variation according to the x angle for different values of the h angle of incidence.

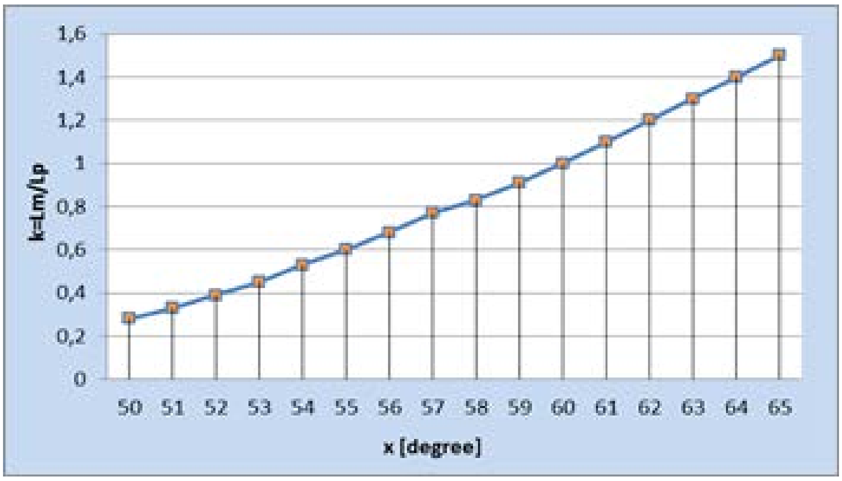


Fig. 12. The evolution of ratio *k* for different values of the angle of incidence *h*

In a graphics evolution it can see as a gauge of system increases with increasing angle x.

Partially reflected beam sweeps photovoltaic module width. To determine the ratio of the width swept is introduced c coefficient, described as the ratio between the shares swept width (cLm) and PV module width (Lp).

Considering the known Lp width of the PV module, Lm width of the two mirrors and x tilt angle mirror- photovoltaic module (Fig. 11) can determine the coefficients c1 and c2, which describe what part of PV module width (Lp) is swept by rays reflected from each mirror.

$$c_1 = \frac{L_m \cdot \cos(x+h)}{-L_p \cdot \cos(2 \cdot x + h)} \tag{9}$$

$$c_2 = \frac{L_m \cdot \cos(x-h)}{-L_p \cdot \cos(2 \cdot x - h)} \tag{10}$$

Evolution of coefficients c1, c2, ie c for different values of the h angle of incidence of sunlight for the best case of the angle of the mirror (x = 60°) is shown in Figure 13.

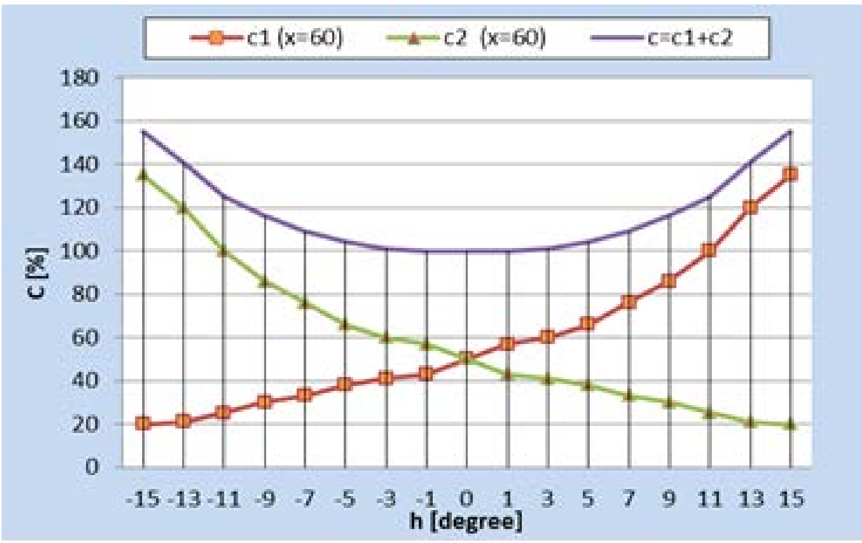


Fig. 13. Evolution of the coefficient *c* for different values of *h* at (*x* = 60°)

Complete sweep PV surface condition is satisfied only if c1+c2≥100%; in Figure 13, c1+c2 curve show that for the θ = 60° is equal to 100% in the case of continuous orientation (angle of incidence corresponding to zero) and increases with the value of the maximum angle of incidence (i.e. the length tracking step in the case to steps tracking). By multiplying the coefficients c1 and c2 with the width and length of photovoltaic module is obtained surface covered by reflected radiation to PV panel.

Due to the orientation in steps, the angular deviations of elevation of the orientation system induce the longitudinal deviation of the reflected ray, whose geometric pattern is depicted in Fig 14 for both mirrors. Consequently, the reflected ray can meet the condition of complete sweep of the photovoltaic module solely if the mirror length will be increased, on both sides, with the maximum longitudinal deviations of the solar rays reflected.

The mirror elongation, due to the longitudinal deviations of the rays reflected (see Fig.14) can be modelled with the help of the ratio [13]:

$$k_1 = \frac{2C'_1E_1}{C_1C'_1} = \frac{2C'_2E_2}{C_2C'_2} = \frac{2C'E}{CC'} \qquad (11)$$

For obtaining the analytical modelling it had been considered that the solar ray reaches an extreme point of mirror (A_1, respectively A_2, see Fig. 14) and it is reflected under an incidence angle, in a point E_1, respectively E_2, on the surface of photovoltaic module.

In order that whole surface of photovoltaic module to be swept by the ray reflected, the mirrors should be elongated so that the points E_1 and E_2 (see Fig. 14) to move in C_1', respectively in C_2'. This elongation can be modelled geometrically based on Fig.14 by determination of the deviation C_1'E (respectively C_2'E), and implicitly of the longitudinal ratio k_l, [13].

Based on these relations and on elevation deviations in Fig.15 had been traced the curve family for the pseudo-equatorial system.

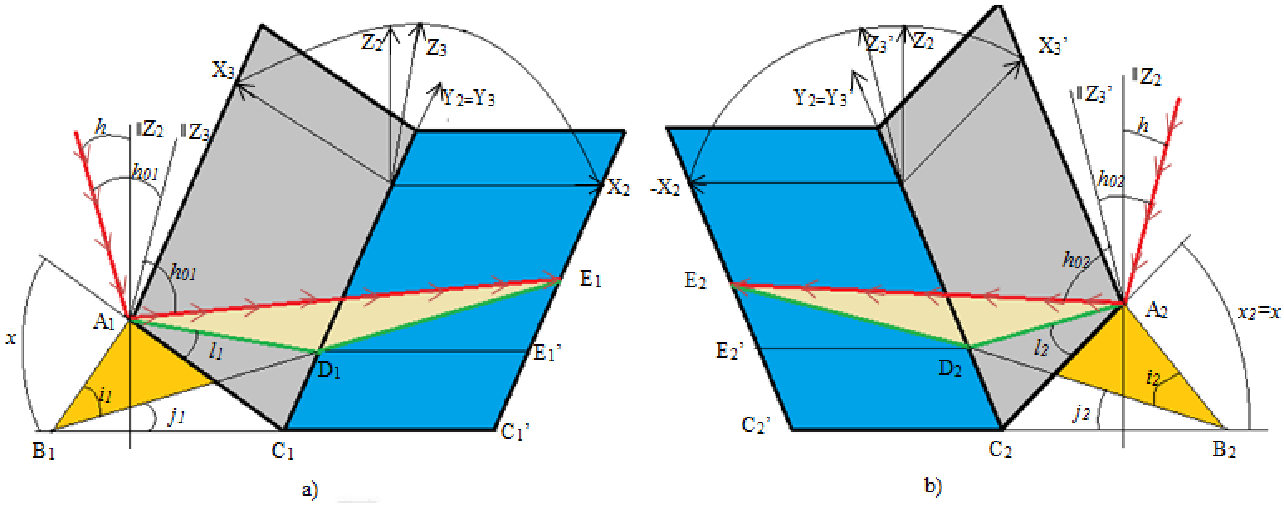


Fig. 14. Longitudinal deviation E_1C_1' and E_2C_2' at LCPV for: a) left mirror; b) right mirror

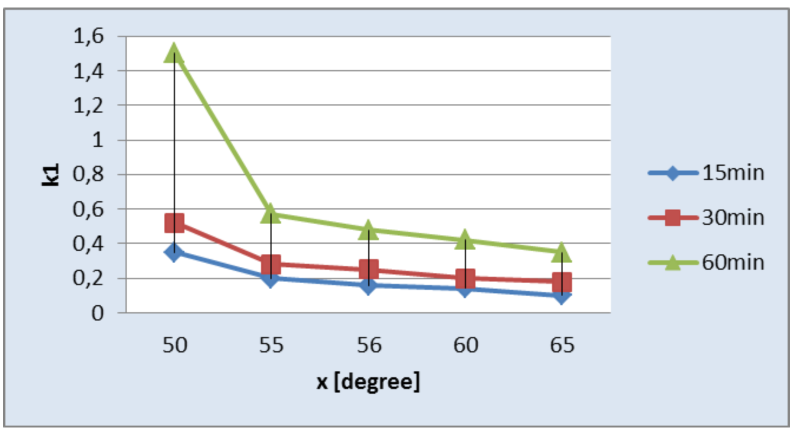


Fig. 15. Variation of longitudinal factor k_l, depending on angle θ, at different durations of orientation steps

The results show that the additional length decreases with the angle x, and increases with the incidence angle h, meaning with the duration of the orientation step.

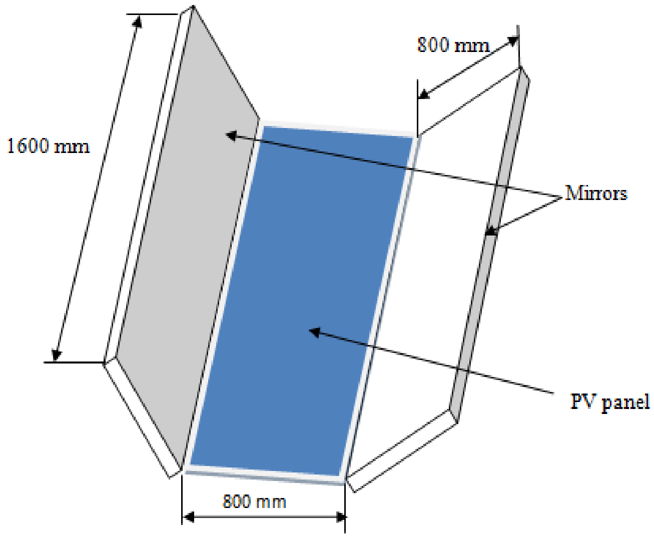
5 Design of LCPV prototype

Usually, the low radiation concentration systems are made of flat mirrors located on the extreme sides of the photovoltaic panels.

In order to avoid the excessive heating of the photovoltaic panel one could propose that the concentration systems do not be provided with mirrors but to be made by materials with high reflection index, for instance thin aluminum foil.

Also, in order do not overweight the supporting structure of the LCPV system there have been utilized materials with light weight.

In Fig.16 is presented the prototype of the LCPV system realized.



a)


b)

Fig. 16. Prototype of LCPV system realized: a) sketching, b) real system

In order that the system LCPV be used for different types of PV modules, aiming to study their behavior at concentration, the assembly LCPV had been made as a modular system, using specific aluminum profiles, and ensuring the mobility of the concentration elements to the photovoltaic module.

6 Conclusions

In this work are presented some geometric aspects to be considered when designing the tracking systems for PV panels with low concentration of radiation.

Developed mathematical models have been custom for a specific location in order to study the efficiency of PV panels tracking with low concentration of solar radiation in specific conditions of a particular geographical area.

On simulation graphs can be drawn some conclusions:

- the concentration ratio increases with the increase of angle x;
- for the same PV width Lp, the mirror width Lm increases proportionally with the angle x;
- the total radiation depends on the angle x;
- the mirror width decreases with the tracking step duration.

Implementation models on physical prototype have been achieved. Experiments and interpretation of the results on the effectiveness of this system will be subject to future work.

Acknowledgment

This work was partially supported by the grant number 29C/2014, awarded in the internal grant competition of the University of Craiova.

References:

[1] I.L. Alboteanu, G. Manolea, F. Ravigan, Positioning Systems for Solar Panels Placed in isolated areas, *Annals of the University of Craiova, Electrical Engineering series*, No. 30, 2006, ISSN 1832-3804, pp.163-168.

[2] I. L. Alboteanu, F. Ravigan, S. Degeratu, C. Sulea, Aspects of Designing the Tracking Systems for Photovoltaic Panels with Low Concentration of Solar Radiation, *Computational problems in Engineering*, 2015, Springer-Verlag, in press.

[3] I. L. Alboteanu, C. Sulea, Gheorghe Manolea, Innovative Technologies for Romanian Anti-hail System, *Wseas Transactions on Power Systems*, ISSN: 1790-5060, Issue 4, Volume 5, October 2010, pp. 297-308

[4] I. L. Alboteanu, *Advanced stand-alone photovoltaic system*, Craiova, "Universitaria", Publisher, 2013.

[5] M.A. Benecke, EE. Van Dyk, F.J. Vorster, Investigation of the Design Aspects on the Performance of a LCPV Syste", Nelson Mandela Metropolitan University, Centre for Renewable and Sustainable Energy Studies.

[6] M.A. Benecke, EE. Van Dyk, F.J. Vorster, The Design and Analysis of a Vertical Receiver LCPV System, Nelson Mandela Metropolitan University, Centre for Renewable and Sustainable Energy Studies.

[7] A.W. Bett, H. Lerchenmüller, *The FLATCON System from Concentrix Solar. Concentrator Photovoltaics*, Springer Series in Optical Science, 2007.

[8] I. Bostan, V. Dulgheru, I. Sobor, V. Bostan, A.Sochirean, *Renewable energy conversion systems*, Chisinau, "Tehnica-Info" Publisher, 2007.

[9] M. Comşiţ, Specific orientation mechanisms of solar energy conversion systems, *PhD thesis, Transilvania University of Brasov*, 2007.

[10] D. Diaconescu, et al., The Incidence Angles of the Trackers Used for the PV Panels' Orientation. Part I: Equatorial Trackers. In: *ICEEMS – International Conference on Economic Engineering and Manufacturing Systems, Jurnalul RECENT*, Vol. 8, nr. 3a (21a), Brasov, Romania, October 2007, p. 281-286.

[11] G. Grasso, F. Morichetti, A. Righetti, S.M. Pietralunga, Trackless LCPV modules: A competitive solution, *Photovoltaic Specialists Conference (PVSC)*, 2012 38th IEEE, ISSN: 0160-8371, pp. 2048 -2051.

[12] I. Hermenean, I. Vişa, D. Diaconescu, On The Geometric Modelling of a Concentrating PV-Mirror System, *Bulletin of the Transilvania University of Braşov Vol. 2 (51) – 2009 Series I: Engineering Sciences*, pg. 73-80.

[13] I. Hermenean, I. Vişa, A. Dută, D. Diaconescu, Modelling and Optimization of a Concentrating PV-Mirror System, *Renewable Energy and Power Quality Journal, No.8*, April, 2010.

[14] A. Luque, S. Hegedus, *Handbook of Photovoltaic Science and Engineering*, Wiley-VCH, 2003.

[15] A. Luque, V.M. Andreev, *Concentrator Photovoltaics*, Springer-Verlag, Berlin Heidelberg, 2007.

[16] R. Messenger, J. Ventre, *Photovoltaic System Engineering*, CRC Press, 2004, Sec. Edition.

[17] T. Palmer, et al., Tracking Systems for CPV: Challenges and Opportunities, *Solar Power International*, 2007.

[18] O. Stalter, B. Burger, S. Bacha, D. Roye, Integrated Solar Tracker Positioning Unit in Distributed Grid-Feeding Inverters for CPV Power Plants, *ICIT 2009*, Australia.

[19] I. Vişa, D. Diaconescu, V. Popa, B. Burduhos, On the Incidence Angle Optimization of the Dual-Axis Solar Trackers, *11th International Research/Expert Conference TMT - Trends in the Development of Machinery and Associated Technolog*y, Hamammet, Tunisia, 04-09 Septembrie 2007, ISBN 994861733-X, pg. 1111-1113.

[20] ***http://europa.eu/pol/ener/flipbook/ro/files/energy_ro.pdf.