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ANALYSIS OF CONCENTRATION RATIO OF THE PHOTOVOLTAIC SYSTEM WITH ONE TRACKING FLAT MIRROR

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Solar concentration photovoltaic (CPV) technology is a promising way to increase the conversion efficiency of solar energy. In CPV systems, a large area of sunlight is focused on the smaller area of solar cells with the help of optical light collectors, such as lenses or mirrors. There are different types of CPV systems, among which the simplest is the system consisting of a PV module and a flat plate solar tracking mirror. Due to its simplicity, this CPV system can be successfully applied for building integrated - purpose and hybrid PV and thermal systems.

The output power of CPV systems strongly depends on the concentration ratio of solar rays. To characterize the CPV systems, generally, the geometrical concentration ratio is considered. Meanwhile, the output power of a CPV system depends on the reflectance of mirrors and light transmission into the PV module, which are functions of the light incident angle.

In this paper, an accurate method for analyzing light energy concentration in the CPV system with one tracking flat plate mirror is presented. The proposed method considers both the angular-dependent mirror reflection coefficient and the PV module`s surface absorption properties. The effective concentration ratio is obtained. It is shown that the value of the geometrical concentration ratio is more than the effective concentration ratio. It is also shown that during the analysis of the power output of the concentrating photovoltaic system with one solar tracking flat mirror, the effective concentration ratio must be considered instead of geometric concentration ratio, since the effective concentration ratio, proposed in this paper, can more accurately assess the energy of solar light absorbed by the photovoltaic receiver.

Keywords: solar, photovoltaic, concentrated, mirror, tracking, concentration ratio.

Introduction. The concentrating photovoltaic (CPV) is an approach for generating electric energy with limited solar cell areas. In CPV systems, a large area of sunlight is focused on the smaller area of solar cells with the help of optical light collectors, such as lenses or mirrors.

There are different types of CPV systems, among which the simplest is the system consisting of a PV module and a flat plate solar tracking mirror. Due to its simplicity, this CPV system can be successfully applied for building integrated purposes. The combination of this type of CPV technology with the hybrid PV and thermal systems, supplying electric and thermal energies, will significantly increase the system efficiency.

In a CPV system with one tracking mirror, the PV module is illuminated by direct solar rays and by reflected rays from the mirror, which is tracking the Sun during the day. The PV module is also illuminated by diffused rays. Thus, the solar rays are striking the solar cells of the module at different incident angles, which influences the light transmission into the PV module. Note that the reflectance of the mirror is also affected by the light incidence angle.

To characterize the CPV systems, generally, the geometrical or optical concentration ratio is considered. Meanwhile, the output power of a CPV system depends on the reflectance of mirrors and light transmission into the PV module, which are functions of the light incident angle.

The effect of the light incident angle on the short circuit current of different types of solar cells with the use of different techniques and methods is investigated [1-5]. It is shown that the relative angular light transmission into the PV module (or relative angular optical response) decreases with the increase of the light incident angle. The effect of incidence angle on the reflectance of solar mirrors is investigated [6-9]. In a V-trough CPV system, the approximations for mirror reflectivity and modifier of angular losses in the PV module are considered [10].

In this paper, an accurate method for analyzing light energy concentration in the CPV system with one tracking mirror is presented. The proposed method considers both the angular-dependent mirror reflection coefficient and the PV module`s surface absorption properties.

Concentration rate of a CPV system with one solar tracking flat mirror. Let us consider the low-concentration CPV system with one flat plate planar reflecting mirror (Fig. 1). The width of the mirror, a, equals the width of the PV module. The solar direct illumination and the reflected light, with a number of reflections equal one, strike the PV module. The diffuse radiation due to the sky scattering is neglected due to the small percentage of the total radiation. The PV module is fixed, and the mirror tracks the sun so that the beam reflected from the upper point of the mirror strikes the edge points of the PV modules. It is assumed that the illumination is uniform on the receiver. Note that in the perpendicular direction to the plane in Fig. 1, the PV module and the mirror can have any dimension, and it is not considered in the frames of this paper.

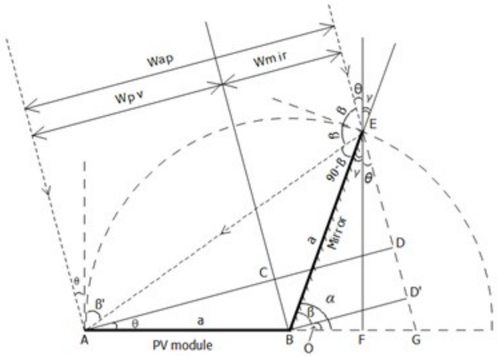

Fig. 1. A concentrating PV system with one planar reflecting and solar tracking mirror

For a CPV system, the maximum power output is defined as [11]:

P*max = Pmax Copt (1+kT/q (lnCopt/Voc)),

where Pmax is the maximum output power at maximum power point, Copt is the optical concentration ratio and Voc is the open circuit voltage. If in the concentrating system the image covers the entire surface of the receiver and the radiation flux is uniform over the aperture and over the receiver, the geometrical concentration ratio Cgeo is used. The geometrical concentration ratio of the planar mirror reflecting PV system (Fig. 1) is defined as the ratio of aperture area, Wap, to the PV module area, a:

$$\boldsymbol{Cgeo = \frac{Wap}{a}}.$$

The geometrical concentration ratio can be written as:

$$\boldsymbol{Cgeo = \frac{Wap}{a} = \frac{AC+CD}{a} = \frac{a\cos\ (\theta) + a\cos(\beta\,)}{a} = \cos(\theta) + \cos\left(60 - \frac{\theta}{3}\right)}. \quad (1)$$

The geometrical and optical (or flux) concentration ratios characterize the rate of amplification of light flux over the receiver area. Meanwhile, as mentioned above, the absorption of solar energy by the PV receiver, as well as the reflection coefficient of concentrating mirrors, depend on the incident angle of solar rays. Therefore, to more accurately determine the light power absorbed in the CPV system, both the angular-dependent mirror reflection coefficient and the PV module`s surface absorption properties should be taken into consideration. With this approach, the effective concentration ratio will be determined.

The effective concentration ratio will be defined by dividing the solar light flux into two components. The first component of the light flux is the direct component with aperture of Wpv illuminating the PV module under the incident angle of θ (Fig. 1). The second component is the light flux with aperture of $Wmir,$

reflected from the mirror and illuminating the PV module under the incident angle of β`. Then, the effective concentration ratio can be presented as:

$$Ceff = Ceff(Wpv) + Ceff(Wmir). \tag{2}$$

The first component of the effective concentration ratio can be determined as:

$$Ceff(Wpv) = \tau(\theta)\frac{AC}{a} = \tau(\theta)\frac{a\,cos\,(\theta)}{a} = \tau(\theta)cos(\theta), \tag{3}$$

where $\tau(\Theta) = Isc(\theta)/[Isc(0)\ cos(\theta)]$, and characterizes the relative angular light transmission into PV module or solar cell [1], $Isc(\theta)$ is the short circuit current of PV module measured at inclination angle of θ, and $Isc(0)$ is the short circuit current of PV module measured at inclination angle of $\theta = 0$.

The second component of the effective concentration ratio depends on the reflectivity of the mirror $R(\beta)$, where β is the light incident angle. The second component depends also on the relative angular light transmission into the PV module $\tau(\beta`)$, where $\beta`$ is the incident angle of the reflected light on the PV module. The second component of the effective concentration ratio will be:

$$Ceff(Wmir) = \tau(\beta`)R(\beta)\frac{Wmir}{a}. \tag{4}$$

Let us express the angles β and β` by $\Theta$. Using simple geometric principles from the right triangle *AEF*, we can write: $\beta = 60 - \Theta/3$. Considering that the triangle *AEB* is isosceles, we shall get $\beta` = \beta$. Considering the right triangle *BED*`, we can get that $Wmir = a\ cos(\beta)$. Then, substituting $\beta`$, β, and $Wmir$ into (4), we shall have:

$$Ceff(Wmir) = \tau(60 - \theta/3)R(60 - \theta/3)\cos(\,(60 - \theta/3). \tag{5}$$

Thus, by substituting (3) and (5) into (2), the effective concentration ratio can be written as:

$$Ceff = \tau(\theta)cos(\theta) + \tau(60 - \theta/3)R(60 - \theta/3)\cos(\,(60 - \theta/3). \tag{6}$$

Note that the relative angular light transmission $\tau(\theta)$ for the given PV module (or solar cell) can be determined experimentally, by measuring the short-circuit current $Isc(\Theta)$ under different angles of incidence of the surface and by plotting the $\tau(\theta) = Isc(\Theta)/[Isc(0)cos(\theta)]$. The reflectivity of the given mirror $R(\beta)$ can also be determined experimentally by measuring the reflectivity at different incidence angles of solar light.

Experimental investigation of angular light transmission into the PV module and the angular dependence of reflectivity of the mirror. To analyze the effective concentration ratio of the CPV system with one mirror, experimentally, the relative angular light transmission $\tau(\Theta)$ for the silicon solar cell, and the reflectivity of the reflective film mirror R(β) are measured.

The relative angular light transmission into the PV module is measured using the monocrystalline silicon solar cell. The sample of the solar cell was placed on the rotating table and illuminated by the solar light simulator (Fig. 2). The short-circuit current at different incident angles was measured.

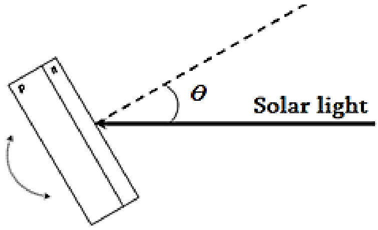

Fig. 2. The experimental setup for measurements of the relative angular light transmission into the solar cell

The obtained experimental results of the relative angular light transmission into the solar cell $\tau(\Theta)$ are presented in Fig. 3.

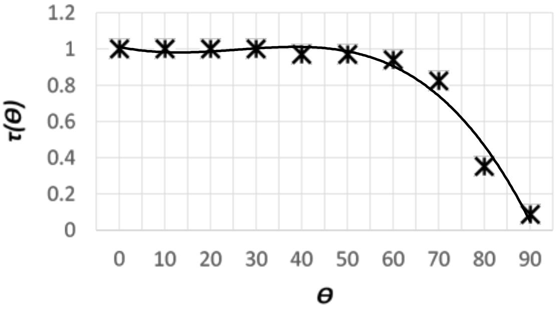

Fig. 3. Relative angular light transmission into the solar cell τ(Θ) vs. light incident angle Θ

As could be expected, the relative angular light transmission into the solar cell *τ(Θ)* decreases with increasing the solar light incident angle (Fig.3).

For calculations of *τ(Θ)* for the given solar cell, the following polynomial model was developed:

$$\tau(\theta)=-5.999\times10^{-9}\cdot\theta^{4}-3.045\times10^{-6}\cdot\theta^{3}+2.623\times10^{-4}\cdot\theta^{2}-5.24\times10^{-3}\cdot\theta+1.012. \quad (7)$$

The R-factor, also called residual factor or relative error, is defined, and it has the value R = 0.045568, which can be considered as a good fit.

The reflectivity of the sample of a mirror-reflecting film at different incident angles of the light *R(α)* is also measured with the use of the same rotating table (Fig. 2). The intensity of the specular reflected solar beam is measured by measuring the short circuit current of a silicon p-n junction. To avoid the influence of the scattered and diffused beams, the p-n junction was placed in a specially developed box with a narrow incident gap. The obtained results are presented in Fig. 4.

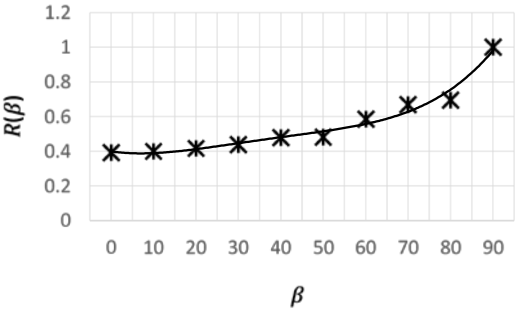

Fig. 4. Reflectivity of the mirror reflecting film $R(\beta)$ *vs. solar light incident angle* β

It can be seen from Fig. 4 that the reflectivity of the given type of mirror film is comparatively low at small incidence angles of the solar light, and it increases at high values of incident angle.

For calculations of $R(\beta)$ for the given type of reflective mirror, the following polynomial model is developed:

$$R(\beta) = 4.74\times10^{-8}\cdot\beta^{4}-6.842\times10^{-6}\cdot\beta^{3}+3.51\times10^{-4}\cdot\beta^{2}-4.069\times10^{-3}\cdot\beta+0.4. \quad (8)$$

The R-factor is defined, and it has the value R = 0.036446.

Analysis of the concentration ratio of PV concentrating system with the flat solar tracking mirror. With the use of formula (6) and experimentally obtained dependences for $\tau(\Theta)$ *and* $R(\Theta)$, the effective concentration ratio *Ceff* of the PV system with the flat solar tracking mirror is determined. The curve of *Ceff* for the positive values of the Sun inclination angle Θ is presented in Fig. 5.

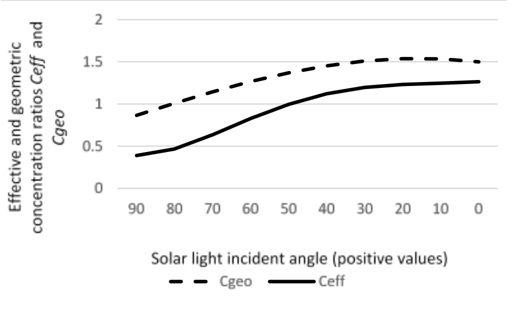

Fig. 5. The effective and geometric concentrations of the PV module with one flat tracking mirror in dependence on the solar light positive incident angles

The geometric concentration ratio *Cgeo* calculated by formula (1) is also presented in Fig. 5. It can be seen that there is a difference between the concentration ratios *Cgeo* and *Ceff*. The maximum difference of 0.54 (54%) is obtained at the inclination angle of $\Theta = 80°$, when *Cgeo* = 1 and *Ceff* = 0.46. Consequently, during the analysis of the power output of a CPV system with one tracking mirror, the effective concentration ratio *Ceff* must be considered instead of the geometric concentration ratio *Cgeo*.

The effective and geometric concentration ratios of the CPV system with one tracking mirror determined for the negative values of the Sun inclination angle Θ, are presented in Fig. 6.

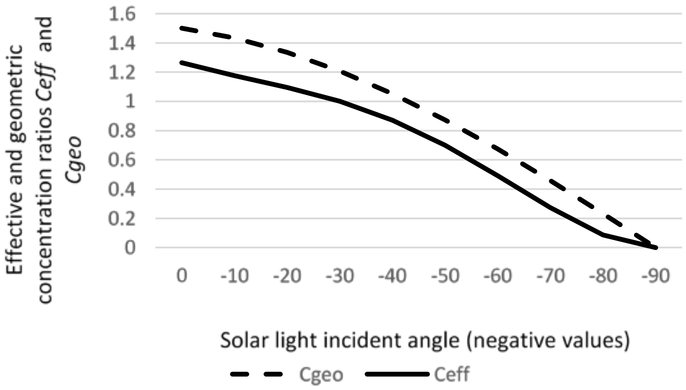

Fig. 6. The effective and geometric concentrations of the PV module with one flat tracking mirror in dependence on the solar light negative incident angles

In this case, also, there is a difference between the concentration ratios *Cgeo* and *Ceff*. The maximum difference of 0.25 (17.5%) can be observed at $\Theta = -10^\circ$, when *Cgeo* = 1.43 and *Ceff* =1.18. This also proves that instead of geometric concentration ratio, the effective concentration ratio must be considered during the analysis of CPV system.

Conclusions

1. The analysis of geometric and effective concentration ratios of the concentrating photovoltaic system with one solar tracking flat mirror is conducted.

2. The accurate method for analyzing light energy concentration in the CPV system with one tracking mirror is developed, where the angular-dependent mirror reflection coefficient, as well as the PV module`s surface absorption properties are considered.

3. It is shown that the value of the geometrical concentration ratio is more than the effective concentration ratio.

4. During the analysis of the power output of the concentrating photovoltaic system with one solar tracking flat mirror, the effective concentration ratio must be considered instead of geometric concentration ratio, since the proposed method for

the determination of the effective concentration ratio assesses the energy of solar light absorbed by the photovoltaic receiver more accurately.

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ՀԵՏԵՎՈՂ ՄԵԿ ՀԱՐԹ ՀԱՅԵԼԻՈՎ ՖՈՏՈՎՈԼՏԱՅԻՆ ՀԱՄԱԿԱՐԳԻ ԿՈՆՑԵՆՏՐԱՑԻԱՅԻ ԱՍՏԻՃԱՆԻ ՎԵՐԼՈՒԾՈՒԹՅՈՒՆ

Ռ.Ռ. Վարդանյան, Ջ.Ս. Դավթյան

Արեգակնային կոնցենտրացիոն ֆոտովոլտային (ԿՖՎ) տեխնոլոգիան արևային էներգիայի փոխակերպման արդյունավետությունը բարձրացնելու հեռանկարային միջոց է: ԿՖՎ համակարգերում արևի լույսի մեծ մակերեսը կենտրոնանում է արևային մարտկոցների ավելի փոքր մակերեսի վրա՝ օպտիկական լույսի կոլեկտորների միջոցով, ինչպիսիք են ոսպնյակները կամ հայելիները: Կան ԿՖՎ համակարգերի տարբեր տեսակներ, որոնցից ամենապարզը ֆոտովոլտային մոդուլից և արևին հետևող հարթ հայելուց բաղկացած համակարգն է: Իր պարզության շնորհիվ՝ այս ԿՖՎ համակարգը կարող է հաջողությամբ կիրառվել շենքերին ինտեգրման նպատակներով և հիբրիդային ֆոտովոլտային ու ջերմային համակարգերի դեպքում:

ԿՖՎ համակարգերի ելքային հզորությունը մեծապես կախված է արևային ճառագայթների կոնցենտրացիայի աստիճանից: ԿՖՎ համակարգերը բնութագրելու համար, ընդհանուր առմամբ, հաշվի է առնվում երկրաչափական կոնցենտրացիայի աստիճանը: Միևնույն ժամանակ, ԿՖՎ համակարգի ելքային հզորությունը կախված է հայելիների անդրադարձումից և լույսի թափանցելիությունից դեպի ֆոտովոլտային մոդուլ, որոնք ֆունկցիաներ են լույսի անկման անկյունից:

Աշխատանքում ներկայացված է արևին հետևող մեկ հարթ հայելիով ԿՖՎ համակարգում լույսի էներգիայի կոնցենտրացիայի վերլուծության ճշգրիտ մեթոդ: Առաջարկվող մեթոդը հաշվի է առնում ինչպես հայելու անդրադարձման գործակիցի անկյունային կախվածությունը, այնպես էլ ֆոտովոլտային մոդուլի մակերեսի կլանման հատկությունները: Արդյունքում ստացվում է արդյունավետ կոնցենտրացիայի աստիճանը: Ցույց է տրվում, որ երկրաչափական կոնցենտրացիայի աստիճանը մեծ է արդյունավետ կոնցենտրացիայի աստիճանից: Ցույց է տրվում նաև, որ արեգակին հետևող մեկ հարթ հայելիով կենտրոնացնող ֆոտովոլտային համակարգի ելքային հզորության վերլուծության նպատակով պետք է հաշվի առնել արդյունավետ կոնցենտրացիայի աստիճանը՝ երկրաչափական կոնցենտրացիայի աստիճանի փոխարեն, քանի որ աշխատանքում առաջարկվող արդյունավետ կոնցենտրացիայի աստիճանը ավելի ճշգրիտ է գնահատում ֆոտովոլտային ընդունիչի միջոցով կլանված արևային լույսի էներգիան:

Առանցքային բառեր. արևային, ֆոտովոլտային, կոնցենտրացված, հայելի, արևին հետևող, կոնցենտրացիայի աստիճան:

АНАЛИЗ КОЭФФИЦИЕНТА КОНЦЕНТРАЦИИ ФОТОЭЛЕКТРИЧЕСКОЙ СИСТЕМЫ С ОДНИМ СЛЕДЯЩИМ ПЛОСКИМ ЗЕРКАЛОМ

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Технология солнечной концентрации фотоэлектрических (КФЭ) систем является одним из перспективных способов повышения эффективности преобразования солнечной энергии. При КФЭ систем большая площадь солнечного света фокусируется на меньшей площади солнечных элементов с помощью оптических коллекторов, таких как линзы или зеркала. Существуют различные типы КФЭ систем, среди которых наиболее простой является система, состоящая из фотоэлектрического модуля и плоского зеркала, следящего за Солнцем. Благодаря своей простоте такая система КФЭ может успешно применяться для целей построения интегрированных в здания фотоэлектрических и гибридных фотоэлектрических и тепловых систем.

Выходная мощность КФЭ систем сильно зависит от коэффициента концентрации солнечных лучей. Для характеристики КФЭ систем, как правило, рассматривается геометрический коэффициент концентрации. Между тем выходная мощность КФЭ системы зависит от отражательной способности зеркал и пропускания света в фотоэлектрический модуль, которые являются функциями угла падения света.

В данной статье представлен точный метод анализа концентрации световой энергии в КФЭ системе с одним плоским следящим за Солнцем зеркалом. Предложенный метод учитывает как коэффициент отражения зеркала, зависящий от угла падения, так и свойства поглощения поверхности фотоэлектрического модуля. Получен эффективный коэффициент концентрации. Показано, что значение геометрического коэффициента концентрации больше эффективного коэффициента концентрации. Показано также, что при анализе выходной мощности концентрирующей фотоэлектрической системы с одним плоским зеркалом, следящим за Солнцем, необходимо рассматривать эффективный коэффициент концентрации вместо геометрической концентрации, поскольку эффективный коэффициент концентрации, предложенный в статье, точнее оценивает энергию солнечного света, поглощаемую фотоэлектрическим приемником.

Ключевые слова: солнечный, фотоэлектрический, концентрированный, зеркало, слежение, коэффициент концентрации.