ABSTRACT

This paper is about the researches conducted in the fields of development of prismatic stationary concentrators of solar energy and design of photovoltaic modules on their base. The developed concentrators and modules can be used with the silicon solar cells. The modules can be installed stationary without tracking systems.

This paper shows the results of researching and development of the two classes V-shape stationary prismatic concentrators with the shapes of their edges’ sections as a straight line and the arcs of circles. The researches show the relations between the created mathematical models for these classes of concentrators.

Basing on the conducted researches there are designed the schemes of the photovoltaic modules with the stationary prismatic concentrators, silicon solar cells and passive heat sink. The theoretical approach is supported by the experimental researches of the designed prototype of the stationary photovoltaic module with the V-shape prismatic concentrator.

The paper is finished with the economical evaluation of the photovoltaic modules with the prismatic stationary concentrators and comparing them with the standard plain photovoltaic modules. The evaluations show the cost reduction for the photovoltaic modules up to 30% by using prismatic concentrators in them.

1. THE STATE OF ART.

There are at least two reasons to use concentrators of solar energy in photovoltaic modules. The first one is to increase the efficiency of the photovoltaic modules, because efficiency of the PV transformation of solar energy increases as a logarithm of concentration. And, the second one is to reduce its cost and consequently the cost of the produced electrical energy reducing the number of expansive solar cells working with the concentrators. However, there is a tradeoff here, because high levels of concentrations demand precision tracking systems to keep the PV system in work and reliable in operation cooling systems to maintain the solar cells with the safety temperature conditions. These two factors can increase the cost of PV systems working with high levels of concentrations.
The low concentration’s levels below 10 X could be successfully produced by stationary concentrators of solar energy. The advantages of this approach are using of concentrators to increase the efficiency and decrease the cost of PV systems and not using of the tracking systems at the same time.

The first stationary concentrator was recognized the CPC (compound parabolic concentrator) concentrator invented independently by Prof. Winston in the USA [1] and Prof. Baranov in Russia [2]. Fig. 1. This concentrator has the field of view defined by its parametric angle and is able to focus radiation, which is falling on it with different angles less than the parametric. All parameters of this concentrator are directly dependent on its parametric angle. Formula 1.

\[ d = D \cdot \sin \alpha \quad H = \frac{(D + d)}{2} \cdot \cot \alpha \quad (1) \]

Today, this concentrator is successfully being used as the second concentrator in the high temperature solar thermochemical reactors, but it is seldom used in the photovoltaic with solar cells because of its highly non uniform energy distribution in the focal spot.

The classical example of the stationary prismatic concentrator is the triangle prism. Fig. 2. This concentrator was invented and developed by Mills and Giutranich from Australia [3]. The solar radiation falls on the front edge, goes into the prism and reflects from the back reflective edge. After reflection radiation approaches the front edge with the angle bigger than full inner reflective angle for the prism material, catches by the prism and follows to the output edge of the prism. This classical prism can catch radiation from the different directions without tracking of itself and allows reaching up to 2 X concentration ratio for the stationary mode. Unfortunately for this concentrator’s design, the level of concentration falls fast when the sun changes its position during the year. The main advantage to use this type of stationary concentrators in the PV systems is - its focal spot has very uniform energy distribution which is very suitable for the solar cells.

2. THE MODULE WITH THE PRISMATIC CONCENTRATORS.

2.1. The models of prismatic concentrators.

To improve the characteristics of the prismatic concentrators, we developed two classes of symmetric V - shaped prismatic stationary concentrators. The first one is the V-shaped prismatic concentrator with the linear edges [4]. Fig. 3.

\[ K = \frac{D}{d} = \frac{\sin \left(2 \cdot \gamma + \arcsin \frac{1}{n} - \frac{\pi}{2}\right)}{\sin \beta \cdot \sin \left(\gamma + \arcsin \frac{1}{n}\right)} \cdot \cos (\beta + \gamma) + 1 \quad (2) \]
And, the second one is the V-shaped prismatic concentrator with the edges in the form of the arc or circumference [5]. Fig. 4.

![Fig. 4. The circumferential V-shaped Concentrator.](image)

The concentrators are combined from two symmetrically placed triangle prisms with some extension toward the output edge. The inner edges serve for receiving of the incoming radiation, and the reflective surfaces are located on the outer edges of the prism. These concentrators’ designs allow us sufficiently increase productivity during the year and level of concentration for these concentrators in compare with the classical triangle concentrator prism.

For the value of parametric angle is equal to $24^\circ$, the developed mathematical model for the linear V-shaped concentrator gives us maximal feasible concentration ratio which is about 3.2 X, but can be increased up to 3.5-3.7 X without sufficient losses of energy. The optical efficiency of concentrators is about 0.75 - 0.8 and can be improved by using more efficient reflective film materials.

The math modeling graph of the energy distribution achieved on the output edge of the linear V-shaped concentrator is shown on the Fig. 5. The maximal concentration levels’ deviation appears when the direction of incoming radiation is close to the parametric angle of the concentrator. However, even in this case, this deviation is fewer lesser than the deviation for the CPC concentrators with the same parametric angle. This parameter is good enough to use prismatic concentrators with the silicon solar cells in the photovoltaic modules.

By the results of computer simulations based on the mathematical models of the classes of prismatic concentrators, we were able to compare their geometrical and optical characteristics. The Fig. 6 shows us the achieved levels of concentrations for the circumferential V-shaped concentrator. As we can see, this level never increases above 3.2 X – the concentration level for the linear V-shaped concentrator and become closer to this value when the curvatures of the edges go to zero and the upper and lower angles of the edges go to the slope angle of the linear concentrator. So, between the developed classes of prismatic concentrators, the class of the linear V-shaped concentrators becomes preferable for using in the stationary PV systems.

2.2. Choice of the cooling system.

To choose the appropriate schemes of the heat sinks for the silicon solar cells working with selected concentrators, there was created the thermodynamic model of the solar cell - concentrator pair. The solar cell is assumed to be in optical contact with the output edge of concentrator and in the thermal contact with the heat sink. The cupper and aluminum plates with different thickness were chosen as the possible heat sinks. The area of heat supplying was chosen proportional to the size of solar cell, and the area of heat removing was chosen proportional to the incoming concentrator’s area. This design allows placing compactly
several rows of concentrators – solar cells in one PV module. The resulting temperature profile for the 25 mm solar cell and 1 mm copper heat sink plate is shown on Fig. 7. Researches show that it is possible to use passive heat transfer from the back surface of the solar cells through the aluminum or copper heat removing plates. The calculated ΔT was about 550 W/sq.m., the total radiation was about 1000 W/sq.m. and the air temperature was about 31°C (304K).

The Volt-Ampere characteristics of the prototype insulated from the different directions is shown on the Fig. 9. The gray line on the Fig. 9 represents an etalon line of the solar cells insulated without concentration.

Fig. 7. Temperature distribution along the output edge.

working temperatures of the solar cells should be in the range of 60-80°C when the environment temperatures range was 10-30°C. It is possible to use simple radiators if the additional predicted temperature reduction is necessary.

2.3. The Photovoltaic module development.

For testing purposes, there was developed the prototype of the PV module with the selected linear V-shaped prismatic concentrator. The prism of the module was constructed from Plexiglas, and the line of the silicon solar cells was imbedded into the output edge of the prism. The module picture is shown on the Fig. 8. Module was tested in the outdoor summer condition when the direct solar radiation was about 550 W/sq.m., the total radiation was about 1000 W/sq.m. and the air temperature was about 31°C (304K).

The energy distribution on the output edge measured by a tiny solar cell is shown on the Fig. 10.

Fig. 8. The prototype of PV module.

Fig. 9. The Volt-Ampere characteristics.

Within the 3 – 3.5 V voltages range, the PV module with the concentrator delivered twice more power than the etalon line by itself. At the operation time, the temperature mode of the solar cells measured by a thermo-couple embedded in the rear wall of the module was in the range 65 - 75°C.

The energy distribution on the output edge measured by a tiny solar cell is shown on the Fig. 10.
Even though the real energy distribution from the Fig. 10 and the math modeling distribution from the Fig. 5 shape little differently, they have the same main characteristics. Concentration levels in both energy distributions increase in the central area when the direction of incoming solar radiation closes to the axes of the concentrator. While the radiation’s direction close to the parametric angle, the concentration levels increase monotonically. The differences in the distributions can be explained by the non-parallelism of the real solar radiation directions, the diffusion radiation level in the atmosphere and the quality of the concentrator and reflective coating.

3. THE ECONOMICAL FEASIBILITY.

The analysis of the factors influencing on the productivity of the PV modules with concentrators shows that for the same peak power, these modules must be on 20 – 40% bigger than the standard planar PV modules. This gives the clue for the estimation of the PV modules’ cost and the unite cost of the delivered energy. The Table 1 shows basic relationships between PV module without concentrator and with concentrator for the 150 W (peak power) PV modules with the 15% solar cells efficiency. Assuming concentration ratio is equal to 4 X, optical efficiency 0.75, and solar flux is 1000 W/m².

**TABLE 1. THE MODULES COSTS RELATIONSHIPS.**

<table>
<thead>
<tr>
<th></th>
<th>Planar module.</th>
<th>With concentrator.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power</td>
<td>150 W</td>
<td>150 W</td>
</tr>
<tr>
<td>Size factor</td>
<td>100%</td>
<td>130%</td>
</tr>
<tr>
<td>Module size</td>
<td>1 m²</td>
<td>1.3 m²</td>
</tr>
<tr>
<td>Solar cells</td>
<td>1 m² ($200)</td>
<td>0.33 m² ($66)</td>
</tr>
<tr>
<td>Concentrators</td>
<td>-</td>
<td>18 kg of prism ($66)</td>
</tr>
<tr>
<td>Covering glass</td>
<td>$15</td>
<td>$20</td>
</tr>
<tr>
<td>Al plate</td>
<td>$6</td>
<td>$10</td>
</tr>
<tr>
<td>Wiring and montage work</td>
<td>$150 + $200</td>
<td>$50 + $220</td>
</tr>
<tr>
<td>Total ($)</td>
<td>$571</td>
<td>$432</td>
</tr>
<tr>
<td>Total ($ per W)</td>
<td>$3.81 per W</td>
<td>$2.88 per W</td>
</tr>
</tbody>
</table>

So, 1 W of the peak power for the PV modules with concentrators with optical efficiency 0.75 is about 25% cheaper than the same W of peak power for the planar modules. Improving of the concentrators optical efficiency to the 0.85 allows increase this parameter up to the 30%.

With the average useful solar flux during the year 1200 kW/m², the 150 W modules deliver 180 kW h of electricity per year. If we assume 10 years payback period, the average cost for electricity delivered by these modules will be about $0.31 for planar modules and $0.24 and lower for modules with the stationary concentrators.

**CONCLUSION**

This work shows technical and economical feasibility for using V-shaped prismatic stationary concentrators in the Photovoltaic modules. Developed concentrators have the concentration level up to 3.5 – 3.7 X and can be used in the PV modules with the passive cooling systems. The experimental results on the prototype of the PV modules show good matching to the theoretical results by the concentration ratio, energy distribution, module’s power output and temperature mode of the solar cells. The developed PV modules with concentrators should be 25 - 30% cheaper that the planar modules with the same power. The cost of electricity delivered by the PV modules with the stationary concentrators is about $0.24 per kW h and lower.

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