Improving the efficiency of the use of photovoltaic stations in the republic of Cuba

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Abstract. This article is devoted to the study of the reasons for the low efficiency of solar generators in the Republic of Cuba. The work provides one of the possible technical solutions to this problem. The introduction of new technological solutions requires an integrated approach that evaluates the possibility of applying more efficient technologies for capturing sunlight in specific climatic conditions of the country, as well as evaluating the economic benefits of a particular solution. Therefore, this article discusses the existing problem of low efficiency of solar power plants, due to the absence of any tracking systems for the sun. The paper presents ways to solve this problem. Also, the paper presents a model of a photovoltaic solar system generator developed in the Matlab Simulink software, which makes it possible to study the main electrical variables of the complex. The experience gained in the course of the study presented in this paper can be applied in similar studies in Russia.

1. Introduction

This paper presents an investigation of the influence of different content of additives of the pre-treated aluminium oxide powder on the structure of lead-tin-base bronze under formation.

The climatic characteristics of the Republic of Cuba are such that the most natural way to develop the island’s energy system is through the widespread introduction of solar energy production systems. In recent years, programs have been developed in the Republic of Cuba to build nationwide solar power plants connected to national medium-voltage electronic power systems (up to 13.8 kV).

Currently, some solar power plants have problems with the efficiency of some of the components that make up the electrical system of these facilities. Studies conducted at a solar power plant in the province of Santiago de Cuba found that the main reasons for the low efficiency of this solar power plant are solar generators.

This implies the need for an in-depth study, which will identify the main reasons for the low efficiency of solar generators of these solar power plants, and will allow finding technical solutions to eliminate these problems.

In addition to solving the current problems of the efficiency of solar generators in order to increase the energy production of the mentioned solar installations, it is also necessary to assess the technical and economic aspects for the introduction of more efficient technologies for capturing solar rays.

Today, two ways to maximize the energy received from a photovoltaic installation are widespread. The first solution is to improve the structure of the photovoltaic panel, aimed at increasing its productivity. The second is an increase in the amount of solar radiation captured by the panel. To improve the structure of the solar module, semiconductor materials are used with a high efficiency of...
converting solar energy into electrical energy, multilayer combinations of semiconductor materials with different characteristics, and solar panel cooling systems.

Currently, there are three types of photovoltaic panels corresponding to the type of production. Table 1 shows the efficiency of converting solar radiation energy into electrical energy.

Table 1. Summary of the types of silicon solar cells.

| Properties          | Monocrystalline Solar Panels | Polycrystalline Solar Panels | Amorphous Solar Panels |
|---------------------|-------------------------------|-----------------------------|------------------------|
| Efficiency          | up to 20%                     | up to 15%                   | about 10%              |

Currently, at a 2.5 MW solar power plant, solar generators are equipped with 10,400 panels of polycrystalline technology (15% efficiency). With the development of technology, the values of the efficiency of solar panels are gradually increasing, since currently solar panels have been developed, the efficiency of which exceeds 40%. However, it should be noted that the economic costs of acquiring high-efficiency solar modules will increase. This involves the implementation of additional feasibility studies.

The development of these new photovoltaic panels with greater efficiency can improve the performance of a 2.5 MW solar power plant in the province of Santiago de Cuba, Republic of Cuba. This technological improvement should be justified by technical economic studies that justify the investment [1].

To achieve the best results when applying the second method, the area of the photovoltaic panel should remain perpendicular to the radiation of the light source. For this, solar trackers are used in photovoltaic systems [2-3]. A promising technology in the field of solar generation systems is the introduction of solar trackers that track the position of the sun and position of the solar panel perpendicular to the radiation, providing the greatest efficiency in generating electricity. However, the question of a real increase in the generation and cost-effectiveness of introducing the described technology remains. Therefore, the issue of assessing the effectiveness of the use of solar trackers in the conditions of the island of Cuba is relevant. Currently, there are no solar installations using this technology on the island, so there is no way to obtain data from which it would be possible to evaluate its real effectiveness.

2. Materials and methods

As part of this study, a model was developed in Matlab software for modeling a 2.5 MW photoelectric solar system generator (Figure 1). The model allows you to study the main electrical variables that make up the system of connection to the solar network, taking into account specific weather conditions in the region. The main variables studied by the model in the Matlab / Simulink program are the energy generated by the photovoltaic system without monitoring and with solar monitoring. These variables are necessary to evaluate the effectiveness of solar monitoring systems in the specific climatic conditions of the Republic of Cuba.

There are several reasons that determine the low efficiency of obtaining electrical energy from solar in the region. The main reasons are that the solar modules that are used in solar power plants do not meet the technical standards of the manufacturer [4]. On the other hand, there are some design aspects of solar generators that are part of the electrical complex, which are inadequate. An example of this is that the separation of solar generators, which is not optimal, leads to partial shading of the surfaces of the generators in December, when the sun has the lowest height all year round [5-6].
There are several reasons that determine the low efficiency of obtaining electrical from solar energy in the region. The main reasons are that the solar modules that are used in solar power plants do not meet the technical standards of the manufacturer. On the other hand, there are some design aspects of solar generators that are part of the electrical complex, which are inadequate. An example of this is that the separation of solar generators, which is not optimal, leads to partial shading of the surfaces of the generators in December, when the sun has the lowest height all year round [7].

In the course of the study, the angles of solar height and the angle of inclination of the photovoltaic panel were calculated using the example of climatic and geographical conditions of the Republic of Cuba. In accordance with Equations 1, 2, 3, 4, 5, and 6, the solar altitude ($\alpha_s$) was calculated for each month of the year in the region of Santiago de Cuba, Republic of Cuba, with a latitude of 20.02° and a longitude of -75.82° (Table 2).

### Table 2. Calculation of the optimal angle ($\beta_{opt}$) for each month of the year

| Parameter | month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|-----------|-------|---|---|---|---|---|---|---|---|---|----|----|----|
| $\alpha_s$ | min | 46.9 | 52.4 | 61.6 | 73.9 | 84.8 | 86.8 | 86.8 | 78.2 | 66.3 | 55.0 | 48.0 | 46.9 |
|            | max | 52.2 | 61.2 | 73.5 | 84.5 | 88.1 | 87.9 | 88.2 | 87.9 | 77.8 | 65.9 | 54.7 | 47.9 |
|            | averg | 50 | 57 | 68 | 79 | 86 | 87 | 88 | 83 | 72 | 60 | 51 | 47 |
| $\beta$ | angle | 40 | 30 | 20 | 10 | 5 | 5 | 5 | 10 | 20 | 30 | 40 | 40 |
| $\beta_{opt}$ | angle | 20 |

Equations used in the study:

$$\delta = 23.45 \times \sin \left(\frac{360 \times (284 + n)}{365}\right)$$  \hspace{1cm} (1)

$$E = 9.87 \times \sin \left(2 \times \frac{360}{364} \times (n - 81) \times n\right) - 7.53 \times \cos \left(\frac{360}{364} \times (n - 81) \times n\right)$$  \hspace{1cm} (2)

$$HS = HF + E + 4 \times (L_{left} - L_{loc})$$  \hspace{1cm} (3)
\[ w = -\left(\frac{15}{h}\right) \ast HS + 180 \quad (4) \]
\[ \alpha_s = 90 - \cos^{-1}\left(\sin(\delta) \ast \sin(\varphi) + \cos(\delta) \ast \cos(\varphi) \ast \cos(w)\right) \quad (5) \]
\[ \beta = 180 - (90 + \alpha_s) \quad (6) \]
\[ \beta_{opt} = \cos^{-1}\left[\frac{\cos(\alpha_{max}) - \cos(\alpha_{min})}{2}\right] \quad (7) \]

where: \( \delta \) - The angle of solar declination \( [^\circ] \), \( \theta_2 \) - angle senital \( [^\circ] \), \( \varphi \) - latitude of the place \( [^\circ] \), \( h \) - Time of day \([\text{hour}]\), \( \beta \) - angle of inclination of the solar panel \( [^\circ] \), \( \gamma \) - angle azimut \( [^\circ] \), \( n \) - days of the year \((1-365 \text{ days})\), \( E \) - equation of time, \( HS \) - solar time \([\text{hour}]\), \( HF \) - official time \([\text{hour}]\), \( Llef \) - length of the reference meridian, \( Lloc \) - Meridian Length, \( w \) - angle of solar time \( [^\circ] \), \( \alpha_s \) - sunny elevation angle \([^\circ] \).

According to the calculations, it can be verified that the optimal angle of inclination of the solar generators is 20 degrees, which is equal to the latitude of the study site, and therefore corresponds to the current inclination of the panels in the central part of 2.5 MW of solar energy in the province of Santiago de Cuba, Republic of Cuba. Figure 2 shows the main installation parameters of solar modules that affect the generation of electrical energy.

\[ w = -\left(\frac{15}{h}\right) \ast HS + 180 \quad (4) \]
\[ \alpha_s = 90 - \cos^{-1}\left(\sin(\delta) \ast \sin(\varphi) + \cos(\delta) \ast \cos(\varphi) \ast \cos(w)\right) \quad (5) \]
\[ \beta = 180 - (90 + \alpha_s) \quad (6) \]
\[ \beta_{opt} = \cos^{-1}\left[\frac{\cos(\alpha_{max}) - \cos(\alpha_{min})}{2}\right] \quad (7) \]

Figure 2. The position of the supports of the solar generator of a solar power plant with a capacity of 2.5 MW [1].

Table 3. Actual data of the supports of the solar generator (Figure 2).

| Generator length \((L)\) | Generator height \((H)\) | Generator angle \((\beta)\) | Separation between generators \((D_1)\) |
|--------------------------|--------------------------|----------------------------|-----------------------------------|
| 6.6 m                    | 2.5 m                    | 20 deg                     | 2 m                               |

According to the calculations obtained according to equation 9, the minimum distance that generators should have is 2.8 meters \((D_2 = 2.8 \text{ m})\), currently the generators are at a distance of about 2 meters \((D_1 = 2 \text{ m})\), which causes partial shadows between solar generators in the month of December, since the solar altitude is minimal at this time of year for the region of Santiago de Cuba, Republic of Cuba.

\[ H = L \ast \sen(\beta) \quad (8) \]
\[ D_2 = \frac{H}{\tan(61-\varphi)} \quad (9) \]

where: \( D_1 \) - distance between current photoelectric generator, \( D_2 \) - distance between optimal photoelectric generator, \( H \) - generator length, \( \beta \) - generator angle.

According to other studies conducted on solar modules (model DSM-240C) that operate on this
photovoltaic station, the power values developed by these photovoltaic modules deviate on average by 15% of the rated power declared by the manufacturer in specific climatic conditions, from the region where this photovoltaic power station operates [1]. The main reasons why photoelectric generators show an average of 15% deviation in electrical energy from the rated power of the solar module are due to the fact that these solar modules do not correspond to the electrical parameters reported by their manufacturers in the product data sheet [8-10].

Figure 3 shows the results of the simulation performed in the Matlab program (Figure 1). The energy produced by the 2.5 MW station during a typical day (October 23, 2018) was obtained at various tilt angles ($\beta$) in a static solar generator, that is, without any moving part, and for the azimuthal angle $\gamma = 0$ (this means that the solar generator is ideally directed south).

![Energy generated in a typical day by both solar systems in the 2.5MW photovoltaic plant](image)

Figure 3. Comparison of the energy generated by a 2.5 MW solar system with a solar tracking system and a stationary solar generator with a 20-degree slope.

As can be seen in Figure 3, for the same simulated climatic conditions in the region of Santiago de Cuba, in the Republic of Cuba, the energy generated by the solar tracking system is 24% higher compared to the stationary system. This confirms the fact that solar tracking systems are an effective alternative to improving the efficiency parameters of these systems, as well as to increase energy production [11-13].

It should be noted that the results obtained from the energy transmitted between the stationary photovoltaic system and the solar monitoring system during modeling in the Matlab program correspond to 1 day (10/23/2008) out of 365 days a year, 24% of the increase in energy obtained using the solar tracking system, corresponds to one day.

3. Conclusion

Based on the work done, the scientific team made the following conclusions.

1. It was shown that solar tracking systems are a favorable alternative to improve the efficiency of the solar systems' electrical systems and the energy delivered to the region’s electricity system to which they are connected. The study shows that the energy delivered by the solar tracking system
increases by 24% compared with systems that do not have a tracking system for the sun. These results were obtained in the specific climatic conditions of the region of Santiago de Cuba, Republic of Cuba.

2. In order to find out the exact value of the energy gain of solar tracking systems compared with fixed systems, it is necessary to analyze at least 365 days a year, therefore the presented results give a preliminary idea of the effectiveness of the solar monitoring system for specific climatic conditions in the Republic of Cuba.

3. It can be argued that the angle of inclination of the solar generators of a photovoltaic installation with a capacity of 2.5 MW in the province of Santiago de Cuba is at an optimal angle of inclination of the solar panels (20 degrees) according to the latitude and longitude of the geographical region.

4. The distance between the photovoltaic generators of the 2.5 MW photovoltaic station in the province of Santiago de Cuba is not optimal, which leads to additional energy losses.

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