Varying spatial orientation of photoelectric panels as method of managing graph of electric energy generation

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Abstract. One of the main issues in the determining layout of photovoltaic installations is choosing optimal parameters for photovoltaic panels and auxiliary equipment and duplicating energy sources, which makes it possible to justify economically the electrical energy generation. Regularity of solar radiation variation for the studied geographical point throughout the year, and the influence of atmospheric phenomena, as well as the dynamics of daily and seasonal electrical energy consumption must be considered, which will help to predict the operation mode of the plant, and match generation and consumption schedules. Variation of tilt angle of the photovoltaic module receiving surface relatively to horizon and cardinal points makes it possible to manage the schedule of power generation at solar plant and to match it with the load curve, due to the maximum possible convergence of them, as change in the spatial orientation of the photovoltaic panel surface makes it possible to shift the maximum of solar radiation flux in time. The results of the experimental research also revealed the dependence of the current produced by the photoelectric panel on its spatial orientation due to the change of the incoming solar radiation flux on it.

1. Introduction
The widespread usage of photovoltaic plants is due to first of all infinity of the Sun as renewable energy source, ecological purity of the production of electric energy, the simplicity in the implementation and operation of equipment. During last 6 years prompt and high evolution of solar power plant engineering became evident even under conditions of availability of fossil raw materials and fuel.

Such dynamics is primarily associated with decrease in the capital expenditures of projects and equipment of photovoltaic installations, decreasing their payback period. This is result of mostly of reduction in the specific primary expenditures and increase of total efficiency ratio of solar modules [1].

Most of the information presented in the open press is presented in general outlooks describing general indexes of the energy sector functioning. First of all, the utility photovoltaic plants that are connected to the National Grid of the country, and produce electric energy in large volumes, are described there. Most authors name high price of generated electricity to be the basic problem in the ubiquitous installation of solar systems, and argue the application of network and autonomous low-power plants to supply consumers of housing and communal sector, small-power production facilities, social and health sector, resort zones, outlying and rural territories to be one of the methods to solve it [2]. The listed categories also include objects of distributed generation, the projected growth of which for the next nine years in the world is 200% [3]. In [4] it is noted that number studies how to increase
efficiency and decrease expenditures reduces and most of them are dedicated to the design of new layouts of low-power photovoltaic installations that would meet the need for electric power of small-capacity consumers. Introducing such low-power photovoltaic installations decrease both in the load of the power supply system and in power losses in the components of power grid at electric energy transportation to the consumer can be achieved.

One of the main issues in the determining layout of photovoltaic installations is choosing optimal parameters for photovoltaic panels and auxiliary equipment and duplicating energy sources, which makes it possible to justify economically the electrical energy generation [5]. Regularity of solar radiation variation for the studied geographical point throughout the year, and the influence of atmospheric phenomena, as well as the dynamics of daily and seasonal electrical energy consumption must be considered, which will help to predict the operation mode of the plant, and match generation and consumption schedules. Such multicriteria selection of the required power of photovoltaic modules allows to reduce the costs of equipment, installation and maintenance of the system by reducing the number and power of photovoltaic modules and duplicating energy sources, and to justify their operation modes. Without changing design and configuration of projected solar power installation, increase of indicators of its efficient functioning and coordination of the schedules of electric energy generation and consumption by determining the optimal spatial orientation of the photovoltaic modules with respect to horizon and the sides of the world can be achieved.

2. Background

The variation of the tilt angle of coming the sun's rays on the receiving module surface has direct influence on the intensity of its irradiation, which allows the most complete utilization of the incoming solar radiation flux by means of trekking systems at power stations. The installation structure that observes the Sun, depending on the day time and season is 28–35% more efficient than the fixed installation [6]. However, this approach requires the presence of a mobile base for photovoltaic panels oriented for the Sun position in the sky, which is associated with the manufacture of a more complex system of their constant spatial displacement, and also the use of high reliability attachments requiring special maintenance. For the adjustment and operation of the tracking sensor for un movement in the sky, special high-precision means of software and electronic control of this process are necessary, which would have individual settings considering both level of actinometrical conditions, various influencing climatic factors [7, 8]. As a result, tracking systems have a high cost [9], and the character of the generation schedule corresponds only to the schedule of the solar radiation arrival during the day.

This leads to difficulties in matching the modes of electrical energy generation and consumption. The solution of such issues is carried out, most often, on the basis of monthly or annual amounts of electricity production, without taking into account the fact that the selection of spatial orientation, first of all, affects the justification and forecasting of operating modes of power equipment [10].

Therefore, it is advisable to study the effect of the tilt angle relatively to horizon and cardinal points of the unregulated fixed photovoltaic module, characterized by the simplicity of the system design and its relatively low cost, on the position and value of the maximum of the solar radiation that comes on it.

Analysis of scientific literature has revealed that large number of such studies is most often aimed at increasing the level of incoming insolation upon module by varying its tilt angle by means of analytical and experimental approaches.

The existing computational methods for determining the optimal inclination angle on horizon and orientation along the sides of the world are designed to solve the problem of maximizing the arrival of direct component of solar radiation at any time and are intended for systems for tracking the Sun [11]. But this approach cannot be applied to fixed photovoltaic panels, since all the components of solar radiation are not taken into account. For the south of Russia, a high proportion of diffused radiation in the radiation balance is typical, which is within 25% in summer and 60% in the winter months [10]. Neglecting the diffused and reflected components of solar radiation will lead to an overestimation of
the generating equipment power and low accuracy in predicting its operation mode. To maximize the arrival of total solar radiation on receiving surface, there are no strict analytical dependences.

In [12–14], the effect of tilt angle relatively to horizon and cardinal points of the stationary module on the form schedule and value of solar radiation maximum is widely studied.

In [12], the values of the cosine of the incidence angle of the sun's rays on the differently orientated in space areas were analyzed. The regularities of the variation in the maximum value of insolation at diverse tilt angles relatively to horizon for 4 directions along the sides of the world were noted. It can be concluded from the analysis results that at the oriental orientation the maximum is reached at inclination angles of more than 40° for 90° and 60° for 830. It is not possible to make inferences about the evening time, since there are no corresponding data, because the studies were carried out only for a period of time from 900 to 1500.

In [13], the average monthly values of hourly values of the total and diffused solar radiation, arriving at the horizontal and vertical surfaces with different orientations around the world for June and January, were studied. It was revealed that in June, due to the high altitude of the Sun in comparison with January, the horizontal surface gets much more insolation than the vertical one. It was also noted that in the morning and in the evening a large irradiation was detected at the vertical platform, oriented to the east and west respectively. And although the direction of the receiving surface oriented to the south gives maximum at noon, for January, greater decrease in its value compared with other orientations was found. In work [13], the influence of only the extreme values of the inclination and orientation angles of the photovoltaic panel on the amount and regularities of the arrival of solar radiation was studied.

In the last three above-mentioned works, the issues of the effect of tilt angle relatively to horizon and cardinal points of the stationary module on the position and maximum value of the insolation arriving at it under different angles are considered. However, the dependence between spatial orientation and maximum of the incoming insolation, are not fully considered, since in most cases only strict orientation along cardinal points and/or the vertical and horizontal position of the receiving surface are taken into account. This is caused by the fact that attention has been paid to the research of irradiance of buildings, rather than photovoltaic panels in a solar power plant.

Thus, in order to justify the parameters of the photovoltaic installation components and also to harmonize electric energy generation and consumption schedules by choosing the operation mode of installation, it is necessary to evaluate of spatial orientation effect of the stationary module on the position and maximum value of insolation coming on them must be studied.

3. Methods of Research

3.1. Method of experimental research
Photo of designed and manufactured experimental set-up for experimental studies is shown at Figure 1.

The installation consists of photovoltaic panel 1 (P_{max} = 5W, U_{mp} = 9V) and control photovoltaic element 2 (8.84 W/m²/mA for a horizontal surface) fixed on a movable base allowing to adjust their inclination angle relatively to horizon and cardinal points with the help of rotary-tilt mechanism 7 providing two degrees of rotation freedom, which makes it possible to model change in spatial position of module by means of mechanism levers. To perform precise adjustment of the tilt angle relatively to horizon electronic protractor 3 is used, and to the sides of the world - a scale with a calibration step of 1°, located at the fastening base. The adjustment is from 0° to 85° in the vertical plane and from 0° to 360° in the horizontal plane.
To simulate the connected load, laboratory resistance 6 from 1 ohm to 9999 ohms is used. Fixation of current and voltage at the terminals of the photovoltaic panel and the control element is carried out with the help of multimeters 4 and 5. All the components of this experimental installation are fixed rigidly to the wooden base of the folding structure, which makes it possible to move, deploy, adjust and operate it at any geographical point.

The method of experimental research was as follows. The volt-ampere characteristics of the photovoltaic panel and the determination of its output power were taken at natural sunlight on a site unshadowed by neighboring building structures and green plantations according to [15, 16] at a geographic coordinate of 46.8°N, 40.3°E. (Zernograd, Rostov Region).

3.2. Method of computational research
In order to solve the problem of estimating tilt angle effect on the schedule graph and maximum value of output of electric energy during the day, there must be detected orientation (p) of module, in which, at a constant power and a specific number of photoelectric panels, the amount of insolation coming on it at considered time period will be the maximum as the generation directly depends on the flux of the sun’s rays. The theoretical thesis to solve this task is the mathematical formulation of the optimization issue using the criterion – the maximum of the hourly values of total insolation at time t, with the objective function being:

\[
R_{\text{sum}}^P = R_{\text{dr}}^P + R_{\text{df}}^P + R_{\text{rf}}^P \rightarrow \text{max}
\]

\[
\text{for } t = t_1, t_2, \ldots t_n
\]

where \(R_{\text{sum}}^P, R_{\text{dr}}^P, R_{\text{df}}^P, R_{\text{rf}}^P\) are hour sums of the total, direct, diffused and reflected insolation components, respectively, falling on the receiving surface at position p corresponding to the angle \(\beta\) to horizon and \(\gamma\) to the sides of the world, kWh/m². Calculation of the hourly sums of solar radiation is carried out using express methodology to calculate the solar energy potential at set geographic location [17, 18].

Following limitations were adopted solving above optimization issue:

- values of inclination angle of module relatively to horizon equal \(0^\circ - 90^\circ\);
- values of tilt angle of module by cardinal points equal \(-90^\circ - 90^\circ\);
- considering technical implementation possibility of the obtained solutions calculations accuracy is limited by \(\beta\) and \(\gamma\) integer values.

The solution to the objective function is in fact a solution to the search for the optimal orientation of the PV panels for each hour of the day in question, the purpose of which is to increase the utilization of the solar potential of the area, as well as the efficiency of the photovoltaic panels used.
The solution to the objective function is actually solution of the search for the optimal orientation of the PV panels for each hour of the considered day, the purpose of which is to increase the solar potential utilization of the area, as well as the efficiency of the used photovoltaic panels.

4. Results and their discussion

Figure 2 presents graph of the solar radiation flux on the receiving surface at the selected optimal positions for each hour by the example of June 22.

![Figure 2. Hourly values of total insolation on the module at hourly optimal tilt angles.](image)

By varying the tilt angle of the photovoltaic panel of experimental setup, shift in the maximum of the solar radiation flux in time was also revealed. The results of the analysis of the nature of the coming solar radiation on the differently oriented receiving surfaces of photovoltaic panels have revealed that due to different combination of the spatial placement of module surface respectively to cardinal points and horizon, it is possible to shift the maximum power take-off relatively to noon for the morning and evening time by about four hours.

Figures 3, 4 present the daily energy production curves obtained by calculation and experimentation for 4 variants of tilt angle of module – in this case of the photovoltaic panel of the experimental setup.

![Figure 3. Daily graphs of electric power generation by a photovoltaic panel, obtained by calculation and experimental way for the following spatial orientations: \( \beta = 20^\circ, \gamma = 0^\circ \) (a); \( \beta = 40^\circ, \gamma = -45^\circ \) (b).](image)
Figure 4. Daily graphs of electric power generation by a photovoltaic panel, obtained by calculation and experimental way for the following spatial orientations: \( \beta = 40^\circ, \gamma = 45^\circ \) (a); \( \beta = 60^\circ, \gamma = 90^\circ \) (b).

The results of experimental and computational research have shown that the obtained error value between them is acceptable and does not exceed 10\%. The difference between the actual actinometric and the calculated data is caused by the fact that the calculation model is based on data averaged over 22 years, and the experiment was carried out for a day of one year. The instantaneous total insolation value is affected by cloudiness, which can change dynamically for short time periods (even few minutes), and be different for the one and the same day of various years.

5. Summary

Thus, it can be stated that the variation of photovoltaic module’s tilt relatively to horizon and cardinal points makes it possible to manage schedule of power generation at the solar power plant and to match it with the load graph, due to their maximum possible convergence, as variation in the spatial orientation of the photovoltaic panel surface makes it possible to shift the maximum of the coming solar radiation in time. The results of the experimental research also revealed the dependence of the current produced by the photoelectric panel on its spatial orientation due to the change in the incoming solar radiation flux at it.

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