Comparative Analysis of Energetic Performance of Various Photovoltaic Power Stations

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Abstract. Factors affecting the production of electricity by photovoltaic (PV) power plants are studied. It is worth noting that reducing the shade and orientation to the sun are effective solutions for an increase in the production of electricity by these PV plants. A brief overview of the features of stationary installations and installations in the tracking of the sun is presented. The purpose of the paper is to justify, develop, and describe a generalized approach to analyzing the operation and methods of tracking the sun by the platforms with photovoltaic modules so as to increase the specific energy density obtained from a given surface of the photovoltaic installation. A concept is formulated and the generalized mathematical model is developed for different photovoltaic plants with fixed and mobile platforms, taking into account the shading effect of photovoltaic modules mounted on different platforms. Based on the decomposition concept, the optimization problem is solved on the criterion of the maximum value of the electric energy and the occupation of the smallest area of the site for a PV plants. A software for calculating the electricity produced by PV plants with stationary and mobile platforms was elaborated according to their location on the land meant for a certain PV plants. Specific electricity production kWh / (m^2*day) indices were determined for different PV plants, taking into account the shading factor. It was found that the PV plants equipped with three-coordinate orientation systems can produce the largest amount of energy, in addition, providing higher energy performance indices compared to those of other types of PV plants.
***Keywords*:** photovoltaic plants, mathematical model, tracking the sun, shading factor, three-coordinate orientation system specific electricity production.
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Analiza comparativă a performanțelor energetice ale diferitelor centrale fotovoltaice

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Abstract. Se analizează factorii de influență asupra producerii energiei electrice de către centralele fotovoltaice. Se constată, că micșorarea umbririi și orientarea după soare sunt soluții eficiente pentru sporirea producerii energiei electrice. Se prezintă o vedere generală privind particularitățile centralelor cu platforme staționare și platforme mobile cu orientare după soare. Scopul lucrări constă în argumentarea, elaborarea și descrierea abordării generalizate privind analiza funcționării și a modalităților de dirijare cu orientarea centralelor electrice PV după soare întru majorarea densității efective a energiei produse de diferite centralele fotovoltaice. S-a formulat conceptul și s-a elaborat modelul matematic generalizat pentru diferite centrale fotovoltaice cu platforme staționare și mobile, luând în considerare efectul de umbrire al modulelor fotovoltaice montate pe diferite platforme. S-a propus algoritmul de optimizare a orientării platformelor pentru fiecare interval de timp selectat. La bază a stat conceptul de descompunere a problemei optimizării după criteriul producerii valorii maxime a energiei electrice și ocupării celei mai mici suprafețe a terenului de amplasare a centralei. S-a elaborat softul de calcul a energiei electrice produse de către centralele fotovoltaice cu platforme staționare și mobile comandate în funcție de amplasarea lor în terenul destinat pentru această centrală. S-au determinat indicii specifici de producere a energiei electrice kWh/(m^2*zi) pentru diferite centralele, ținând cont de factorul de umbrire. S-a constatat, că centralele dotate cu sisteme de orientare pe trei coordonate pot produce cel mai mare volum de energie, concomitent, asigurând indici de performanță energetică ridicați în comparare cu alte tipuri de centrale fotovoltaice.
***Cuvinte-cheie*:** centrale fotovoltaice, model matematic, urmărirea soarelui, factor de umbrire, sistem de orientare cu trei coordonate, producție specifică de energie electrică.

Сравнительный анализ энергетических характеристик различных фотоэлектрических электростанций

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Аннотация. Рассматриваются факторы, влияющие на выработку электроэнергии фотоэлектрическими установками, отмечая, что уменьшение тени и ориентация по солнцу являются эффективными решениями для увеличения производства электроэнергии этими установками. Выполнен обзор особенностей работы стационарных установок и установок в режиме слежения за солнцем. Целью данной работы является обоснование, разработка и описание обобщенного подхода к анализу работы и способов слежения за солнцем платформ с фотовольтаическими модулями для увеличения удельной плотности энергии получаемой с заданной поверхности участка монтажа фотовольтаической установки. Была сформулирована концепция и разработана обобщенная математическая модель для различных фотоэлектрических установок со стационарными и мобильными платформами с учетом эффекта затенения активных поверхностей фотоэлектрических модулей, установленных на разных платформах. Был предложен и реализован алгоритм оптимизации ориентации платформ разных фотовольтаичских установок для выбранного интервала времени. На основе концепции декомпозиции решена задача оптимизации наиболее выгодного расположения платформ с фотовольтаическими модулями по критерию максимальной выработки электроэнергии и наименьшей занимаемой площади. Разработана программа для расчета электроэнергии, произведенной фотоэлектрическими электростанциями со стационарными и мобильными платформами, которое позволяет учитывать их местоположение на участке монтажа модулей. Получены численные значения удельных показателей выработки электроэнергии кВтч / (м^2 * день) для разных фотовольтаических станций с учетом коэффициента затенения. Было установлено, что установки, оснащенные трехкоординатными системами ориентации по солнцу, обладают повышенными показателями энергетической эффективности по сравнению с другими типами фотоэлектрических установок.

Ключевые слова: фотоэлектрические установки, математическая модель, отслеживание солнца, фактор затенения, трехкоординатная система ориентации, удельная выработка электроэнергии.

I. INTRODUCTION

The energy mix is evolving over the years, depending on the development of primary energy production and conversion technologies. A general objective, is the sustainable development accepted [1]. The sustainable development includes three components: ensuring ecological balance, economic security and social stability. The latter can be referred to as the Energy Trilemma [2, 3]. The interests of several countries for the promotion of environmental protection measures and energy policies are aimed at reducing the dependence on imports of energy resources. This has led to a global increase in the use of pure energy produced on the basis of renewable energy sources, including the Republic of Moldova [4].

Renewable Energy Sources (RES) technologies have reached a high level of development and have become competitive versus the traditional technologies based on the conversion of fossil fuels into electricity and heat. However, the extensive use of these pure energy sources is inhibited by the intermittent nature of energy generation as well as by the need to use large areas for the location of wind farms and photovoltaic PSs. We will also mention that the cost reduction of the power unit of photovoltaic cell has also increased electricity production by converting solar radiation [5, 6].

The development of the solar energy segment depends on the efficiency of using the power capacities of the PV PSs throughout the day. The volume of electricity generation depends on orientation (or non-orientation) of the PV modules towards the sun during the day [7, 8], the maintenance of the solar modules at the maximum power point [9], the meteorological conditions [10], the degree of the dust pollution (snow and other impurities impair the transparency of the cell surfaces, in particular in urban areas). Sedimentation of different impurities on the PV cell surfaces decreases the transparency of the solar rays, which reduces the intensity of the incident solar radiation fuse in the PV cell junction space [11]. Using various measures of protection against photovoltaic cell surface contamination and reducing the influence of negative factors renewable energy on the process of conversion of solar radiation increases the volume of produced electricity. Thus, the use of the solar tracking technologies increases the electricity production by 35-40% compared to the stationary technology of the PV module placement in the PV plants [11, 12].

Another significant factor of influence on the electricity generation index is the phenomenon of mutual shading during the day of the PV modules within the PV plants [13, 14]. The share of shading increases with an increase in the density of the PV module platforms, which usually results from reaching the installed power value of the PV plants if the extension is limited by the area designated for this purpose [14, 15]. This issue is of high priority in the case of advancement of renewable energy in the urban environment, including solar electricity generation systems by converting solar radiation [9, 10, 16]. It is noted that of all kinds of energy systems, photovoltaic PSs that use the largest areas of land with respect to the amount of energy produced are most promising, and the production of electricity by these systems can compete with food production [17]. The actual power generation of a photovoltaic system depends on three factors, namely, the PV cell conversion efficiency, the technical characteristics of the system and the solar radiation intercepted by the PV modules [17].

An increase in the share of radiation intercepted by the PV cells as a result of the solar tracking, and a decrease in the impact of the reciprocal shading of the PV modules [18-20] are the most efficient solutions for increasing the production of electricity and reducing the area of the land occupied for the PV plants. Thus the economic competitiveness of these PV plants enhances.

II. The General Feature of a Solar PV Plants. Formulation of the Investigation Problem

The energy efficiency and the amount of electricity produced by the photovoltaic solar stations depend on a number of factors:

- the number of sunny days per year in the location of a certain source of generation;
- the intensity of the solar radiation flux in the location area;
- the quality of photovoltaic cells and modules;
- the method of installing and placing the photovoltaic modules within the PV plants;
- PV-platform type with tracking or non-tracking the Sun.

The method for the PV modules being located on platforms (taking into account the absence of the Sun light) has a direct impact on the efficiency of conversion of solar radiation into electricity.

Intensity variations in the solar radiation, due to clouds or shading of the PV modules on the support platforms, result in a decrease in the generation of the electrical energy by these installations.

It is considered optimal to place stationary platforms with PV modules in the line in the east-west direction, at the angle θ =const., which is considered optimal for a given latitude (Fig.1).

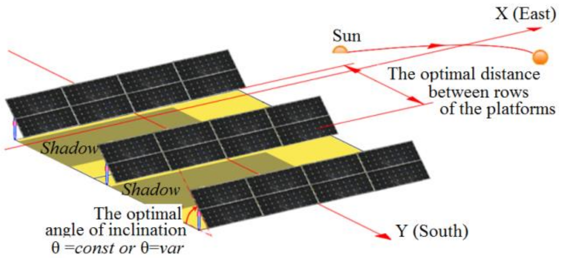

Fig.1. Placing in line installation of the PV module platforms: stationary (θ = const) or with one coordinate orientation (θ = var).

Installing PV modules on rotating platforms make it possible a more efficient orientation towards the direction of solar radiation. Installations with automatic control systems are called tracking systems. A special kinematic scheme of the platform and automatic control system, the two-coordinate platforms make a solar radiation flux fall straight onto the surface of the modules at any position of the sun in the visible ecliptic sector (Fig.2).

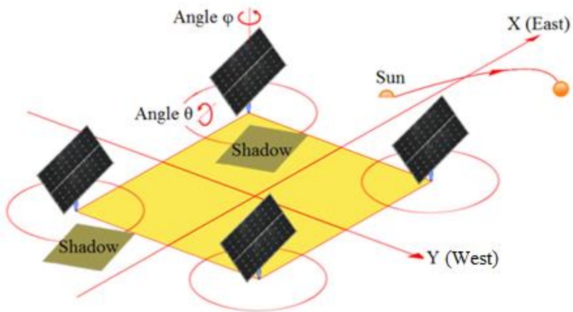

Fig.2. Location and movement of rotating platforms controlled by two-coordinate automatic guidance systems.

Figure 3 shows an installation with PV modules or platforms (the ABCD figures, whose peaks are marked with dots) and the shadows of these figures (not marked). This installation is referred to as a "petal" type and the PV modules can be oriented to three co-ordinates to decrease the degree of mutual shading. However, due to the overlap of shadows of different modules, these shadows are not homogeneous, causing difficulties in estimating the influence of the shading factor on power generation by the PV plants with guidance systems.

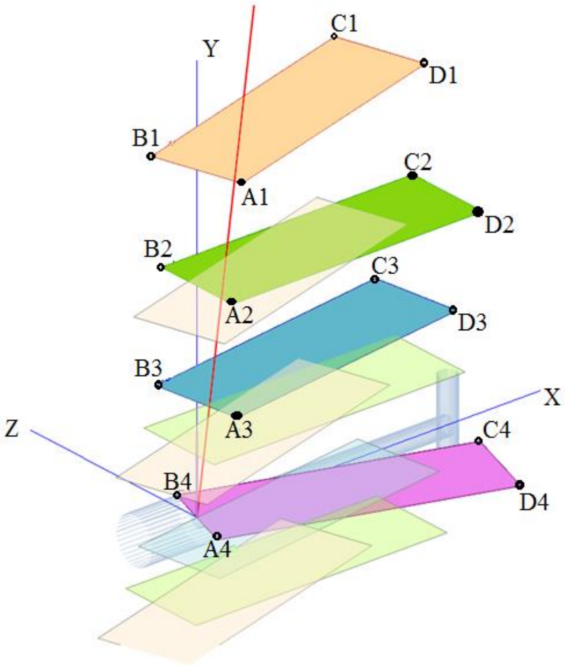

Fig. 3. The non-homogeneous character of the shadows on the surfaces of PV modules in systems with three-coordinate orientation systems (petal type).

The reciprocal shading effect of the PV modules mounted on the support platforms is characteristic both of stationary platforms and mobile or rotating platforms (Fig.1-Fig.3). The longest shadows are typical to large sunset angles (small zenith angles). As a result, the installation of modules or platforms in rows significantly shades the back planes that are located at the back during the day, thus reducing the capacity for generating electricity by the PV plants. For these reasons, the rational placement of the PV plants platforms itself presents a problem for optimization of constructive realization with direct economic impact, including the duration of the reimbursement of investments.

In general, PV plants can be classified into two groups according to the targeting system, i.e., tracking of the sun and without the pursuit of the Sun. Depending on the orientation, three types of guidance systems can be indicated:

- single coordinated systems;
- 2-coordinate systems;
- 3-coordinate systems [14].

The positioning of platforms with PV modules is aimed at ensuring the optimal angle of incidence of solar radiation on the surface of the PV modules. During the day, the sun changes its position in the sky and the PV modules on stationary fixed platforms cannot provide the maximum possible power generation. At the same time, 2-coordinate platforms can capture the maximum radiation value for any sun position in the visible ecliptic sector.

However, in the case of the operation of the PV plants, electricity generation indices are lower compared to those of a platform with the 2-coordinate orientation system. This difference in the efficiency of the operation of PV plants results from the phenomenon of reciprocal shading. For the phenomenon of shading, two factors can be indicated: the mutual shading of the PV module platforms and the topological feature of the location of the PV platforms. As an additional factor, which can influence the energy conversion efficiency according to the angle of orientation, the type of the platform used can be mentioned - its constructive realization.

In this context, it can be assumed that the problem of designing a PV plant with performance indices of converting solar energy into electricity is a complex problem, which can be solved on the basis of a multi-criteria analysis that takes into account various factors of influence.

Multicriterial comparative analysis requires the use of a specific set of procedures and many calculations for the parametric analysis of the problem of location optimization and routing of the PV module platforms in order to obtain the maximum amount of electricity produced. To carry out this analysis it is necessary to elaborate a specialized software for calculating the energy efficiency and economic efficiency indices of the PV plants. Here, we should take into account the area, the topology peculiarities, the orientation and the dimensions of the location, the technical solution of the platform mounting, the capacity of the PV plant, and the characteristics of the PV cells. To perform the complex analysis for the optimal solution of design of the PV plants it should be based on a mathematical platform that describes the peculiarities of the operation of the PV plants and highlights the factors of influence on the efficiency of the power generation of this kind of PV plants.

The purpose of this paper is to justify, elaborate and describe the generalized approach to the analysis of the operation and the way of routing with the operation of the PV plants equipped with solar guidance systems in order to increase the effective power density installed for different PV PS options.

III. Generalized Mathematical Model of PV Plants

The energy and economic performance of the PV plants is influenced by the factors that may or may not have mutual correlation, time functions, seasonal and weather conditions, geographic location and spatial orientation in the geographic coordinate system, the peculiarities of the location, energy efficiency indices of the PV cells and modules, etc. The multitude factors of influence as well as the existence of many solutions for the constructive realization of the PV plants create difficulties in optimizing the solution for constructive realization and optimization of the electrical energy production regimes.

We will also mention the fact, that different factors can have different impacts on the efficiency of the operation of the PV plants. A trivial search in the impact analysis of various factors of influence with the aim of estimating the optimal conditions for the construction and operation of a PV plant does not represent the most reasonable design solution. For these reasons, the development of software to ensure the energetic and economical performance of the PV plants designed using the parametric analysis concept of the energy conversion regimes is a reasonable and effective solution for obtaining the desired result at low cost even in the stage of design. This software must be based on reliable and valid mathematical models, so that the results obtained are perceived as the best and most advantageous of the many possible constructive realizations of the PV plants.

Using mathematical models and performing simulations based on these models is the most reasonable and motivated procedure for obtaining the feasible solutions in terms of ensuring the economic and energy efficiency of the PV plants for the concrete location, as well as the control algorithms of the solar systems of the PV platforms. We will also point out to the following peculiarity: there is uncertainty about the degree of mutual correlation between the factors identified in the mathematical model as the factors of significant influence and the degree of impact of these factors on the performance indices of the PV plants. The above hypothesis suggests that in the context of increasing the efficiency of power generation by the PV plants it is necessary to identify the factors with the most significant impact on the efficiency of electricity generation.

As a significant factor, it is worthwhile to designate the shading of the PV modules surfaces mounted on the support platforms either stationary or with adjustment of space positioning. In the case of guided positioning platforms the problem is reduced to the use of a specific algorithm for the instant positioning of the PV model. In this context, the problem of the instant positioning of platforms can be viewed theoretically as a problem of optimizing the orientation of platforms in space and time. Obtaining the optimal solution through simple iterations of different real-time options presents a difficult problem in obtaining the optimal solution even when using modern computers to minimize reciprocal shading.

To solve this problem, it is necessary to elaborate both the mathematical model of a certain structure and the numerical method valid to perform complex parametric analyses to determine the solution considered optimal. As criteria for selecting the optimal solution, it is possible to propose the indicators, which characterize the energy efficiency and the economic efficiency of the PV plants in the electric power production.

3.1. The concept of the mathematical model

Whether, we have a PV plant, which includes several PV module platforms located on the ground with the surface denoted by the symbol S. There are many variants of a constructive realization of a PV plant and location of the platforms with the PV modules on the field. In a word, it is possible to formulate in mathematical terms the issue of optimizing the operation of the PV plant, taking into account several factors of influence on the electricity generation.

Knowing the functional links and positioning features of the platforms, as well as the shadow formation mechanism, on the PV modules' absorption surfaces, allow us to generally address the optimization problem of the PV plant operation, taking into account the factors of influence on the electrical energy production, which are referred to as the input data. It is not difficult to form such an optimization model, but the development of a numerical calculation method for obtaining the solutions sought may become a complex theoretical problem that is difficult to solve.

Taking into account the aforementioned, we shall present the problem of obtaining the optimal solution for the operation of PV PSs as a general problem of mathematical programming. Whether, we have n factors of influence that can be represented by the following vectors:

$$\mathbf{X} = (\mathbf{x_1}, \mathbf{x_2}, \mathbf{x_3}, \ldots\ldots, \mathbf{x_n}) \qquad (1)$$

where $\mathbf{x}_i$ are the vectors of independent variables.

Vector (1) must satisfy the conditions imposed by the limitations formulated by the following matrix relation:

$$\mathbf{g_i}(\mathbf{x_1}, \mathbf{x_2}, \mathbf{x_3}, \ldots\ldots, \mathbf{x_n}) \le \mathbf{b_i} \qquad (2)$$

where $i = 1,2,3,\ldots,k$; $\mathbf{b}_i$ are the sizes defined as limit values.

It is necessary to determine the maximum value of the function $\mathbf{E_d^t}$, which represents the value of the electricity produced during the time $\mathbf{t}$ of day $\mathbf{d}$, hence:

$$\mathbf{E_d^t} = f(\mathbf{x_1}, \mathbf{x_2}, \mathbf{x_3}, \ldots, \mathbf{x_n}) = \mathbf{max.} \qquad (3)$$

In the formulas (1) - (3) as independent variables can be selected: coordinates of the PV modules mounted on the support platforms, the "shadow" and "angle" efficiency coefficients, as well as the azimuth and zenith angles of the sun for time interval ***t*** of day ***d*** of the year. As a criterion for determining the optimal solution we look for, we will consider the amount of electricity produced during the selected time interval ***t***.

Total energy $\mathbf{E}_\Sigma$ produced during the year will be determined using the following expression:

$$\mathbf{E}_\Sigma = \Sigma_j \Sigma_t \mathbf{E_d^t}, \qquad (4)$$

where ***d*** is the current day of the year; ***t*** is the discreet size, showing the time interval of day ***d***, during which angles of azimuth and zenith of the sun are considered constant values.

3.2. Mathematical models of PV plants with different constructive designs

In order to exclude some repetitions, we will describe how to use the mathematical models applied to calculate the produced electric power based on the concept described by relations (1) - (4). This treatment of the problem involves calculating the daily and annual volumes of electricity produced by the PV plants. The formulated approach extends both to the PV plants with solar tracked control platforms and to those with fixed positioning platforms.

We will examine these models in the following order: positioning of PV platforms using two-coordinate guidance systems, single-coordinate platforms, stationary (fixed positioning) platforms and three-coordinate oriented platforms.

A. Platforms with PV modules ordered after two coordinates

The vector coordinate of the PV module platforms in the plant is described by the relationship:

$$\mathbf{X} = (\mathbf{x_1}, \mathbf{x_2}, \mathbf{x_3}, \ldots\ldots, \mathbf{x}_N), \qquad (5)$$

where $\mathbf{x}_i$ is the coordinates of the PV modules mounted on the platforms. In the mathematical models of the PV modules mounted on the support platforms, index ***i*** is accepted, hence, $\boldsymbol{i} = \overline{\mathbf{1}, \boldsymbol{N}}$, where ***N*** is the number of the PV modules in the PV plants.

The multidimensional matrix of the coordinate projections of the modules ***j*** on the surface of the module ***i*** in time interval ***t*** for day ***d*** is described by the following relation:

$$\boldsymbol{MY} = \left\{ \boldsymbol{y_{ij}^{td}} \right\} \qquad (6)$$

where y_{ij}^{td} is the coordinates of the projections of the contour of the modules ***j*** on the surface of the PV modules ***i*** in time ***t*** of day ***d***, where $\boldsymbol{i} = \overline{\mathbf{1}, \boldsymbol{N}}$ and $\boldsymbol{j} = \overline{\mathbf{1}, \boldsymbol{J}_i}$, $\boldsymbol{J}_i$ is the multiplicity of projections of modules ***j*** on the surface of module ***i***.

The multidimensional matrix of the shadow projection surfaces created by modules ***j*** in the plane of module ***I*** looks like as follows:

$$\boldsymbol{MS} = \left\{ \boldsymbol{S_{ij}^{td}} \right\} \qquad (7)$$

in which the surface of the contour of modules ***j*** on the surface of module ***i*** in time ***t*** of day ***d***, where $\boldsymbol{i} = \overline{\mathbf{1}, \boldsymbol{N}}$ and $\boldsymbol{j} = \overline{\mathbf{1}, \boldsymbol{J}_i}$, $\boldsymbol{J}_i$ is the plurality of projections of modules ***j*** on the surface of module ***i***.

The matrix of orientation angles of the platforms with two operating coordinates is described by the following relationships:

$$\boldsymbol{M\gamma} = \left\{ \gamma^{td} \right\}; \qquad (8)$$

$$M\delta = \{\delta^{td}\}, \quad (9)$$

where α^{td} and β^{td} are the angles of rotation of the PV modules with indices i in time interval t of day d.

The functional relationships on the independent variables of the mathematical model, defining the required limit conditions, are as follows:

a) Coordinates of projections of the PV modules' shadows on the other modules mounted on support platforms depending on the positioning of the PV modules that are shaded and depending on the angles of the ecliptic are described by the following relationship:

$$Y = f_y(X, \alpha, \delta). \quad (12)$$

b) Areas of shadow projection areas formed by the PV modules according to their coordinates, taking into account the overlaps of the PV module shadows is determined by the following formula:

$$S = f_S(Y) - \Delta S(Y). \quad (13)$$

c) Functional dependence of orientation angles of the PV modules platforms on ecliptic angles is as follows:

$$\gamma = f_\gamma(\alpha, \beta), \quad (14)$$

$$\delta = f_\delta(\alpha, \beta). \quad (15)$$

d) The energy calculation relationship produced by the PV modules taking into account the shading shares of the surfaces of the PV modules located on the support platforms with two coordinates:

$$E = f_E(S_{shad}, S_{full}). \quad (16)$$

For the mathematical model of the PV plants, equipped with two-coordinate orientation systems and taking into account the conditions imposed by the shading phenomenon of the PV modules on the oriented platforms, we obtain the following relation for calculating the maximum value of the energy produced for this kind of the PV plants (equation criteria):

$$E = \sum_i \sum_t E_i^{td} \rightarrow max. \quad (17)$$

B. PV plants with stationary platforms

In the case of the PV plants, the algorithm for the realization of the mathematical models for the calculation of the electric power produced by the PV plants equipped with stationary mounted platforms is simplified in comparison with the algorithm described for the use of two-coordinate orientation rotary for the platforms. In the calculation algorithm for this embodiment of the PV plants, the matrix options $M\gamma$ and $M\delta$ are excluded. The functional dependence of coordinate's projections of the PV modules according to the positioning coordinates is represented by the following relationship:

$$Y = f_y(X, \alpha, \beta, \gamma_{fix}) \quad (18)$$

where: γ_{fix} is the fixed pitch angle of the PV module platforms selected for the location area of the PV plant.

The other relationships of the mathematical model for the case of the PV installation with stationary mounted platforms coincide with the mathematical model relations of the two-coordinate orientation rotary platforms. Following the substitution of the relation (12) for the relation (18), the mathematical model of the PV plant with stationary platforms changes the relation of calculating the electric energy produced as follows:

$$E = f_E(S_{shad}, S_{full}, \gamma_{fix}). \quad (19)$$

C. PV plants with oriented platforms on a single coordinate

The mathematical model for this type of the PV PS includes elements of the calculated energy algorithm produced in p.1 and p.2, taking into account the fact that the determination of the multidimensional matrix $M\gamma = \{\gamma^{td}\}$ or $M\delta = \{\delta^{td}\}$ is done only for an orientation angle.

D. Algorithm of the mathematical model for the PV plants with three-coordinates of control

The development of an optimization model for the PV plants with the orientation of platforms with modules on three spatial coordinates is a much more complex problem than the realization of control systems for platforms with a degree of freedom of less than three. In the case of the realization of three-coordinate orientation systems, the PV modules mounted on the support platforms can not be considered as having a definite geographical positioning when performing the calculation procedure for the selected time intervals ***t***. These difficulties result from the fact that although the core coordinates of the PV plant platforms are set at the design stage, according to the selected field characteristics and annual solar radiation cycle characteristics for the given area, hence, the modules placed on these platforms can change their position every time interval ***t*** for which the electricity production is calculated.

The fundamental feature of the algorithm for calculating the energy produced by this kind of the PV plants is determined by the need to perform the procedure of optimizing the orientation of each PV module platform for each calculation step, i.e., for each time interval ***t*** of day ***d*** at the annual cycle calculation of the energy produced under these conditions.

This leads to an increase in the complexity of the algorithm and the mathematical model of computation of energy produced by the three-coordinate platforms of the PV plants. However, the introduction of control on the third coordinate has the advantage in that it is possible to minimize the total area of the shaded areas of the PV modules every time within the individual platform positioning options. Such an approach can be interpreted as a decomposition of a more general optimization problem. Of course, such an approach to the decomposition of the shadow-shadowing problem does not contradict the general concept of calculating the power produced by the PV plants and leaves the possibility to take into account various options that relate to the base coordinates of the support platforms and the PV modules within a "global" optimization.

Note that in solving the problem of location of the PV platforms and modules in order to achieve a "global" optimization in real time it is substantially diminished due to the increasing size of the problem solved. At the same time, computational experiments with the use of software that implements these computational models show that the achievement of the state formulated as a "global" optimization is not necessary.

Performing optimization procedures for each discrete time interval based on mathematical modeling can very effectively flatten the performance criterion values for different placement options for three-coordinated platforms.

As a result of the implementation of the optimization algorithm of the platform orientation for each selected time interval (decomposition of the optimization problem), insignificant deviations occur in the values of the energy efficiency criterion (the volume of electricity produced during time ***t***) compared to the "global" optimization option.

Therefore, when using the proposed decomposition concept, there is no need for real-time "global" optimization of the platform placement and orientation to obtain the highest electricity generation index, of optimal options for placement of the PV module platforms in the land allocated for the construction of the PV plant.

We will point out to the mathematical models that are designed to optimize the power generation process by “petal” topology systems with two-coordinate control algorithm. Such installations are, as a rule, monoblocks installed on mobile devices (for example, in space stations) and therefore do not involve optimizing the placement of individual modules on the platform. For this type of the PV plant, the rotation angles of the PV modules mounted on the support pillar are optimized to form a rigid construction entity. The PV installations with this constructive topology are equipped with a specific kinematic scheme of orientation after two co-ordinates of the PV modules, leading to the appearance of some peculiarities of the formation of shadows on the PV modules. In this module location topology, shadow projections of the PV modules are not orthogonal [21]. This considerably influences the homogeneity of the shadow created by the projections of the PV modules on the shaded surface of other PV modules. This complicates the process of calculating areas shaded by several shadows (Fig. 3).

IV. OVERALL FEATURE OF PV PLANTS EFFICIENCY SOFTWARE

In order to determine the energetic and economic indicators of the PV plants with stationary or controlled support platforms (on a single coordinate, two or three coordinates) it is necessary to make a calculation software using the mathematical models presented by relations (1) - (19).

The software is based on methods and algorithms that solve the following tasks:

- determination of ecliptic parameters for any PV modules for different types of PV installations;
- calculating of the areas of the shadow projection, taking into account possible "overlaps" of shadows created by different non-transparent elements (PV modules and supporting platform constructions);
- optimization of rotation angles of the PV modules mounted on support platforms (for 3-coordinate and "petal" control systems).

From a mathematical viewpoint, the shadow is a projection of a figure (for PV modules - a polygon) on a plane selected in three-dimensional space. Determining the coordinates of projections, including shadows, is not considered as a difficult problem for resolution. It can be difficult aspect to determine the degree of homogeneity or homogeneous areas of the shadow on the surfaces of the PV modules in case of overlapping several shadows on this surface. This can be referred in particular to “petal” installations, in which the projections of the shading elements on the selected planes are not orthogonal. Selecting overlapped portions of multiple shadows, including double shadows (Fig.3), complicates the procedure of calculating the energy produced by these PV plants. For the "petal" controlled and 3-coordinate plant, it is necessary to calculate the optimal orientation angles of the platforms in order to minimize the areas of the shadows on the PV modules for each discrete time interval ***t***.

4.1. The structure of the electricity calculation software

The complexity of obtaining the solution of the problem of increasing power generation using the PV plants leads to the hypothesis, that it is reasonable to use heuristic methods for this scope. The heuristic approach can provide a relatively slight effort to obtain satisfactory results in controlling the individual positioning of real-time PV modules in order to ensure maximum energy generation over the selected time interval ***t***.

The software developed and applied for the calculation of the energy produced by each PV module in the PV plant of this type includes two blocks made on different interface forms. In the first block, the initial parameters of the installation are selected and established, including the following steps:

- determination of the latitude of the PV plant site;
- selecting of the platform installation type;
- determining of the number and dimensions of the individual PV modules of the plant;
- establishing of the number of rows and line spacing between each platform and the PV modules;
- determination of the sloping angles of the PV module platforms (for stationary and mono-coordinated installations).

The positioning of the PV module platforms on the land is done automatically by the developed software. The software includes manual positioning of the PV module platforms on the land. To do this, the navigation tools are used that appear on your computer screen. In each positioning operation of the platform (s), whether performed in automatic or manual mode, the "density" indicator, which is defined as the ratio of the active surfaces the PV modules to the total area of PV plant placement, is calculated.

The second block of the software has the visual presentation of the results of the parametric analysis. This block includes effective parameter viewing formats and also provides the opportunity to demonstrate the graphical "shadow" image for each azimuth angle of the ecliptic sector (for the selected day of the year).

The set of parameters generated when applying the software includes:

a) the amount of electricity produced for the selected day of the year, kWh;

b) the annual and daily averages of the energy efficiency indicators, taking into account the impact of the PV modules shading, %;

c) the annual and daily values of indicators that characterize energy efficiency for the angle of inclination (for stationary and mono-coordinated installations), %;

d) the indicators listed in a), b) and c) for the azimuth angles of a selected day of the ecliptic sector (for manual operation) on their evolution in the ecliptic sector;

e) graphical presentation of the "shadow pattern" image for the selected azimuth angle value.

4.2. Information and initial data taken into the calculation

The problem of shrinking power generation due to the fall of the shadow on the surface of the PV module is poorly studied both theoretically and in practice. The most interesting results of the investigation of this problem are elucidated in [22, 23]. The calculation of the energy generated under shading conditions of the PV modules requires the introduction of empirical coefficients, which are used in the proposed mathematical models and in the computational software developed.

We note that the values of these coefficients used in the software have a degree of uncertainty that can influence the accuracy of the estimates of the energy and economic efficiency indices of the PV plants. However, this factor can not change the essence of the qualitative analysis of the problem under consideration. This aspect presents research and analysis activities in the future.

To obtain quantitative results using the proposed mathematical model it is necessary to know a priori the values of these coefficients. For example, at the 10% shading of the module surface, the power generation of this module also decreases by 10%. We will mention that this is a conventional estimate of the upper limit of the degree of shading influence on the power generation capacity in the PV plants. In fact, the impact of the PV module's surface shading depends on a number of factors: the density of the shadow, its configuration; placement of shadows on the module surface; the technical characteristics of the module as well as the intensity of solar radiation. For these reasons, it can be assumed that, in reality, the effect of lowering the PV plant generation capacity has a non-linear characteristic. This makes complex both problems, as well as the method of energy generation analysis, according to the peculiarities of the shading phenomenon of the PV modules.

Since the purpose of the work is to elaborate and test the reliability of the method of calculation of the amount of energy produced by different PV plants, we shall focus on examining a conventional example that we consider as the input data, i.e., the location latitude of the PV plant of 47^0 latitude north; the average annual sunshine period duration of 12 hours; and sunny days throughout the calculation period ***t***. The last condition is common for all types of PV plants examined. This enables us to obtain quantitative data presented in the relative unit system, which characterize the technical (and conventional economic) performance of the PV plants after the volume of energy produced during the selected time interval ***t***.

It is assumed that stationary and mobile platforms have the same installed power. This has led to the fact that the active surface of the PV modules in the PV plants with fixed platforms is a function of how mobile platforms are located. The orientation of the platforms towards the sun depends on the evolution of the azimuth and zenith angle. It was assumed that the functional constructive elements considered are the typical blocks of the PV plant from the viewpoint of its topology.

The generation capacity of the PV plants is increased by multiplying the number of typical blocks in the field. Increasing the generation capacity of the PV plants with an increase in the number of typical unitary functional blocks does not change the shadow character on the active surfaces of the PV modules.

The use of this hypothesis allows us to simplify the problem examined in the analysis of the typical blocks of the PV plants. Presenting the PV plant as a plurality of unit blocks ensures not only the simplification of the mathematical model and the process of calculating the amount of electricity produced, but also makes it possible to take into account the peculiarities of the land on which these mobile platforms are located, of the land surface.

As a case for the study, a PV plants of about 4.5 kW has been selected including four platforms in the case of biaxial and tri-axial orientation. Stationary platforms of the PV plants are placed in line in the east-west direction. The stationary platform module includes three rows. Each row is made up of three platforms. The dimensions of the platforms are determined from the condition of providing the installed power equal to 4.5 kW (Fig.1).

V. ENERGY EFFICIENCY OF PV PSS

A. *Estimation the efficiency of PV PSs with stationary and two-axis oriented platforms*

The optimal positioning of both the stationary platforms (Fig.1) and the two-axis platforms (Fig. 2) was reached after having calculated the power produced by the PV plants.

In order to produce a maximum amount of electricity, the option of adjusting the angle of inclination of the stationary platforms, which can be performed monthly or at least seasonally, is practiced. The implementation of the platform inclination change option requires a special performance of these platforms for discrete adjustment of the angle. Platforms with discrete and slow adjustment of the inclination angle must also ensure the mechanical rigidity of these structures at the wind gusts that may occur in the area of location.

For all types of installations, the exclusion of shadow formation (integral or partial) is achieved by increasing the distances between the support platforms on which the PV modules are mounted.

As a subject of the study, PV plants of about 4.5 kW power were used:

- the plant with stationary platforms includes 3 conventional structural elements located in line in the east-west direction;
- PV plant with the biaxial oriented platforms includes 4 separate platforms.

The area of PV modules mounted on stationary platforms is determined based on the criterion of generating of the quantities of electricity equal to the energy generated by the PV plants with bi-axially controlled mobile platforms.

For example, the total area S_{bi} of PV modules placed on biaxial mobile platforms is S_{bi} = 4 * (2m * 3m) = 24 m^2. For this case, the total area S_{st} of PV modules mounted on stationary platforms will have a higher value compared to the value of the S_{bi} area in fulfilling the equivalence condition of the electrical energy value produced under the conditions characteristic of the selected time interval. In the calculation, the S_{st} area is variable and is determined from the production index of the PV plant with two-coordinate mobile platforms when positioned within the selected $\boldsymbol{t_i}$ time ranges of each day ***d*** during the year. Thus, the $\mathbf{E_{PV}}$ = const criterion is satisfied. Both mobile platforms and PV stationary platforms are mounted on land with the size of (6.9mx 5.9m) ~ 40m^2 at latitude 47^0 north. The small axis of this rectangular shape of the PV plant site is considered "north-south".

Determination of the area increase rate of PV modules mounted on stationary platforms to meet the criterion $\mathbf{E_{PV}}$= *const*. must be done taking into account the instantaneous shading factor of the PV modules over the time interval ***t*** selected for the analysis of the power generation. As a consequence, the procedure for determining energy indices for comparative analysis over the time interval ***t*** (for example one year) of the stationary platform of the PV plants and 2-axis controlled platform becomes complex and requires the use of specialized software calculation of the produced electricity. As a result of the calculations, it has been found that the significant increase in the surface area of the PV modules in stationary platforms, for example resulted from increasing the vertical dimension as compared to the ground surface of the platforms, cannot satisfy the condition of reaching the maximum production value of electricity compared to the formulated scenario (no shading).

At the same time, the following unfavorable result can be indicated for the case of fixed mounting platforms, which consists in the following. In order to ensure the maximum power of the PV plant generation, it is necessary to increase the mounting height of the platforms to reduce the impact of the shading phenomenon. This will negatively affect the mechanical stiffness of the platforms at wind gusts.

It has been determined by calculation that the typical block of 4 solar-oriented PV platforms can produce in the time interval ***t*** = 365 days approximately 19270 kWh/year. The installation with stationary platforms can only produce 12250 kWh/year. As a result, in order to ensure the same amount of the energy produced, it is necessary to increase the active surface of the PV modules mounted on the fixed platforms in the perimeter of the surface area available for this scope.

The procedure for determining the surface elevation coefficient for PV modules for stationary platforms by dividing the energy generated by the PV plant with mobile platforms (19270 kWh / year) at the value of the stationary power plant (12250 kWh / year) is incorrect. In this case, the shading phenomenon is not taken into account. To obtain a correct result, it is necessary to calculate the energy produced by these plants, taking into account the shading phenomenon of the PV module surfaces during the selected calculation time ***t***. For example, at a linear approximation (without taking into account the shading factor), the increase in surface area of the PV modules on the fixed platforms should be equal to k_S = 19270/12250 = 1.57. In fact, this coefficient has a higher value.

It has been found that using the fixed platform elevation solution (to reduce shading) of the typical block up to 2.2 m and the active surface of the PV modules up to 45.5 m^2 cannot ensure the level of energy production which is characteristic of the PV plant with mobile tracking platforms that orient the sun. The conventional volume of electricity produced by PV plants with the fixed platform will only be 18243 kWh / year in this case.

Mounting fixed platforms at a higher height leads to the need to solve the problem of mechanical stiffness. As a result, they will lead to increased costs of this kind of a PV plants.

The cost of the PV plants will also increase due to the use of a larger number of PV modules in the device with fixed platforms compared to mobile platforms that can produce equal volumes of electricity in equal time intervals.

Due to the calculations made we estimated the impact of shading and the indicator called impact angle (orientation), defined as annual average values, on the generation of electricity by the constructive variants of PV plants mounted in the perimeter of the site location of these installations. Thus, the impact of the shading of the modules is manifested by the decrease in electricity production by 7.3% (PV plants with mobile platforms biaxially oriented has S_{bi} = 24 m^2), 20.6% (PV plants with fixed platforms has S_{st}= 24 m^2) and 38.4% (PV plants with fixed platforms has S_{st} = 45.5 m^2) compared to their ideal production capacity for the active surfaces of the PV modules. The impact conditioned by the angle of orientation is manifested by the lack of reduction of energy production compared to the optimum condition for the solar-powered mobile platform and the reduction of this production by 32.6% for PV plants with stationary platforms.

Using the mathematical models-based calculations makes it possible to determine the advantages of the PV plants with different constructive achievements.

B. Estimation the efficiency of bi- and triaxial PV plants

We shall consider that the PV plants are located on the land with the size of AxB = 5.9 mx6.9 m with the area of approx. S_{AB} = 40 m^2. PV plants with controlled platforms include 4 platforms, and PV plants with stationary platforms include 3 platforms. The active surface of PV modules with mobile platforms is S_{bi} = 24 m^2, and the surface of PV modules mounted on fixed platforms has a value of approx. S_{st} = 45.5 m^2.

The orientation of the location of PV plant is the same as in the previous case. As a result of the calculations, the volume of electricity produced by photovoltaic PV plants with two-coordinate tracking and PV plants with stationary mounted platforms was estimated. Thus, for the conditions indicated, the volume of electricity produced by these plants has the following values: 20770 kWh (triaxial case), 19270 kWh (biaxial) and 18243 kWh (stationary platforms).

Correspondingly, the decrease in the electrical energy generated by the shading phenomenon of the PV modules is: 0% (triaxial), 7.3% (biaxial), 38.4% (fixed platforms), and the one caused by the angle of orientation - 0% biaxial) and 32.6% (with stationary platforms). The control of the orientation of the mobile platforms on three coordinates leads to the reduction of the shadow impact on the electricity generation compared to the guidance system by two coordinates by about 7.3%.

We will consider that the number of PV modules mounted on the available ground is an independent variable. In this context, it is possible to examine the evolution of electricity generation over time ***t***, for example considering that ***t*** = 365 days, depending on the increase in the number of mobile platforms from 4 to 6 and 7 units, and the number of stationary platforms from 3 units on 4 platforms.

From the condition of equalizing the amount of electricity produced by the biaxial platform, we will change the size of the installation site, e.g., from 9x8 to 19x19 m. For simplicity, we will consider that the area of the mobile and stationary platforms coincides with the surface area of the PV modules mounted on these platforms. If necessary, a correction coefficient can be used to recalculate the respective values obtained from the calculation model.

Because we operate with conventional virtual installations to estimate power performance indices, it is acceptable to use any selected time interval ***t*** of sunny days. Considering that in our analysis ***t*** = 365 days, it simplifies the procedure of taking into account the variation of the angles of the ecliptic in the selected period ***t***, thus also simplifying in some way the model of calculating the produced electric energy.

This is acceptable because we examine the mutual performance of different PV plants and not the amount of electricity produced.

Full data on constructive embodiments of stationary PV PS and those with bi- and triaxial mobile platforms and various electricity generation indices, including those present in the system of relative units, are included in Table 1.

Table 1.

*R*esults of calculations of the efficiency of electric energy generation of different types of PV plants

The parameters	Variants of the PV plants										
	Three-coordinate orientation			With two-coordinate orientation					With stationary platforms		
Land size (AxB), m	6.9x5.9	9x4.5	9x8	6.9x5.9		9x4.5	9x8	19x16	6.9x5.9		9x4.5
Area of land S_{AB}, m^2	40.7	40.5	72	40.7	40.7	40.5	72	304	40.7	40.7	40.5
Number of platforms N_{PV}	4	6	7	2	4	6	7	7	3	3	4
Platform size (axb), m	2x3	2x3	2x3	2x3	2x3	2x3	2x3	2x3	6.9x 1.16	6.9x 2.2	4.5x 2.5
Area of the platform surface S_{PV}, m^2	24	36	42	12	24	36	42	42	24	45.5	45
Specific density $k_{PV}=(S_{PV}/S_{AB})$	0.59	0.89	0.58	0.3	0.59	0.89	0.58	0.14	0.59	1.1	1.1
Electricity produced $\boldsymbol{E_{Sh.t}}$, kWh	20770	29847	34721	10385	19270	26088	29994	34624	12253	18243	17382
Energy density over time $\boldsymbol{t}$: $k_E= \boldsymbol{E_{Sh.t}}/ S_{AB}$, kWh/$m^2$	510	734	482	256	473.5	644	416	114	301	448	429
Specific density of energy: $k_{Et}=k_E/t$, kWh/(m^2*zi)	1.4	2.0	1.32	0.884	1.3	1.76	1.14	0.312	0.824	1.23	1.18
The impact of shading $\Delta E_{Sh.}=[(E_t-E_{Sh,t})/E_t]*100$, %	0	4.5	4.9	0	7.3	17	17.2	5.3	20.6	38.4	39.4
Impact of orientation angle $\Delta E_{\gamma,\delta}= =[(E_t-E_{\gamma,\delta})/E_t]*100$, %	0	0	0	0	0	0	0	0	32.6	32.6	32.7

The results in Table 1 indicate that PV plant with bi-and triaxial orientation platforms have value of the specific energy production indices more than the ones compared to stationary platform installations. In turn, three-coordinate plants have the higher capacity to produce electricity compared to two-coordinate plants. For all types of installations, shading leads to reduced power. The smallest impact of this factor is characteristic of three-coordinate PV plants. At the request of a certain amount of electricity produced by the PV plants, the area of the platforms can be increased in order to diminish the shading factor. This leads to a significant increase in the land area even for two-coordinated PV plants.

Under the condition that the shadow impact on the electric power generation by the bi- and triaxial PV plants is identical (decrease of the production is by about 5%), it is necessary to increase the area of the S_{AB} site for the platforms with two coordinates about 4 times (S_{AB} = 304 m^2) compared to the three-coordinate installation (S_{AB} = 72 m^2). In this context, the selection of the type of PV plants for its realization is necessary to be considered as an optimization problem based on the technical and economic criteria.

IV. CONCLUSIONS

1. The energy efficiency of PV plants depends on several factors. The shading of the active surfaces of the PV modules and the positioning of the sun are the factors with the most significant impact on the power generation capacity of this type of a PV plants. The use of the orientation technology of the platforms with the PV module either on a single coordinate, two or three co-ordinates ensures increased power generation as compared to the PV plants with stationary platforms.
2. The implementation of the PV plants with three-coordinate orientation is the most reasonable solution for the case that there are limitations due to the impossibility of extending the terrain area on which the platforms with PV module are installed.
3. The developed mathematical model of the PV plants for the analysis of the energy efficiency of these plants is reliable for both stationary platforms and axis-based, two-axis and three-axis mobile platforms. Parametric analysis of the operation of the PV plants allows us to select and argue the most efficient and competitive constructive solution based on the energy and economic efficiency indicators, taking into account the possible constraints.

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