Ministry of Education and Science of Ukraine
Ternopil Ivan Puluj National Technical University

Faculty of Applied Information Technology and Electrical Engineering
(full name of faculty)
Electrical Engineering Department
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QUALIFYING PAPER

For the degree of

Bachelor
(degree name)

topic: ***Design of positioning systems for solar panels***

Submitted by: fourth year student, group IEE-42
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Ministry of Education and Science of Ukraine
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ASSIGNMENT
FOR QUALIFYING PAPER

for the degree of Bachelor
(degree name)

specialty 141 Electrical Power Engineering, Electrical Engineering and Electromechanics
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Paper supervisor *Kotsiurko Roman Volodymyrovych, Assistant of department*
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Chapter	Advisor’s surname, initials and position	Signature, date	
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7	*Getting feedback and review of master’s thesis*	*12.06.21 – 20.06.21*	
	And drafting a report for the master’s defense.		

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ABSTRACTS

Bachelor work «Design of positioning systems for solar panels» contains: ___ pages, __ figures, __ tables, __ references and __ pages of A4 presentation.

Object of study – solar tracking system of photovoltaics panels.

Subject of study – is to increase the level of energy efficiency of autonomous PV power plant by reducing energy consumption, by implementing automatic tracking of the Sun reducing the energy consumed by electromechanical actuators of the tracking system.

Purpose of the work – creation of a positioning system that makes it possible to increase the efficiency of the solar panel when changing the incoming radiation flux and reduce the cost of finding the angular position of the solar panels, at which these panels generate maximum electrical energy.

As the result, two-coordinate low-power information-measuring scanning system was introduced. In the scope of this work the method for processing the measurements of the VAC of PV modules with different shading and analytical calculation of the average daily output was developed. It allows to find the intervals of optimal values of the tilt angles and inter-row spacings of solar panels for specific regions of the location of the PV power plant. Mathematical models have been developed to obtain the parameters of the "ground" ecliptic for any given moment in time, and a relatively accurate mathematical model has been developed that takes into account sidereal days. Constructive changes in the kinematic scheme of standard two-coordinate platforms are proposed. It is possible to adapt the developed software applications for use as one of the design tools for solar power plants of space stations.

Keywords: SOLAR ENERGY, SOLAR PANELS, POSITIONING SYSTEMS, TRACKERS, PHOTOVOLTAICS, PV POWER PLANT, ENERGY GENERATION, SHADING, TILT ANGLE.

CONTENT

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INTRODUCTION

In many countries, the top three energy sources of electricity are coal, natural gas, and nuclear. These forms of energy are nonrenewable meaning they will eventually be depleted. For this reason, it is important to seek renewable sources of energy for they are cleaner, easier to use, require less maintenance, and will always be available. This project focuses on solar energy, which is a renewable form of energy. On average the earth surface receives about 600 W/m2 of solar energy. This value depends on several factors such as the time of the day and the atmospheric conditions. In 2012, only 0.11% of solar energy was used to generate electricity. It is estimated that solar energy will become the largest source of electricity by the year 2050. For this reason there should be a larger investment in harnessing solar energy.

Sun is responsible for most of accessible energy resources. Solar energy can be used both directly and indirectly. It can be used directly in a variety of thermal applications like charging of batteries, heating water or air, drying, distillation, cooking etc. The heated fluids can in turn be used for applications like power generation. A second way in which solar energy can be used directly is through the photovoltaic effect in which its energy is converted to electrical energy. Indirectly, the sun causes winds to blow, plants to grow, rain to fall and temperature differences to occur from the surface to the bottom of oceans. Useful energy can be obtained for commercial and non-commercial purposes through all these renewable energy sources.

A photovoltaic panel is a device that turns light into electric potential ("Photo" means light and "voltaic" means voltage). Commonly, these devices are referred to as "solar panels" because the light source in many applications is the sun. Yet the term "solar panel" can also refer to other devices that capture the sun's heat but do not produce electricity. Photovoltaic panels use layers of special materials to create a voltage and current when sunlight is absorbed.

The amount of electricity generated by photovoltaic power plants (PVPs) largely depends on how optimal the arrangement of the rows of photovoltaic modules (PM) is. To increase the generation level of PVS, modules must be installed at certain angles of inclination and azimuth. In addition, the inter-row distances and their relationship with the height of the rows are significant, as well as the placement of modules within the rows: horizontal (landscape) or vertical (portrait). Numerous works are devoted to the problem of optimizing these angles as applied to different countries and regions. In most works, the optimal inclination and azimuth of the panels are selected from the condition of the maximum amount of solar radiation arriving per unit area of the receiving surface during the calendar period of the station operation. At high-power photovoltaic power plants, the rows of modules have, as a rule, the azimuthal direction of the receiving surface to the south and are located on a free land plot, where there are no large shading objects. However, there remains the problem of partial shading by neighboring rows of modules at hours when the angle of the Sun's altitude is not very large. With partial shading, the location of the maximum power point on the *I–V* characteristic changes, and additional maxima appear on the “load power-voltage” curve, which complicates the operation of the Maximum Power Point Tracking algorithms for PV inverters. But the main negative consequence of partial shading is a drop in the output power of the shaded PV module rows.

Calculations and experiment show that the factor of partial shading is essential in the design of PV power plants and optimization of the configuration of module rows, as well as to minimize the cost of equipment. The significant influence of non-uniform illumination on the power of PVS was confirmed by numerous examples when performing the program "1000 photovoltaic roofs" (1000-Roofs-PV-Program), launched in Germany in 1990.

At the design stage of the PV power plant, an analysis of the effect of partial shading on the daily output of the power plant must be carried out. This analysis is performed by simulating possible changes in the PM shadow configuration and, accordingly, the station's output power. To date, various analytical and numerical models have been developed that take into account the shading factor. This work is focused on the approach previously proposed by the authors, which is based on the experimental determination of the power factor of shaded panels $f(s)$ and on its further application to optimize the row spacing and tilt angles of solar panels.

The determination of the power factor in our work is based on measuring the volt-ampere characteristics (VAC) of PV modules at various degrees of partial shading and on further calculating the maximum output power of the PV plant. With the help of a specially developed experimental setup and software, measurements and data processing were carried out for various shading conditions of photo modules with various variants of arrangement in rows (landscape or portrait). The measurements were carried out on an FM made of monocrystalline and polycrystalline silicon.

Amount of solar energy, which reaches to the Earth's surface, changes due to the movement of the Earth around its axis and the Sun. These changes depend on the time of day and season. Usually in the afternoon the Earth gets the highest amount of solar radiation, than at early morning or late evening. Sun is at its zenith at noon, and the length of the path of the Sun's rays through the Earth's atmosphere is reduced. Because of this, a smaller number of solar rays refracted and reflected, and therefore, a greater amount of solar radiation reached the surface of the Earth.

Amount of energy, that falls on the 1 m^2 of area per 1 second of time depends on a number of factors: latitude, local climate, season, the angle of inclination of the surface in relation to the Sun. Amount of solar energy, which reaches the surface of the Earth, differs from its average value. In winter this deviation is less than 0.8 $kW{\cdot}h/m^2$ per day for North Europe and in summer, it is more than 4 $kW{\cdot}h/m^2$ per day in the same region. The difference decreases as we approach the equator.

Amount of solar energy depend also on the geographical location of the object, the closer to the equator, the more amount you get. For example, the average annual total solar radiation, falling on a horizontal surface is: in Central Europe and Central Asia is approximately 1000 $kW{\cdot}h/m^2$; in the Mediterranean approximately 1500 $kW{\cdot}h/m^2$; in the most desert regions of Africa, Middle East and Australia – is about 2200 $kW{\cdot}h/m^2$. Thus, the amount of solar radiation significantly varies depending on season and geographical position. This factor plays an important role in calculating the efficiency of PV power plants.

The density of solar radiation in the middle geographical lane of Ukraine is higher than in some European countries. Ukraine has a huge area and do not always have the opportunity to bring electricity to individual objects. Therefore, interest to use autonomous power and sources of emergency uninterruptible power supply with recharge from solar energy grows more and more. Interest in the use of solar power increases more and more, taking into account the steady decline in prices for solar components, producing some of which have already started on the territory of Ukraine. Constantly reduces cost of equipment, environmental friendliness and low running costs make autonomous solar power optimal choice for individual objects on the territory of Ukraine.

1 ANALITYCAL SECTION

1.1 Analysis of problems and systems

Currently, unconventional energy based on solar batteries is widely developing, which are used as a source of energy for houses, cottages and various devices: traffic lights, monitoring systems for overhead power lines, vehicles, etc. The main requirement for the design of a solar battery is to obtain maximum power per unit area of the battery. Solar panels of small dimensions usually contain an automatic control system that allows continuous orientation to the energy source (Sun). Such control systems are equipped with a sensor for determining the coordinates of the source, which is installed on the solar panel itself [1].

The main disadvantage of such a system is the continuous operation of the automatic control system for the position of the battery relative to the source, and, consequently, the high energy consumption for moving the massive panel. The energy spent on movement can be commensurate with the generated electricity. The complexity of the system operation lies in determining the angular coordinates for positioning the battery in cloudy weather, since in this case the maximum energy flux can come not from the source, but from reflective surfaces (clouds, buildings, snow, etc.), which reduces the efficiency of the installation. Often, the reflected energy flow can be greater than the direct flow from the Sun, which is blocked by clouds.

In this regard, a very urgent task is to create a control system that makes it possible to increase the efficiency of the solar panel when the incoming radiation flux changes and to reduce the cost of finding the angular position of the solar battery at which this panel generates maximum electrical power.

To solve this problem, it is also known a device [2] containing solar panels fixed on three mutually perpendicular axes with the ability to rotate around their axes (figure 1.1). The rotation of solar panels is carried out in such a way that during daylight hours the panels are constantly facing the Sun and generate maximum power by increasing the total area of all panels. Solar panels are in different planes and reflect light from each other, which helps to increase the efficiency of the batteries. The position of the batteries is controlled by a computer program that takes into account the date, time of day, weather conditions and air temperature. Solar panels are connected to a storage battery.

Figure 1.1 – Solar positioning system

The disadvantage of this device is the complexity of the mechanical structure for controlling the position of the batteries. In addition, it is rather difficult to identify the position at which the maximum power can be obtained. Namely, a mathematical dependence of the influence of these factors on the generated power is required. In addition, this device uses solar panels as reflectors, however, the solar battery is not an ideal reflector with coefficients close to 1 and therefore there is doubt about the possible increase in efficiency due to the reflection of light from solar panels.

Known intelligent uniaxial solar tracker [3]. The tracker control system includes a square array of photovoltaic cells, an electric power output unit, a motor control source with a microcontroller, a power sampler and an maximum power point (MPP) calculator.

The optimal position angle of the array of photovoltaic cells corresponding to the maximum power is calculated by the MPP calculator and set by an electric drive. The orientation control process of a uniaxial solar tracker consists of the following sequential phases:

a) observation of the cloud cover over the sun tracking device;

b) comparing the observed cloud cover with cloud cover models stored in the database, each cloud cover model being associated with an orientation setpoint value for the solar tracker;

c) Comparison of the observed cloud cover with the cloud cover model;

d) controlling the orientation of the solar tracker by applying the orientation setpoint value to the cloud model selected in step c).

The main disadvantage of this device is the limited accuracy of positioning the matrix to the position at which maximum power can be obtained. The limitation of accuracy is due to the cloud cover models stored in the database, since it is almost impossible to take into account cloud cover in the model at other times in advance.

Known intelligent solar tracker [4]. The principle of its operation is based on the use of an iterative method for finding the optimal positioning angle by a mathematical expression. This device has the same disadvantages as the previous device. The closest in terms of the problem of developing the most efficient device for positioning a solar energy source is a system for automatic orientation of the solar panel in the direction of the light flow, which is devoid of the disadvantages of the previous device. This device contains a solar panel with four digital light sensors installed in conjunction with a solar panel on a rotating mechanism. The control system of the device is connected to light sensors and a stepping motor mounted on the base and providing automatic rotation around the vertical axis. The device contains a rod with a length adjuster that rotates the panel about the horizontal axis [5].

The main disadvantage of this device is that the energy source, namely the Sun, can be covered by clouds and the solar panel receives light reflected from various objects: mountains, snow, buildings, clouds, and therefore this automatic orientation system does not allow determining the position of the battery, when which it is possible to obtain maximum energy.

That is, the battery must be oriented in those coordinates of space where the maximum energy can be obtained, and the source of radiation of light energy is no longer point and therefore this device does not allow determining this position.

In addition, the very principle of orientation of the solar battery to a point source (Sun), which must work continuously, is relatively energy-intensive.

From the analysis of existing positioning systems, it follows that in order to increase the energy efficiency of solar cells in cloudy weather, it is necessary to develop an intelligent positioning system that allows determining the angular position of the solar battery at which the power output is maximum. The development of such a system is shown below.

1.2 Types of panels for a solar power plant

Photovoltaic module (also known as solar panels) is the main component of any photovoltaic system, designed for the production of electricity. Solar panel consists of several connected photovoltaic elements. The most common technologies for the production of photovoltaic cells are:

1. Crystalline photocells:

- Monocrystalline silicon photocells;
- Polycrystalline photocells;

2. Thin-film photocells:

- Photo cells with the use diselenida indium and copper (CIS technology);
- Photo cells with the use of Telluride Cadmium (Cadet technology);
- Photo cells with the use of amorphous silicon;

Production of **monocrystalline solar cells** provides with the use of the Cholesky method. In order to obtain a silicon monocrystalline, the initial crystal is immersed in a melt of silicon with boron and gradually raising a few meters above the surface of the solution. At that time after the seed crystal the extracted solution is crystallized.

The edges are cut off from the obtained monocrystalline blank in order to obtain square elements. Then it is cut into elements with a thickness of approximately 0.3 mm. After that, the elements are alloyed with phosphorus to add n-conductivity and create a p-n junction, polished, applied anti-reflective coating and current-carrying tracks and we get a ready-to-use monocrystalline photovoltaic cell. Its efficiency is from 15 to 18 percent.

Figure 1.2 – Monocrystalline PV element

Polycrystalline solar cells are produced by using uniform directional cooling of the vessel with silicon and boron solution. In this case, unidirectional homogeneous crystals are formed in the vessel in size from a few millimeters to several centimeters.

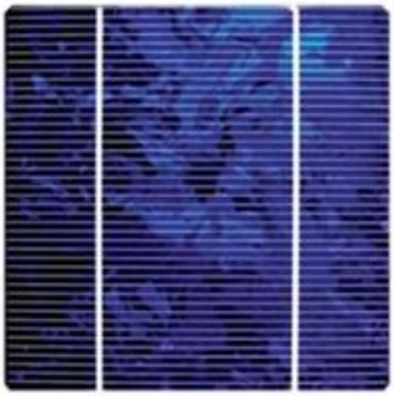

Figure 1.3 – Polycrystalline PV element

The resulting block of polycrystals is processed as well as a single crystal blank. Efficiency from 13 to 16 percent;

The active semiconductor material in CIS photovoltaic cells is indium selenide and copper. CIS compound is often alloyed with gallium and (or) sulfur. In the production of the element, the glass is covered with a layer of molybdenum, which conduct an electric current. For the photocell this layer will be the cathode.

CIS compound layer in the photocell has p-conductivity and is applied to a layer of molybdenum. Zinc oxide with an admixture of aluminum ZnO + Al is used as a transparent anode, that conduct electricity. This layer has n-type conductivity and it is sprayed with an auxiliary layer of zinc oxide i-ZnO.

Figure 1.4 – CIS PV element

The intermediate layer of cadmium sulfide CdS is used to reduce losses, associated with a mismatch of the crystal lattice CIS and ZnO layers . Efficiency of this type of PV elements are from 9 to 11 percent [8];

Figure 1.5 – Cadmium telluride CdTe

Photovoltaic cells with the use of **telluride cadmium CdTe** are produced on a substrate with a transparent TCO conductor, which is made of oxide of indium and tin ITO and used as a front contact. This substrate is coated with a layer of cadmium selenide CdS with n -type conductivity. After this the absorbent layer telluride cadmium CdTe with p-type conductivity is applied. Then module is closed with metal current-conductive plate. Its efficiency is near 8.5 percent;

Amorphous silicon in photocells does not form a homogeneous structure, but forms a chaotic network. As a result, hydrogen is absorbed through the open boundaries of the crystals. This hydrogenated amorphous silicon a-Si: H is generated in the reactor plasma from the gas phase of silicon hydride SiH 4.

Figure 1.6 – Amorphous silicon photocell

Silicon alloying is produced by gases mixing, which contain alloying element – hydride boron B2H6 for p-conductivity and hydride phosphorus PH3 for n-conductivity. Because of small distance penetration alloying additives into amorphous silicon, lifetime of charge carriers is not very long, so the layer of silicon applied additional layers of n-and p-conductivity. A transparent TCO conductor with tin oxide SnO2, indium oxide and tin ITO or zinc oxide ZnO is used as the front contact. A metal conductive plate is used as the back contact. Its efficiency is from 5 to 7 percent [9].

1.3 Overview of different solar positioning systems

After the start of the solar panels use to produce electricity on an industrial scale, engineers and designers began to look for ways to increase the efficiency of such power plants. The total dispersion of sunlight, which is determined by the change in the direction of incidence of the sun's rays on the panel, did not allow the rational use of solar panels throughout the day. The way out of this situation was the installation of solar panels on a movable base connected to a tracking system for the trajectory of the Sun.

To get the maximum power from solar panels, it is necessary that the sun's rays hit the plane of the batteries perpendicularly. In this direction of the rays, the efficiency of solar panels can reach 50-55%. For stationary batteries, this value can be reduced to 10-15% due to changes in the angle of incidence of sunlight.

The illumination of solar panels must be maintained at an optimal level. To maintain this level, various surveillance systems have been developed – from the simplest analog to analog-digital ones.

A solar tracking system is a device for orienting a solar panel or for keeping a solar reflector facing the Sun [10].

1.4 Purpose and scope of tracking electric drives

Tracking electric drives or position control systems are closed electric drives that control the movement and provide stabilization of the position of the regulation object relative to some basic coordinate system.

In this case, the adjustable value (position of the object) with one or another degree of accuracy must correspond to the control effect applied to the system. Tracking electric drives can provide both linear and angular movement of the adjustable object. For example, it could be a solar positioning system.

1.5 Overview of tracker actuator control systems

1.5.1 Control with multiple photodetectors

The general scheme of the tracker on photocells is given in figure 1.7.

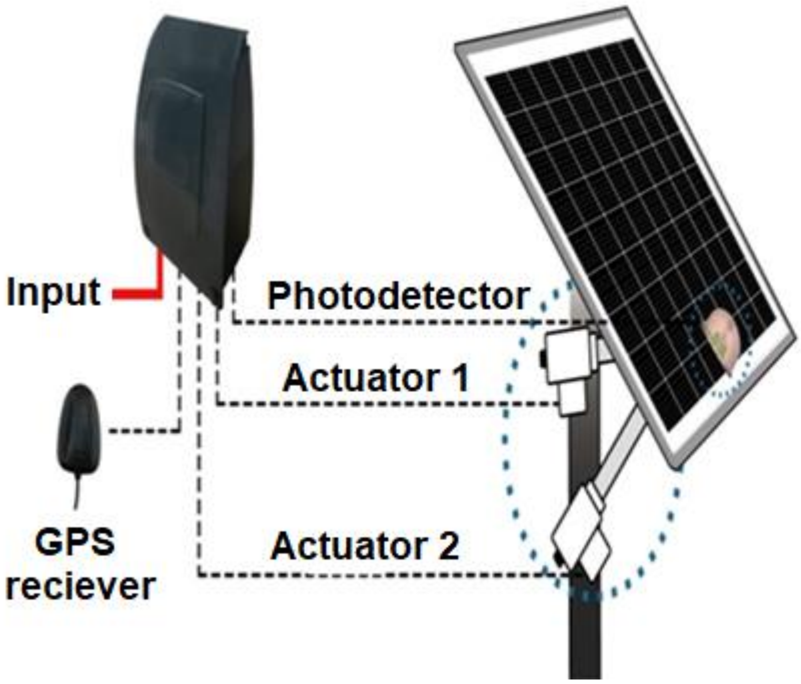

Figure 1.7 – Tracker on photocells

Such a device has two or more photodiodes. When the sun is moving, the illuminance of the photodiodes becomes different, the device analyzes the illuminance and transmits control signals to the actuators until the light flux on all photocells is the same. At the same time, the electric motor rotates the solar battery from west to east.

During the day, the solar platform will rotate following the movement of the sun. As dusk falls, the system enters standby mode. Schematic diagrams of such devices are simple and inexpensive. But they have one significant drawback: in cloudy weather and contamination of photodetectors, the system's performance deteriorates.

The simplest typical scheme of the device for tracking the movement of the Sun (Solar Tracker) is shown in figure 1.8.

To determine the position of the Sun, two photoresistors are used.

The tracker circuit includes:

- electric motor of the actuator M;
- operational amplifier LM1458 (K140UD20);
- transistors BD139 and BD140;
- LDR photoresistors;
- diodes 1N4004;
- simple and adjusting resistors.

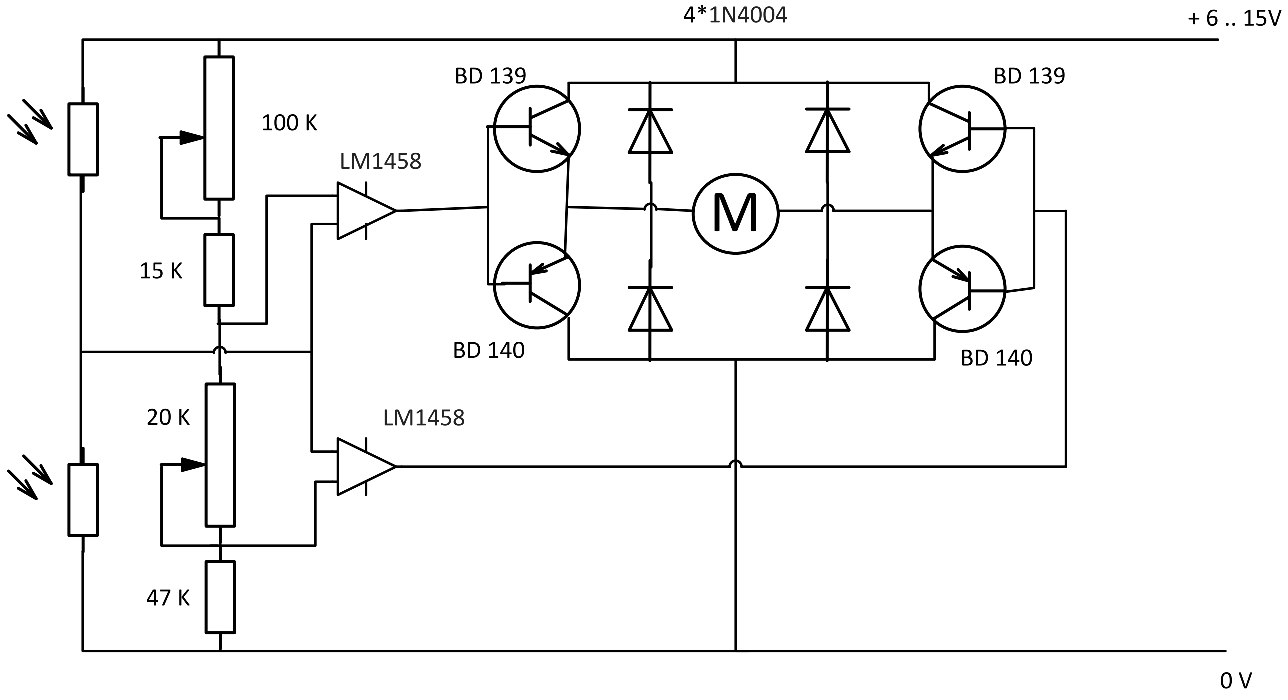

Figure 1.8 – Diagram of the tracking device on photoresistors

1.5.2 Control according to azimuthal and zenith angles

The idea of such devices is based on the fact that for the correct positioning of solar panels, you need to compensate for two movements of the Earth:

- diurnal movement associated with the rotation of the Earth around its axis;
- annual movement associated with the rotation of the Earth around the Sun.

Such a device includes a timer. Actuators begin their work with a daily timer program (if desired, and the annual program). But the accuracy of orientation with such devices is small, as the Sun during the year constantly changes the time, place of sunrise and sunset, the zenith angle.

1.5.3 Method of control according to the program for calculating the location of the Sun

This method can be considered the most effective. According to the internal clock of the device, the program outputs information about the values of azimuth and zenith angle (figure 1.9) to the control unit. This will take into account the location of the tracker, i.e. parameters such as latitude, longitude and altitude. After that the new (necessary) position of the tracker is calculated and its reorientation is carried out.

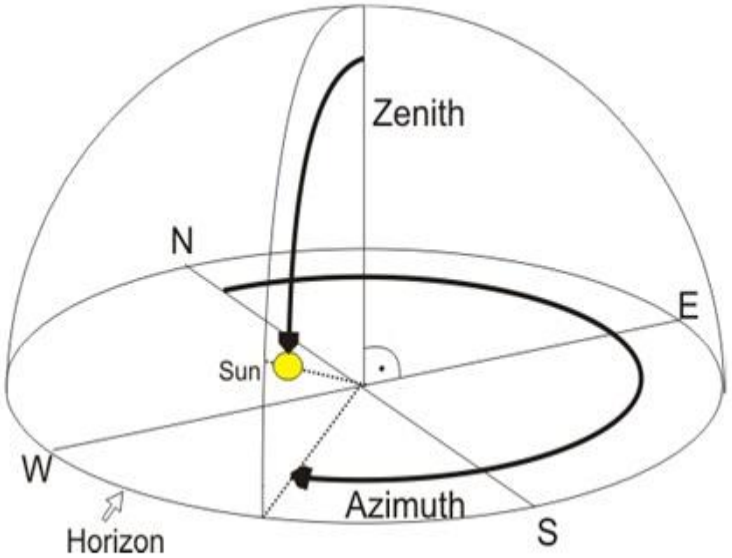

Figure 1.9 – Scheme for determining the position of the sun in azimuth and zenith angle

1.6 Mechanisms of rotation and tilt of the batteries depending on the direction of sunlight

The tilt mechanism allows you to use the following tracking systems at any latitude: when installing solar panels in an area corresponding to 32° degrees north latitude, the axis of the device must be rotated 32° degrees relative to the horizon.

The drives of all mechanisms of the tracking system are built on the basis of electric motors, which are influenced by the control system. Power supply of electric motors and control systems is carried out from the solar batteries therefore such installations are independent.

Thus, the scheme and device of the solar tracker are quite simple. Naturally, more complex systems are used on an industrial scale, but such a scheme can be assembled independently for a household installation for the production of electricity based on solar panels.

The information network contains a large number of ready-made schemes and solutions for solar tracking systems. So, if there is a need to improve the design of solar panels and increase their performance, there is always the opportunity to do it by yourself.

1.7 Overview of existing photovoltaic solar observation power plants

The main direction of increasing the energy efficiency of the industrial control system (ICS) in electricity generation process is the creation and use of a two-coordinate solar tracking system, which provides an increase in energy efficiency by at least 30 – 50% [10] compared to power plants that do not have tracking systems for The sun.

Currently, a number of well-known Ukrainian and foreign companies are engaged in the production of photovoltaic power plants with solar observation [11]: Seltek and DITRAS (Ukraine), Sunpower, Konza Portable Solar Trackers (USA), Gintech (China), Canadian Solar (Canada), Motech (Taiwan), First Solar (USA), Yingli Green Energy (China), Titan tracker (Spain), TRAXLE (Czech Republic) and others.

In the installations of the A.F. Ioffe Institute of Physics and Technology (Russia) uses a specially designed sensor for the position of the Sun, which provides tracking accuracy of 1°. The installation area of the panels is 5.54 m^2. Individually designed solar concentrator modules with solar tracking devices are used. Solar hub modules contain Fresnel lenses and cascade photoconverters located in the focus of each lens. The solar cells are located in the focus of the Fresnel lenses and are mounted on a copper base mounted on the rear glass plate. In a photovoltaic installation the modules are arranged step by step on an electronic-mechanical tracking system.

Figure 1.10 shows the power plants developed at A.F. Ioffe Institute of Physics and Technology [11]

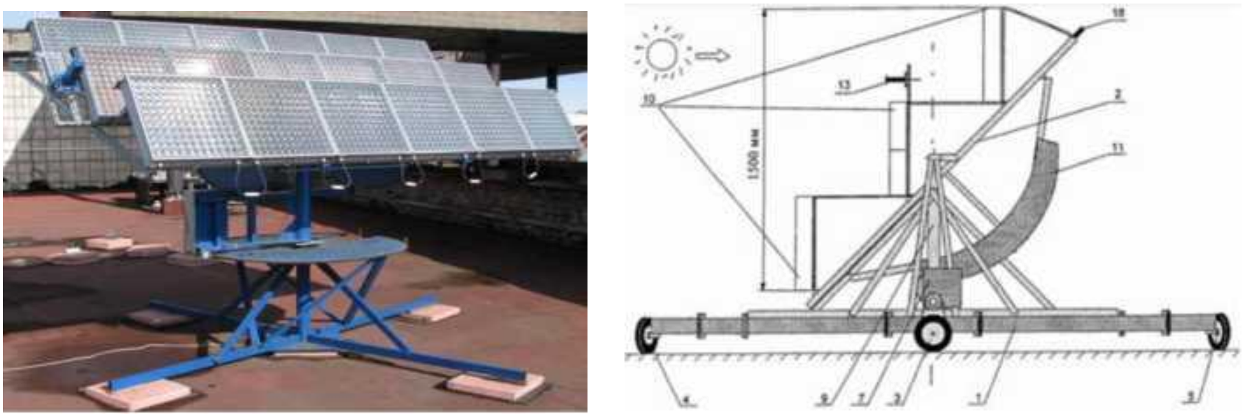

Figure 1.10 – Power plants developed at A.F. Ioffe Institute of Physics and Technology (Russia)

Konza Portable Solar Trackers (USA) [12] manufactures transportable solar power plants. Figure 1.11 shows a photograph of the power plant. Tracking is carried out on the sensor of position of the Sun.

Figure 1.11 – Konza Portable Solar Trackers power plant

Figure 1.12 shows photos of Seltek power plants [13]. The installation can accommodate solar panels up to 6 m2. The tracking system uses DC electric drives, tracking controller and solar position sensors. Accuracy of observation (guidance) 1 degree. If the weight of the solar panel is more than 50 kg, it is necessary to install counterweights, which increases the energy consumption for tracking.

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Figure 1.12 – Seltek power plants

Figure 1.13 shows a photograph of the power plant of DITRAS [14]. The DITRAS installation uses a solar position sensor and provides tracking accuracy of up to 1 degree. The system provides the ability to increase the number of solar panels.

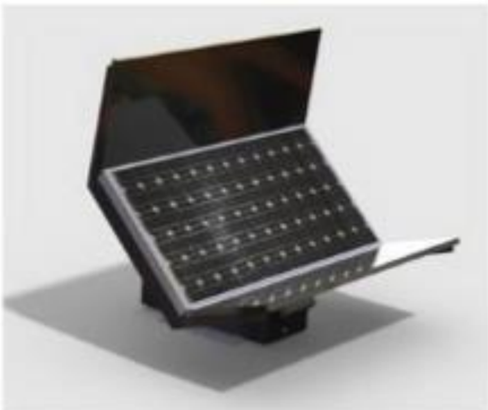

Figure 1.13 – DITRAS power plant

Figure 1.14 shows a photograph of the Titan tracker power plant (Spain) [15]. The Titan tracker installation uses a large number of solar panels (with a total area of up to 216 m2). Tracking is performed on two axes. Minimization of power consumption during tracking is not reported, unknown engine type.

Figure 1.14 – Titan tracker power plant (Spain)

Figure 1.15 shows a photograph of the SUNPOWERT20 TRACKER power plant (USA) [16].

The photovoltaic power plant is mounted at an angle or horizontally. Tracking the position of the Sun is carried out on one axis. On one horizontal axis there are 9 modules consisting of 128 cells, or 12 modules consisting of 96 cells.

Figure 1.15 – SUNPOWERT20 TRACKER power plant

The company Merlin Power Systems (USA) [17] is engaged in the production of solar power plants, characterized in that they have a base in the form of a height-adjustable tripod, which allows you to easily install the structure in any conditions. Mobility and fast assembly of the installation allow to satisfy needs of military equipment, to use in places of natural disasters. The units can be connected in parallel or in series and used in hybrid systems. Figure 1.16 shows a photograph of a solar power plant from Merlin Power Systems.

Figure 1.16 – Solar installation by Merlin Power Systems

The University of Malaysia (University Malaysia Sarawak (UNIMAS), Sarawak, Malaysi) has developed a solar installation [18] with one solar panel. Figure 1.17 shows a photograph of a solar power plant. The installation uses a tracking system that contains linear movement mechanisms. Tracking is carried out on a predetermined trajectory.

Figure 1.17 – University of Malaysia Sarawak solar installation

In the Czech Republic, TRAXLE has developed a solar photovoltaic installation [19] with eighteen panels, which uses a linear movement mechanism. Tracking is carried out on one coordinate by means of the sensor of position of the Sun. Figure 1.18 shows a photograph of a solar power plant.

Figure 1.18 – TRAXLE solar power plant

Eco-$mart, Inc (USA) has developed various solar photovoltaic systems [20]. Figure 1.19 shows photographs of the solar power plants used (one- and two-coordinate tracking systems for solar installations). The types of motors and solar position sensors used are not specified.

Autonomous Solar power plants distinguishes between designs based on nanoheterostructural photoconverters and radiation concentrators (solar concentrator modules), photovoltaic panels, photovoltaic panels in combination with flat mirror concentrators and others.

а *б*

Figure 1.19 – Solar power plants from Eco-$mart, Inc.

Table 1.1 shows the technical characteristics of solar power plants of several companies. Moreover, some important technical characteristics of solar power plants are not specified in the technical documentation of foreign companies.

Table 1.1 – Technical characteristics of solar power plants

Characteristic	A.F. Ioffe Institute	Saltek	DITRAS	Titan tracker	TRAXLE
Angles of movement on an azimuth and on a corner of a place, deg.	360°, 90°	180°, 70°	360°, 90°	360°, 75°	360°, 90°
Type of actuator	Not specified	DC	Not specified	Not specified	DC
Tracking accuracy, deg.	1	1	1	0,01	Not specified
Output power, kW; panel area, m^2	Concentrator modules, area 5,54 m^2	area 6 m^2	0,3 kW, area 2 m^2	area 216 m^2	area 45 m^2
Sun tracking system	Continuous, according to the panel sensor	Continuous, according to the position sensor of the Sun.	Continuous, according to the position sensor of the Sun.	Continuous, according to the position sensor of the Sun.	Not specified

From the analysis of the technical characteristics of the autonomous Solar power plants (see Table 1.1) it follows that it creation uses different types of two-coordinate electromechanical actuators, including DC motors (DC), AC motors, stepper motors, synchronous-jet motors, as well as with linear motors. Thyristor and transistor converters are used as the power converter, including converters with pulse-width modulation (PWM) on field or IGBT-transistors. To obtain good static and dynamic characteristics, multi-circuit control systems with different position, speed and current regulators are used. To ensure high tracking accuracy, multi-bit position sensors, high-precision solar position sensors, as well as multi-engine systems are used to compensate for gearbox backlash.

1.8 Adaptive positioning system

In figure 1.20 shows the design of an automatic solar panel orientation system, figure 1.21 is a diagram of the scanning of heavenly space.

The system contains a rotary device on which a solar panel 1 (figure 1.20) is installed with the possibility of two coordinate angular displacements α and β using a rotary device. The rotary device is a vertical shaft 2, on which a stepper motor 3 is installed to rotate the solar panel 1 around a vertical axis and a rotary frame 4 that can be rotated about a horizontal axis using a stepper motor 5.

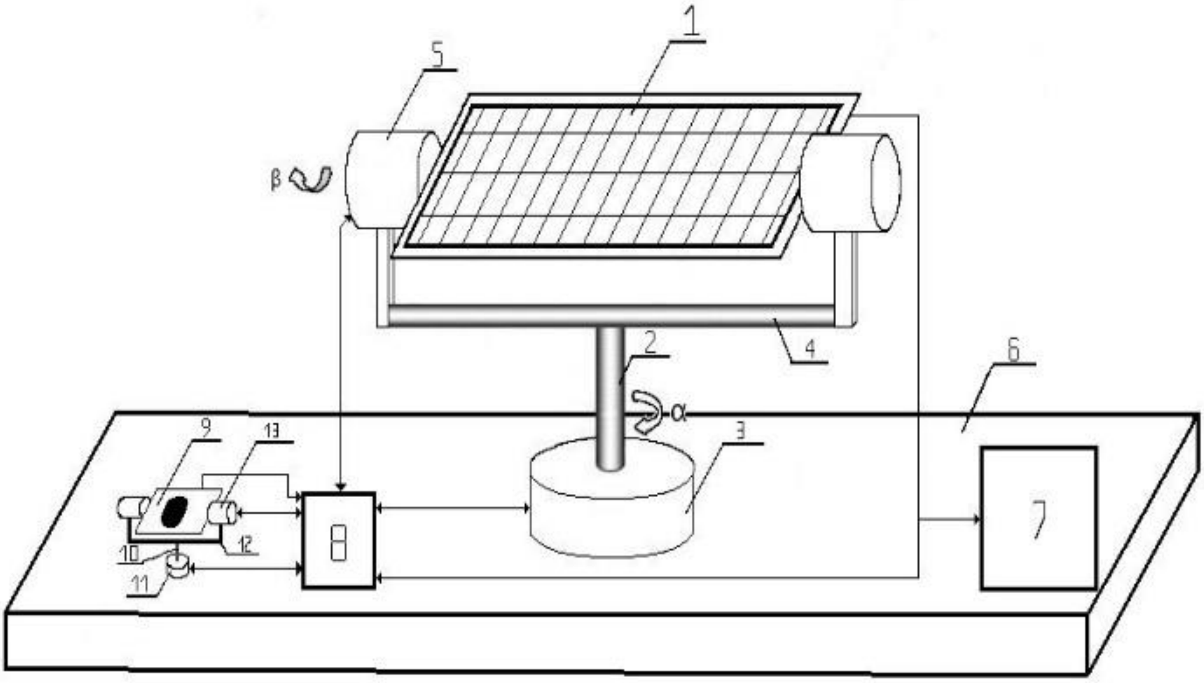

Figure 1.20 – Design of an adaptive solar panel positioning system

The rotary device of the panel 1 is fixed on a massive frame 6. Solar panel 1 is connected to an energy storage device and an output device 7. Stepper motors 3 and 5 are connected to a digital control unit 8. A single-element luminous flux sensor 9 with an optical system is connected to the control unit 8. The sensor 9 is fixed on a two-coordinate scanning device [6] with the possibility of angular displacements α and β using a rotary device, the kinematic diagram of which is identical to the kinematic diagram of the drive of the solar panel 1. The scanning device of the sensor contains a vertical shaft 10, on which a stepping motor 11 is placed for rotating the sensor 9 about a vertical axis and a rotary frame 12 with the possibility of rotation about a horizontal axis using a stepping motor 13. The rotary device of a two-axis scanning device is fixed on a massive frame 6.

The spatial field of view of the single-element luminous flux sensor 9 corresponds to the field of view of the solar panel.

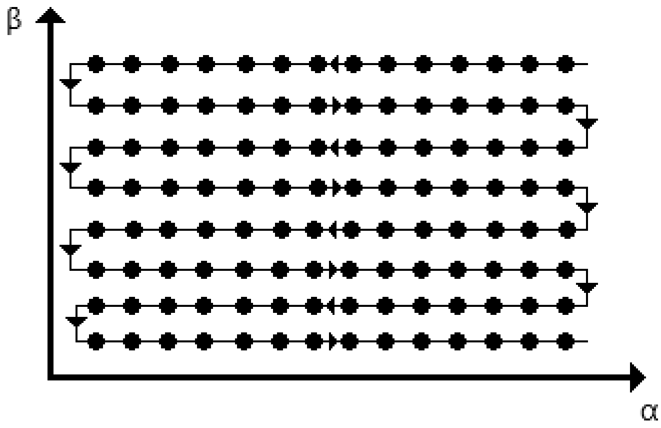

Figure 1.21 – Scheme of scanning of heavenly space

Before the operation of the solar battery, the sky is scanned with a single-element luminous flux sensor 9 (the scanning scheme is shown in figure 1.21). Scanning is carried out by stepper motors 11 and 13 using the control unit 8. In the process of scanning by the digital control unit 8, the brightness of the areas of the zone is registered. Upon completion of the scanning of the sky zone sections, information processing is performed by the control unit 8, namely: determination of the section with maximum brightness. The control unit 8, using stepper motors 3 and 5, sets the panel 1 to a position so that the normal to the plane of the panel 1 is directed to the area with maximum brightness. After that, the solar panel 1 is connected to the storage device 7 or an external circuit.

1.9 Cloudy radiation

The problem of studying the structures of optical radiation of cloudiness in relation to the detection and selection of radiation of artificial objects against its background was posed back in the 50s. [7]. In addition, these works contain references to earlier sources. They considered the issues of radiation of clouds, as well as radiation and reflection of various natural environments. These issues were considered in relation to the design problems of optoelectronic systems for various purposes. At present, the problems of optical radiation of cloudiness arise in solar energy, since cloudiness affects the efficiency of solar batteries. In connection with the widespread introduction of solar power plants and their inclusion in the general energy system, the problem of the inconstancy of the generated energy arises. Therefore, to compensate for the dips in the generated solar power plant with the help of reserve sources, it is necessary to predict the generated and consumed energy. One of the sources of information for forecasting the generated energy is the cloud forecast, which is the responsibility of the meteorological service. Thus, according to meteorological forecasts, it is possible to predict the amount of generated energy. For a quantitative assessment of the generated energy, we present the basic theoretical information on the optical radiation of clouds [7].

The atmospheric radiation reaching the earth's surface is mainly formed by scattered solar radiation and the intrinsic thermal radiation of atmospheric components (gases). Scattered solar radiation dominates only during the day in the wavelength range of less than 2 μm, and the intrinsic thermal radiation in the wavelength range of more than 4 μm. The reasons for this division are explained in figure 1.20, which shows the emission spectra of an absolutely black body (ABB) at 300 K. This approximately corresponds to the temperature of the surface air, and 6000 K, which corresponds to the radiation temperature of the Sun. Along the axis of ordinates, the spectral density of the radiance is plotted in $W \times cm^{-2} \times sr^{-1} \times \mu m^{-1}$. The abscissa shows the wavelengths (μm).

To assess the value of scattered radiation, it is assumed that all solar radiation is scattered at the earth's surface, uniformly in directions and non-selective in wavelengths. The spectrum of the scattered solar radiation is about 2×10^{-5} spectral density of the radiance.

In reality, the total amount of scattered solar radiation reaching the earth's surface is less, since a significant part of it is scattered by the atmosphere and clouds and is reflected from the earth's surface. One tenth of the scattered solar radiation (curve 2) can be attributed to reflection. This part is represented by curve 3. Thus, an estimate of the average emission spectrum of atmospheric and terrestrial natural formations can be obtained by summing the spectra shown in the figure by curves 3 and 4.

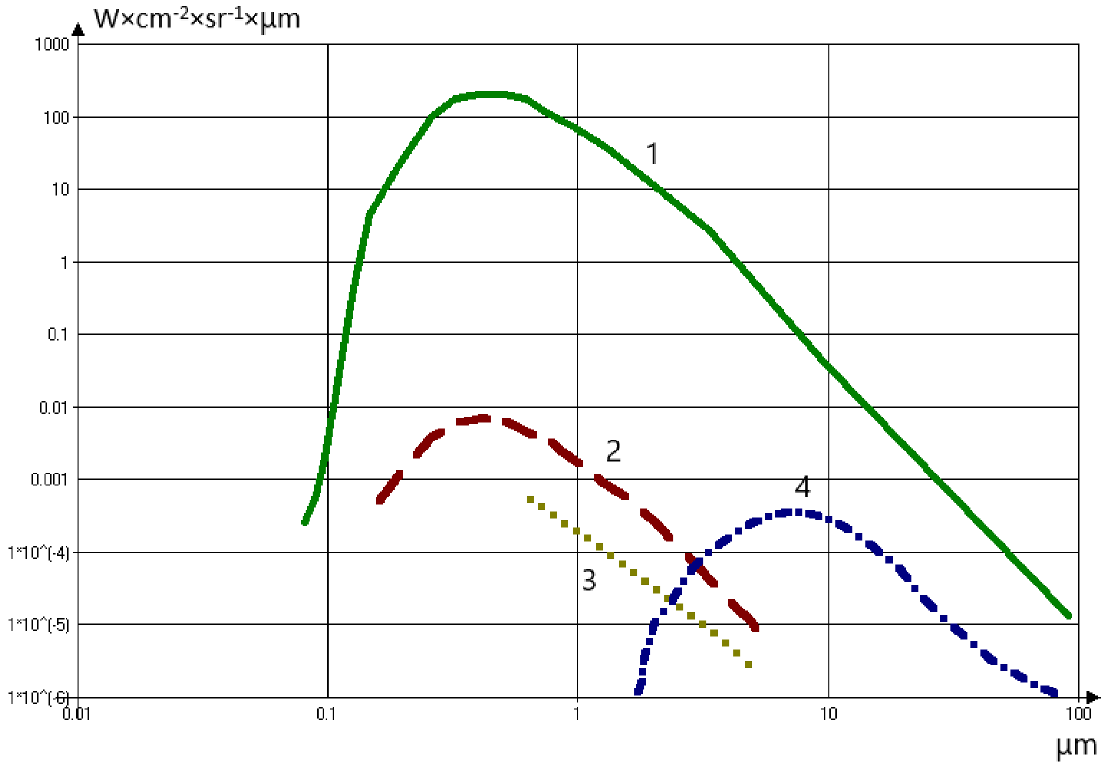

Figure 1.22. Idealized radiation spectra:

1 - solar radiation; 2 - scattered solar radiation;

3 - reflected radiation from the earth's surface; 4 - blackbody radiation at 300 K

Often the emission spectra of the underlying surface elements, as well as clouds, are similar in appearance to this average spectrum. The real emission spectra of a cloudless and cloudy atmosphere in the wavelength range of 0.4 - 15 microns are distinguished by high selectivity, since strong vibrational-rotational bands of various gases are concentrated here. In atmospheric transparency windows, under average conditions, no more than 10-20% of solar radiation is absorbed by the vertical column of the atmosphere. In absorption ranges, the scattered solar radiation decreases, while the thermal solar radiation of the atmosphere increases.

The spatial distribution of brightness over the sky, especially in the short-wavelength region of the spectrum, is largely determined by the nature of aerosol scattering. Aerosol scattering, in contrast to molecular absorption, has a significantly lower spectral selectivity. Its spatial-angular distribution is characterized by anisotropy with a maximum in the direction of radiation propagation. The spatial distribution of scattered solar radiation over the sky is also anisotropic. In this case, the angular distribution of the scattered radiation of cloudy and cloudless areas of the atmosphere is different and depends both on the position of the Sun and on the angles of the direction of observation. Therefore, describing and predicting solar radiation is a difficult task.

Conclusion to the section

In this section we considered the analysis of problems and systems of solar positioning. We learned how unconventional energy based on solar batteries is developing and widely used as a source of energy for various devices.

We looked at various types of panels for a solar power plant which include crystalline. Under crystalline we have monocrystalline silicon photocells, and polycrystalline photocells we talk about Thin-film photocells and the ones related to it.

We then further looked at the overview of different solar positioning systems, where we know how panels use to produce electricity on an industrial scale before when the solar starts, later the engineers and designers began to look for a way to increase the efficiency. To get the maximum power from solar panels, it is necessary that the sun’s rays hit the plane of the batteries perpendicularly.

In the case of tracking electric drives, they are drives that controls the movement and also provide stabilization of the position of the regulation object relative to some basic coordinate system. Two movement of the earth is compensated for correct positioning of solar panels: earth around its axis, and earth around the sun.

The use of two coordinate solar tracking system is the most effective in term of increasing the energy efficiency of the industrial control system in electricity generation. The two-coordinate solar tracking system provides an increase in energy efficiency by at least 30~50% compared to power plant that do not have tracking system for the sun.

Finally, we considered the optical radiation of cloudiness in solar energy. Cloudiness affects the efficiency of solar batteries The atmospheric radiation reaching the earth's surface is mainly formed by scattered solar radiation and the intrinsic thermal radiation of atmospheric components.

2 PROJECT DESIGNING SECTION

2.1 Measurements of PV parameters

In this work, a measuring circuit of the current-voltage characteristic was implemented using a variable load resistance (from 0 to 300 Ohm), designed for photo modules with a power of 80 - 150 W and shown in figure 2.1. Experimental data on the *I-V* characteristic (VAC) were fed to a data acquisition system based on an Atmel 328 microcontroller with an input voltage limitation of 5 V and a resolution of 5 mV. The voltage across the load R_{load} was measured through a voltage divider $R_1 - R_2$, and the current in the load was controlled using a current shunt $R_{shunt} = 0.23$ Ohm Simultaneously with the measurements of the voltages across the resistors, the illumination was measured using a BH 1750 module on a photoresistor, which made it possible to introduce corrections for the changing solar radiation during the measurements.

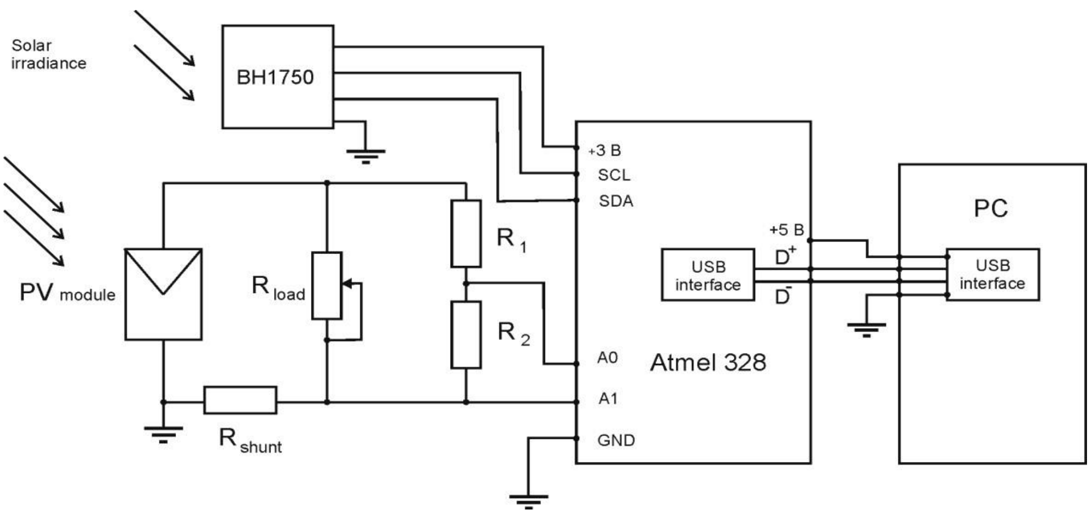

Figure 2.1 – Scheme for measuring of electrical characteristics of PV modules

Data from the ADC of the microcontroller was transmitted via a USB interface to a PC and written to a file. Further processing and approximation of the VAC were carried out using specialized programs in the MATLAB package. In the course of experiments, the VAC of PV modules from monocrystalline and polycrystalline silicon were taken at

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Developed	Usman Barau				PROJECT DESIGNING SECTION	Letter	Sheet	Sheets
Checked	Kotsiurko R.V.							
Consultant	Kotsiurko R.V.					TNTU, FAT, gr. IEE-42		
Compliance	Kotsiurko R.V.							
Head of Dp.	Tarasenko M.H.							

various degrees of shading and the characteristics of the main operation modes of the module were determined: maximum of power (MP), no-load (NL) and short circuit (SC).

2.2 Simulation of VAC of PV modules in conditions of partial shading

In this work, we investigated the mutual shading by rows of solar panels, which is most often observed in the morning and evening hours of PV plant operation, as well as the effect of shading on the PV module parameters characterizing electrical losses. The shadow begins to appear in the lower part of the PV module and spreads upward as the Sun's altitude decreases, which corresponds to the gradual shading of the rows of series connected photovoltaic cells. The experimental results obtained for this type of shading are shown in figure 2.2.

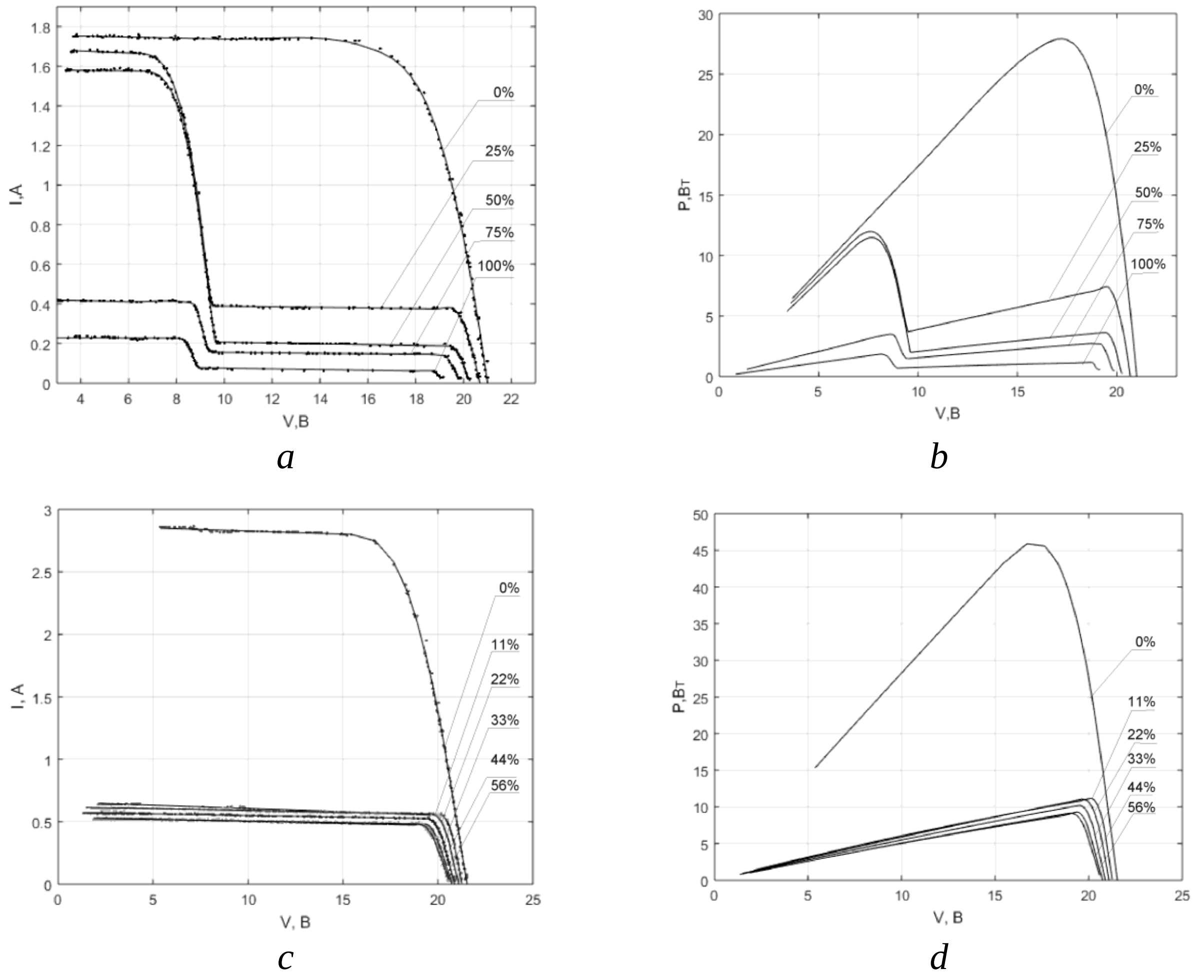


Figure 2.2 – VAC (*a*, *c*) and dependence of power on load voltage (*b, d*):

a, *b* - poly- Si module Kvazar KV -100 W with landscape orientation;

c, d - mono- Si module SunRise SR 100 W with portrait orientation

Curves with lower values of the short-circuit current correspond to an increasing area of partial shading. If the module is located horizontally (landscape orientation), then with partial shading of the lower part of the module, the photogeneration of one of the series of series-connected photovoltaic cells decreases. As a result, VAC has a multistage character (figure 2.2*a*) and, accordingly, the dependence of the power on the voltage across the load PV module is characterized by several maxima (figure 2.2*b*). If the module is located vertically (portrait orientation), then with the lower shading, the photogeneration of all series of sequentially connected cells decreases simultaneously. In this case, the $I(V)$ curve only shifts along the current without changing its shape (figure 2.2*c*), and the $P(V)$ curve does not split into several maxima (figure 2.2*d*).

For the correct determination of the PV module parameters, a necessary stage is the preliminary processing of the measurement results, which consists in sorting the data and their approximation using model curves.

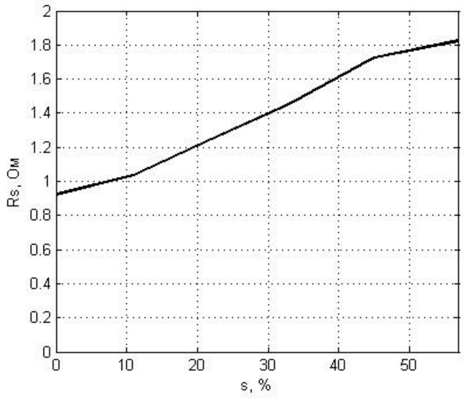
The functions representing these curves make it possible to find pairs of values (I, V) at experimentally unattainable points of the SC. and NL. To date, a number of works are known in which the VAC of PV module is simulated using various classes of functions (exponential, as in the Shockley formula [32–34], Lambert functions [35–37], neural networks [38], etc.). In this work, when modeling the VAC, a piecewise polynomial approximation was applied. According to [39], the approximating function was set on four intervals of VAC around SC, NL, and MP. The coefficients at the powers of the approximating polynomials were determined by the least squares method and satisfied the conditions of continuity of the approximants and their derivatives. In the process of fitting the model curve to the experimental data, the location of the matching points of the approximating curves was also optimized.

The next stage after the approximation of the experimentally obtained VAC is to determine ("extract") the main parameters of the PV module, which describe the behavior of the module within the framework of an equivalent circuit (see review [33, 40]). To find these parameters, it is necessary to solve a system of nonlinear equations, both in the problem of direct determination of parameters, and in the problem of fitting parameters to the experiment by nonlinear optimization. As is known, when solving such systems, it is required to set the initial values of the parameters, on which the result of the subsequent iterative process depends to a decisive extent. For five- and seven - parameter models of single - diode and two - diode equivalent circuits, an adequate result can be obtained if the initial values are well chosen [26, 33]. Experience shows that only small changes in starting values lead to non-physical and unpredictable results. This is especially true for parameter extraction based on PV plant field measurements. Determining the starting values in these cases is a separate task, largely dependent on the skills of the operator. Therefore, it is important to build a stable algorithm for determining the characteristics of the PV module, which can be used when the parameters of the equivalent circuits are not known in advance. The work [41] is devoted to the development of such an algorithm for determining the parameters and its application to experimental PV module data. The extraction method developed in this work does not require initial parameters and is stable when performing iterative computations.

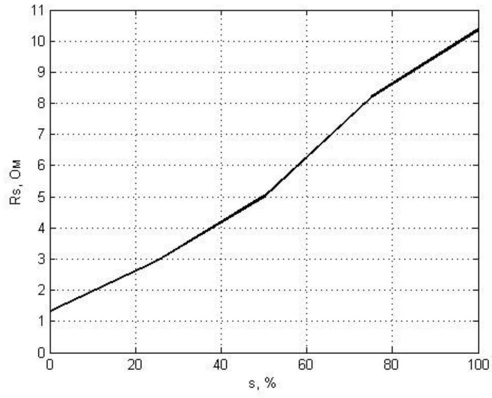
For a single - diode equivalent circuit, we are talking about calculating a set of parameters $\theta = \{I_{ph,} R_{s,} R_{p,} I_{o,} A\}$, where I_{ph} is the photogeneration current, R_s and R_p are sequential and parallel (shunt) loss resistance, A is the diode imperfection coefficient, the values of which lie in the range from 1 to 2, I_0 is the reverse saturation current of the diode, describing the p-n junction.

The algorithm for solving the system of equations for the set θ [41] is based on the analytical expansion of nonlinear equations for the main modes of operation of the PV module with respect to small parameters, which are combinations of quantities from the set θ.

The application of this method to the experimental data shown in figure 2.2 makes it possible to find, for example, the resistance $R_{s,}$ which is responsible for the main electrical losses in the PV module (losses in the bulk layer of semiconductors and in the contact system). The corresponding curves showing the dependence of losses on the degree of shading are shown in figure 2.3.



a



b

Figure 2.3 – Dependences of the series loss resistance R_s on the relative area of the lower shading *s*:

a – portrait orientation of the mono-Si module SunRise SR 100 W ;

b – landscape orientation poly-Si module Kvazar the KV -100 the W

Series resistance R_s most strongly affects the behavior of the VAC of the module in the area of the maximum power and near NL. It can be seen from the graphs in figure 2.3 that in the absence of shading, R_s is less than in PV module from monocrystalline silicon. With the appearance of partial shading and its increase to full shading, the loss resistance increases significantly: R_s increases approximately twice for portrait orientation and approximately 10 times for landscape orientation, if we estimate this resistance in the area of the idle point.

2.3 Loss of power when shading PV module

The influence of mutual shading on the PV module power will be characterized by the loss coefficient, which is equal to

$$K_{loss} = (s, I_{s,} I_{to}) = \frac{P(s=0, I_{to}) - P(s, I_{s,} I_{to})}{P(s=0, I_{to})}, \qquad (2.1)$$

where $P(s, I_{s,} I_{to})$ is the electrical power in the load at the degree of lower shading *s*, I_s and I_{to} are the radiation intensity in the shadow and on the illuminated inclined surface; $P(s=0, I_{to})$ is the load power in the absence of shadow. The degree of shading is determined in work [28] as the ratio of the area of the shaded part of the row to the total area of the row (figure 2.4):

$$s = \frac{S_{shad}}{S_o} = \frac{l\cos\beta}{L}, \qquad (2.2)$$

where l is the height of the frame of PV module, β is the tilt angle of the panel, L is the period of regular arrangement of panels.

We also introduce the power loss factor of the shaded panel [28], that is equal to

$$f(s, I_{s,} I_t) = 1 - K_{loss} = \frac{P(s, I_{s,} I_t)}{P(s = 0, I_t)} \qquad (2.3)$$

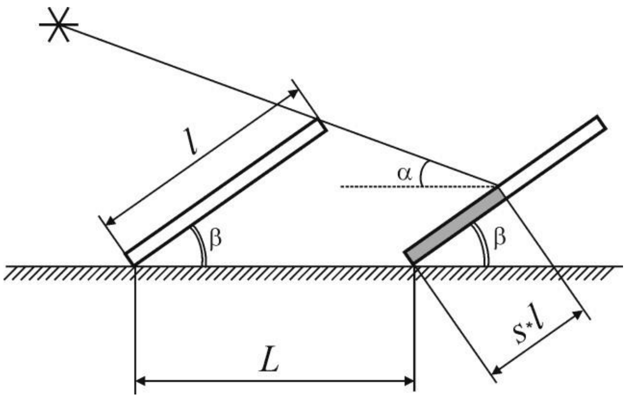


Figure 2.4 – Self-shading geometry of solar panels rows

The illumination in the shadow region is, generally speaking, non-uniform: it is higher near the edge of the shadow compared to areas farther from the edge. This inhomogeneity should be taken into account when modeling the effect of PV module shading on power. However, as the experiment showed, the value of the pair of VAC quantities is determined precisely by the least illuminated area in the shadow region. Therefore, in further calculations, we consider the shadow to be uniform, and the radiation intensity in the shadow area equal to the minimum value over the entire shaded field of the module. This fact is reflected in formulas (2.1) – (2.3), in which only one value I_s, is presented, which is depended on the relative area of the shadow s.

To obtain the dependences of the factor *f (s)* , the experimental data in the form of pairs of values (P_m, V_m) for the power maxima were interpolated for the entire interval of values of the degree of shading s using Hermite polynomials. figure 2.4 shows the dependences *f (s)* (3) for Sunrise SR 100 W PV modules made of mono- Si with a portrait and Kvazar KV- 100 W PV modules made of poly- Si with a landscape orientation, obtained on the base of the *P* (*V*) curves on figure 2.2*b* and 2.2*d*.

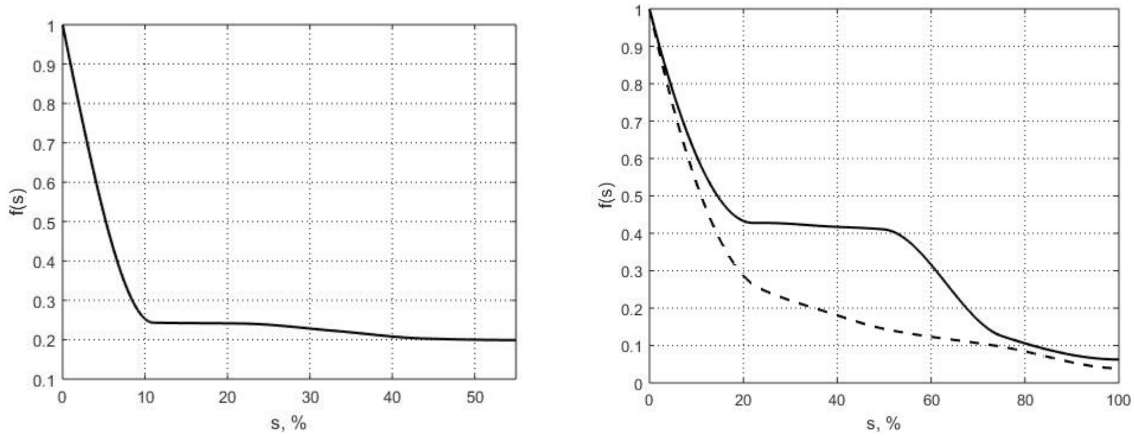


Figure 2.5 – Dependences of the power loss factor *f*(*s*) on the relative area of the lower shading:
portrait (*a*) and landscape (*b*) orientation of mono-Si module;
the solid curve refers to the main maximum of power, the dashed curve refers to the secondary maximum

It can be seen from these figures that the effect of the degree of shading on the output power of the PV module system is essentially nonlinear, namely: the value of the factor *f(s)* at the initial portion of the curve decreases disproportionately with the increase in *s*. This is due to the fact that when several cells of the module are completely shaded, the current flows through the bypass diode, and not only several shaded cells are excluded from the generation process, but also all cells shunted by the diode. Accordingly, the module's power is reduced by tens of percent. With a further increase in *s, the* decrease in the current generation slows down.

The research of this work was carried out at NTUU "Kyiv Polytechnic Institute". The azimuth of the normal to the surface of the investigated photo modules was directed to the south, and the tilt angle of the modules (the angle between the horizontal plane and the PM plane) was 35° . This angle of inclination, as shown in the next section of the article, is optimal for the Kyiv region.

2.4 Influence of the power factor on the optimal row spacing and angle of inclination of solar panels

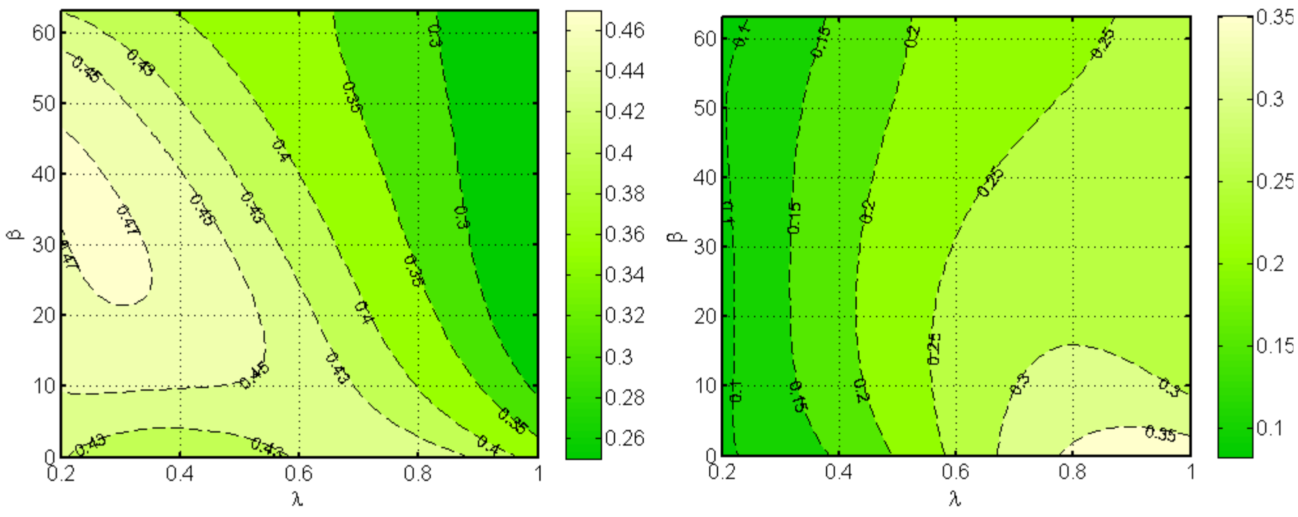
On the basis of the obtained dependences of the power factor *f(s)* on the degree of shading, it is possible to calculate the power generation of a PV plant with a parallel arrangement of rows of PV module panels, equally oriented in azimuth and having a certain angle of inclination β. In this case, we will use the approach [28], according to which, for a given geographic location, the arrival of radiation on an inclined surface during the calendar period *T* of the station operation is calculated, the corresponding number of peak sunny hours and electricity generation $E\ (T\ ,\ \beta\ ,\ \lambda)$ per unit area of PV module or per unit area of a land plot, depending on two parameters: the angle of inclination β and the density of the rows $\lambda = l\,/\,L$. Method of calculation allows to build surface $E\ (T,\ \beta\ ,\ \lambda)$ and to optimize the geometric parameters of the PV power plant.

As an example, let us give the results of calculating $E(\beta,\ \lambda)$ for a PV power plant operating throughout the entire calendar year and installed in the Kyiv region. In this case, we use the reference radiation data for the horizontal surface [42], obtained over a long period of time. The power factor *f*(*s*) is described by interpolated dependences shown in figure 2.4 *a*, *b*.

Figure 2.6 shows two types of contour plots $E(\beta\ ,\ \lambda)$ for the portrait orientation of the PV module: the average daily output per unit area of the panel (figure 2.6*a*) and the output per unit area of the land plot (figure 2.6*b*). Using the first type of graphs we can find the optimal λ and β to maximize generation per unit area of PV module. The second type of graphs should be used when the task is to optimize λ and β to obtain the maximum output per unit area of the land plot on which the PV plant is located with equally oriented rows of solar panels.

Similar plots are shown in figure 2.6. These graphs for the average daily output but with the landscape orientation of the PV modules i.e. using the power factor for main maximum power (see figure 2.5*b*) which is followed by an inverter.

From the graphs of the surfaces $E\ (\beta\ ,\ \lambda)$ on figure 2.6*a* and 2.7*a*, it can be seen that for the considered region, the maximum output per unit area of the PV module can be achieved with a row density not exceeding 0.35 and an inclination angle (35 ± 3)º for both portrait and landscape orientation of modules.

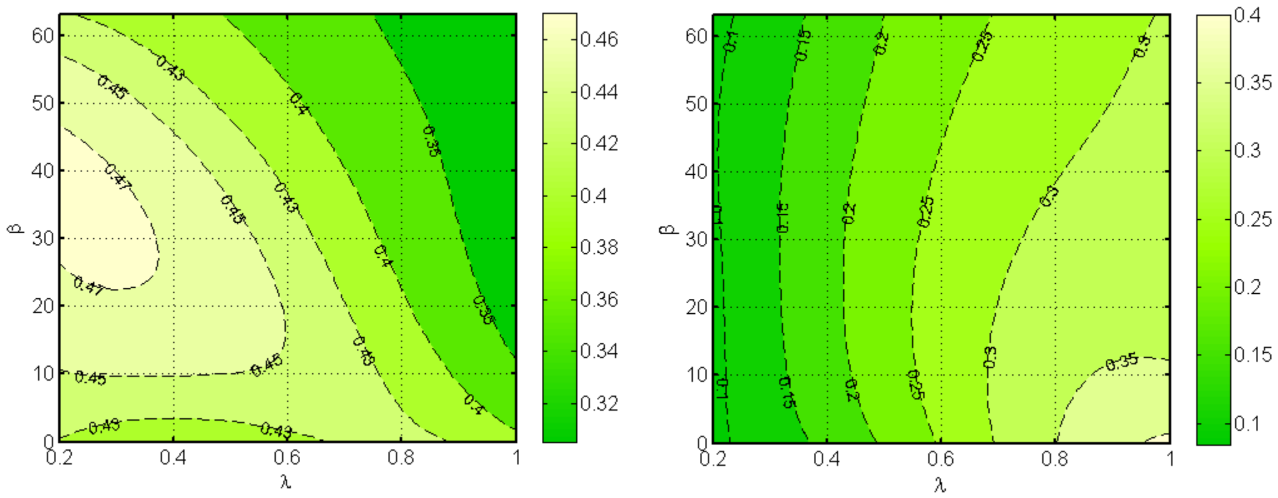


a *b*

Figure 2.6 – Contour graphs of the average daily output of PV systems in Kyiv region with a portrait orientation of the PV modules:

a – energy production (kW×h) per 1 m^2 of the module area;

b – energy production (kW×h) per 1 m^2 of land site



a *b*

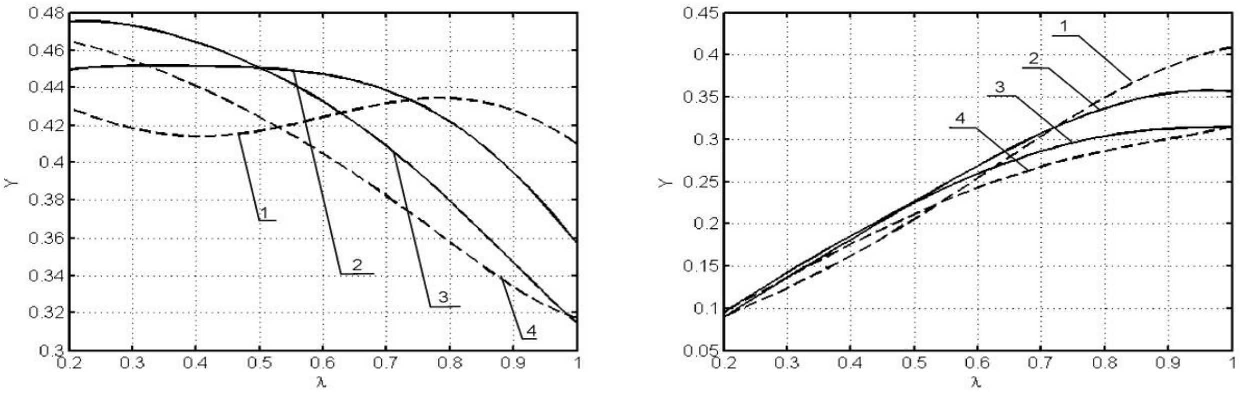
Figure 2.7 – Contour graphs of the average daily output of PV system in Kyiv region with landscape orientation of PV modules:

a – energy production (kW×h) per 1 m^2 of module area;

b – energy production (kW×h) per 1 m^2 of land site

If the optimization condition is to obtain the maximum yield per unit area of the land plot for the PV power plant, then the highest output (~ 0.35 kWh / 1m^2) with the portrait orientation of the panels according to the graph on figure 2.5*b* is achieved when the area is filled λ = 0.8-0.95 and the angle of inclination of the panels is less than 3º. The landscape orientation allows a slightly higher output (~ 0.4 kWh / 1m ^{2}) at λ ≥ 0.95 and an almost horizontal arrangement of the PV module (see figure 2.6*b*).

For clarity, we will depict the dependences of the average daily output on the density of rows in the form of two-dimensional graphs for landscape (figure 2.7) and portrait (figure 2.8) orientations of the PV modules at the PV power plant in the Kyiv region.



a *b*

Figure 2.8 – Dependences of the average daily output on the density of module rows in landscape orientation for various tilt angles β and calculations per 1m^2 of module area (*a*) and per 1m ^{2} of land site (*b*): 1 – β = 0º; 2 – β = 10º; 3 – β = 35º; 4 – β = 50º

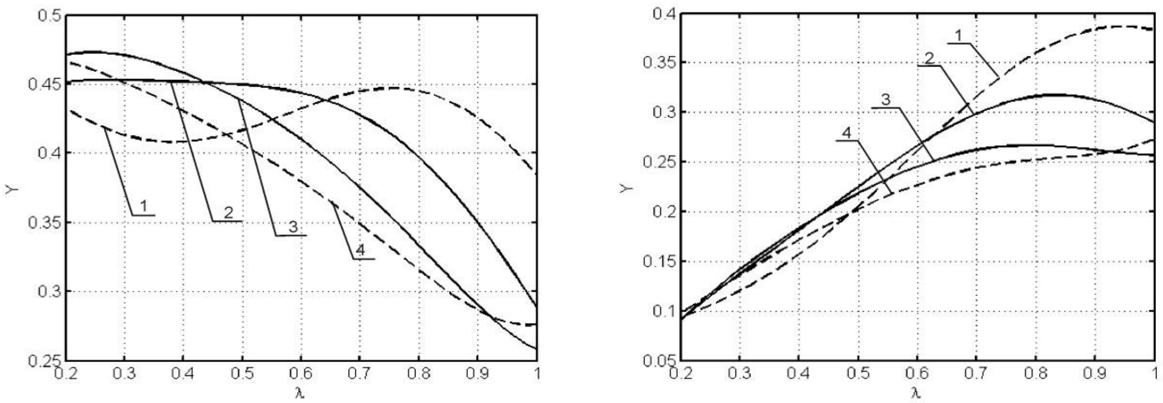


Figure 2.9 – Dependences of the average daily output on the density of module rows in portrait orientation for various tilt angles β and calculations per 1m^2 of module area (*a*) and per 1m^2 of land site (*b*): 1 – β = 0º; 2 – β = 10º ; 3 – β = 35º ; 4 – β = 50º

The graphs on figures 2.8 and 2.9 show the surfaces $E(\beta, \lambda)$ at fixed angles β. The highest generation for 1 m^2 of the module area with both types of orientation is achieved when the density of rows is less than 0.3, and the angle of inclination is equal to the optimal value of 35° for isolated panels. To obtain the maximum output from 1 m^2 of land the horizontal position of the panels ($\beta = 0^o$) and the most dense arrangement of rows ($\lambda > 0.95$) are optimal. If the optimal tilt angle $\beta = 35°$ (as for isolated panels) is chosen , then the shortfall in the average daily output will be about 30% at a density of, for example, ~0.75 compared to the horizontal arrangement of the panels (see figures 2.8*b* and 2.9*b*).

Conclusions to the section

In this section, measurement of PV parameters were discussed. A measuring circuit of the current-voltage characteristics was implemented using a variable load resistance from 0 to 300 ohm. It was design for photo modules with a power of 80 – 150 W. Atmel 328 microcontroller with an input voltage limitation of 5 V, resolution of 5 mV is used.

Mutual shading by rows of solar panels was investigated, which is most often observed in the morning and evening hours of PV plant operation. Also the effect of shading on the PV module parameters characterizing electrical loss was discussed

Power loss when shading PV module is characterize by the loss coefficient which is equal to equation (2.1).

At the end of this section we considered how to obtain the dependences of power factor *f(s)* on the degree of shading. it is possible to calculate the power generation of a PV plant with a parallel arrangement of rows of PV module panels, equally oriented in azimuth and having a certain angle of inclination β.

3 CALCULATIONS AND RESEARCH SECTION

3.1 Formulation of the problem

Solar photovoltaic panels are able to generate the maximum possible (nominal) energy only at a normal angle of incidence of sunlight on the plane of the panel [43, 44].

There are empirical dependencies that reflect the effect of reducing the generation power of PV modules, and hence the reduction of the amount of electrical energy produced when their surface deviates from normal (Snell's law). With a slight error, we can assume that this dependence obeys the cosine law in the range from 0 to 90 degrees. (see table 3.1).

Table 3.1 – Loss from deflection angle

Angle of incidence of light rays (deg.)	Losses in %	
	Empiric (%)	Cosine (1-cosγ)100%
9	1.2	1.23
18	4.9	4.89
40	19.0	23.39
45	29.0	29.29
90	100	100

For the normal orientation of the plane to an arbitrary vector, it is necessary and sufficient to give the plane any two degrees of freedom of rotation out of the three possible. The kinematics and control systems of all two existing coordinate platforms, the tracking systems, are based on this principle. For the normal orientation of the plane to an arbitrary vector, it is necessary and sufficient to give the plane any two degrees of freedom of rotation out of the three possible.

The kinematics and control systems of all two existing coordinate platforms are based on this principle - tracking systems [45].

The study of the decrease in the efficiency of the generation of PV units due to the shading of the surface of the panels seems to be quite difficult both in the physical aspect and in the mathematical (from the point of view of optimal orientation) [46]. In the physical aspect, the essence of the problem is to establish a functional relationship between the area of the shaded surface and the possible amount of non-generated electrical energy due to partial mutual shading of the active surfaces of individual modules. There is a fairly large number of expert assessments in this regard [47-51]. The most complete study in this area is the work of G. Rauschenbach [46]. Interesting results were also published in [50].

Note that when placing a complex of panels on two coordinate platforms, in principle, it is impossible to avoid the formation of shadows on their surfaces. Based on this remark, it seems interesting to consider the issue of using platforms with three-coordinate control [47]. However, the transition to the consideration of three coordinate systems of spatial orientation is accompanied by the emergence of new theoretical and practical problems associated with the transition to more complex control objects. One of their main problems is the development of mathematical methods and algorithms for optimal positioning of panels (in particular, for controlling the third coordinate).

The complexity and urgency of this problem is confirmed by the interest in it of such organizations as NASA (NASA's task), the terms of which were published on the website "http://topcoder.com/" in January 2013 [52]. This problem is of well-known interest in the mathematical aspect.

The essence of the problem is to provide a solution for controlling the positioning of the panels (the American module of the International Space Station - ISS) in such a way as to generate the maximum amount of energy in each discrete time interval. It was required to take into account the factor of the appearance of shadows and their influence on energy efficiency, and this condition translated this task into the rank of extraordinary tasks.

Analysis of this problem showed that it is close to the class of so-called NP - problems, at least in the context of combinatorial optimization [53]. One could assume the possibility of searching for a theoretical solution by examining the patterns of the appearance of shadows (projections of some panels onto others located along the beam) at different angles of orientation of the panels. But the problem is complicated by the appearance of homogeneous groups of shadow projections on the active surfaces of the modules, i.e. duplicated overlays of shading projections and the consequent need to isolate duplicate areas.

The purpose of this work is to develop a numerical method for solving the optimization problem of controlling the motion of a complex of platforms and a rational kinematic scheme for three coordinate platforms with obtaining the maximum possible amount of electrical energy from PV installations

3.2 The concept of solving the problem

The only real possibility of solving such a problem was the search and use of heuristic methods and algorithms based on the use of numerical methods. To illustrate the effectiveness of the developed approach to solving the problem of optimizing the generation of electrical energy according to the criterion of its maximum production, the NASA problem was considered at the first stage [52]. The scheme of mobile platforms (2-coordinate scheme) used on the International Space Station (ISS) is considered. A parametric analysis of the operation of this installation showed that the control of the positioning of PV modules according to a 2-coordinate scheme does not completely eliminate the phenomenon of shading of the active generating surfaces of the panels. It is only possible to provide the best compromise between the potential "loss" of energy from shading and from the deviation of the orientation angles of the panels from the normal. The results of using the proposed algorithms for optimizing the orientation of PV modules using the known schemes of moving platforms (2-coordinate scheme) kinematic and their modifications are shown in figure 3.3.

Let us note such an important aspect as the issue of increasing the efficiency of generation of renewable energy installations that are connected to electric power systems. Conceptually, the task of increasing the efficiency of the generation of such systems does not differ from the “space task” of using such installations, since in the case of a ground installation there are restrictions on the area of their installation. Power plants based on PV modules require the alienation of significant plots of land for these purposes, including arable land. Reducing the alienated land for the production of electricity by this method is not only a technical and economic task, but also has social aspects. In this context, increasing the efficiency of generation of ground-based solar energy installations is a very urgent and economically important task.

Therefore, for optimal control of the positioning of PV modules of ground-based solar power plants, a three-coordinate control option seems to be very promising. At the same time, we proceed from the hypothesis that such an approach to solving the problem for ground-based three-coordinate orientation systems is able to fundamentally solve the problem of eliminating shadows on the surface of the panels, and, consequently, increase the production of electrical energy from a unit of the occupied area of the PV module installation.

The validity of this formulation of the problem for increasing the generation of electrical energy has an experimental confirmation of the effectiveness of this approach [54].

3.3 The efficiency of the three-axis control system

For the case of ground-based photovoltaic plants based on mobile platforms, the results have been very encouraging, both from a management and economic point of view. For a comparative analysis of the control system based on optimizing algorithms, as well as for assessing the complexity of debugging platform control systems with a three-coordinate kinematic scheme, the data obtained on a laboratory experimental setup with three-coordinate control can be used [54].

Table 3.2 shows some comparative parameters of electric solar power plants using the principle of two and three coordinate control systems. An operating station based on two coordinate platforms of the German company DEGERenergie GmbH & Co. KG was used as an example for a comparative analysis [55].

Figure 3.1 and 3.2 show plans for the placement of two and three coordinate platforms, respectively, at standard and critical distances.

Table 3.2 shows comparative indicators corresponding to the placement of both types of platforms on a plot of 660 m^2.

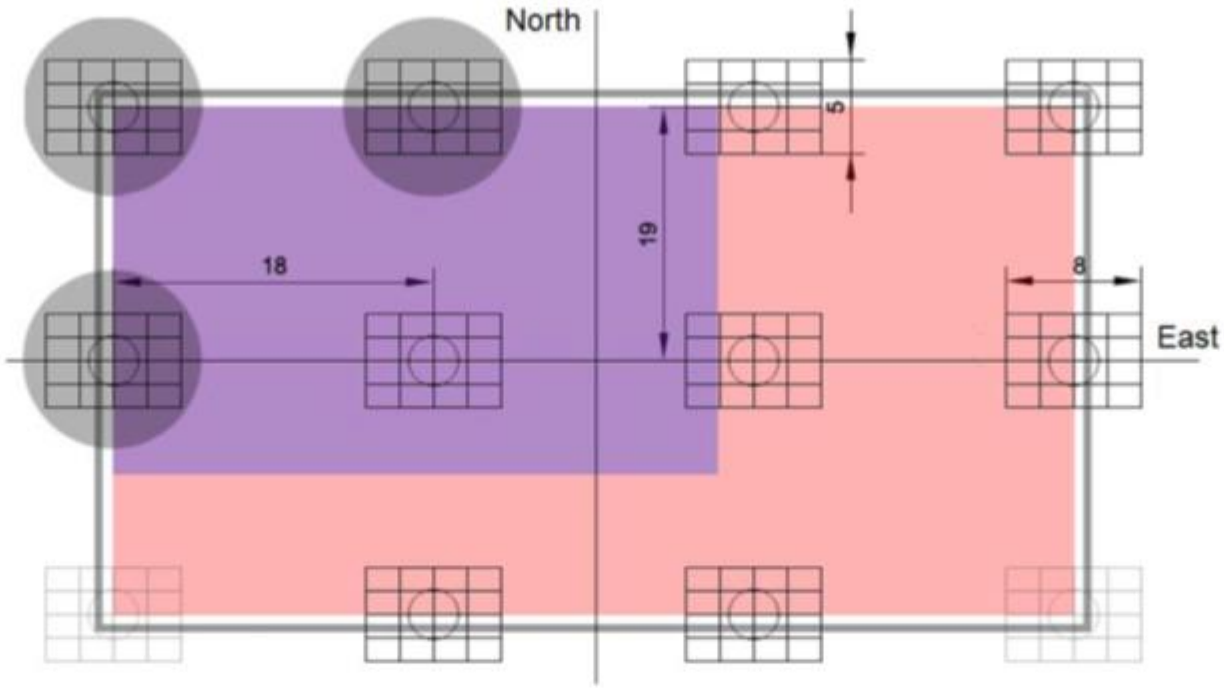


Figure 3.1 – Layout of 2-coordinate platforms at standard distances. S = 2052 m^2 (54x38), the coefficient of compactness of placement – 0.195

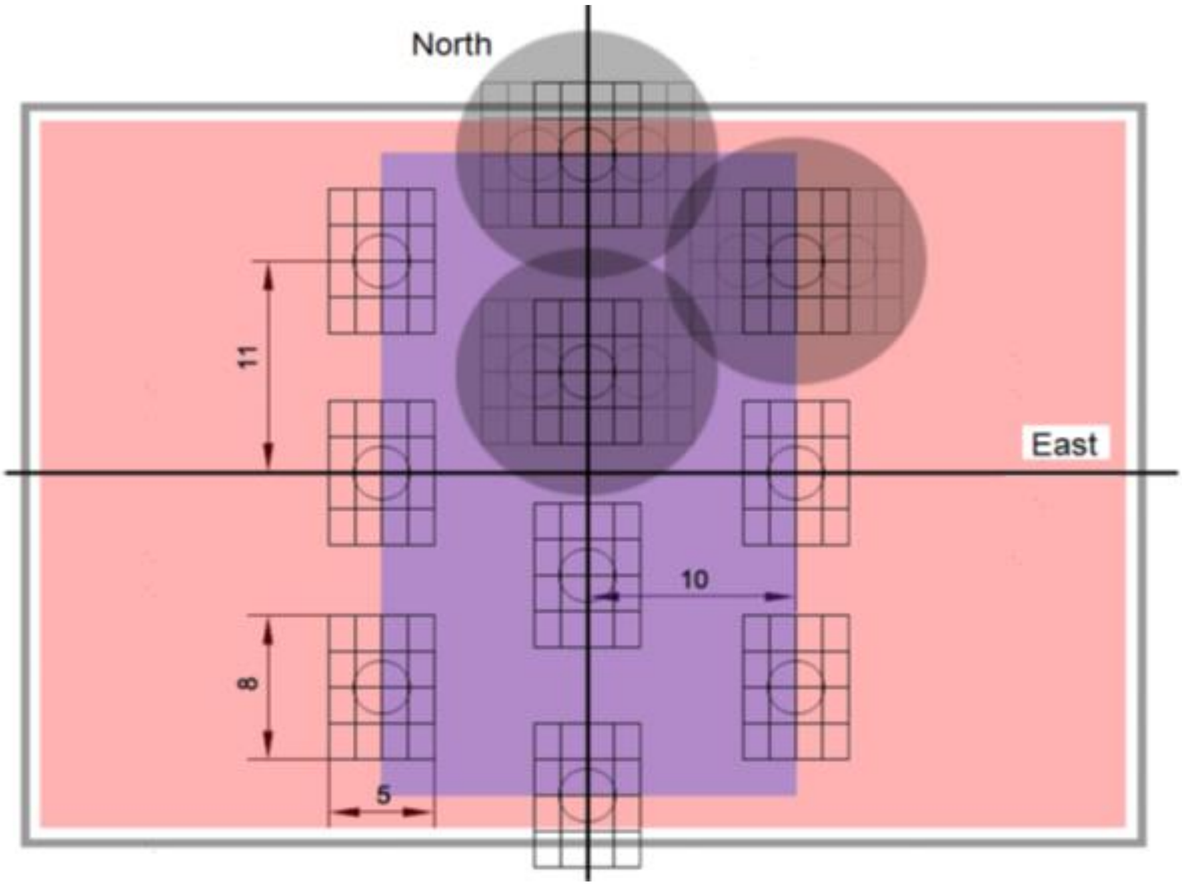


Figure 3.2 – Plan of placement of 3-coordinate platforms at critical distances. S = 660 m^2 (33x20), compactness factor – 0.606

Table 3.2 – Parameters of stations based on 2 and 3 coordinate systems

№	Parameter title	Parameter value	
		2nd cordinate model 5000NT	2nd cordinate. modif. model
1	Panel area of one platform (m^2)	40	40
2	Overall dimensions of the panel on the platform (m)	5.3 x 8.3	5.3 x 8.3
3	Number of platforms (units)	10	10
4	Overall dimensions of a non-standard area (m)	33 x 20	33 x 20
5	Land area (m^2)	660	660
6	Rated power of the station (kW)	70	70
7	Relative value of the area free from shade, average annual value (%)	85.35	95.69
8	The amount of generated energy for the period of operation of 30 years (kW)	2375721	3070368
9	Costs excluding the cost of the site ($)	104000	116800
10	Gross income at price 0.2$/kW×h ($)	371144	497273
11	Profitability (%)	456.87	525.75
12	Payback period (years)	7	6

If a station based on two coordinate platforms were placed at standard (normative) distances (figure 3.1 and 3.2), then it would occupy an area of 2052 m^2 (54 mx 38 m). And in this case, on a real site with an area of 660 m^2, only four out of ten platforms could be placed, without providing 60% of the declared nominal capacity.

At the same time, the placement of 2-coordinate platforms at critical distances leads to a significant loss of station power due to the intense formation of shadows.

Thus, one of the main advantages of 3-axis platforms is compactness of placement, due to the ability to reduce the distances between platforms up to critical dimensions (closer to which they will touch each other when rotating) without significant power losses due to shading.

3.4. Optimization of the positioning of solar panels on the ISS

After the creation of the experimental setup and the development of software applications (for design and proper optimal control), we considered the "space problems" - about the possibility of using three coordinate systems on the ISS. These studies are theoretical in nature, but there is hope that there may be a "grain of reason" in them.

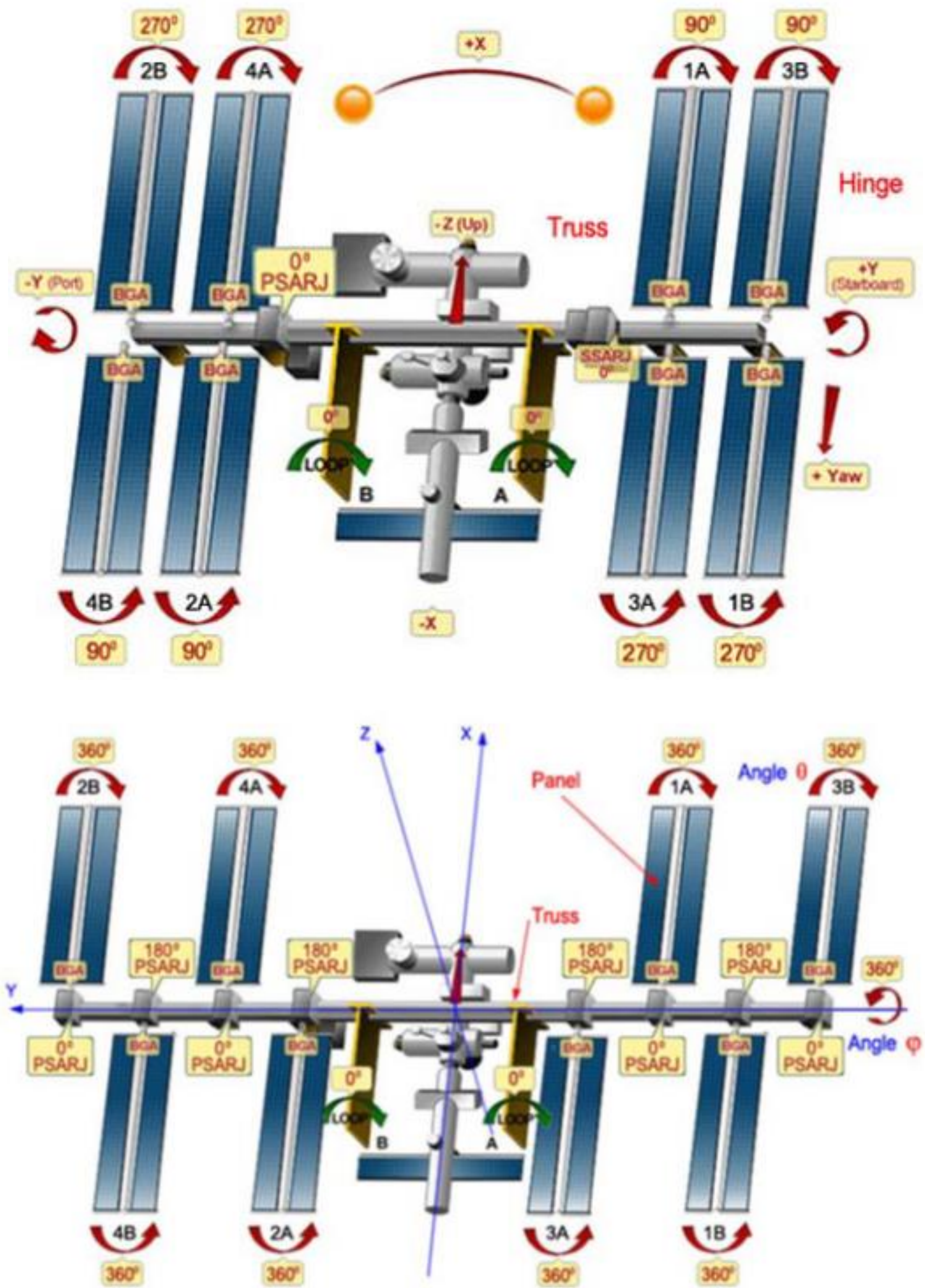
We divide the subsequent presentation into two parts. In the first part, we present the results of solving the optimization problem (for the American ISS module in a modified version) for two coordinate platforms, and in the second part we will consider some issues related to replacing two coordinate platforms with three coordinate platforms.

3.4.1. Optimizing the positioning of solar panels when using a two-coordinate system.

We changed the kinematic scheme (changes are shown in figure 3.3*a* and 3.3*b*), giving each pair of panels (Array Wings) the ability to have two independent degrees of freedom. Surely, NASA's designers had reason to use such a kinematic scheme, but from a theoretical point of view, it is a special case in which each tandem of two pairs has zero distances between the points of attachment to the mast. In addition, since the two pairs in tandem are interlocked (according to angle φ), it can be assumed that each of the two pairs of panels of the combined unit does not actually have two independent degrees of freedom for rotation.

If necessary, solving a general problem, you can always get a particular solution. Perhaps there are prerequisites for such a kinematic scheme (figure 3*a*), but from a theoretical point of view, locking of two pairs of panels on one drive makes it meaningless to have independent rotation for each pair. This conclusion was made on the basis that for each pair of angles (α_{sun}; β_{sun}) defining the position of the radiation vector, there is only one single pair of angles (φ_k; θ_k) that ensure the normal orientation of the panels).

Any deviation of the interlocked group (from the optimal position) around the mast by an angle Δφ or the deviation of any pair of the group around the longitudinal axis by an angle Δθ will lead to a decrease in energy production. Otherwise, the planes of the panels in the optimal (in terms of angle) mode should have collinear normal vectors. It can be assumed that this is dictated by the problems of ensuring the temperature mode, the operating conditions of the batteries or other reasons unknown to us. As a result of this modification, the variability of the system has increased, and as a result, the range of feasible solutions of the optimization problem has expanded.



a

b

Figure 3.3 – Layout of solar panels on the ISS.

a) - paired-blocked (real); *b*) - independent modified

Consider the essence of the task. At certain angles of the solar ecliptic, the panels can cast shadows on each other. For any pair of angles (α_{sun}; β_{sun}) it is necessary to find such a positioning (ie, pairs of angles (φ_k; θ_k)) for all panels of the system – k = 1, 2...N (N is the total number of panels in the system), which would ensure the maximum power generation. We point out that an attempt to "spread" the panels so as to minimize the total area of the resulting shadows, in the general case, will lead to a deviation from the optimal angles (deviation from the normal). And the optimal angle positioning of the panels can generally lead to a deviation from the minimum the achievable value of the total area of shadows (optimal position "in the shadow").

Formally, the use of the view optimization criteria (minimizing the deviation of the angle from the normal and minimizing the area of the shadow) allows us to class it as a multicriteria optimization problem.

Thus, within the framework of this concept, the panel system on the ISS can be represented as rectangular "petals", cantilevered on the mast (figure 3.4).

In figure 3.4*a*, it can be seen that at these angles of the radiation vector, there is a significant shading of the panels, although they are located optimally along the angle. The only way to reduce the shaded area (for this kinematic scheme) is to spread the panels around the OY axis (change the angles φ_k).

Figure 3.4*b* shows one of the options for the optimal positioning of the panels, which minimizes the shading area. As can be seen from the figure 3.4*b*, the optimality condition for the angle is not preserved for all panels. Panels 1 and 4 have angles θ_k less than the optimal one, equal in this position to 15 degrees.

It should be noted that for each deviation from the optimal position in angle, which occurs when the panels are rotated by an angle $\Delta\varphi$, the angle θ is corrected in such a way as to ensure the maximum possible energy production (see the cosine law) for a given angle $\varphi' = \varphi + \Delta\varphi$.

An essential feature of such a kinematic scheme for a certain range of declination angles is the following fundamental position - the optimal solution is always characterized by a compromise between the underdevelopment of energy from shading and from deviation from the normal.

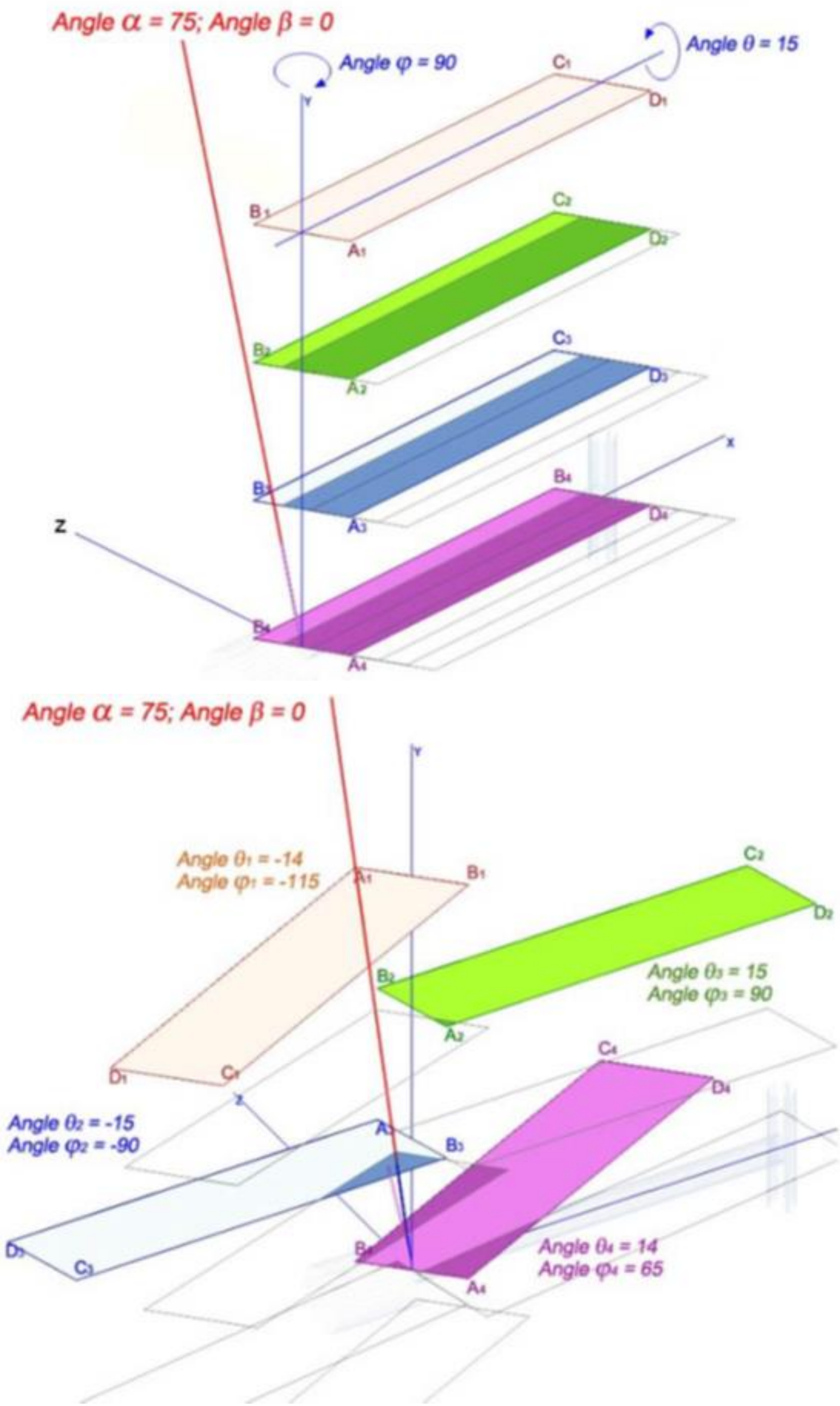


Figure 3.4 – Schematic representation of a 2-coordinate multi-level panel system

The term "defined range of angles" here also has a specific meaning and depends on the width of the panels and the distances between their attachment points on the mast. To establish the value of the range, it is necessary to introduce the concept of the critical angle for this particular system. Figure 3.5 shows the scheme for determining this angle.

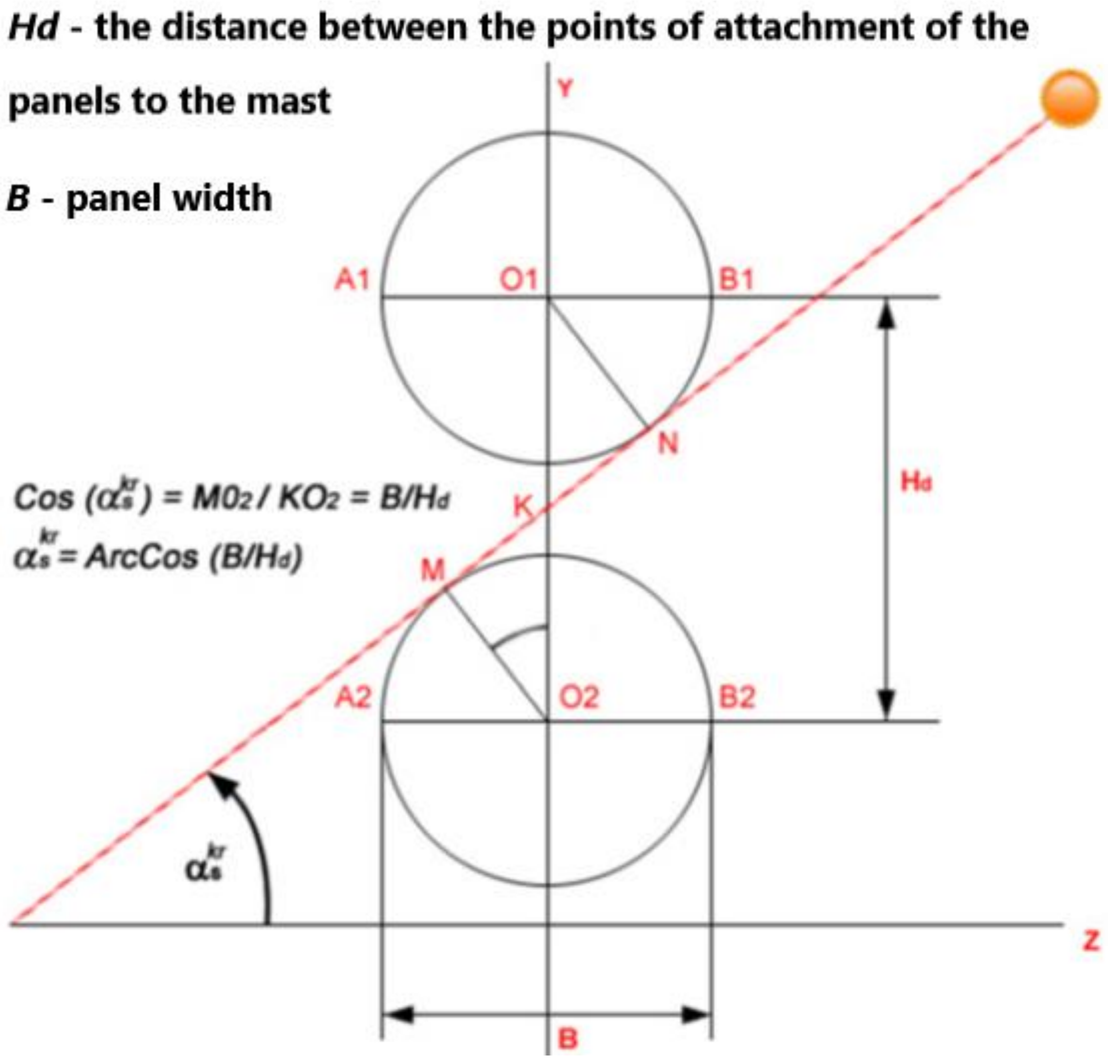


Figure 3.5 – Scheme for determining the critical declination angle

In the less critical declination range, it is always possible to position the panels in such a way as to optimize their angle position, avoiding the appearance of shadows.

Accordingly, in the range of angles exceeding the critical angle, shadows will inevitably occur, and a "compromise optimization" is needed.

Of particular interest is the 3-dimensional visualization of the "topology" of the area of feasible solutions (though this is possible for no more than 2 panels).

For a system consisting of two panels (trivial case), a 3-dimensional computer model of the dependence of the relative efficiency of energy production on the value of the orientation angles $E = E$ (φ; θ) was built, both for the dependence of the efficiency "by angle" and for the dependence of its from the area of the shadow. In figure 3.6 shows a graphical interpretation of these dependencies (3-dimensional "topologies" of solutions). It is not possible to display this dependence in 4 or more dimensional spaces (i.e. for a system that includes three or more panels).

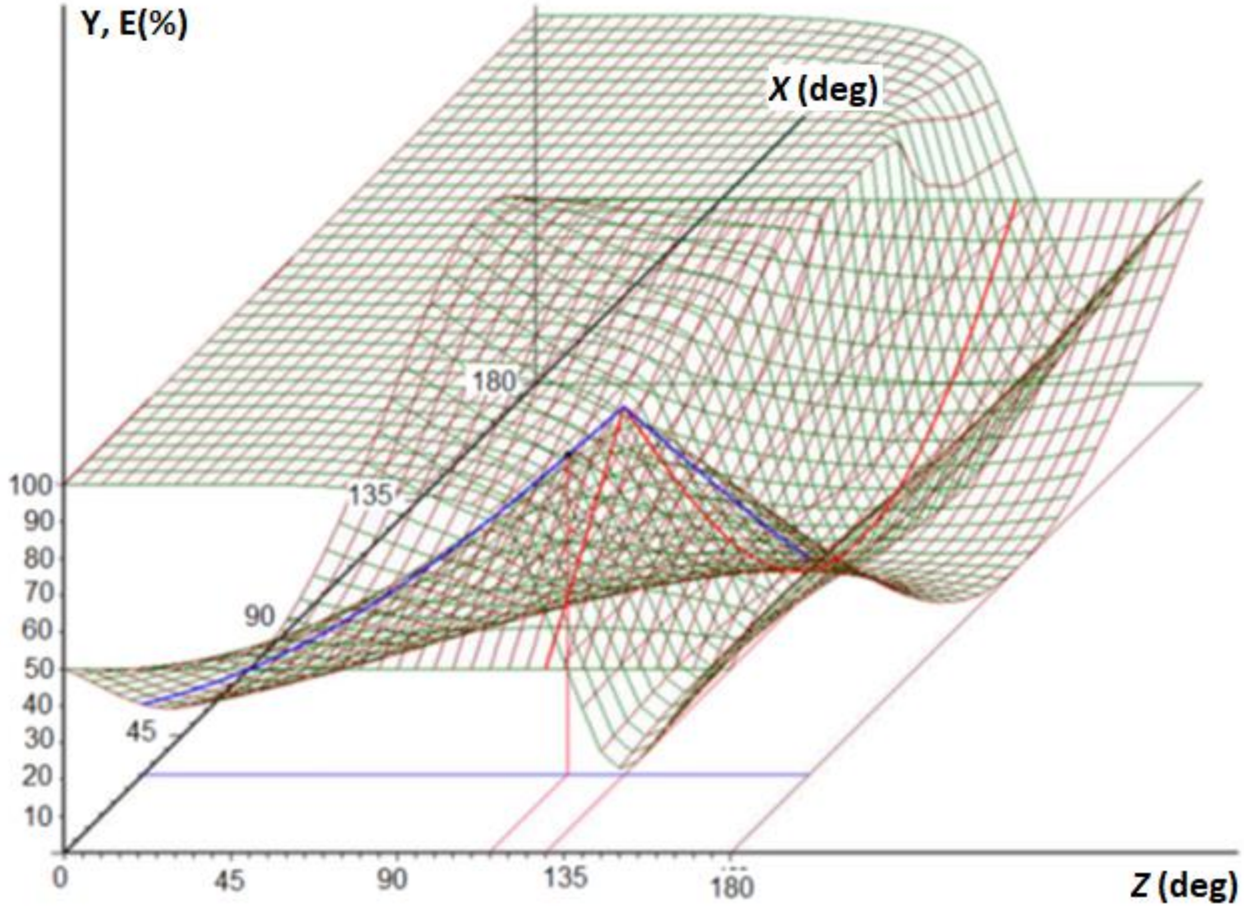


Figure 3.6 – Graphic interpretation of empirical dependencies Eangle = E(φ; θ) and Eshad = E(φ; θ) for two panels (discreteness level - 5 degrees)

These three-dimensional interpretations, in particular, were performed to analyze the patterns of system behavior and were subsequently used to develop a heuristic method for optimizing the positioning of panels.

In figure 3.7 are shown to illustrate the dependence of the angles of orientation of the panels φ on the angle of declination α_S. For convenience, as the azimuthal angles φ_k their deviations δ_k from some given initial values δ_k are presented. In this case, the zenith angles φ_k correspond to the optimal value for a given deflection angle φ_k.

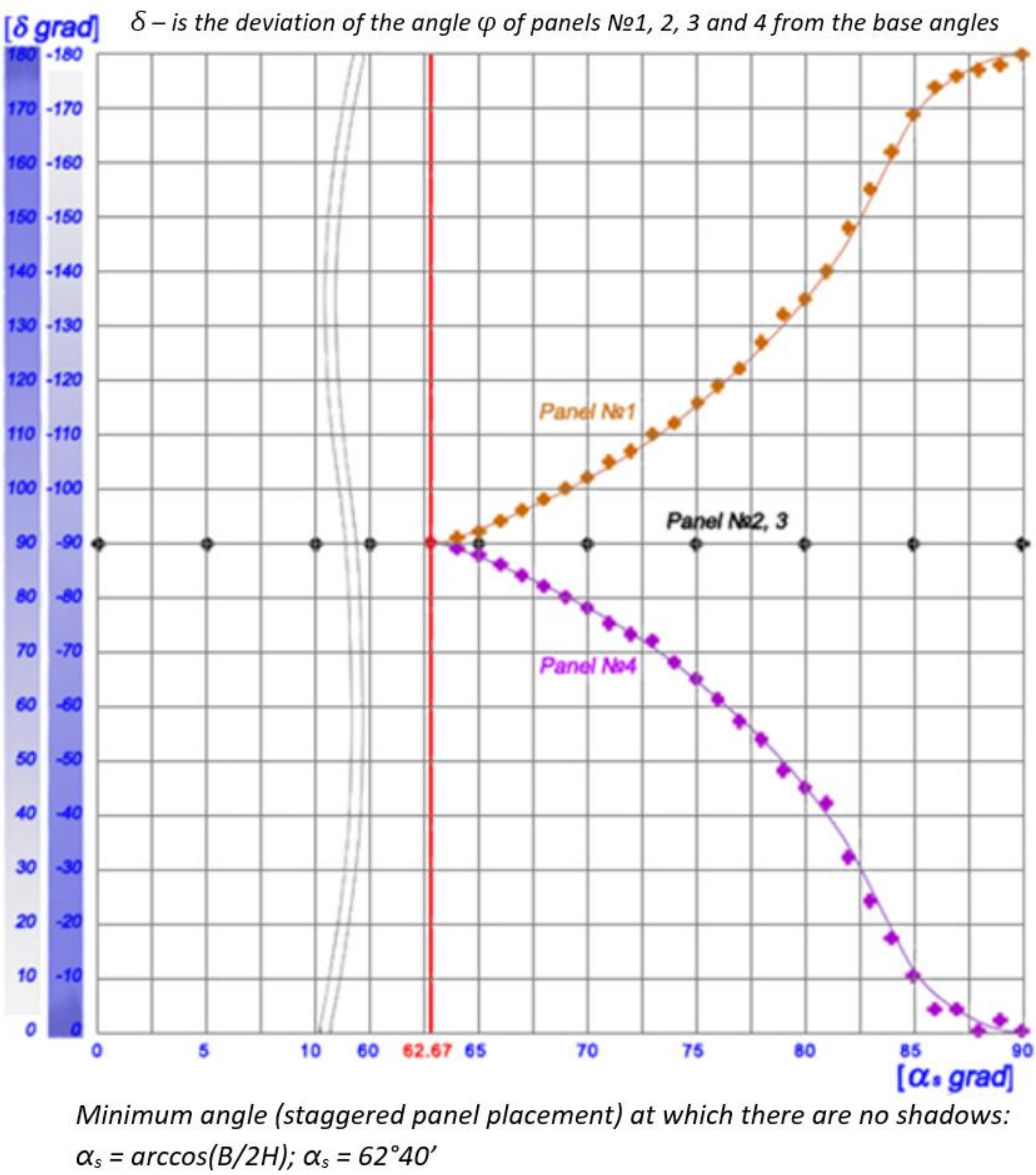


Figure 3.7 – Empirical curves reflecting the "optimal" dependence of the angles φ_k panel orientation from declination angle α_s (N= 4) for 2-axis installations

Figure 3.8 shows the changes in power generation in the zone of "post-critical" declination angles in the optimal mode.

We did not start to improve the optimization methods developed for 2-coordinate systems. The reason is the obvious futility of such a kinematic scheme for the complete elimination of shadows on the surface of the panels.

Nevertheless, some methodological provisions and intermediate results were used later in the development of optimizing algorithms for three coordinate systems.

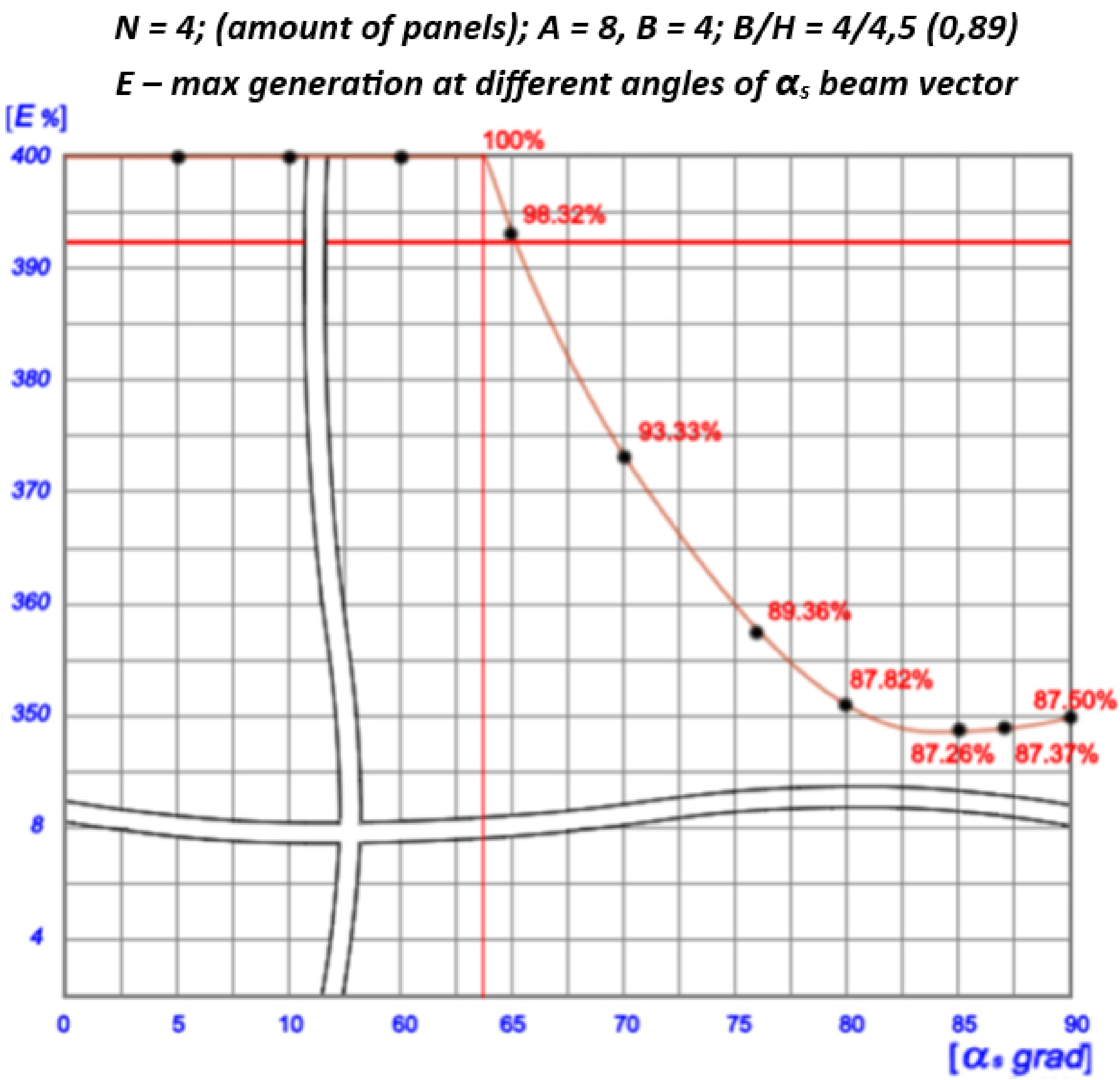


Figure 3.8 – Dynamics of changes in the efficiency of power generation in the zone of "post-critical" declination angles in the optimal mode for 4 panels

In the next subquestions we will present some of the provisions and results of this bachelor work.

3.4.2. Optimizing the positioning of solar panels for three coordinate systems

Considering the problems of using three-coordinate systems for power plants of space stations (SS), we came to the following conclusion. Despite the fundamental similarity of conditions, it is necessary to take into account a number of circumstances (at least obvious to us), dictated by the "cosmic" specifics. Let's consider them.

To carry out a comparative analysis of the effectiveness of 2 and 3 coordinate systems, it is necessary to integrate statistics - the results of solving the optimization problem for the annual cycle. But, for this, it is necessary, as initial data, to have the parameters of the "space" ecliptic for the annual cycle, and for specific parameters of the station's orbit. As far as we know, such mathematical models exist (the so-called "equations of time"), but we do not have them.

We only note that to carry out similar calculations for ground-based installations, either Cooper diagrams [43] or more accurate "equations of time" taking into account sidereal days [56] were used.

Based on the developed optimization program, it is possible to obtain comparative data only for any arbitrary pair of angles (α_{sun}; β_{sun}), which uniquely determine the orientation of the solar radiation vector relative to the coordinate system associated with the station. In addition, in the "ground" program, the deviation angles along the third coordinate are limited.

In real conditions, a priori knowledge of the ecliptic parameters may not be required to control the movement of platforms along three coordinates. The use of MDL sensors in the control system is sufficient for this. Another fundamental circumstance concerns, in fact, the kinematic diagram of the movable platform and its constructive implementation.

If we compare the kinematic diagrams of mobile platforms shown in figure 3.9 (pictograms in the upper part of the figure), we can see that the "space" platform does not correspond to the so-called principle of "non-commutativity" of displacements.

Otherwise, in order to ensure the plane-parallel movement of the panels, rotation along the third coordinate should occur in a plane perpendicular to the longitudinal plane of the panel (a vertical plane passing through the longitudinal axis of the panel, which has taken the optimal angle position). And the shown kinematic diagram provides rotation only in the plane perpendicular to the mast axis. Such displacements allow the plane of the panel to be normalized to the radiation vector, but at the same time the contours of the planes of the panels will not be parallel to each other. And this, in turn, will lead to a complication of the procedures for calculating projections (for determining the areas of shadows), and, as a consequence, an increase in the time for obtaining a solution. Moreover, it cannot be unambiguously asserted that it is possible to completely eliminate shadows with non-plane-parallel movements of the panels.

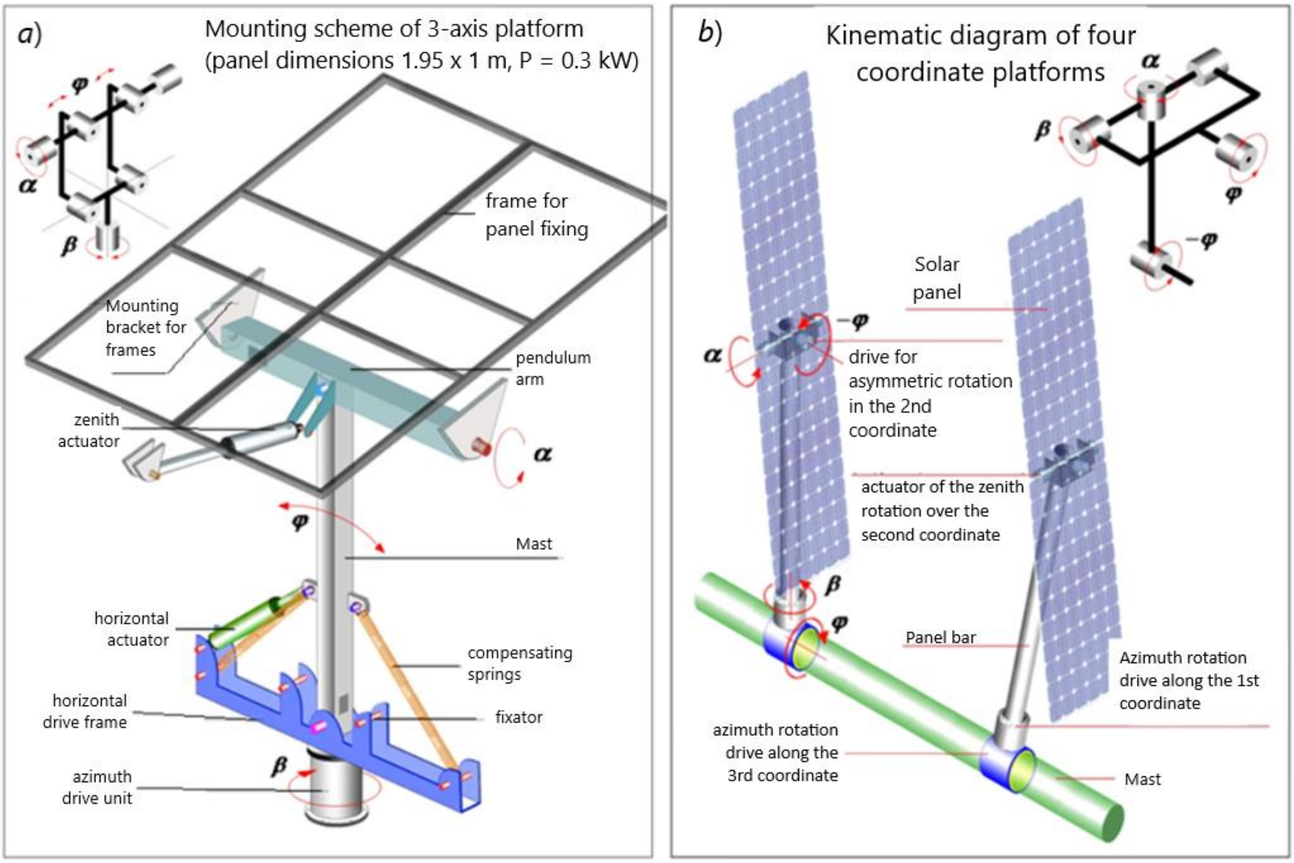


Figure 3.9 – Three-coordinate kinematic diagram of the platforms:

a) for ground installations, b) for a space station

Only the kinematic diagram in figure 3.9*a* corresponds to the conditions of normalization in angle and, at the same time, parallelism of the contours of the planes of the panels when moving along the third coordinate.

Note that the deflection of the bar by an angle φ when the plane of the panel is oriented occurs under the influence of the force of gravity, and to implement the control process, it is sufficient to lower the center of gravity of the upper part of the platform below the metacentre and balance it. Since, in space, gravity is practically absent, there is a need for an appropriate structural modification of the rotary mechanisms. These features lead to the following important consequences:

Consequence 1. It is necessary to assess the costs of implementing certain design solutions of rotary drives and actuators and compare these costs with the benefits achieved.

Consequence 2. Control along the third coordinate is possible only in real time for each pair of angles of the solar radiation vector. Therefore, strict restrictions are imposed on the time of solving the optimizing problem (determination of the angles φ_k and their signs). For ground installations, including from 7 to 13 platforms, in which corrective controls are performed, for example, after 2 degrees (or 480 seconds) in azimuth angle, this time does not exceed 10-20 seconds.

It should be noted that the single-row layout of the platforms (figure 3.10) on the mast of the space station can be considered as a special case of the multi-row layout of the panels of a ground-based solar power plant (figure 3.11). Therefore, the developed "shadow" optimization method for ground stations can be used without any fundamental changes, taking into account the requirements arising from Consequences 1 and 2.

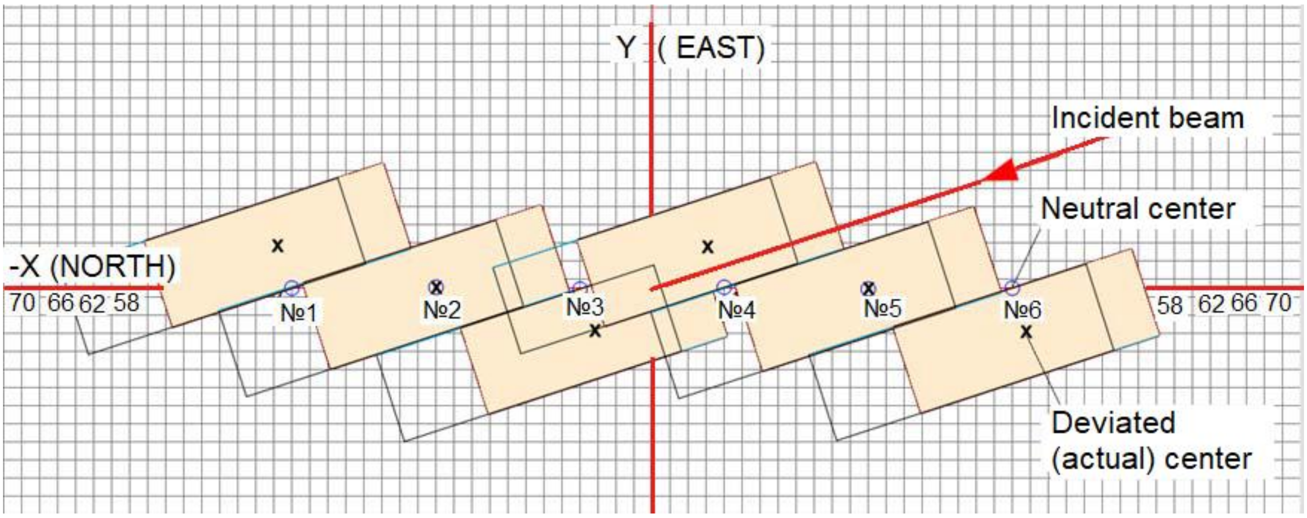


Figure 3.10 – Optimal orientation "by angle" and "by shadow" for a given vector of solar radiation for installation on a space station with a 3-coordinate control system

The need for controls on the third coordinate arises only in a certain range of azimuthal and zenith angles (α_{sun}; β_{sun}). The variation ranges of these angles (critical angles) fully depend on the geometric parameters of the installation (distances between the platform rods, overall dimensions of the panels, etc.), as well as on the parameters of the orbital ecliptic.

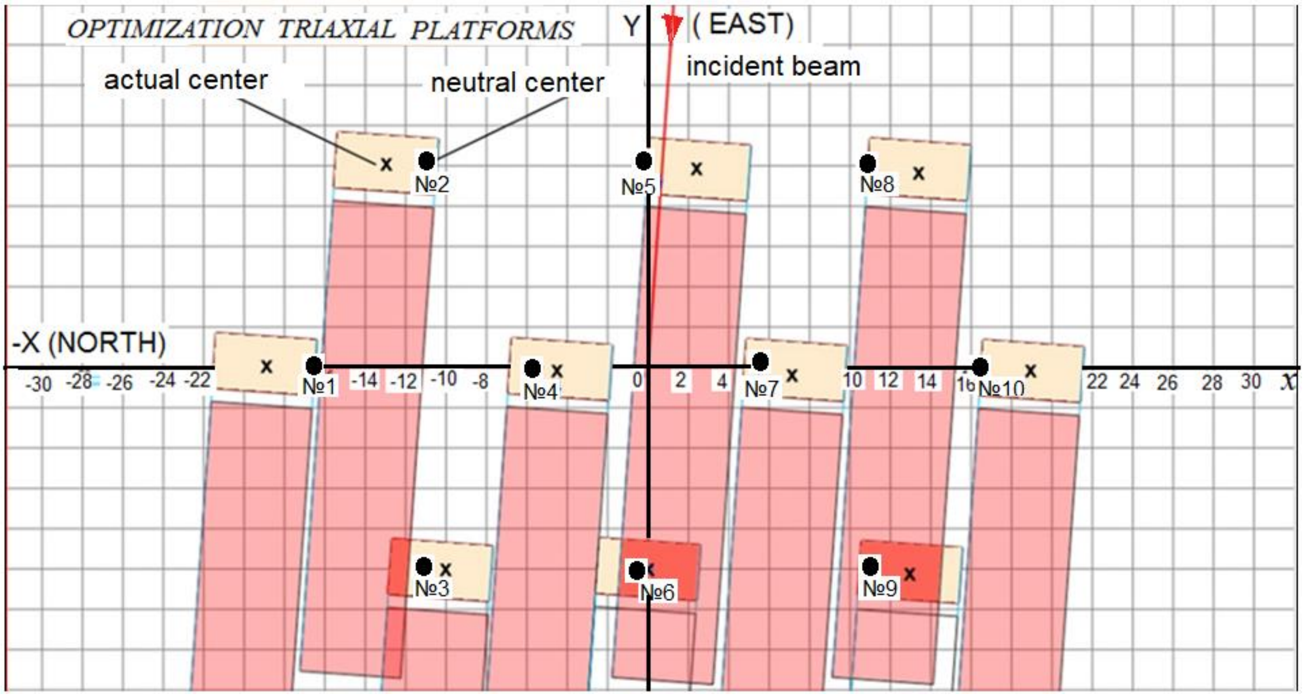


Figure 3.11 – Optimal orientation "by angle" and "by shadow" for a given vector of solar radiation for a ground installation with a 3-coordinate control system

Since, as indicated above, it is impossible to carry out a full cycle of calculations without knowing the parameters of the orbital ecliptic, we present here only comparative results of calculations for one of the critical angles ($\alpha_{kr} = 68; \beta_{kr} = 72$).

In figure 3.10 there is a "screenshot" from software applications, which shows 6 panels of 10x30 m, placed on a mast with a distance of 16 meters (single-row platform system). It is found that the efficiency at a given critical angle of the radiation vector is, respectively, 55.126% for a 2-coordinate system and 94.541% for a 3-coordinate control system. Since in both cases there is an angle optimization (the planes of the panels are normal to the radiation vector), this difference is entirely due to non-shadow optimality.

Note that the software application for calculating the efficiency of energy production was developed for the case of studying ground-based solar installations, for which the limiting angle of horizontal deviation φ_{lim} is limited. This is due to the fact that, under gravitational conditions, significant deviations of this angle will lead to an increase in energy consumption for control. In space conditions, this angle can be increased and, thus, it is possible to completely eliminate shadows in critical areas.

Since we do not know the parameters of the orbital ecliptic, it is not possible to perform comparative calculations of the “shadow” efficiency, even assuming some conditional initial data. Nevertheless, it is possible to put forward a very realistic hypothesis that the energy efficiency of the installation will increase when using 3-coordinate control systems.

The practical significance of the problem of eliminating shadows on the elements of generating systems in space should also be taken into account. Shadow formation results in significant temperature gradients between the lighted and shaded areas of the panels. The resulting thermal deformations will lead to more intensive aging of active and structural elements of the power plant, up to failures associated with their mechanical destruction. This leads to a deterioration in the parameters of the reliability and durability of the power supply system and the need for expensive repairs.

Conclusion to the section

The formulation of the problem of solar photovoltaic panels are discussed in this section, the maximum possible energy can be generated by solar photovoltaic panels only at a normal angle of incidence of sunlight on the plane of the panel. With a slight error, we can assume that this dependence obeys the cosine law in the range from 0 to 90 degrees.

To solve such problem, the use of heuristic methods and algorithms is used, based on the use of numerical methods. The issue of increasing the efficiency of generation of renewable energy installation that are connected to electric power systems is an important aspect, the task does not differ from “space task” of using such installations, since in the case of a ground installation there are restrictions on the area of their installation. increasing the efficiency of generation of ground-based solar energy installations is a very urgent and economically important task.

The result of ground base photovoltaic plants based on mobile plat forms, have been very encouraging, both from a management and economic point of view. Some comparative parameters of electric solar power plants using the principle of two and three coordinate control systems are shown in table 3.2.

Optimization of the positioning of solar panels on the international space station was discussed at the last part of the section. The possibility of using three coordinate systems on the International Space Station was considered after the creation of the experimental setup and the development of software applications (for design and proper optimal control). These studies are theoretical in nature, but there is hope that there may be a "grain of reason" in them.

SECTION 4
LABOUR OCCUPATIONAL SAFETY AND SECURITY IN EMERGENCY SITUATIONS

Solar tracking system shall be designed and installed by putting very accurate attention to the local rules, the relevant standards and the best practice available from worldwide experience in the PV field. Hazards and risks to user's safety and health should be identified and assessed on a frequent basis. Preventive and protective measures should be implemented.

The installation of solar tracking system has different safety implications. It does not affect only the structural load but also wind loads that can be particularly significant in case of storms.

Installing solar tracking systems might introduce overloads that can affect their structural integrity. Not only does the support the dead load of the panel itself, but also external forces introduce structural loading. Outside installations exposes the PV system and also the whole assembly, to specific weather conditions such as wind, hail, debris, and the effects of air temperature [12]. Tracking systems must withstand escalated weather scenarios such as windstorms. Uplifts from strong winds can create appreciable additional loads or load concentrations. These factors may determine stress conditions on the solar tracking system support and through wind up-lift, thermal expansion, and debris build-up. In some cases, excessive stress conditions can lead to damages or injury to users.

4.1. Analysis of hazardous and harmful production factors of the designed solar power plant

The solar power plant project includes:

- inverter equipment;

- photovoltaic modules;
- complete transformer substations with power transformer;
- distribution point;
- production and housing buildings;

Only local emergencies may occur in the SPP (emergencies, not beyond the territory of the site). Emergencies are possible as fires in buildings, communications and technological equipment. The main source of danger is the electrical elements of SPP, namely the possibility of electric shock during their operation. The place of work of the service personnel of the power plant (security, operators) can be chosen production building, which contains video surveillance computers, system for monitoring its efficiency. According to Ukrainian ГОСТ 12.0.003-74 during the work of personnel in the production building and near the complete transformer substations and distribution point may be present the following dangerous factors:

- Monotony of work;
- Increased electromagnetic field strength;
- Increased brightness of sunlight.

The average annual air temperature is 8.8 °C. The coldest month of January has an average monthly temperature of -4.3 °C. The absolute minimum temperature is - 42 °C. The hottest month of July has an average monthly temperature of +21.5 °C. The absolutemaximum temperature is + 41 ° C.

4.2. Engineering and technical measures for labor protection

For creation and observance of safe and not harmful working conditions at operation and repair of networks and equipment it is necessary to be guided by requirements of national rregulations on labor protection – НПАОП 40.1-1.21-98, НПАОП 40.1-1.07-01 and ГОСТ 12.3.032-84, and at performance of separate types of works which are not specific for electrical personnel – the requirements of intersectoral regulations on labor protection. Only specially trained staff of electrical personnel, provided with all necessary means and equipment for repair work, is allowed to operate the equipment. To ensure labor protection and safety is provided:

- use of technically advanced equipment;

- placement of open current-carrying parts of equipment, tires and wires with the provision of standardized distances by the Rules of Arrangement of Electrical Installations (ПУЕ);

- placement of equipment that ensures its free maintenance;

- arrangement of earthing devices of elements of electrical installations with the normalized value of resistance and a design that meets the requirements of ПУЕ;

- protective and working grounding of the equipment of complete transformer substations and distribution point, inverters according to ПУЕ;

- automatic shutdown of the equipment in case of abnormal and emergency situations;

- placement of 0,8 kV switchgear in metal cabinets (cells), which are locked and have safety signs;

- laying cables to the normalized depth in the ground;

- protection of cable lines from mechanical damage (PVC pipe);

- precautionary measures – laying a signal tape over the cable, installation of appropriate signs along the route of the cable;

- use for construction and installation works and mechanisms, in the construction of which the principles of labor protection are laid down;

- high level of mechanization of construction and installation works;

- execution of construction and installation works according to standard technological maps.

To ensure labor protection and safety, it is necessary that construction, installation and commissioning work and operation of electrical installations are performed in compliance with current regulations.

To ensure the safety of production personnel during the operation of solar modules, the working project provides for the following measures for labor protection and safety:

- fence of the object 2,0 m high;

- lighting of the object at night is provided.

When working in the existing electrical installation, the personnel of electrical organizations are prohibited to perform work without de-energizing near live parts and on live parts under voltage. The equipment provided must be operated in accordance with the rated values of rated current and voltage.

During operation it is necessary to constantly monitor the condition of contact connections, insulation of fittings, normal noise of operating equipment, absence of traces of arc and melting of tires, insulation resistance of electrical panels, power networks, correct connection of neutral grounding conductors.

Ensuring safety in power electrical equipment and electric lighting is made by choosing the appropriate design of electrical equipment, devices and networks.

Maintenance and repair of electrical equipment and electrical networks is provided by the staff of repair services.

Electrical work must be carried out in accordance with applicable building codes, in particular СНІП 3.05.06-85, ПВЕ, in compliance with labor protection and safety measures.

In addition to the measures provided in the project, instructions for safety must be developed, taking into account specific features of the work in accordance with the requirements of the norms.

The working project provides a set of measures to ensure the protection of workers from occupational injuries in accordance with applicable regulations.

Basic documents to be used by staff:

- executive working documentation;
- safety instructions, industrial sanitary and fire safety;
- technical operating documentation for the equipment;
- job descriptions. During operation it is inadmissible:
    - overloading of equipment above the passport and designed values;
    - violation by service personnel of the rules of technical operation of equipment, rules of engineering and fire safety.

During operation, the administration must ensure periodic monitoring of the technical condition of the equipment and the detection of harmful factors, the manifestation of which is possible in this case. To exclude occupational diseases, it is necessary to conduct preliminary and periodic medical examinations of staff in accordance with current regulations.

Workers must be provided with special clothing and personal protective equipment in accordance with current regulations. To ensure the safety of personnel during the work:

- instruction must be provided before the start of work;
- safety signs must be installed in accordance with the requirements of ПТЕЕС;
- voltage must be removed at the place of work the and the electrical equipment must be grounded;
- when performing work at height, it is necessary to take measures to protect against the possibility of people or objects falling (order №62 of 27.03.2007 on the approval of the Rules of labor protection during work at height).

During the fire extinguishing of the transformer, oil is drained into the emergency oil collector, which is arranged individually under the transformer. In the event of a transformer fire, oil and water are fully accepted by the oil sump, which allows you to quickly locate and eliminate the emergency situation. In the oil sump, after extinguishing the transformer, the water contaminated with oil must settle to separate the media. Then the top layer of oil is pumped out and taken for regeneration to a specialized enterprise. The delicate layer of water, contaminated with petroleum products, is taken for treatment to specialized treatment facilities.

It can be concluded that due to the design decisions, in compliance with the rules of construction and operation, the designed object will not cause a negative impact on the soil cover.

4.3. Fire prevention

The designed electrical installations are located on the territory of the station (SPP) and belong to group III in accordance with ДСТУ Б В.1.1-36:2016 (with power transformers with a primary voltage of 35 kV) does not provide for fire water supply and fire tanks, and therefore automatic fire extinguishing.

SPP technical buildings have IIIa degree of fire resistance. Indoors, the exit is provided directly to the outside. The door opens to the outside, during the evacuation.

The project provides means to prevent fires and explosions, namely:

- automatic shutdown by action of relay protection of separate elements of electric networks at occurrence of short circuits;
- placement of equipment in complete transformer substations at the distances normalized by ПУЕ, between current-carrying parts and the oil-filled equipment;
- laying of cables in the soil;
- application of non-combustible structures for construction of cable;
- execution of connections and branches of wires and cores of cables by means of crimping, welding, special clamps for decrease in transient resistances, safe in the fire relation;
- grounding of the equipment according to ПУЕ;
- primary means of fire extinguishing at transformer substations in accordance with the rules of fire safety in companies, enterprises and in organizations of the electrical industry of Ukraine;
- explanatory signs according to ДСТУ ISO 6309:2007, indicating the location of fire extinguishers;
- providing access of fire engines to the object.

Fire safety is ensured by the use of non-combustible structures, grounding of equipment, automatic disconnection of short-circuit currents, compliance with regulatory dimensions and requirements of insulating materials, performance of branches to the inputs in the insulated wires of complete transformer substations.

Special fire shields (stands) must be installed to place primary fire extinguishing equipment in production, storage, auxiliary premises, buildings, structures, as well as on the territory of enterprises. The project envisages 1 fire shield (stand) on the territory of the object. The set of fire extinguishers, which are placed on the fire shield, includes: powder fire extinguishers - 3 pcs., sandbox - 1 pc., fire cover - 1 pc., excavator or crowbar and hook - 2 pcs., shovels - 2 pcs., axes - 2 pcs.

On fire boards (stands) those primary means of fire extinguishing which can be applied in the given premise, construction, installation have to be placed. Fire shields (stands) and fire extinguishers must be painted in the appropriate colors in accordance with ДСТУ ISO 6309:2007.

The main fire receiver-control device "Tiras-PRIME 8" is installed in the Premises of the building №1 on the wall made of non-combustible materials.

4.4. Safety measures during installation of PV panels

Install solar positioning systems that use friction clips to secure PV modules to the beams of the framing system. Supports are attached to the building by screws, clips, or adhesives. One must consider each of these loads separately and in combination to identify the worst-case scenario loading situation.

Make sure that the installation of solar tracking system is carried out to the exact specifications and meets all existing standards and regulations. The inspection shall verify that the design and installation of the plant has been carried out according to relevant specifications and international standards.

Avoid looking directly at the sun during installation as permanent eye damage might result. Instead, encourage the use a maximum current reading to indicate when a solar panel faces the sun directly.

As a general measure, check the presence of anti-glare on panels especially when the location could affect visual interaction. Reflections from a PV system on a roof may hit the taller buildings near the installation. Check the PV system layout to prevent disturbance to inhabitants around.

GENERAL CONCLUSION

Introduced into the positioning system of a two-coordinate low-power information-measuring scanning system. It registers the brightness of the heavenly space and determines the angular coordinates of solar panels, at which solar panels generate maximum power from the scattered radiation flux, which makes it possible to increase the energy efficiency of the solar station.

To optimize the system of Sun tracking, it is necessary to consider the step-by-step mode of auto-tracking of the Sun. Advantages of search engine control systems – high accuracy of support of an extreme at the minimum quantity of sensors irrespective of type of the engine. Thanks to the control capabilities that monitor the electric drive, it allows to increase the efficiency of the solar photovoltaic power plants with rational energy consumption.

The analysis of terrestrial autonomous solar photovoltaic power plants, tracking systems, solar position sensors, allowed to form the technical requirements for the tracking system by two-coordinate electromechanical actuator, solar position sensors, specialized tracking controller.

The structure of the tracking system should provide continuous-discrete tracking with an adjustable cycle and have a nonlinear algorithm for tracking the solar panels on the Sun. Also it should providing a given accuracy of observation up to 1° and increase the energy efficiency of the system by increasing electricity generation consumption of electric energy in electromechanical actuators with collector drives during the monitoring of the Sun by the Sun up to 30%.

VAC of PV modules were provided of mono- and polycrystalline silicon in terms of varying degrees of partial shading using the measuring device based on Atmel 328 microprocessor. The horizontal (landscape) and vertical (portrait) arrangements of the modules were investigated, which, with the lower partial shading of the modules, lead to a difference in VAC and power curves.

It is shown that the output of PV power plant with partial shading can be reliably computed, if take into account the introduced power factor *f*(*s*) of PV modules, which depends on the degree of shading *s*, which in its own turn can be determine by experimentally obtained based VAC. A method for calculating the PV power plant generation for a certain calendar period on the basis of the calculated function *f* (*s*) and meteorological data on the average monthly amounts of radiation has been developed.

The analysis of the constructed models of generation and power loss with partial shading is conveniently divide into two parts according to two types of tasks: ensuring the maximum output per unit area of PV modules and per unit area of the land plot. In this work, maps of the distribution of the average daily generation $E(\beta, \lambda)$ are constructed for the two types of optimization problems indicated. The maximum output from the unit area of PV module is provided according to the calculations using function *f*(*s*) for Kyiv and region under $\lambda \leq 0{,}35$, $\beta \approx 30°$. This applies to both landscape and portrait orientation of PV modules. The calculation of the output in the problems of the second type showed that the maximum output per thew unit area of the land plot is achieved at the most complete filling of the site, when $\lambda \geq 0{,}95$ and the angle of inclination is less than 1º for both orientation of the PV modules.

The numerical results and graphs obtained on the basis of optimization calculations make it possible to judge the trends of changes in the efficiency of large photovoltaic power plants depending on the design parameters of the rows of solar panels and the orientation of modules. The method developed in this work for processing the measurements of the VAC of PV modules with different shading and analytical calculation of the average daily output allows us to find the intervals of optimal values of the tilt angles and inter-row spacings of solar panels for specific regions of the location of the PV power plant.

Mathematical models have been developed to obtain the parameters of the "ground" ecliptic for any given moment in time, and a relatively accurate mathematical model has been developed that takes into account sidereal days (the so-called "equation of time"). It was found that in practical calculations, without significant errors, Cooper diagrams can be used.

Mathematical models, algorithms and numerical methods have been developed for solving the optimization problem of controlling the orientation of mobile platforms with PV modules along the third coordinate, moreover, in a strictly regulated real-time mode.

Special software shows that for the parametric analysis of the efficiency of generating plants, both ground-based, which is important for large-scale power engineering, and space-based. The use of this approach makes it possible to reduce the area of the installation site for a ground-based solar power plant of the same capacity by almost three times, for example, from 2052 m^2 to 660 m^2. The coefficient of compactness of PV modules placement increases in this case from 0.195 to 0.606.

Constructive changes in the kinematic scheme of standard two-coordinate platforms are proposed, which made it possible to implement a method of three-coordinate control of mobile platforms, both ground-based and space-based, which determines the novelty of the results obtained.

In the presence of a mathematical model of the "space" ecliptic, it is possible to adapt the developed software applications for use as one of the design tools for solar power plants of space stations.

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