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High-Efficiency Solar Tracker Development and Effectiveness Estimation

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***Abstract* — The photovoltaic (PV) systems are of great interest nowadays due to the depletion of fossil sources and environmental problems (greenhouse gas emissions, air pollutions and effects of accidents at nuclear power plants). The maximum power point tracking (MPPT) systems and solar trackers allow significantly efficiency increase of PV systems. This article presents the efficiency calculations for 2-axial active solar tracker taking into account losses on panel orientation for the three most specific months – December, June and September. An algorithm for tracker control is proposed and tested on the developed experimental prototype. It was established, that the optimal PV panel orientation change time interval (based on the ratio of efficiency increasing and orientation losses) is 15 minutes.**

Keywords— PV system; 2-axis solar tracker; efficiency; PV panel orientation; motor control.

I. INTRODUCTION

The renewable energy sources become increasingly important nowadays. This is due to the rises in price and shortage of fossil sources, and environmental concerns of nuclear power. By experts' assessments, the real cost of electricity generated by nuclear power plants (taking into account additional costs for disposal of spent fuel and accident consequences mitigation) may be more expensive than wind and solar energy. Photovoltaic (PV) has become the fastest growing branch of renewable energy in recent years. At the beginning of 2013 the total installed capacity of all PV plants have reached 100 GW [1], and continued to grow in 2013. The low efficiency and output dependence on the day time are some of the largest problems which prevent further spreading of PV.

Increasing the total efficiency of PV systems can be provided by the development of new materials which are able to improve the solar irradiance conversion, as well as by the use of the maximum power point tracking (MPPT) on the *V-I* curve of PV panels [2], [3], [4], [5]. PV panel orientation systems (solar trackers), which alter its position so Sun rays are always perpendicular to the photosensitive surface, allow partially compensate the irregularity of electricity production during the day (especially in the morning and in the evening). The efficiency of solar trackers depends on many conditions, including tracker type, PV system location coordinates, irradiance, etc. As shown in the literature, the average annual efficiency improvements of PV systems can reach 40% [6], but exact value can vary widely, and requires more detailed study.

This paper in the III section proposes an active 2-axis solar tracker with the control system verified on the developed experimental prototype. The efficiency calculations of the proposed tracker were carried out in the IV section for three specific days of the year that allows to determine the PV system efficiency increasing range taking into account PV panel orientation losses. The optimal panel orientation time interval obtained by simulations, taking into account an extra generated power and control consumptions.

II. SOLAR TRACKER SYSTEMATIZATION

There are many kinds of orientation systems which can be classified by the hanger type, by the tracking principle and by the type of Sun position sensors.

A. *Trackers classification by the hanger type*

The main types of solar trackers, classified by hanger type are shown in Fig. 1 [7].

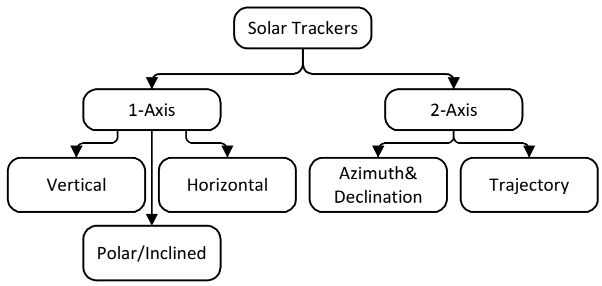

Fig. 1. Solar tracker systematization.

Single-axial trackers can be with azimuth tracking (vertical) [8], with declination angle tracking (horizontal) [9] and with a fixed declination angle, which chosen for the location latitude (polar or tilted trackers) [8], [10]. The vertical trackers are recommended to use at high latitudes where the Sun even in summer days doesn't rise high above the horizon, while the length of the day is very long (days can last even 24 hours – "polar day"). On the other hand, the horizontal trackers have the highest efficiency in the regions located near the equator and the simplest structure. Efficiency increase in such trackers in comparison with fixed panel can reach 20% [11]. The polar trackers have the highest efficiency among all single-axial trackers. Their rotation axis is tilted at an angle to the line north-south.

The 2-axis trackers can be either with independent azimuth and declination tracking and with tracking in a coordinate system directed perpendicular to the Sun movement plane (polar floating axis trackers or Sun path trackers). The first type of trackers has the highest efficiency among all types of trackers, but on the other hand they are also the most complex in design and control. Meanwhile, trajectory trackers have smaller moving losses. The total drawback of all 2-axis trackers is the difficulty of performing orientation of multiple panels.

B. Trackers classification by the tracking principle

There are many approaches in PV panel orientation toward the Sun position. They can be divided into three types.

- *Open-loop trackers* determine the position of the Sun for a specific location and time by using special mathematical formulas [12]. Such systems are insensitive to the side illumination and problems with determination the exact position of the Sun when it's cloudy. However, these trackers must be periodically calibrated. In addition, it is necessary to use actuators with position feedback.
- *Closed-loop trackers* provide orientation of the panel due to a feedback signal from the sensor. The advantage of this system is the ability to use any actuators, insensitivity to setting errors and even using in mobile units (no need for the precise setup by the cardinal directions after transportation).
- *Hybrid trackers* have a sensor of the Sun position, which can adjust orientation based on calculated setup. During sunny weather system can be configured by the signals from the sensors, while in cloudy sky the coordinates that are calculated by program can be used. Hybrid systems can provide the highest precision in orientation. They are widely used in concentrator PV.

C. Trackers classification by the type of Sun position sensors

If the highest precision in orientation is required (i.e. concentrator solar cells) a camera with PC images processing can be used as a sensor [7]. Such systems are reasonable to use only in powerful solar installations. The most common sensor in active solar tracker is an optic-electrical converter (photocell) – e.g. semiconductor photoresistor. Its resistance varies with the irradiance changes – the more light, the better conductivity of the photoresistor, and therefore, less resistance.

Typically, the photocells are used in pairs in solar PV trackers, utilizing the difference signals from a pair of photocells as a signal to the control system. They are placed in parallel to the surface of the PV panels with high accuracy. The typical sensor design is shown in Fig. 2 [13]. In the simplest, so called "shaded" sensors (Fig. 2a) an obstacle to the Sun's rays perpendicular to the surface of the photosensors is used to determine the position. "Shaded" sensors have low sensitivity and they are sensitive to parasitic side illumination (e.g. caused by rays, reflected from clouds, buildings, etc). Increasing sensitivity is possible in pyramidal sensors, placing photocells at a certain angle to the surface of the panel, as shown in Fig. 2b. The tunnel sensors are insensitive to parasitic illuminations (Fig. 2c) which photocells are placed at the bottom of the tube with a hole on the opposite side (aperture). The value of the aperture determines the sensitivity and accuracy. At the same time, the tunnel sensor has a limited operation angle where the Sun can be found.

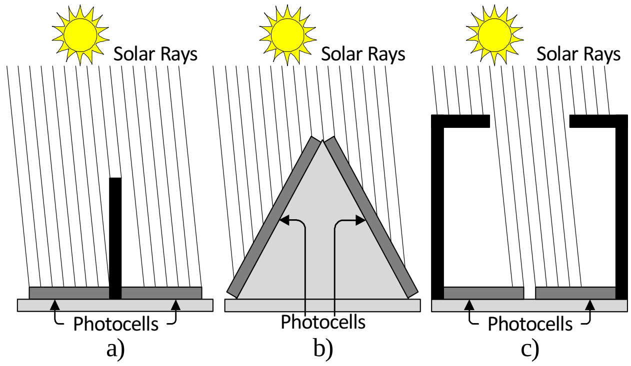

Fig. 2. Sun sensors: shaded (a), pyramidal (b), tunnel (c).

To maintain the low cost and complexity of the system a modified pyramidal sensor was proposed (Fig. 3), which provides high sensitivity and protected from the parasitic illuminations. A compromise between the range of operating angles and protection can be achieved by adjusting the angle and height of the protective cone.

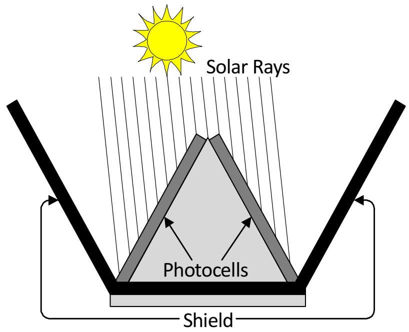

Fig. 3. A modified pyramidal sensor.

III. EXPERIMENTAL PROTOTYPE OF 2-AXIS SOLAR TRACKER

A scheme of 2-axial solar tracker is shown in Fig. 4. The prototype includes a rack with polar hanger, two linear motors MP-100M-2, a solar panel S-180C, a pyramidal Sun sensor and a control system. Tracker is fed by a rechargeable battery that is charged through a voltage converter with MPPT system followed by the battery charge and load protection controller.

A simplified scheme of the solar tracker control unit is shown in Fig. 5. A modified pyramidal sensor has been used as element of the control system providing information about panel orientation relative to the Sun rays. The control system is based on the microcontroller STM32F100C4T6B (ARM Cortex-M3 family) using a real time operating system FreeRTOS. The RTOS allows creating a flexible control system with the simplicity of functional enhancement.

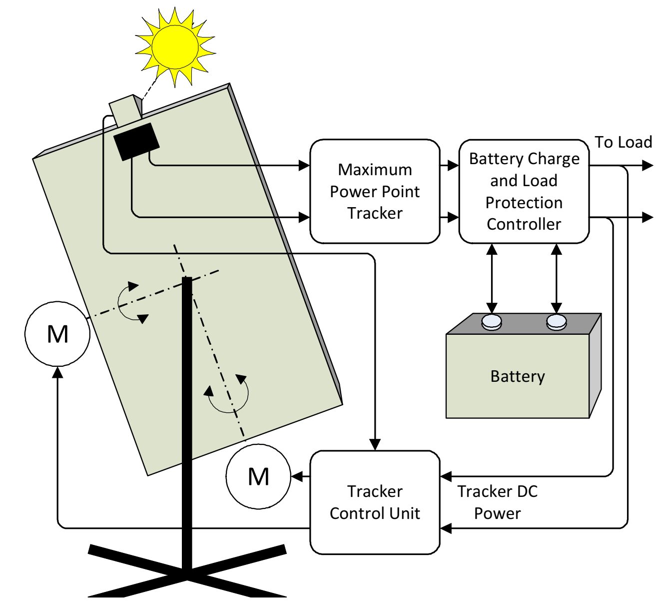

Fig. 4. 2-axis solar tracker schematic diagram.

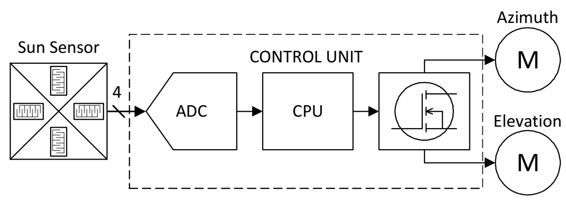

Fig. 5. Solar tracker control unit functional diagram.

A. Solar Tracker Control Algorithm

All the major actions of the panel orientation are provided by the program, which simplified scheme is shown in Fig. 6.

The control program reads the Sun position sensor data from the memory. In the next step the obtained values are adjusted using calibration data and compared with the tolerance. Thus, the difference in resistances of sensors is taken into account. If deviation from the optimal position at least in one plane exceeds permissible value, the process of panel turning begins in the direction of the greatest deviation. The process is repeated until the panel is set in the optimal position and deviation signals from two pairs of sensors will be less than permissible value. Thus, orientation process is completed and control system proceeds to low power mode until the next orientation change. The low power mode time is determined by the chosen orientation time discrete.

B. Experimental Implementation

The developed 2-axial tracker is shown in Fig. 7. To determine the control losses and evaluate the effectiveness of the tracker, time dependences of the actuator drive current during panel rotation were obtained for different motor supply voltages. Using (1) the dependence of energy consumed for rotation per day (maximum rotation is 280 degrees for June) from the angle of the elementary rotation (Fig. 8) was obtained.

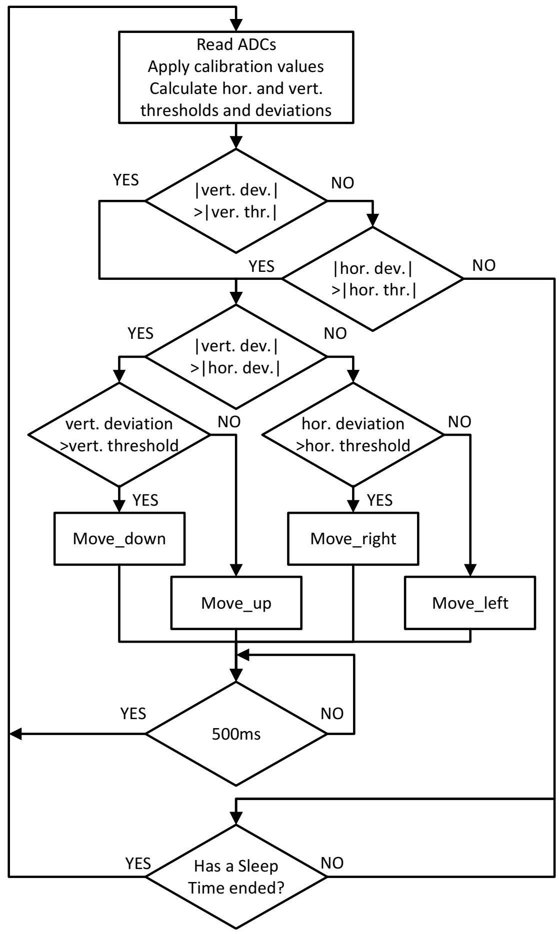

Fig. 6. A simplified control process flow chart.

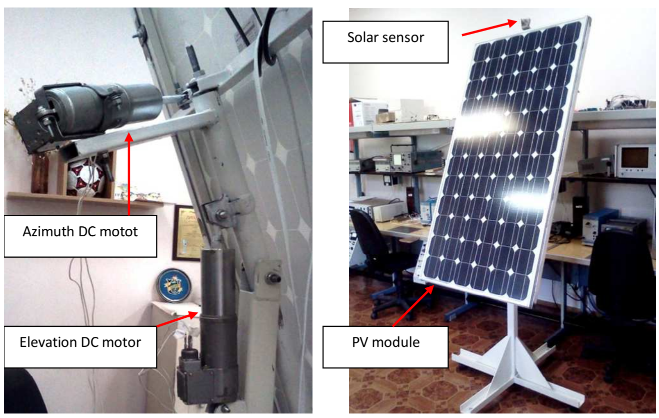

Fig. 7. An experimental 2-axis solar tracker.

$$E_{FT} = t_{FT} \cdot V_D \cdot \frac{1}{T_\alpha}\int_0^\alpha I_D(t)dt \qquad (1)$$

where E_{FT} – the full panel turn energy, J; t_{FT} – the time of full panel turn at a given supply voltage of the motor V_D, s; $I_D(t)$ – the supply current of the motor during panel rotation, A; T_α – the time of the elementary rotation for angle α, s.

According to calculations the optimal supply voltage for the motor is 18V. In this case the energy required to rotate the panel by 1 degree will be minimal.

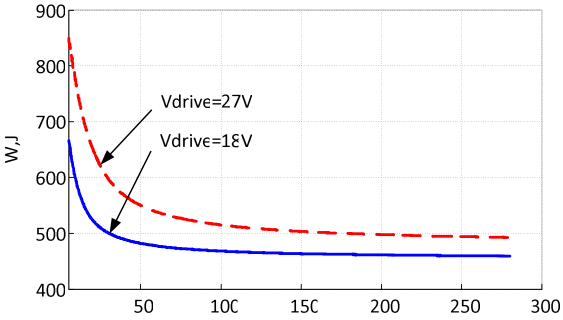

Fig. 8. The energy consumpted for full turn vs. the elementary rotation angle.

Fig. 8 shows that in the worst case (under motor supply voltage 27V and elementary rotation about 5 deg) the energy consumed per day is 814 J (~ 0.23 W·h). Thus, the daily energy consumption for panel orientation is much less than energy produced by panel within 1 hour under the nominal irradiance (180 W·h). So, the panel rotation losses were omitted in subsequent calculations.

IV. Efficiency Calculation

The Sunlight irradiance close to the earth surface can be calculated using:

$$I_G=1.1\cdot 1.353\cdot 0.7\char`^AM^{0.678} \qquad (2)$$

where I_G - irradiation near the earth's surface on a plane perpendicular to the radiation, kWh/m^2; AM - correction factor, which shows the degree of the radiation power absorption when passing through the atmosphere. It can be calculated by the (3), where θ - angle between the normal to the surface and the direction to the Sun, deg.

$$AM=1/(\cos\theta+0.50572\cdot(96.07995\text{-}\theta)^{-1.6364}) \qquad (3)$$

For the geographical coordinates of Chernihiv (Ukraine), using the Sun position data [14] and the formula of solar irradiance (2), which takes into account the absorption of the atmosphere and diffused solar radiation [15], [16], [17], graphs of solar irradiance near the earth's surface during the day for a surface perpendicular to the radiation were built (Fig. 9).

The calculations were performed for three specific days of the year 2013: June 21 (summer solstice), September 22 (equinox solstice) and December 21 (the winter solstice), without taking into account the weather conditions (e.g. cloudiness). Generally, the energy produced by PV modules is directly proportional to its irradiance. The dependence of the instantaneous power for ideal trajectory tracking of the Sun will be similar to the one shown in Fig. 9.

Calculation of the panel irradiance when the panel surface is not perpendicular to the Sun rays can be done using [18]:

$$I = I_G \cdot (\cos(\alpha)\cdot \sin(b)\cdot \cos(\psi-\theta)+\sin(\alpha)\cdot \cos(\beta)) \qquad (4)$$

where I – solar irradiance on the panel surface, kWh/m^2; α – Sun elevation angle, deg; β – the panel tilt angle (0˚ for horizontal, 90˚ for vertical, (90-α) for panel tracking) in deg; ψ – the azimuth angle of panel (the clockwise angle between the north direction and the panel facing direction, for panel with tracking $\psi=\theta$, for the panel at an angle of 45˚ to horizon ψ=180˚), deg; θ – the azimuth of the Sun in deg.

Using (4) the dependence of the solar panel irradiance on the time of day three cases was analyzed: horizontal panel; panel at an angle of 45˚ to the horizontal (the optimum angle for mid-latitudes [19]); panel with 2-axis tracker. The daily energy production of panels for the following three cases has been calculated based on these dependencies and using (5). The calculation results are summarized in Table I.

$$E = \frac{P_{nom}}{I_{nom}} \cdot \frac{1}{T_{day}} \int_0^{T_{day}} I(t)dt \qquad (5)$$

where P_{nom} – rated panel power, W; I_{nom} – nominal panel irradiance, kWh/m^2; $I(t)$ – irradiance on solar panel surface, kWh/m^2; T_{day} – the duration of day, h.

A comparison of Fig. 9 and the data represented in Table I shows that the panel irradiance for panel without tracker significantly reduced when the Sun is not at its zenith. At the same time panel with tracker during the day have irradiance at its maximum level (same as irradiance near the earth surface on Fig. 9), as the panel is always perpendicular to the Sun rays.

In general, the panel at an angle to the horizon all along the year shows a relatively high efficiency, and it does not require high installation costs and additional equipment like actuators and sensors. Therefore, the panels placed at an angle to the horizontal are so widespread and it will be used as a reference for efficiency comparison between different panel types.

The calculation shows that the greatest benefit from using a tracker appears in June. Also there are interesting results in June, which shows the panel at an angle of 45 ˚ to the horizon – it is less effective than the horizontal panel. This can be explained by the fact that in June range of the Sun azimuth variation is greater than 180 degrees (the Sun rises in the northeast and sets in the northwest) [14]. So the Sun at the beginning and at the end of a day is behind the panel, and it does not drop any radiation on it, it is also seen in (Fig. 9 c).

TABLE I. Absolute (relative) daily energy production

Month	**Energy production, W·h (units)**		
	2-axis tracking	***45 degrees***	***Horizontal***
June, 21th	2267 (1.76)	1285 (1.00)	1438 (1.12)
September, 22nd	1514 (1.35)	1119 (1.00)	720 (0.64)
December, 21th	622 (1.27)	488 (1.00)	136 (0.28)

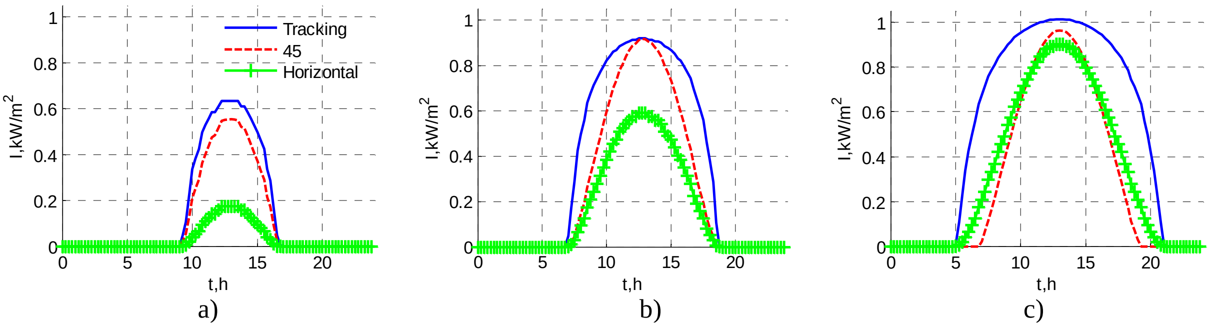

Fig. 9. Solar panel illumination: December (a), September (b), June (c).

At the same time, the horizontal panel is irradiated all the day. In general, throughout the year panel with tracking shows efficiency increase against the tilted panel by more than 27% (Table I).

A. *Estimation of optimal rotation discrete for tracker*

To reduce the engine wear, noise and power consumption of the system some discrete in orientation needs to be introduced. To choose the optimal orientation discrete relations between produced energy and orientation discrete for azimuth and elevation angles were calculated and appropriate surfaces were built (Fig. 11). Results can be found in summary table of the relative efficiency of discrete orientation (Tables II-IV). Calculations were carried out using (5) for the irradiance calculated by (6).

$$I(t) = I_G \cdot (cos(\alpha(t)) \cdot sin(\beta(t-\Delta_E)) \cdot cos(\theta(t) - \theta(t-\Delta_A))) + \\ + I_G \cdot sin(\alpha(t)) \cdot cos(\beta(t-\Delta_E)) \quad (6)$$

where $\alpha(t)$ – Sun elevation angle, d; $\theta(t)$ – azimuth to the Sun, d; $\beta(t\text{-}\Delta_E)$ – the panel tilt angle at the previous step ($\beta(t\text{-}\Delta_E)=90\text{-}\alpha(t\text{-}\Delta_E)$); $\theta(t\text{-}\Delta_A)$ – azimuth of the Sun on the previous step, d; Δ_A – azimuth discrete, h; Δ_E – elevation discrete, h.

From the tables and diagrams can be seen that the azimuth orientation discrete is more critical than the elevation angle discrete. This is due to a much greater range of changes in the azimuth of the Sun compared to the elevation angle changes during the day (i.e. over the same period of time after panel has been set perfectly towards the Sun). The absolute inconsistency of azimuth is greater than that of elevation angle, so it impacts on efficiency.

The most critical to the accuracy of tracking is winter months. This is due to the short duration of the day (about 5h) and low irradiation levels so adjusting the position of the panel through relatively long intervals (2h and more). So, the panel position will be adjusted only a few times per day. This will lead to such situation when during the period of high solar irradiance panel will be misaligned and irradiation level on its surface will be significantly reduced.

In general, as shown in (Tables II), even when tracking discrete is 60-minutes panel performance during the year does not fall below 93% compared to continuous (zero discrete) tracking. On the other hand, tracking with discrete less than 15 minutes does not make any sense, because it does not bring any efficiency gain. So, tracking discrete can be set in the range of 15 to 60 minutes, and should be chosen for reasons of losses to turn the panel, actuators resolution, etc.

TABLE II. RELATIVE EFFICIENCY (JUNE)

Azimuth discrete, min	**Elevation discrete, min**					
	0	***15***	***30***	***45***	***60***	***120***
0	1,00	1,00	1,00	0,99	0,99	0,96
15	1,00	1,00	1,00	0,99	0,99	0,96
30	1,00	0,99	0,99	0,99	0,99	0,96
45	0,99	0,99	0,99	0,98	0,98	0,95
60	0,98	0,98	0,98	0,97	0,97	0,94
120	0,90	0,90	0,90	0,90	0,90	0,87

TABLE III. RELATIVE EFFICIENCY (SEPTEMBER)

Azimuth discrete, min	**Elevation discrete, min**					
	0	***15***	***30***	***45***	***60***	***120***
0	1,00	1,00	1,00	1,00	0,99	0,98
15	1,00	1,00	1,00	0,99	0,99	0,97
30	0,99	0,99	0,99	0,99	0,99	0,97
45	0,98	0,98	0,98	0,97	0,97	0,95
60	0,96	0,96	0,95	0,95	0,95	0,93
120	0,81	0,81	0,80	0,80	0,80	0,78

TABLE IV. RELATIVE EFFICIENCY (DECEMBER)

Azimuth discrete, min	**Elevation discrete, min**					
	0	***15***	***30***	***45***	***60***	***120***
0	1,00	1,00	1,00	1,00	1,00	0,99
15	1,00	1,00	1,00	1,00	1,00	0,99
30	0,99	0,99	0,99	0,99	0,99	0,98
45	0,97	0,97	0,97	0,97	0,96	0,96
60	0,93	0,93	0,93	0,93	0,93	0,92
120	0,65	0,65	0,65	0,65	0,65	0,64

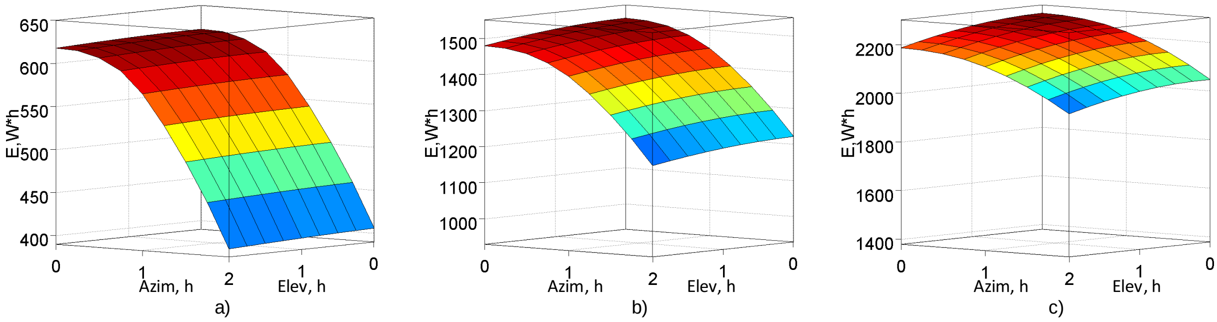

Fig. 10. The daily energy production vs. the orientation discrete: December (a), September (b), June (c).

V. CONCLUSIONS

The Sun tracking system designed to improve the efficiency of photovoltaic cells was developed. Utilization of 2-axial closed-loop Sun tracker system allowed the use of cheap actuators without position feedback and without necessity of precise hanger placement by cardinal directions for its high efficiency. The impact of tracker orientation time discrete on the solar panel efficiency is first taken into the account in this research. The energy losses for orientation were measured, but they turned out significantly lower than panel energy production, do not affect overall system performance and therefore they were omitted in subsequent research. The efficiency of solar panel with tracker was compared with the same panel installed at an angle of 45 degrees to the horizon and amounted not less than 27% throughout the year. The maximum efficiency improvement from tracker usage reaches 76% under the same comparison conditions in summer. To retain compromise between actuators wear and panel efficiency gain, the optimal orientation discrete was calculated and composes 15 minutes.

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