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Small Scale Models of Solar Tracking Systems

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***Abstract* - Increasing the efficiency of photovoltaic panels using solar tracking systems is a current topic. The use of solar tracking systems is a solution, especially in low power applications. The paper presents two types of solar tracking systems, one based on astronomical data, and the other based on tracking the point of maximum illumination. Both systems are made on small scale for educational purposes. These systems can be used for the analysis of methods, principles and particularities in order to use them in practical applications. For the two experimental models of solar tracking made, the hardware and software structure are presented. To orient the photovoltaic panels in the two directions (East-West, respectively South-North) DC motors or stepper motors are used. One motor is used for each axis of rotation. Both structures have the control part composed of a microcontroller development system. This control method has the advantage that can significantly reduce the number of electronic components as well as the cost of designing and building of equipment. For the solar tracking system based on astronomical data, a remote monitoring and control system has been achieved. It uses a friendly graphic interface made on PC with the help of Visual Basic software. Both models were tested and the experimental results showed correct operation according to the imposed protocol. Finally, an energy efficiency analysis was done and it was found that the PV panel that uses the tracking systems produces 35% more energy compared to a fixed PV panel.**

Cuvinte cheie: *sistem de orientare solar, panou fotovoltaic, microcontroler, instruire, eficiență energetică.*

Keywords: *solar tracking system, photovoltaic panel, microcontroller, training, energy efficiency.*

I. INTRODUCTION

In recent years, the evolution of photovoltaic systems has registered an increasing trend in the context of the energy crisis and environmental protection considerations. This upward evolution also requires a specialized and qualified human resource in the field.

Since photovoltaic (PV) panels have a rather low yield (max. 30%, in laboratory conditions), their energy optimization is aimed at. An accessible method of optimizing solar energy conversion with real implementation possibilities is the use of orientation systems.

Specialized literature shows that the use of solar tracking systems increases the amount of energy produced by conversion by 20% to 40% [1].

Ideally, a PV panel should follow the Sun so that the incident rays fall perpendicular to its surface, thus maximizing the capture of solar energy and therefore maximum output power [1], [2].

Practically, passive and active solar systems are distinguished [3], [4]. Passive tracking systems follow the Sun in the absence of a drive motor and are frequently used in equatorial areas because they have a single-axis tracking structure that allows maximum efficiency to be achieved only in those [5], [6], [7] .

Active solar tracking systems use servo motors to move the PV panels. There are two distinct modes of active tracking of the PV panels [4], [6], [8]: along a single axis of rotation and along two perpendicular axes of rotation (biaxial).

The paper presents two types of biaxial active solar tracking systems made on a small scale for educational purposes, based on different tracking methods. The first solar tracking system uses the astronomical data method, and the second one uses the maximum light point method. Both systems use tracking programs implemented in control structures with microcontrollers.

II. SMALL SCALE MODEL OF SOLAR TRACKING SYSTEM BASED ON ASTRONOMICAL DATA

A. *Elements of celestial geometry for the positioning of the PV panel*

In order to understand the essence of the calculations, some notions from astronomy are used, in particular, the analytical relationships that describe the apparent motion of the Sun on the sky [9].

It is known that the Earth carries out a complete rotation movement during a year, around the Sun in an elliptical orbit and a complete rotation movement around its own axis during 24 hours. The rotation axis of the Earth has a fixed direction in space and is inclined with the angle $\delta 0 = 23.4^o$ to the perpendicular to the plane of the orbit (Fig. 1). The angle between the direction to the Sun and the equatorial plane, δ, is named declination and varies throughout the year from $+23.4^o$ at the time of the summer solstice (June 21) to -23.4^o - at the time of the winter solstice (December 21).

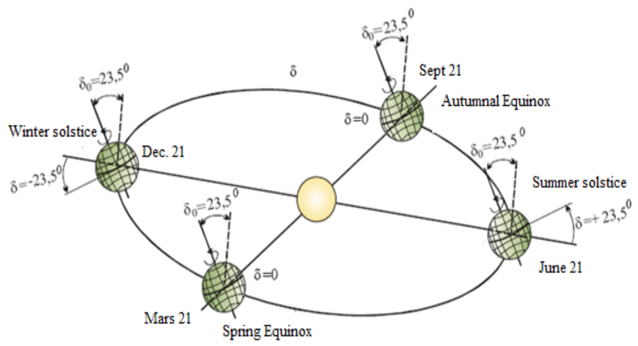

Fig. 1. Earth's orbit and declination angle, δ [7].

On March 21, respectively - September 21, the declination $\delta=0$ and the durations of day and night are equal.

Declination can be calculated with Cooper's formula [1]:

$$\delta = 23{,}45 \cdot \sin\left(360^o \frac{284+n}{365}\right) \qquad (1)$$

where n – is the number of the day of the year, the first day being January 1.

The geometric relations between a plane arbitrarily oriented with respect to the horizontal and the direct solar radiation that falls on this plane at any instant of time, the position of the sun with respect to this plane can be described in terms of several angles [9].

Latitude, φ, - is the angle measured from the equator to the point of interest on the earth's surface, is considered positive for the northern hemisphere and negative - for the southern one.

The angle of inclination of the PV panel β, - is the angle between the plane of the surface in question and the horizontal surface; $0^o \le \beta \le 180^o$ (Fig. 2). For usual solar installations, the maximum value does not exceed 90^o.

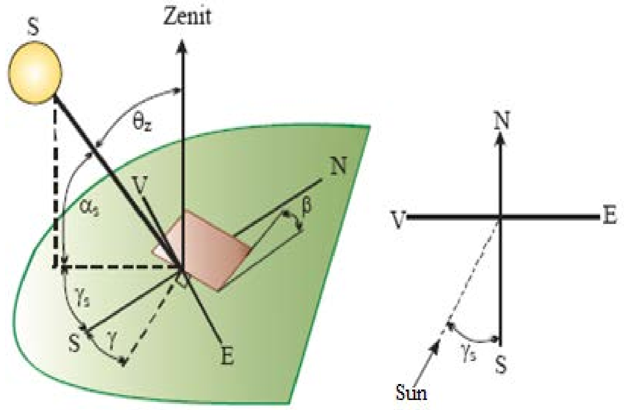

Fig. 2. Explanatory regarding the characteristic angles [9].

The azimuthal angle, γ, - is the angle between the projection on the horizontal plane of the perpendicular on the surface of the plane in question and the local meridian (fig. 3); is equal to zero for the plane in question oriented to the south, negative - to the east, positive - to the west; $-180 \le \gamma \le 180$.

The angle of elevation of the sun, αs, - is the angle between the horizon line and the line connecting the sun to the point of interest, therefore, it is the incident solar ray at the point of interest (Fig. 2).

The zenith angle, θz, - is the angle between the vertical and the line connecting the sun to the point of interest, in other words, it is the angle complementary to the angle αs (Fig. 2).

The hour angle, ω, - determines the position of the sun on the sky at the given moment. It is equal to zero when the sun crosses the local meridian, in other words at noon, positive to the east and negative – to the west (Fig. 3). Respectively, ωs corresponds to the angle of sunrise, and (- ωs), the angle of sunset.

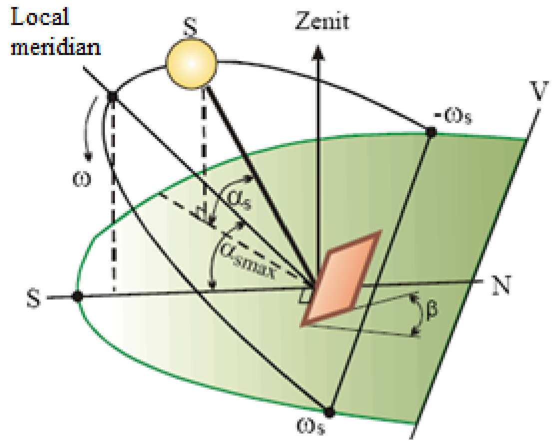

Fig. 3 Explanatory regarding the hourly angle ω, sunrise, ωs and sunset (-ωs) of the sun [9].

It is obvious that in one hour the sun crosses the sky at an angle equal to 15^o, and its position at any hour T is determined with the expression:

$$\omega = 15 \cdot (12 - T) \qquad (2)$$

If we know the angles δ, φ and ω, then it is easy to determine the position of the sun on the sky at the point of interest for any hour and any day, using the expressions [9]:

$$\sin \alpha_s = \sin\delta \sin\varphi + \cos\delta \cos\varphi \cos\omega = \cos\theta_z \qquad (3)$$

$$\cos\gamma_s = \frac{\sin\alpha_s \sin\phi - \sin\delta}{\cos\alpha_s \cos\phi} \qquad (4)$$

Two 5V stepper motors will be used to orient the photovoltaic panel. The pitch angle is 1.8^o. To halve it, mixed control will be adopted. On instance, for a complete rotation, 360/1.8*2=400 command sequences (number of steps) will be required.

In the azimuth direction, it is considered that an opening of 220^o is sufficient. The corresponding number of steps is 220*400/360=245. The photovoltaic panel is placed in the south direction at an azimuth command of 123 steps. From this point he can move 110^o east or west. The relationship that expresses the dependence between the azimuth angle and the position of the photovoltaic panel in the azimuth direction is:

Azimuth number of steps=245/220*(110+ γs) (5)

For the direction of elevation, an aperture of 80 degrees is chosen, i.e. 80*400/360=89 steps. The elevation of the sun and the angle of inclination of the PV panel are complementary. The relationship that defines the connection between the number of impulses and the elevation of the sun is:

Elevation number of steps=(αs-10)*89/(90^o-10^o)

that is:

Elevation number of steps =(αs -10)*89/80^o

where

$$10^{o} <= \alpha s <= 90^{o} \quad (6)$$

We will evaluate a data set for the microcontroller of the PV panel orientation system for each month of the year [10]. The day in the middle of the corresponding month will be chosen as a reference. Positioning of the PV panel will be done every 30 minutes. The PV panel is always initialized at 6:30 a.m. and the first orientation is done at 7:00 a.m. The last orientation takes place at 16:30. The hourly angle will be calculated with relation (2) for the middle of each adjustment interval.

B. Structure of small model of solar tracking system

B1. Hardware structure

The model of solar tracking system using astronomical data [11], [12] is made with a structure developed around an 18F4520 type microcontroller produced by MICROCHIP (Fig. 4). Three functional blocks can be identified: the control module, the amplifier module and the power supply.

The control module, in addition to the PIC18F4520 chip, also contains a keyboard, an alphanumeric display, a real time clock and a TTL/RS232 adapter. The amplifier module ensures the adaptation of the signals to control the two motors step by step. Also, a hardware processing of the position initialization signals for azimuth and elevation (S1 and S2) is done. In the case of the power supply, an industrial model was chosen.

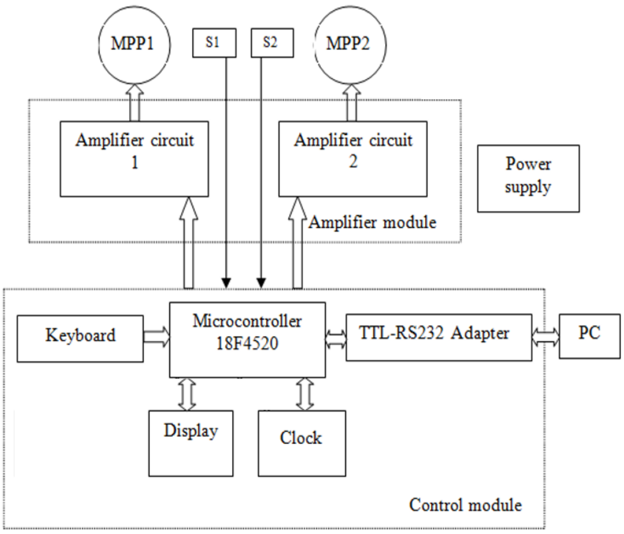

Fig. 4. Block diagram of the automaton for the solar tracking system.

B2. Software structure

Functions of the microcontroller program:

- control of two stepper motors (movement and initialization);
- the acquisition of three analogue inputs;
- setting and saving in the EEPROM memory some values that define the functioning of the microcontroller;
- serial interconnection with an electronic computer through a UART port;
- transmission of data packets to the PC organized according to a pre-established protocol;
- receiving from the PC some data packages organized according to a predetermined protocol;
- adjusting the speed of the two stepper motors;
- the choice of three program menus: testing, tracking by calendar and calendar simulation;
- scanning a keyboard consisting of three push buttons for setting parameters and program configuration;
- displaying some functional messages on a 2x16 character alphanumeric display;
- use and the possibility of configuring your own clock;
- display of error messages when abnormal operating modes are detected.

The C programming language was used for the microcontroller program, because it is easier to understand and maintain. Using such a language closer to the natural way of thinking, the programmer can focus his efforts on the design of the algorithms and less on their individual way of implementation, which leads to obtaining a more understandable code, therefore easier to test and debug.

The program (Fig. 5) starts with the initialization of the microcontroller and the variables used, then enters a loop in which it executes a group of procedures, scans the three human interface keys and calls a new loop, with a similar structure, depending by the value of the „Menu Counter" variable.

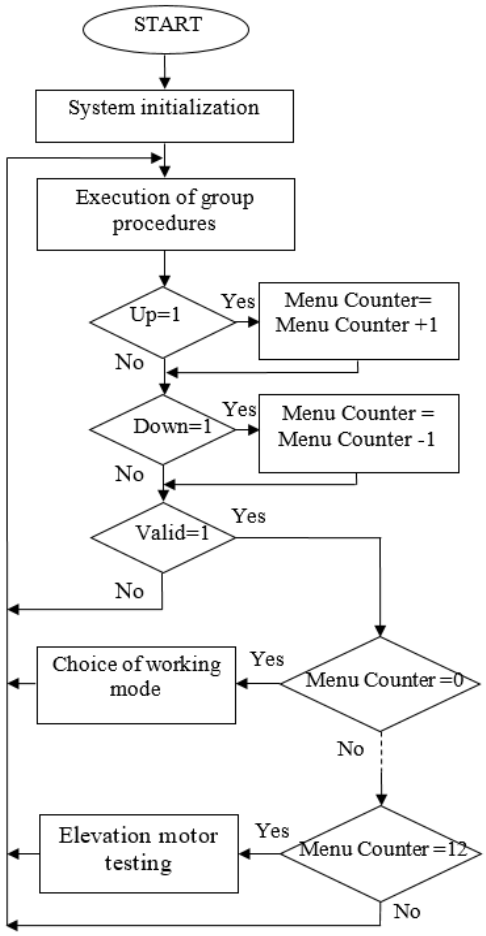

Fig. 5. Microcontroller program flow chart.

Regardless of the loop in which the program is located, the group of procedures will always be executed (fig. 6). Here, the counter system is first decremented, then the three analog inputs are scanned, the three keys are scanned, the motor for azimuth and the motor for elevation are managed. The sequence ends with the processing of the serial communication and with the command of the alphanumeric display.

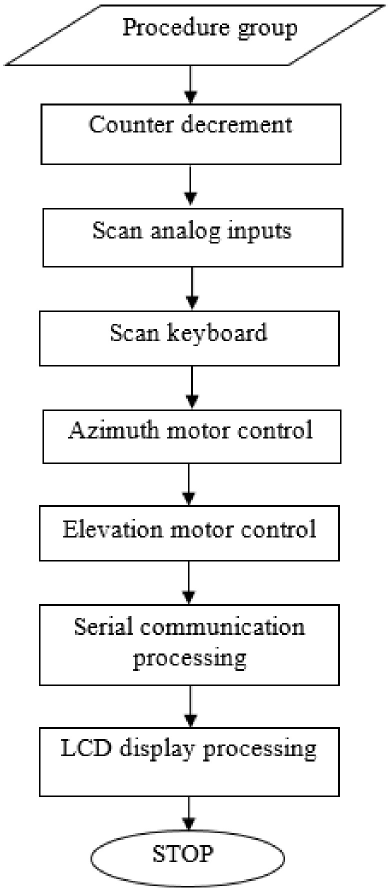

Fig. 6. Flow chart of the "procedure group" sequence.

When the orientation system works according to the calendar, every 30 minutes the required value for azimuth is obtained (Azimuth Prescription - organizational chart from fig. 7) and elevation. For example, for the azimuth direction, the algorithm will test the imposed value (Azimuth Prescribed) with the current one (Azimuth Motor Pulse Index) and depending on the ratio of the two values, the Azimuth Motor Sequence will increase or decrease. It can take only eight values and is the input size in the Azimut Motor procedure. Here, depending on the value, the motor phases are controlled step by step along the azimuth direction by controlling the assigned microcontroller pins (fig. 8).

The data packets D4..D7 in the organizational chart of the program (fig.8) have the following meaning:

D.4- Index of Azimuth Motor Pulse_H

D.5- Index of Azimuth Motor Pulse_L

D.6 – Azimuth prescribed_H

D7. - Azimuth prescribed_L

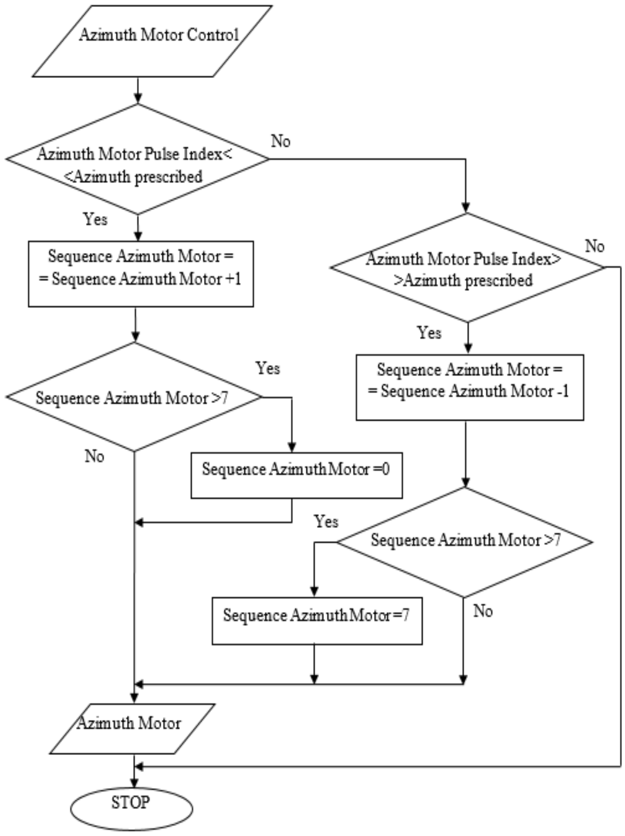

Fig. 7. Flow chart of the motor control in the azimuth direction.

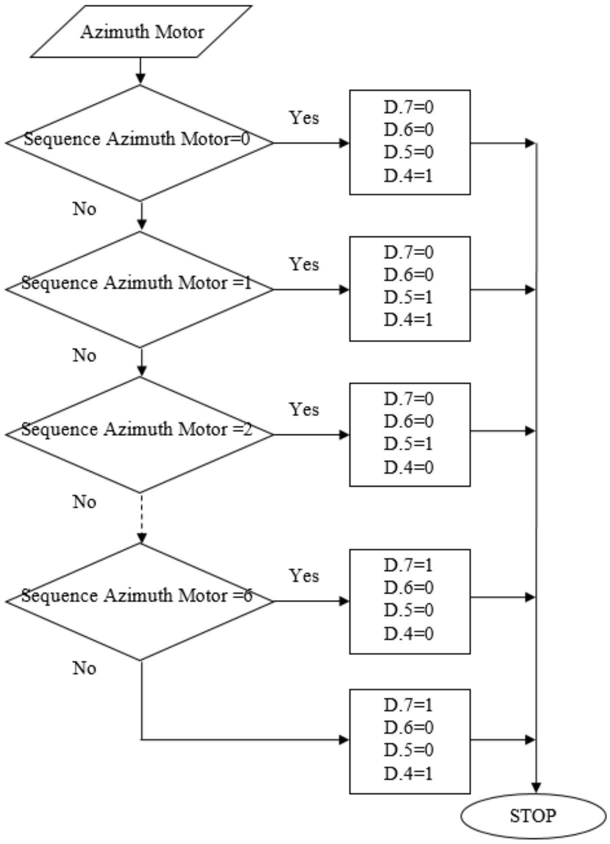

Fig. 8. Flow chart of the actual motor control in the azimuth direction.

C. Solar Trackig system experimentation

Experimentation of the tracking system was done for all work procedures carried out within the tracking program.

The solar tracking system (Fig. 9) contains:

1- Power supply
2- Mechanical structure of tracking system
3- Stepper servomotors
4- Development system with microcontroller
5- PC

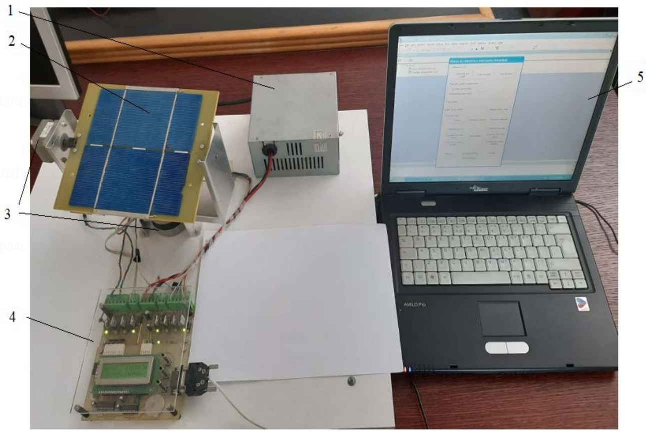

Fig. 9. Solar tracking system achieved.

During a work procedure, information about the date and time as well as the work procedure being executed is displayed on the screen of the development system. As can be seen in figure 10, the date 26.07, time 11:42 and the work procedure "Calendar Orientation" are displayed. For this date and time, the PV panel has the position shown in the figure.

Fig. 10. Solar tracking systen working of „Tracking calendar" mode.

The Visual Basic language was used to create the program for PC, [12]. it is frequently found in industrial applications, being easy to use in human-machine interfaces. It should be noted that it contains an object specialized in ensuring the serial connection with other digital equipment, ensuring practically the only convenient way of transferring information between the PC and the targeted equipment.

Figure 11 shows the graphical interface of the created application, named "Tracking system of PV panel"

Then choose the serial port (Fig. 11) by pressing the Serial port selection button. The establishment of the serial link between the two devices is highlighted by the Received serial packets counter. By pressing the Monitor button, the second window of the program will be activated (Fig. 12). Here you can see the content of the received serial packets, the values scanned by the three analogue channels and the numerical values imposed and achieved by the two stepper motors.

The commands from the PC are valid only when the microcontroller is in the first screen (status screen).

In figure 12, it can be seen that the two stepper motors are at rest, after having executed the PV panel positioning sequence according to the two axes (Index motor azimuth=Azimuth motor prescribed; Index motor elevation=Elevation motor prescribed).

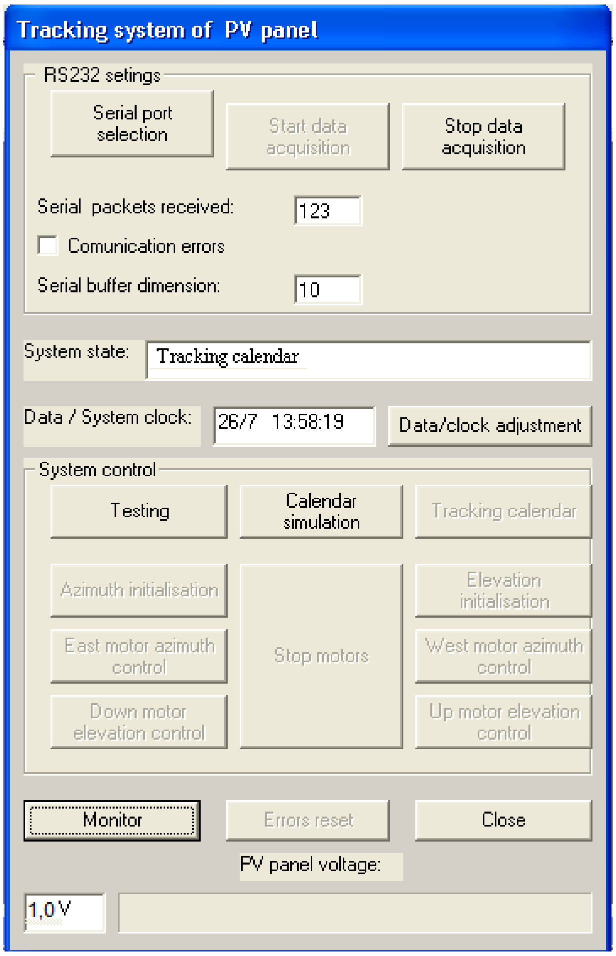

Fig. 11. The main window of the PC program.

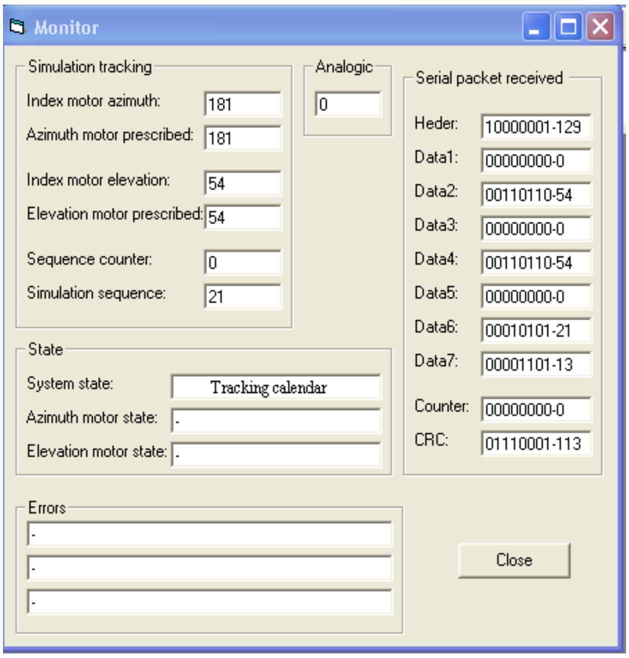

Fig. 12. Additional details window.

In the System Status window, you can see the „Tracking calendar” mode in which the automatic for the orientation of the photovoltaic panels is located

The set serial communication speed is 9600 bits/s. One character is transmitted at this speed in about 1 millisecond (ms) and ten characters in about 10 ms. The recording from figure 13 confirms this – the packet was transmitted in 10.3 ms.

The serial packets are transmitted from the microcontroller to the PC at intervals of 252 ms (verified aspect in the recording from figure 14).

Figures 15 and 16 show the stepper motor control motor at maximum speed, respectively at half of maximum speed. Taking into account the fact that a mixed control is performed, the phase switching interval of 10 ms and 20 ms respectively is checked.

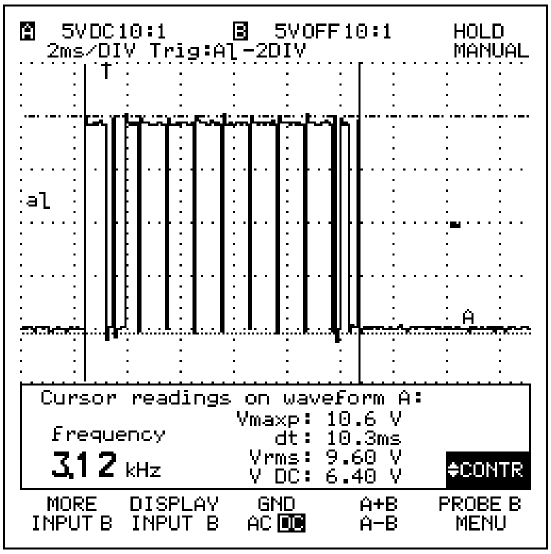

Fig. 13. Data packet transmission to the PC.

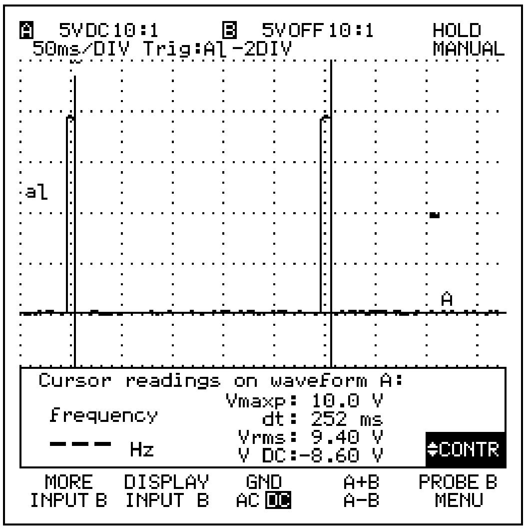

Fig. 14. Illustrative for the rhythmicity of the serial data packets transmitted to the PC.

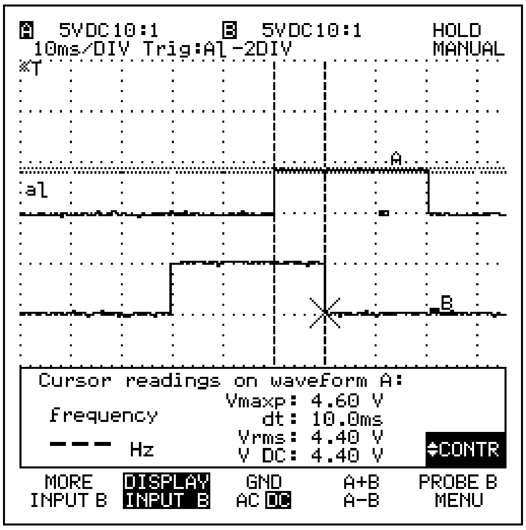

Fig. 15. Illustrative regarding to control of stepper motors at maximum speed

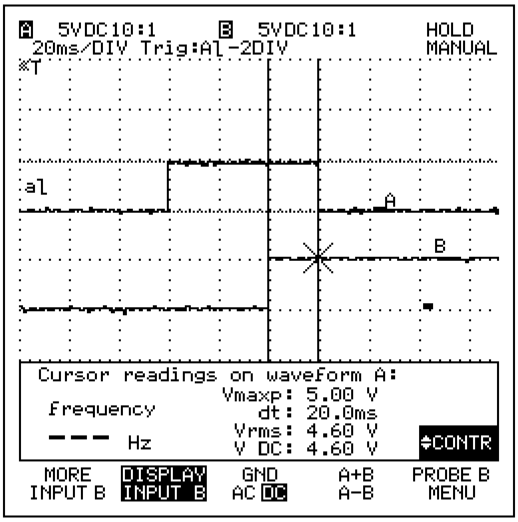

Fig. 16. Illustrative regarding to control of stepper motors at half maximum speed.

The modular nature of the serial communication procedures and the code sequences that identify the received commands, allows their inclusion in the structure of other programs that run on microcontrollers from the same family. The development of a complex serial communication procedure for PC is part of the current trend of PC-equipment interconnection, this duet being almost indispensable especially in the phase of design and verification of programs written for microcontrollers.

The experimental results obtained with the automatic solar tracking system, designed and realized in the work, constitute a convincing method by which the correctness and coherence of the proposed solutions are demonstrated.

III. Small Model of Solar Tracking System Based On Maximum Light Intensity

A. Structure of solar tracking system

The structure of the tracking system based on the point of maximum light intensity [14] is presented in figures 17 and 18. The tracking system is composed of the following blocks: photo resistor block (LRD1...LRD4), command platform with Arduino Uno microcontroller [15], servo motors SM1, SM2 for orientation along both axes of the photovoltaic panel, the power supply.

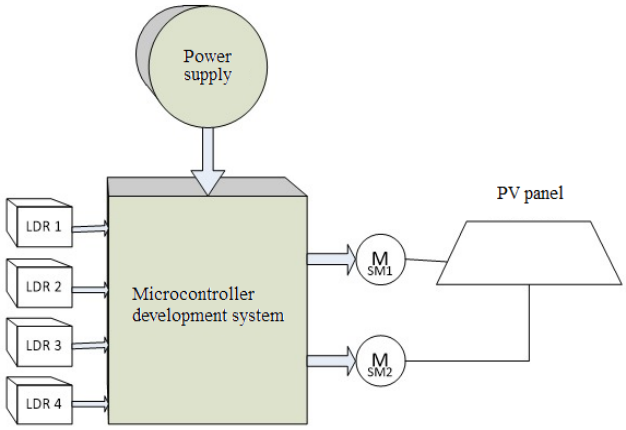

Fig. 17. Structure of Solar tacking system.

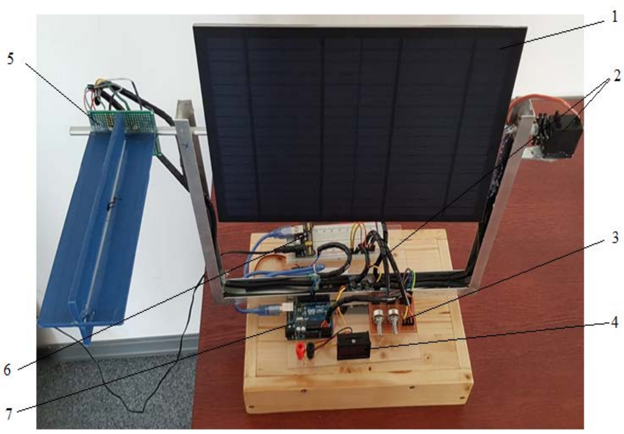

Fig. 18. Solar tracking system achieved: 1-PV panel; 2- servo motors; 3- adjustable resistors; 4- digital voltmeter; 5- photorezistors; 6- power supply; 7- Arduino Uno microcontroller.

Servomotors SM1, SM2 type MG995 that ensure the orientation of the photovoltaic panel according to the two axes have the following technical specifications:

- Operating voltage: 4.8V - 7.2V
- Operating voltage speed at 4.8V: 0.20sec / 60°
- Operating voltage speed at 6.6V: 0.16sec / 60°
- Maximum rotation angle: 180°

Photo resistors type 5528 LDR are passive electronic components that change their electrical resistance depending on the intensity of light radiation.

Technical specifications:

- Maximum voltage: 150 Vdc
- Maximum power consumption: 100 mW
- Operating temperature: - 30°C …. +70°C
- Spectral value : 540 nm
- Light resistance at 10Lux: 2 KΩ

The Arduino Uno R3 platform is a development board based on the ATmega 328 microcontroller, 14 digital inputs and 6 analogue inputs.

The Arduino IDE (Integrated Development Environment) [15] software was used for the tracking program, which supports C, C++ languages using special code organization rules.

The four photo-resistors are placed on the sides of the photovoltaic panel according to [16], [17], (Fig. 18). Photo resistors change their electrical resistance depending on the intensity of solar radiation [18]. Servomotors connected to the microcontroller board position the PV panel in the direction of the Sun [19].

When the light intensity from the two LDRs on the right is higher, the horizontal servo motor moves the PV panel slowly to the right, and if the intensity on the LDRs on the left is higher, the panel direct slowly to the left.

When the light intensity from the two LDRs, located at the top, is higher, the vertical servo motor rotate the panel to the top, and if the intensity in the LDRs located at the bottom is higher, the panel is oriented to bottom.

The tracking accuracy of the solar tracker system is evaluated by calculating the deviation between the solar panel's actual position and the ideal position based on the sun's movement.

B. Analysis of the operation of the solar tracking system

B1. Calculation of the photovoltaic panel efficiency in standard conditions

The characteristics of the photovoltaic panel measured under standard conditions, solar radiation 1000 W/m^2, temperature 25°C are the following:

- Power: 10 W
- Open circuit voltage: 21,6 V
- Short circuit current: 630 mA
- Maximum current: 556 mA
- Maximum voltage; 18 V
- PV cell type: polycrystalline Si
- PV panel size (mm.) 220×340×3 mm

The yield of the photovoltaic panel under standard conditions is:

$$\eta=\frac{P_m}{A\cdot E}=\frac{10}{0.22\cdot 0.34\cdot 1000}=0{,}1336\rightarrow 13{,}36\% \qquad (7)$$

A- PV panel surface [m^2]

E- solar irradiation [W/m^2]

B2. Analysis of the efficiency of the solar tracking system

Table 1 presents the results of measuring the voltage and the short-circuit current of the photovoltaic panel for two scenarios: a fixed panel oriented to the South at 40 degrees and a PV panel with tracking system. The measurements were carried out using the same PV panel, under identical irradiation conditions, at regular time intervals during a day for the two analysed cases.

TABLE I. MEASUREMENTS PERFORMED FOR THE TWO SCENARIOS: FIXED PANEL AND ORIENTED PANEL

Stationary PV panel			PV panel with tracking system		
Voltage U [V]	**Current I [A]**	**Power P [W]**	**Voltage U [V]**	**Current I [A]**	**Power P [W]**
8,1	0,054	0,44	10	0,113	1,13
10,2	0,151	1,55	11,4	0,242	2,76
11,8	0,270	3,19	11,9	0,409	4,87
12	0,466	5,68	14	0,533	7,47

The achieved solar tracking system is a functional prototype. The use of a system for tracking the movement of the Sun leads to a quantity of captured solar energy (and implicitly a quantity of electricity produced by the photovoltaic panel) up to 35% higher, taking into account the own consumption of electricity tracking system.

IV. CONCLUSIONS

The use of a solar tracking system for PV panels implies an increase in the electrical energy provided by the PV system by up to 30-40%. This was observed from the experimental results.

Implementation of a solar tracking system for PV panels requires complex interdisciplinary knowledge of astronomy, geography and engineering sciences, therefore the presented tracking systems were made on a small scale for educational purposes.

The use of a development system with a microcontroller to control and monitor the solar tracking system is a solution that can significantly reduce the number of electronic components as well as the cost of designing and achieved of equipment.

The sensors, electrical equipment and electronic components used in the two solar tracking systems present a high degree of accessibility and performance using standard software and interfaces.

The hardware and software infrastructure used allows monitoring and control of solar tracking systems in real time.

The models achieved can be used by students in the training process or adapted to a suitable scale can be used in real practical applications.

Starting from these models, some students of the Faculty of Electrical Engineering made similar models for their graduation projects. Other engineering graduates work in the field ensuring the maintenance or installing photovoltaic systems.

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Contribution of authors:

First author – 60%

First coauthor – 30%

Second coauthor – 10%

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