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Autonomous control of biaxial tracking photovoltaic system

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Abstract

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Tracking photovoltaic systems maximize solar energy on the photovoltaic cells surface in order to maximize the energy gain at a given moment. Energy gain is dependent on the accuracy of photovoltaic cells direction, control method and tracking period. The control of tracking systems is based on theoretical calculations of sun position for a specific position in specific time. Designed control algorithm of the biaxial tracking photovoltaic system is able of autonomous navigation directed to the sun without knowing the position. It is based on the sun position sensor. The designed solution increases the solar gain by 33.8% in comparison with stable photovoltaic systems. It is usable in the research focused on the control method of step-controlled biaxial tracking photovoltaic devices.

Keywords: tracker; photovoltaic cell; sun position sensor; efficiency; renewable energy

The problems of tracking stands for solar energy collectors have been widely studied recently because they can considerably increase the efficiency of solar panel systems by increasing the energy output and thus decreasing the price of energy produced (Poulek, Libra 2002). The max. intensity of energy from the sun absorbed by a plane perpendicular to direct solar radiation is about I = 1,100 W/m^2. Assuming that quality collectors based on crystalline silicone are about 18÷20% efficient, the max. output for a collector area S = 1 m^2 is P_{max} = 200 W. This value decreases for inclined incidence (Poulek, Libra 2010).

Photovoltaic devices have the best power parameters when they are directed perpendicular to sunrays. Pointing devices – trackers are used for this purpose. These systems are different in design and the control method of situation. According to the number of control axes, pointing devices are divided into uniaxial and biaxial. Single-axis trackers have one fixed set axis, and the second axis is rotational. It is constructed with east-west or north-south orientation with inclination, which is determined from the latitude of the installation place. Biaxial trackers allow adjusting horizontally and vertically.

Tracker's positioning uses two basic principles – continual or stepping. The perpendicular direction of solar panels to the sun is updated every moment in a continual positioning principle. The main tracker's control algorithm is based on the theoretical calculation of the sun position. Then, the photovoltaic (PV) system is directed to a target position with a motor unit. This solution has drawbacks, mainly when the location of the system was changed. The control algorithm must be changed for a new position. These systems are not transferable to another location.

Step positioning is updated only in described time intervals. Step positioning is more energy efficient. Trackers increase the annual production by about 30% in comparison with stable systems (Tkáč, Hvizdoš 2011).

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MATERIAL AND METHODS

The intensity of extraterrestrial solar radiation is changeable because of the change in distance between the Earth and the Sun and because of the Sun activity. The value of this radiation changes in the course of a year in the range from 1,000 to 1,100 W/m^2. The intensity of extraterrestrial solar radiation that falls in a unit of time on square meter of surface can be calculated as follows (Radosavljević, Dordević 2001):

$$I_0 = I_{SC}\left[1 + 0.0333 \times \cos\left(\frac{360 \times n}{365}\right)\right] \quad (1)$$

where:
I_0 – intensity of extraterrestrial solar radiation (W/m^2)
I_{sc} – solar constant (W/m^2)
n – a day in a year that counts from 1st January

For a surface, that is inclined under some angle to the horizontal flat, the direct solar radiation can be calculated according to the following equation:

$$I_{BC} = I_0 \times \cos\theta \quad (2)$$

where
θ – angle between surface normal of collector and sunrays

Cosine of the angle between surface normal of PV panel and sunrays as shown in Fig. 1 is given by (Duursma 2003):

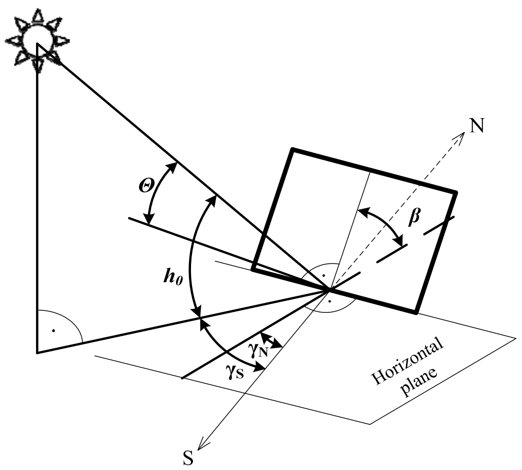

Fig. 1. Determination of the Sun position

S – south; β – surface of the PV panel relative to the horizontal; N – north; θ – angle between surface normal of collector and sunrays; γ_N – azimuth of surface normal of PV panel from south; γ_S – azimuth of the Sun from the south; h_0 – altitude of the Sun

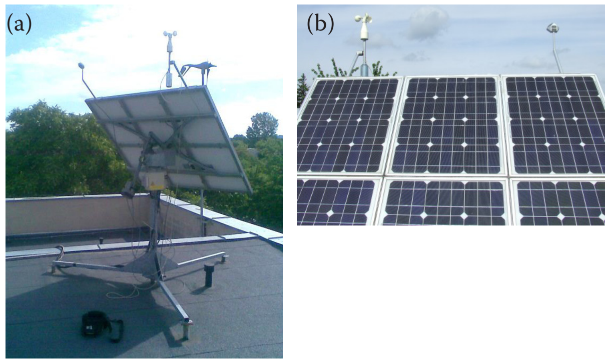

Fig. 2. Autonomous biaxial tracking photovoltaic system (a) back side view and (b) front side view

$$\cos\theta = \sin h_0 \times \cos\beta + \cos h_0 \times \sin\beta \times \cos(\gamma_S - \gamma_N) \quad (3)$$

where
h_0 – altitude of the Sun
β – surface of the PV panel relative to the horizontal
γ_S – azimuth of the Sun from the south
γ_N – azimuth of surface normal of PV panel from south

The result is relationship to calculate the intensity of the incident solar radiation to inclined surface of the PV panel:

$$I_{BC} = I_0 \times e^{(-k\ 1/\sin h_0)} \times [\sin h_0 \times \cos\beta + \cos h_0 \times \sin\beta \times \times \cos(\gamma_S - \gamma_N)] \quad (4)$$

where:
k – attenuation coefficient of solar radiation in the earth atmosphere

The autonomous biaxial pointing PV system (Fig. 2) was designed at the Department of Electrical Engineering, Automation and Informatics, Faculty of Engineering, SUA in Nitra. Six monocrystalline PV panels Suntech STP45S-12/Rb (Suntech, London, UK) were placed on the tracker. The selected technical parameters of the used PV panels are shown in Table 1.

The control of autonomous biaxial pointing photovoltaic system is based on decomposition of so-

Table 1. Selected technical parameters of the PV panels Suntech STP045S-12/Rb

Maximum power	45 W
Open-circuit voltage	22 V
Short-circuit current	2.79 A
Efficiency	12.6%
Peak power temperature coefficient	$-(0.47 \pm 0.05)\%\cdot K^{-1}$

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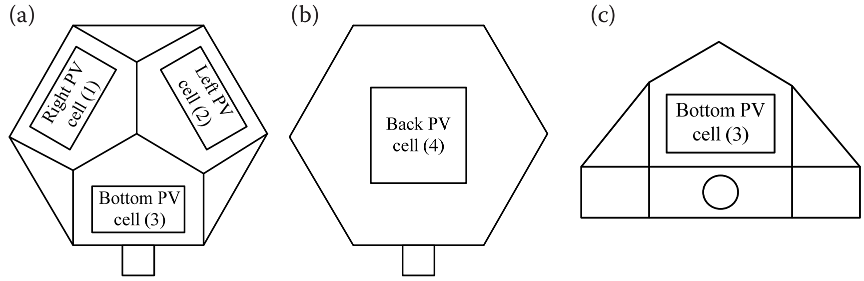

Fig. 3. Sensor of Sun position (a) front side view, (b) back side view and (c) top view

lar radiation to partial parts by the sensor of sun position (SUA in Nitra, Slovak Republic). This sensor contains four photovoltaic cells, as shown in Fig. 3. Solar energy, which falls on the cells surface, is spread according to the impact angle. The actual position of the sun is calculated from the ratio of the energy of each cell.

The main part of the PV system is a control unit (SUA in Nitra, Nitra, Slovak Republic) (Fig. 4). It controls the two direct current (DC) motors (DARL 3610+; Jäger, Mannheim, Germany) on the basis of a defined algorithm. The motor M1 is linear. This one is used for the control of tracker inclination. The motor M2 is rotary and controls the rotation of the PV system. Air velocity is also measured. A cup anemometer is used for this purpose (P2546A-L; Windsensor, Roskilde, Denmark), with the measuring range from 0.5 to 40 m/s. The sensor output is pulse signal, which is connected to the counter input of the microprocessor. It is important for the system protection in case of high air velocity.

The technical solution of the control unit is based on the industrial 8-bit single-chip microprocessor C8051F340 developed by the Silicon Laboratories (Austin, USA). Voltages from the sun position sensor (Fig. 3) are processed by the explain abbreviation analogue to digital (AD) converter in a single-ended mode and converted to a digital value for next processing. The currents of the motors are also measured by this AD converter. When the motors are overloaded, then a special algorithm stops the motors. This is the protection of the motors and output stages. The speed of rotation control is performed by pulse-width modulators (C8051F340; Silicon Laboratories, Austin, USA), which are placed in programmable counter-timer arrays of microprocessor. The general purpose pins are used for the control of motor rotation direction. In addition to this, the communication RS-232E is part of the tracker control system. The tracker state, controlling the motors and setting the period of algorithm can be monitored through this interface. Monitoring and con-

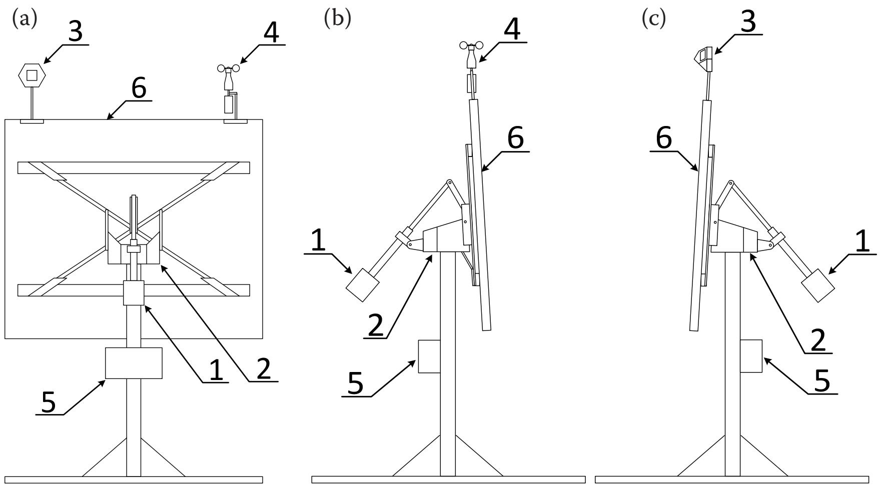

Fig. 4. Schematic principle of autonomous tracking photovoltaic system (a) back side view, (b) left side view and (c) right side view

1 – inclination control motor of PV panels M1; 2 – rotation control motor of PV panels M2; 3 – sensor of Sun position; 4 – anemometer; 5 – control unit; 6 – photovoltaic cells

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trolling allows optimizing the control algorithm for the max. energy gain of the tracker.

Output energy is stored to a lead-acid battery with rated voltage 24 V. Electronic fuse is used for battery protection. Further, the energy in batteries is used for lighting and heating the laboratory. A sine wave inverter is used for energy conversion from 24 V DC to sine wave 230 V/50 Hz. Output current and battery voltage are monitored by a special electronic circuit, and they are evaluated using a programme in the LabView (Labview 2014; National Instruments, Austin, USA) application. All the measured variables are saved to files for each day. The sample frequency of saving is set to five seconds.

RESULTS AND DISCUSSION

The principle of autonomous position control is described by a cyclic repeated algorithm, which is shown in Fig. 5. The voltages U_P, U_L, U_S, U_Z from the sun position sensor are measured at the beginning of each cycle. Firstly, 16 samples are measured from each cell with sample frequency 200 kHz, and then, average values for individual PV cell are calculated. Secondly, voltages are compared with set value 30 mV, which is the threshold of dimming in the evening. When all voltages are less than 30 mV, the PV system rotates to the east and inclination is set to the horizontal position. The "night" position of the system is in time when voltages from all cells are less than the set threshold. If cell voltages are greater than 30 mV, then the navigation part of algorithm will be implemented. It provides an autonomous effective alignment of the PV system.

In the first step, the PV system is rotated using the motor M2 according to U_P and U_L voltages. If U_P voltage is greater than U_L, the PV system rotates to the west. In the opposite side, the PV system rotates to the east. The motor M2 runs until U_P and U_L voltages are not equal. If U_P and U_L voltages are equal, the setting of inclination is needed. Inclination is set by using the motor M1. If the voltage from the bottom cell U_S is greater than the voltage from the right cell U_P, inclination angle increases until these voltages are not equal. This is typical for the afternoon up to the evening. If the voltage from the right cell U_P is greater than the voltage from the bottom cell U_S, inclination angle decreases. The next part of the tracker is the anemometer. When air velocity is greater than 30 m/s, the PV panel is tilted. This is important for preventing

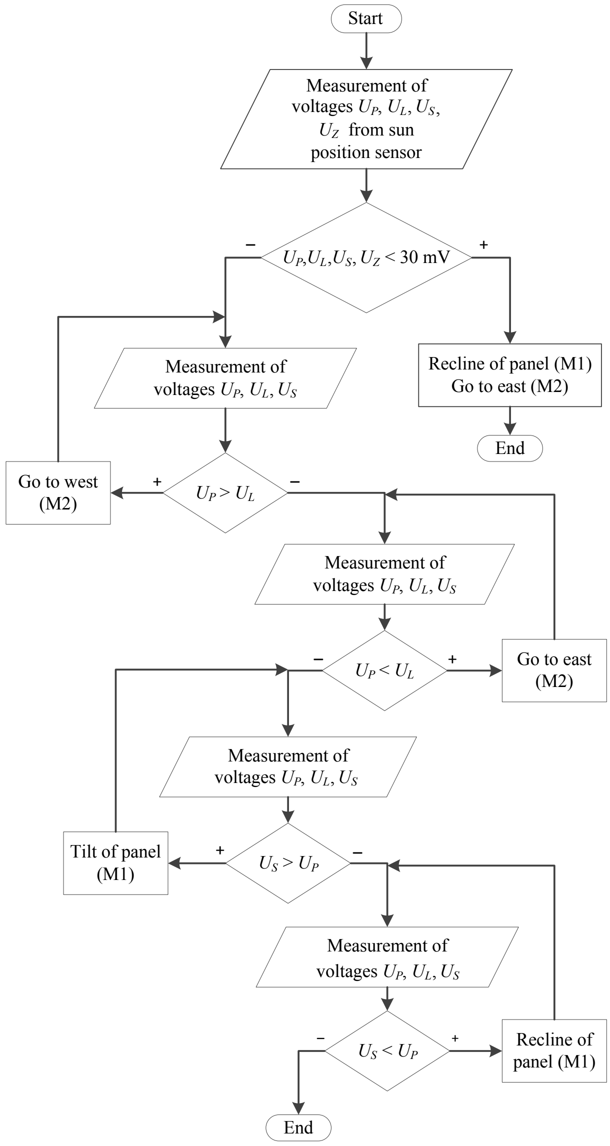

Fig. 5. Part of the algorithm of tracker autonomous control

U_P, U_L, U_S, U_Z – output voltages of cells placed on the sensor of Sun position: U_p – output voltage of right PV cell; U_L – output voltage of left PV cell; U_S – output voltage of bottom PV cell; U_Z – output voltage of back PV cell as shown in Fig. 3

from system destruction. Automatic motor stop must be applied when the system is not set for 60 s. Further, the system waits for the set period.

Table 2. Energy generated from the stable and tracking PV systems on July 29, 2013

Electric energy generated by the tracking PV system	2.0425 kWh
Electric energy generated by the stable PV system	1.5269 kWh
Electric energy difference	33.7678%

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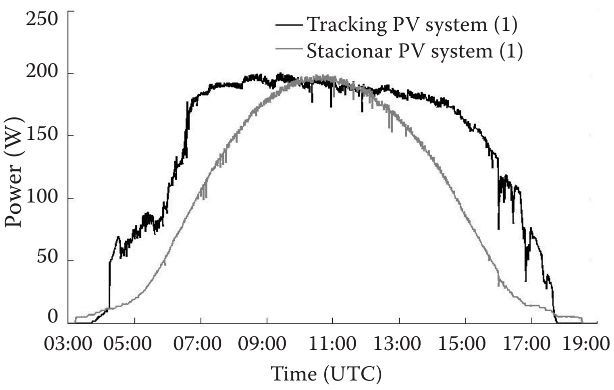

Fig. 6. Time dependences of powers from the stationary PV system and tracking PV system

Output power differences between the stable PV system and tracking biaxial PV system are shown in Fig. 6. The measurement was performed on July 29, 2013 when the sky was clear. The rotating period was set to 60 min, and the sample frequency of output power measurement was 0.2 Hz. As shown in Fig. 6, mechanical parts have disadvantages when the azimuth of summer morning sun is out of the rotation range (4:20 up to 5:25). Output power from the system is lower for this time because perpendicular alignment to sunrays of PV panels is not possible. The mentioned disadvantage does not exist in winter.

The output power difference between the stable system and tracker is 33.8%, as shown in Table 2.

Coefficient $a_{r,t}$ was established for theoretical and practical evaluation of influence rotating period to energy efficiency:

$$a_{r,t} = E_{r,t}/E_{ref} \quad (5)$$

where:

$E_{r,t}$ – real and theoretical solar energy falling to PV panel per day for a set rotating period

E_{ref} – reference solar energy falling to PV panel per day for 10 min rotating period

Results for some rotating period are shown in Table 3. Energy efficiency of PV panel is increased with a decrease of rotating period. Theoretical difference in energy is 17.59% between periods of 10 min and 3 hours. However, energy consumption of the system increases with a decrease of rotating period. It is therefore necessary to further examine the influence of the rotating period to power consumption.

Table 3. Comparison of algorithm effectivity

i (min)	a_r (%)	a_t (%)
10	100.00	100.00
30	95.12	96.82
60	90.65	92.76
120	86.18	90.17
180	81.71	82.41
240	71.14	76.87

i – rotating period, a_r – coefficient from real measurement, a_t – coefficient from theoretical model

CONCLUSION

The designed solution of the biaxial autonomous pointing system allows maximizing the energy gain from the sun compared with stable PV systems, regardless of the Earth's location. The benefit is in the flexibility of designed tracking PV system. The designed solution using the described control algorithm increases the solar gain by 33.8% in the summer time. This obtained value was specified for a clear sky day on July 23, 2013. Tracker position was updated every 60 seconds. Theoretical and real impact of the rotating period to output energy was determined.

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