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Single or dual axis trackers, control systems and electric drive losses for photovoltaic applications

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Abstract. This paper deals with the solar trackers for photovoltaic applications. The solar trackers for photovoltaic system assure that the highest possible share of the available solar radiation reaches the surface of the photovoltaic modules. The electric drive which enables tracking is considered as the loss of the energy produced in the photovoltaic system. The electric power consumption of the photovoltaic tracking system will be written as a function of the angle change.

Key words

Tracking systems, photovoltaic applications, electric drive losses, actuation and control systems

1. Introduction

Nowadays, the main reasons for restarting the production of electric energy from solar radiation are increasing energy dependence, the negative effects of fossil fuels on the environment and the legislation of the European Union and Slovenia. In the middle of the 21st century the electric energy production from solar radiation has risen considerably. Thus, the installed capacity of photovoltaic systems by the end of 2011 in the European Union (EU 27) increased to more than 51.4 GWp (data of publications issued by EurObser'ER), while in Slovenia increased to more than 126.0 MWp (data of the Public Energy Agency from 18/05/2012). The total installed capacity of photovoltaic systems will increase, as will increase the efficiency of photovoltaic modules. The efficiency of photovoltaic modules and consequently the efficiency of photovoltaic systems is defined as the ratio of generated electric energy and energy of incident solar radiation on the photovoltaic modules. The efficiency and price of electric energy produced by photovoltaic systems are important information for investors to decide about the building of such devices.
Investor is interested in how to achieve the maximum of electric energy produced by photovoltaic system installed, which depends mainly on how much solar radiation falls on the photovoltaic modules. The quantity of solar radiation that falls on the photovoltaic modules depends on atmosphere conditions, which we have no influence on, and also on, what angle the sunbeams fall on the photovoltaic modules. The efficiency of this conversion depends on the solar radiation that reaches the surface of the solar cells, quality and the type of the solar cells, their temperature, connections among the solar cells in the PV modules, the impedance matching between the modules and the dc/dc converters and the quality of applied inverters.
This paper focused on increasing energy production of solar radiation that falls on the modules by the tracking systems. The photovoltaic tracking systems follow the path of the sun in such a way that on the photovoltaic modules falls as much solar radiation as possible. For this the electric drives, that are consumers of electric energy, are used. The electric drives of photovoltaic tracking systems are considered as the loss of energy produced in the photovoltaic systems. The ideal energy efficiency of solar radiation is achieved by the continuous tracking of photovoltaic system to sun's trajectory. Because the electric drives have a final speed and discreet way of tracking, an ideal energy efficiency of solar radiation can only be approximate.
The paper is organized over five sections. It contains the general description of photovoltaic tracking systems and controlling of electric drives. The commercial single axis and dual axis tracking systems are described. For mentioned tracking systems the measures of electric drive losses were made.

2. Solar trackers for photovoltaic applications

The solar radiation that reaches the surface of the Earth depends primarily on the conditions in the atmosphere. However, the solar radiation that reaches the surface of solar cells can be influenced by a proper control of the solar trackers. Since in the case of clear days the direct radiation represents the main contribution to the total radiation, the solar tracking system [1] can align the direction of the sun beams and the normal on the solar cell surface, maximizing the available solar radiation that reaches the solar cell surface. Since the solar cells are normally joined in the PV panels, the sun tracking systems actually maximize the solar radiation that reaches the surface of the PV panels.

Generally, the photovoltaic tracking systems can be described as mechatronic systems that consist of mechanical subsystem, electrical drives, and information technology [2]. Photovoltaic trackers can be classified into two types: standard solar trackers and concentrated solar trackers. This paper describes only standard solar trackers. They can be further categorized by the number and orientation of their axes, their actuation architecture and drive type, their intended applications, and their vertical supports and foundation type. Consequently, there are two basic types of solar tracking systems, which are shown in Fig. 1: single axis tracker and dual axis tracker.

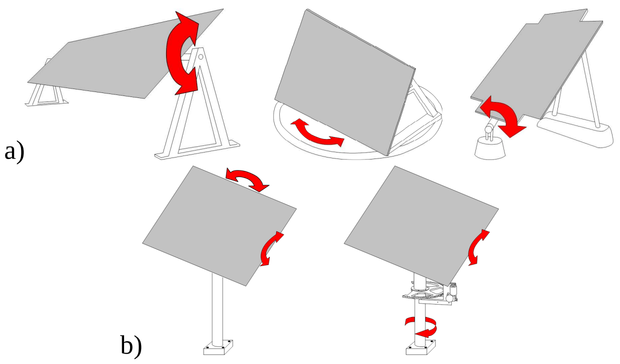

Fig. 1. Solar tracker: a) single axis and b) dual axis.

Fig. 1a shows several common implementations of single axis trackers. These include horizontal single axis trackers, vertical single axis trackers, and tilted single axis trackers. Fig. 1b shows several common implementations of dual axis trackers. They are classified by the orientation of their primary axes with respect to the ground. Two common implementations are tip-tilt trackers and azimuth-altitude trackers [3].

A. Single axis trackers for photovoltaic applications

Single axis trackers have one degree of freedom that acts as an axis of rotation [3]. Single axis solar tracking systems [4] and [5] normally follow the sun's trajectory by only changing the azimuth angle, whilst the tilt angle is constant. They require only one driving motor and can substantially improve utilization of the available solar radiation when compared with the fixed PV systems. However, they are unable to utilize the available solar radiation in the best possible way.

Single axis tracking system shown in Fig. 2 follows the path of the sun by changing the azimuth angle Ψ from east to west, while the tilt angle is fixed. Considered single axis tracking system is designed primarily for commercial implementation of traffic signals, cameras on highways and other places for antennas and street lights and other small consumers. Tracking system is suitable for installation of photovoltaic modules area of 1 m^2 to 3.4 m^2. Tracking system follows the path of the sun by the electric drive $PS_1 1$. The torque required to change the angle is generated by the permanent magnet DC (PMDC) motor supplied by 24 V batteries.

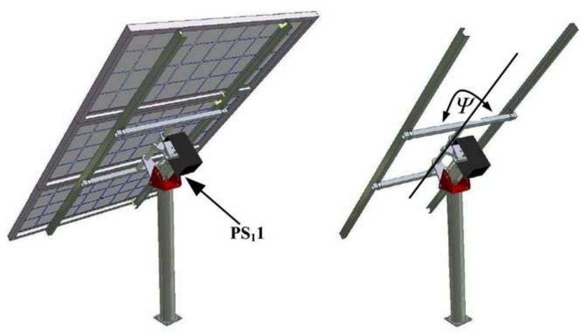

Fig. 2. Single axis solar tracker.

B. Dual axis trackers for photovoltaic applications

Dual axis trackers have two degrees of freedom that act as axes of rotation. These axes are typically normal to one another. The axis that is fixed with respect to the ground can be considered the primary axis. The axis that is referenced to the primary axis can be considered the secondary axis [3].

Dual axis solar tracking systems [6] – [8] follow the sun's trajectory by changing both, the azimuth and the tilt angles, and require two driving motors. They contain more moving parts and are, in general, more expensive than the single axis systems.

The discussed dual axis solar tracking system is presented in Fig. 3, where β is the PV module tilt angle, while aw is the azimuth angle. The upper system (PMDC 2 = $PS_2 2$), shown in Fig. 3, changes the tilt angle β moving in the direction north–south, while the lower system (PMDC 1 = $PS_2 1$) changes the azimuth angle a_w moving in the direction east–west. The torque required to change both angles is generated by the PMDC driving motors supplied by 24 V batteries. The gear ratio for changing the tilt angle β is 12:40:15, while the gear ratio for changing the azimuth angle aw is 12:40:52. The discussed solar tracking system is an industrial product bought to the market. The PV platform with the total mass of 193.6 kg and with the center of gravity in the middle of its surface is schematically shown in Fig. 3. The center of gravity is aligned with the reference axis for the tilt angle β. The total active surface of the PV modules is from 3 m^2 to 9 m^2. They are electrically connected in series and supply the converter.

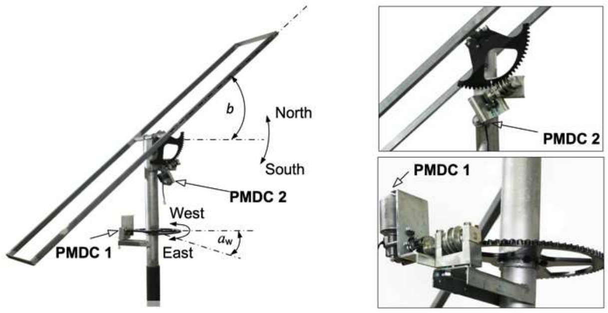

Fig. 3. Dual axis solar tracker.

3. Actuation and control systems of solar trackers

There exist two kinds of tracking systems, the closed- and open-loop control systems. The closed-loop systems, shown in Fig. 4, use photo sensors and feedback controllers to position the PV panels [8]. In cases of changing weather the closed-loop controlled systems can spend more energy than they gain, which is due to the permanent changes in the azimuth and tilt angles. The open-loop systems [9], shown in Fig. 5, are based on different mathematic algorithms that can be applied for off-line calculation of the solar tracking systems trajectories. The calculation of these trajectories is based on the relative position of the sun which can be precisely calculated for any time and any location on the Earth. The hybrid control systems [10] include the closed- and open-loop tracking strategies.

In all these systems the attention must be paid to the energy consumption of drive components, because additional losses for the photovoltaic system are unnecessary.

Fig. 4. Closed-loop control systems.

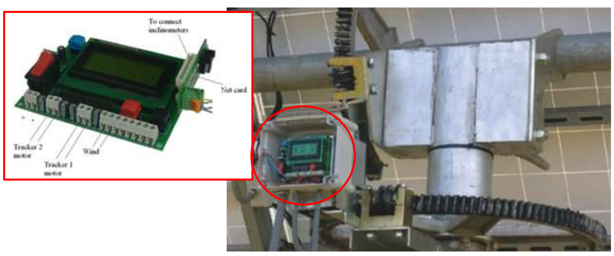

Fig. 5. Open-loop control systems.

4. Actuation and control systems of solar trackers

For the single axis and dual axis solar tracking system, the characteristics of the energy consumption per unit change in the azimuth and tilt angle were determined by the measurements. The energy consumed in the tracking system is often considered as the loss of energy produced in the PV system. The tracking system energy consumption characteristics contain the start-up of the driving permanent magnet DC (PMDC) motors and their operation at a constant speed.

During the tests, the instantaneous values of the tilt angle β and the azimuth angle aw are measured together with the PMDC driving motor voltage u and current i. The angles are measured using the incremental encoders with 5000 pulses per revolution, while the differential probes and the LEM sensors were used for the voltage and current measurement. The control system dSpace 1103 PPC with the sampling time of 1 ms is used for data acquisition. The tests are performed systematically, starting from the different initial angles for β and a_w. Each test contains the start-up of the motor, followed by the operation at constant speed. For each test, the energy consumption in the solar tracking system $W_C(t)$ is calculated by (1) using the measured voltage $u(t)$ and current $i(t)$.

$$W_{C\bullet} = \int_{o}^{t} u(\tau)i(\tau)d\tau + W_C(0) \qquad (1)$$

Where energy consumption $W_{C\bullet}(t)$ are $\bullet\in\{1\Psi, 2\Psi, \text{in } 2\beta\}$ for $PS_1 1$, $PS_2 1$ in $PS_2 2$ and $W_C(0)$ is the initial condition of the energy consumption.

The paper shows the energy consumption as a function of angle changes of the single axis and dual axis tracking system. The first case shows the single axis tracking system that uses one electric drive $PS_1 1$. $PS_1 1$ changes the azimuth angle Ψ. By determining the energy consumption several different tests were performed. The tests showed that the initial position of the azimuth angle Ψ does not affect the determination of energy consumption. In this case, the starting position of the azimuth angle Ψ is changed from 0˚ to 120˚, where the starting position of the azimuth angle Ψ=0˚ means extreme east orientation. Fig. 6 shows energy consumption W_{C1} as a function of change of the azimuth angle Ψ. Fig. 6 shows only the first part of measurements, where the initial position of the azimuth angle is being changed from 0˚ to 50˚. Example: The green line in Fig. 6 represents the energy consumption in changing the azimuth angle W_{C1} from 10˚ to 15˚ ($\Delta\Psi$=5˚).

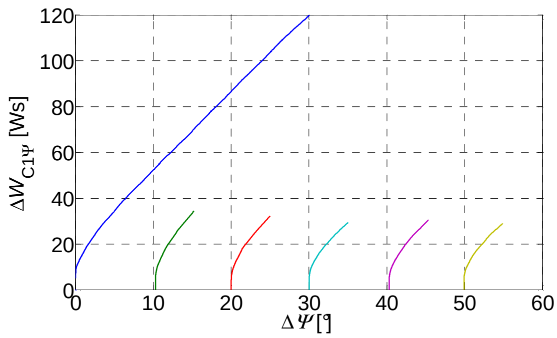

Fig. 6. Energy consumption W_{C1} as a function of angle changes of the single axis tracking system.

The same procedure as described for single axis tracking system was also used for dual axis tracking system. The electric drive $PS_2 1$ changes the azimuth angle Ψ, the electric drive $PS_2 2$ changes the tilt angle β of dual axis tracking system as shown in Fig. 3. Several different tests were performed for determining the energy consumption of $PS_2 1$ and $PS_2 2$. The tests showed that the initial position of the azimuth angle Ψ and tilt angle β does not affect the determination of energy consumption. Figs. 7 and 8 show that measured azimuth angle Ψ and tilt angle β have slightly higher speed when starting-up than in steady state.

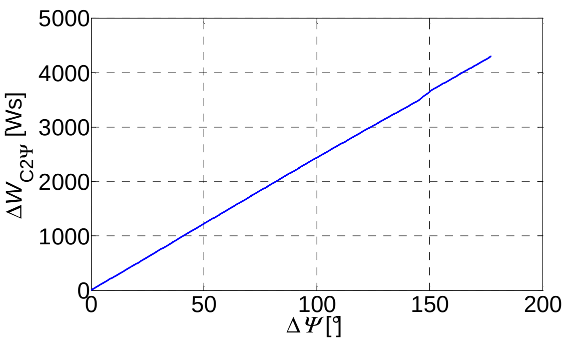

Fig. 7. Energy consumption W_{C2} as a function of angle changes of the dual axis tracking system.

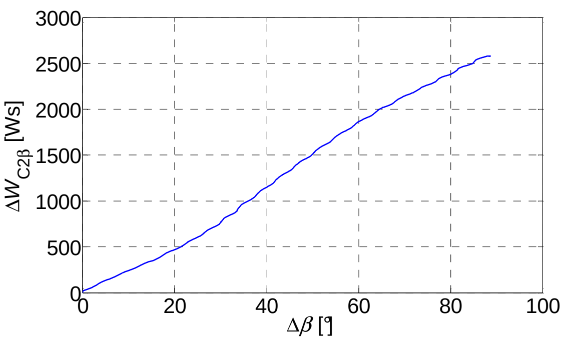

Fig. 8. Energy consumption W_{C2} as a function of angle changes of the dual axis tracking system.

Analysis of measured results shows that the initial state of the azimuth angle Ψ and tilt angle β does not affect the time-dependent characteristic of tracking systems. This means that for the further analysis, the energy consumption of the tracking systems can be written as the characteristics $W_{C1}(\Delta\Psi)$, $W_{C2}(\Delta\Psi)$ and $W_{C1}(\Delta\beta)$.

5. Conclusion

The goal of the paper is to show different types of tracking systems and their controlling. So there are different types of actuation and supplying of electric drive. The electric drives of tracking systems can be supplied directly by the electric grid or by a separate photovoltaic module.

The analysis shows that the energy consumption of the electric drives cannot be neglected and it should be considered in planning of photovoltaic tracking systems. In the case of clear days the production of electric energy by tracking systems can be up to 35% higher compared to a fixed photovoltaic system. In the paper the maintenance and reliability of operation are not considered.

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