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The optimal tracking strategies for two-axis PV system

Abstract. *This paper deals with two-axis tracking system of photovoltaic (PV) systems. The new method for determining the optimal trajectories of the tracking system is proposed. The optimization goal is the maximum of electric energy production in the PV system, considering the consumption of the tracking system. The determination of the tracking system trajectories is described as a non-linear and bounded optimization problem. The stochastic search algorithm called differential evolution is used as an optimization tool.*

Streszczenie. *Artykuł przedstawia system dwu-osiowego sterownia systemem fotowoltaicznym. Zaproponowana została nowa metoda określania optymalnej trajektorii systemu. Celem optymalizacji jest uzyskanie maksymalnej energii wyprodukowanej w systemie fotowoltaicznym z uwzględnieniem wydatku energii na system sterowania. Określenie trajektorii systemu stanowiło rozwiązanie nieliniowego problemu z ograniczeniami. Jako narzędzie zastosowano algorytm stochastyczny ewolucyjny.(**Optymalne strategie sterowania dwuosiowym systemem fotowoltaicznym**)*

Keywords: two axis tracking system, electromechanical system, solar radiation, differential evolution.
Słowa kluczowe: dwuosiowy system naprowadzania, system elektromechaniczny, promieniowanie słoneczne, ewolucja różniczkowa

Introduction

European union's directive upon increasing the production of electricity from the renewable energy till 2020 has contributed to the growth of photovoltaic (PV) systems connected to the electric grid. The main elements of the PV systems are solar modules which convert the solar radiation directly into the electricity. The efficiency of this conversion depends on the solar radiation that reaches the surface of the solar cells, the temperature of the solar cells, the impedance matching between the solar modules and dc/dc converters, and the quality of the inverters.

This paper focuses on the increase of energy conversion efficiency which can be achieved by the use of two-axis PV tracking systems. The solar radiation that reaches the Earth's surface depends mainly on the conditions in the atmosphere, which cannot be influenced by the control of the PV system. However, the utilization of the solar radiation that reaches the Earth's surface can be influenced by the sun tracking system. In the case of clear days the direct radiation represents the main contribution to the total radiation. The solar radiation on the surface of a PV module is the highest, when the normal to the surface of the PV module is aligned with the direction of the sunbeams. This can be achieved by the correct use and control of the electric drives in the sun tracking system.

An overview of the solar cell technologies and their efficiencies is presented in [1] while the impact of the solar cell temperature on the energy conversion efficiency is discussed in [2]. When the solar cell technology, the solar cell temperature and the solar radiation that reach the solar cell surface, are given, the efficiency of the energy conversion in the solar cells connected in PV modules depends primarily on the impedance matching. It is well known as the Maximum Power Point Tracking (MPPT). Some solutions for MPPT are presented in [3] to [5].

This paper focuses on the sun tracking systems which follow the trajectory of the Sun. Tracking systems are the electromechanical systems consisting of the mechanics, electronics and information technology [6]. Basically, there are two types of tracking systems. The authors in [7, 8] constructed and tested a single-axis tracking system, while the authors in [9] to [11] constructed and tested a two-axis tracking system. They reported about 20% to 50% increase in the efficiency of solar energy conversion, when compared with the fixed PV systems. Many companies, like Lorentz.de, Solar-trackers.com, Ecoware.eu, etc., produce the PV tracking systems. However, these companies give only the basic information related to the tracking systems whereas the detailed explanations related to the tracking system trajectories and the control are not available. They could be found in the articles on this topic like [6] to [10].

Generally, there exist two kinds of tracking systems, the closed- and the open-loop controlled tracking systems. The closed-loop systems use photo sensors and feedback controllers for positioning the modules [12]. The photo sensors send the electrical signals to the controller that activates the motor. The other possibility is to use the open-loop systems [13]. They are based on the mathematical algorithms that may provide predefined trajectories for the tracking systems. These trajectories can be accurately determined because the position of the Sun can be precisely calculated at any time for any location on the Earth [14]. The hybrid control systems [15] combine the open-loop tracking strategies based on the solar movement models and the closed-loop control using the dynamic feedback controllers.

This paper presents a new method which maximizes the efficiency of the solar energy conversion in PV systems. The idea is to develop an open-loop two-axis sun tracking system shown in Fig. 1. The tracking system trajectories are determined in such a way to maximize electricity production in the PV system considering the tracking system consumption. The tracking system consumption is subtracted from the PV system produced energy. The characteristics of the energy consumption per unity change in the azimuth and the tilt angle are measured. They contain the start-up of the driving permanent magnet dc (PMDC) motors as well as the operation at constant speed. The tracking system trajectories are determined in an optimization process using a stochastic search algorithm called Differential Evolution (DE) [16] as an optimization tool.

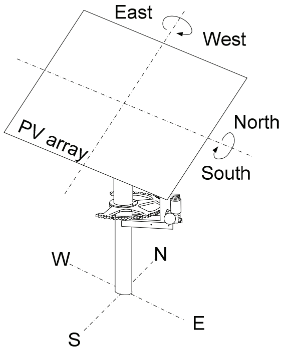


Fig.1. Two-axis sun tracking system

Electric drive of two-axis tracking system

The mechanics of discussed two-axis tracking system is shown in Fig. 2. It follows the path of the sun in two axes which are mechanically decoupled and move independently from each other. The lower electric drive (PMDC 1), shown in Fig. 2, moves the PV panels from East to West while the upper electric drive (PMDC 2) moves the PV panels from North to South. The PMDC 1 changes the tilt angle β, while the PMDC 2 changes the azimuth angle a_w. The torque required to change the both angles is generated by 24 V PMDC driving motors. The gear ratio for changing the tilt angle β is 12: 40: 15, while the gear ratio for changing the azimuth angle a_w is 12:40:52.

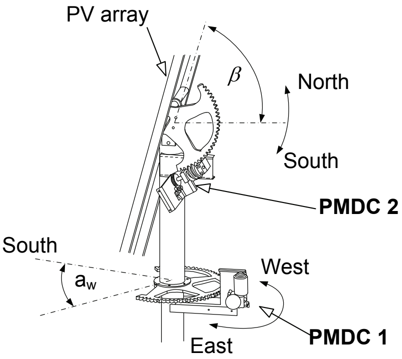


Fig.2. Mechanics of two-axis tracking system

Fig. 3 shows the characteristics of energy consumption E_C in the sun tracking system required to change the tilt angel β and the azimuth a_w for the angle Δ. Both characteristics, shown in Fig. 3, are determined by the measurements performed on the discussed two-axis sun tracking system shown in Fig. 2. Both angles can be changed only by switching on and off 24 V supply voltages of the PMDC motors. After the start-up of the PMDC motors, the angular speed is constant, while the minimum angle change is limited to $\Delta = 2^0$ due to the time delays in switching elements.

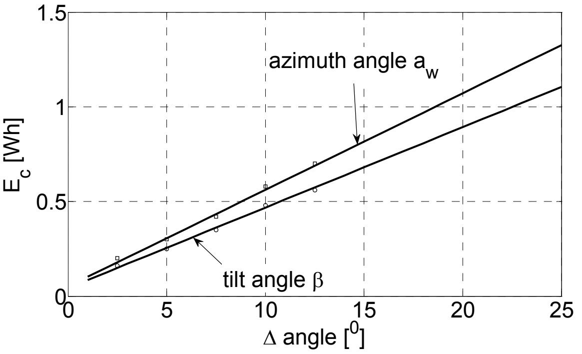


Fig.3. Energy consumption characteristics E_C of both PMDC drives given as functions of angle change Δ

In an ideal case, when the tracking system losses are neglected and the variable speed drives are applied, the azimuth angle and the tilt angle trajectories change in such a way that the normal on the surface of PV modules is all the time aligned with the direction of the sunbeams. Unfortunately, in the real sun tracking system each change of the position spends the energy. After the start-up the angular speed of the PMDC motor is constant. The trajectories of the tilt and the azimuth angle are determined in the optimization procedure. The determined trajectories show when and for how many degrees the angles should be changed in order to achieve the maximum of energy produced in the PV system considering the energy consumption in the tracking system.

Solar radiation on inclined surface

The first step in a calculation of the electric energy produced in a PV system is a calculation of the instantaneous values of a solar radiation that reaches the surface of the PV modules. The instantaneous electric power of the PV system depends on the solar radiation that reaches the surface of the PV panels, the active surface of the panels, their efficiency and applied MPPT. The electric energy produced in the PV system is calculated by the integration of the instantaneous PV system electric power over the given time interval.

The model for prediction of the solar radiation on the Earth's surface in the form of the time dependent function is described in [17]. It is given as a function of the sun beams path length in the atmosphere, whereas the model parameters are determined using the measured data of the solar radiation in the last five years. The procedure for calculating the solar radiation on a tilted surface is presented below. The predicted values of the total I_h, direct $I_{b,h}$ and diffuse $I_{d,h}$ solar radiation on a horizontal surface are required to determine the total solar radiation I_c on the surface of a PV module, with the tilt angle β and the azimuth angle a_w. The angles are shown in Figs. 2 and 4, while the solar radiation I_c is given by (1) [14]:

$$\begin{aligned} I_c &= I_{b,h}\frac{\cos i}{\sin\alpha} \\ &+ I_{d,h}(1+\cos\beta)/2 + \rho I_h(1-\cos\beta)/2 \end{aligned} \tag{1}$$

where ρ is the ground reflectance while i is the incident angle of the direct radiation on the tilted surface. i is related to the solar angles shown in Fig. 4 by (2):

$$\cos i = \cos\alpha\cos(a_s - a_w)\sin\beta + \sin\alpha\cos\beta \tag{2}$$

where a_s is the solar azimuth angle and α is the solar altitude angle given by (3).

$$\begin{aligned} &\sin\alpha = \sin L\sin\delta_s + \cos L\cos\delta_s\cos h_s \\ &h_s = 15^0(12-T) \end{aligned} \tag{3}$$

L is the latitude angle, δ_s is the solar declination, h_s is the solar hour angle and T is the local time.

To determine the tracking system trajectories some presumptions were made. At the present stage, the procedure is appropriate to be applied for the sunny days with the clear sky.

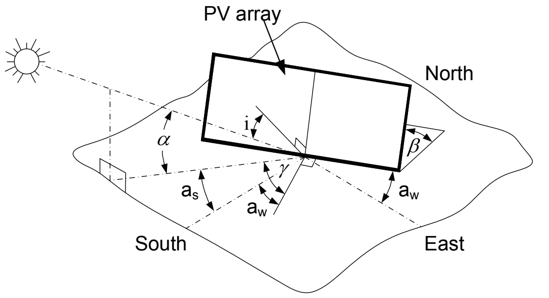


Fig.4. Definitions of solar angles for a tilted surface

The mathematical model for predicting the solar radiation described in [17] and mathematical expressions from (1) to (3) are used to determine the solar radiation on the surface of a PV panel with the tilt angle β and the azimuth angle a$_w$ in any time instant t in the interval $t \in [t_0, t_0+\Delta t]$. Assuming proper operation of MPPT, DC/DC converter and inverter, the total efficiency of the PV system can be given by η_{PV}. Considering the time dependent solar radiation $I_c(t)$ and the surface of the PV modules A_{PV}, the energy E_{PV}, produced in the PV system in the interval $t \in [t_0, t_0+\Delta t]$, is calculated by (4).

$$E_{PV} = \eta_{PV} A_{PV} \int_{t_0}^{t_0+\Delta t} I_c(\tau) d\tau \tag{4}$$

Tracking system trajectories determined by Differential Evolution

The authors in [6] and [18-20] have presented the different sun tracking algorithms which should maximize the energy produced in the PV systems considering the consumption of the tracking system. These intuitive algorithms are based on the maximal change of the angle and the operating time of the tracking system. However, none of these intuitive algorithms are optimization based. The objective functions which should be minimized in the optimization process are not given. On the contrary, this paper presents an optimization based method for determining the optimal trajectories of the sun tracking system. The optimization goal is the maximum of the energy produced in the PV system considering the sun tracking system consumption. The optimal trajectories are determined by the DE [16].

This subsection presents the procedure for determining those trajectories of the tilt angle $\beta(t)$ and the azimuth angle a$_w$(t), which give the maximum of the energy produced in the PV system, considering the energy consumption in the sun tracking system. The energy is consumed for changing the tilt and the azimuth angle during the day and to move the system in its initial position at the end of the day.

Let us suppose an ideal case where the tracking system consumption is neglected, while the sun tracking system continuously follows the trajectory of the Sun in such a way that the normal on the surface of the PV modules is all the time aligned with the direction of the sunbeams. In this case, the energy production of the PV system is maximal and it is marked with the $E_{\mathrm{PV\,ideal}}$. The discussed two-axis sun tracking system does not contain variable speed drives, which means that the continuous tracking trajectories cannot be realized. The driving PMDC motors can only be switched-on and -off, which means that after the start-up they run at constant the speed. In this way the tilt and the azimuth angles can be changed causing the energy consumption according to the characteristics shown in Fig. 3. Thus, the trajectories of the tilt angle β and the azimuth a$_w$ are functions changing in steps. The height of the individual step changes $\Delta\beta$ and Δa$_w$ as well as the time between the two changes of the individual angles Δt_β and Δt_{aw} are determined in the optimization procedure. The objective function q is defined by (5):

$$q = E_{PV\ ideal} / (E_{PV} - E_C)\,, \tag{5}$$

where $E_{\mathrm{PV\,idela}}$ is the electric energy produced in the PV system with an ideal continuous sun tracking without any energy consumption, E_{PV} (4) is the electric energy produced in the actual PV system with the stepwise changing tilt and the azimuth angles of the sun tracking system, while E_C is the energy consumption in the sun tracking system determined by the summing up energy consumption according to the characteristics shown in Fig. 3 for all changes in the tilt and the azimuth angles.

In the optimization process, the DE determines the stepwise changing tilt and azimuth angle trajectories $\beta(t)$ and $\mathbf{a_w}(t)$ over the interval of observation $t \in [t_0, t_0+\Delta t]$. They are given in the vector form (6):

$$\begin{aligned} \boldsymbol{\beta}(t) &= \left[\beta_1(t_{\beta 1}), \beta_2(t_{\beta 2}), \ldots, \beta_n(t_{\beta n})\right] \\ \mathbf{a_w}(t) &= \left[a_{w1}(t_{a_{w1}}), a_{w2}(t_{a_{w2}}), \ldots, a_{wm}(t_{a_{wm}})\right] \end{aligned}, \tag{6}$$

where n and m are the numbers of the individual angle changes, β_1 to β_n, and a$_{w1}$ to a$_{wm}$ are the individual angles, while $t_{\beta 1}$ to $t_{\beta n}$ and t_{aw1} to t_{awm} are the time discrete points of the individual angle changes, all determined in the optimization procedure.

In the optimization process, the time interval is bounded to 24 hours, where $\Delta t = 0.5$ s is the time step for calculations. The DE [16] imitates the evolution in the nature. Each individual in the population is characterized by the trajectories $\beta(t)$ and $\mathbf{a}_w(t)$ (6) determined by the DE. They are used to calculate the instantaneous values of the total solar radiation on the surface of the module I_c (1), the electric energy produced in the PV system E_{PV} (4), the energy consumption in the sun tracking system E_{C} and, finally the objective function value q (5). The value $E_{\mathrm{PV\,ideal}}$ is known. According to the DE algorithm [16], the objective function values improve from generation to generation until the minimum is reached. The subject with the best value of the objective function is characterized by the sun tracking system trajectories (6) which give the maximum of the electric energy produced in the PV system considering the PV system consumption.

The efficiency ε (7) is introduced in [6] to evaluate the effects of the tracking system, where $E_{\mathrm{PV\,fix}}$ is the electric energy produced in the PV system without the sun tracking

$$\varepsilon = (E_{PV} - E_{PV\,fix}) - E_C \tag{7}$$

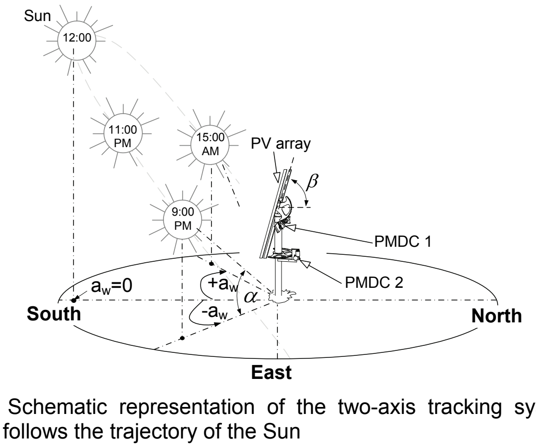


Fig.5. Schematic representation of the two-axis tracking system which follows the trajectory of the Sun

Results

The model used in the optimization procedure is confirmed through the comparison of measured and calculated power of a fixed PV system with the tilt angle 23^0.

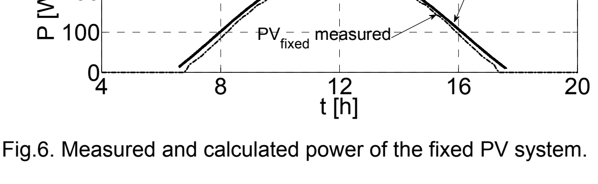
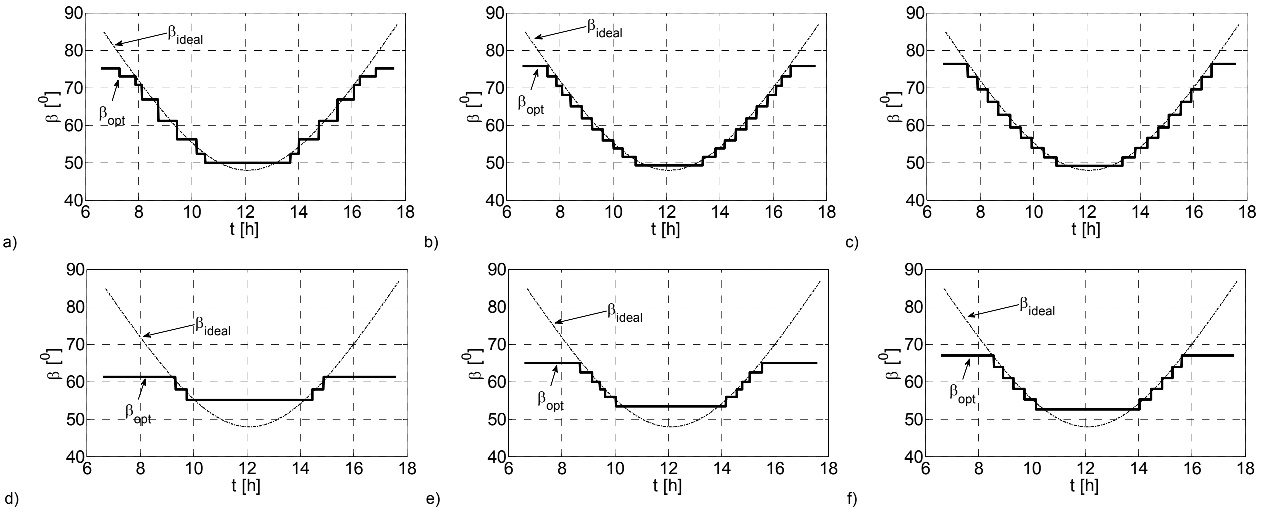
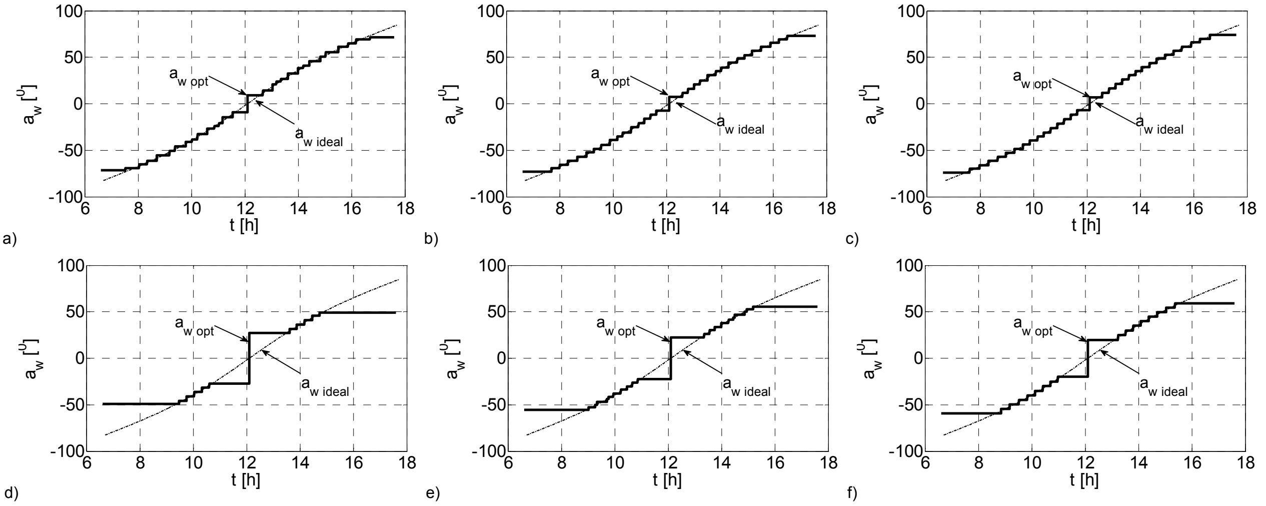


Fig.6. Measured and calculated power of the fixed PV system.



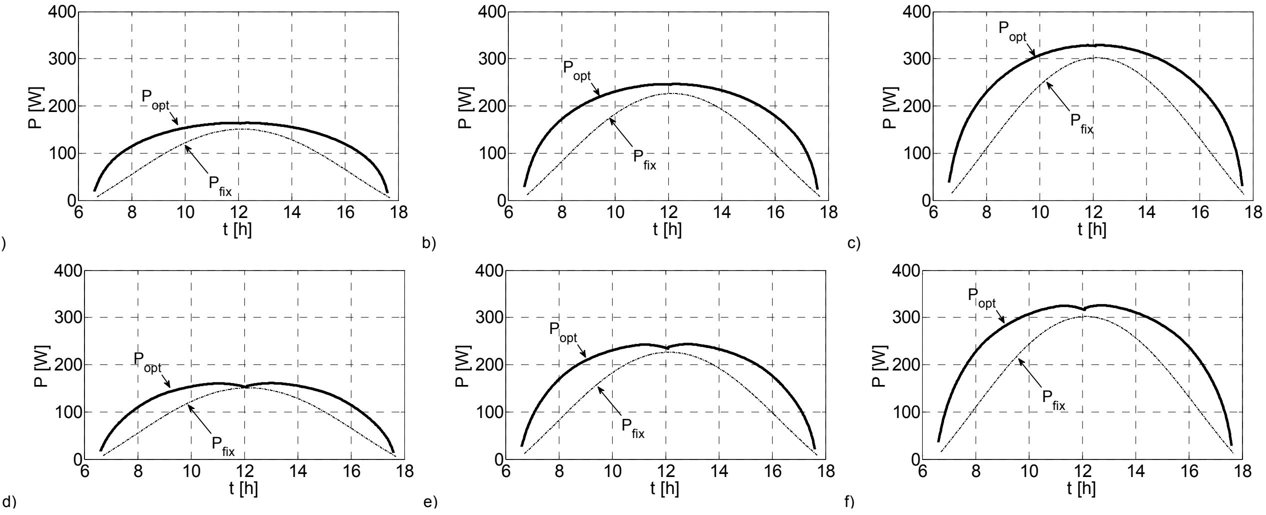
a) b) c) d) e) f)

Fig.7. Trajectories of the tilt angle β. a) for the PV system with η_{PV} = 7.5%, E_c = 0.05 Wh/deg; b) for the PV system with η_{PV} = 10%, E_c =0.05 Wh/deg; c) for the PV system with η_{PV} = 12.5%, E_c =0.05 Wh/deg; d) for the PV system with η_{PV} = 7.5%, E_c =0.5 Wh/deg; e) for the PV system with η_{PV} = 10%, E_c =0.5 Wh/deg; f) for the PV system with η_{PV} = 12.5%, E_c =0.5 Wh/deg.



a) b) c) d) e) f)

Fig.8. Trajectories of the azimuth angle a_w. a) for the PV system with η_{PV} = 7.5%, E_c = 0.05 Wh/deg; b) for the PV system with η_{PV} = 10%, E_c =0.05 Wh/deg; c) for the PV system with η_{PV} = 12.5%, E_c =0.05 Wh/deg; d) for the PV system with η_{PV} = 7.5%, E_c =0.5 Wh/deg; e) for the PV system with η_{PV} = 10%, E_c =0.5 Wh/deg; f) for the PV system with η_{PV} = 12.5%, E_c =0.5 Wh/deg.



a) b) c) d) e) f)

Fig.9. Power of the PV system. a) for the PV system with η_{PV} = 7.5%, E_c = 0.05 Wh/deg; b) for the PV system with η_{PV} = 10%, E_c =0.05 Wh/deg; c) for the PV system with η_{PV} = 12.5%, E_c =0.05 Wh/deg; d) for the PV system with η_{PV} = 7.5%, E_c =0.5 Wh/deg; e) for the PV system with η_{PV} = 10%, E_c =0.5 Wh/deg; f) for the PV system with η_{PV} = 12.5%, E_c =0.5 Wh/deg.

All results presented in this section are given for the PV system with the active surface of 3.4 m^2 and the coordinates 46^{0}33' N and 15^{0}39' E. The trajectories of the tilt β_{opt} and the azimuth $a_{w\,opt}$ angle determined in the optimization process are shown in Figs. 7 and 8, while Fig. 9 shows the corresponding power of the PV system with the sun tracking P_{opt} and the power of the fixed PV system P_{fix}. The fixed PV system is oriented to the South and has the tilt angle β=23^0. All results are given for the 267th day in the year. The Figs. 7 to 9 a), b) and c) are given for the tracking system consumption presented in Fig. 3 and thePV system efficiencies η 7.5%, 10%, and 12.5%, respectively. The results presented in Figs. 7 to 9 d), e) and f) are given for the tracking system consumption shown in Fig. 3 multiplied by 10, and PV system efficiencies η 7.5%, 10%, and 12.5%.

As it can be seen from the results, shown in Figs. 7 to 9, the optimization process determines the optimal trajectories of the tracking system according to the input data. The optimal trajectories of the tracking system depend on the efficiency of the PV system and the tracking system consumption.

Table 1 and 2 show the electric energy produced, the efficiency of the tracking system compared to the fixed system and the efficiency determined by (7).

Table 1. The energy of the PV system

	PV system η_{PV} = 7.5%, E_c =0.05 Wh/deg	PV system η_{PV} = 10%, E_c =0.05 Wh/deg	PV system η_{PV} = 12.5%, E_c =0.05 Wh/deg
Fixed [kWh]	1.048	1.572	2.096
Two-axis (E_{PT} - E_c) [kWh]	1.447	2.172	2.897
Tracking system (E_c) [Wh]	15.9	16.5	16.9
Efficiency [%]	138.07	138.16	138.21
ε	383.5	583.8	784.0

Table 2. The energy of the PV system

	PV system η_{PV} = 7.5%, E_c =0.5 Wh/deg	PV system η_{PV} = 10%, E_c =0.5 Wh/deg	PV system η_{PV} = 12.5%, E_c =0.5 Wh/deg
Fixed [kWh]	1.048	1.572	2.096
Two-axis (E_{PT} - E_c) [kWh]	1.409	2.141	2.869
Tracking system (E_c) [Wh]	77.4	100.1	112.7
Efficiency [%]	134.44	136.19	136.87
ε	283.2	469.2	660.9

Conclusion

This paper proposes a new optimization based method for determining the optimal tilt and azimuth angle trajectories of PV systems with two-axis sun tracking system using the constant speed drives. The optimization goal is the maximization of the energy produced in the PV system considering the consumption in the tracking system, which means the maximum gain of the energy. At the present stage, the proposed method is appropriate for determining the optimal sun tracking system trajectories for all sunny days of the year. The results presented in the paper show that the PV system efficiency and the energy consumption in the tracking system substantially influence the optimal tracking system trajectories.

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