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Innovative bi-axial tracking mechanism for PV modules

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Abstract. The paper deals with an innovative bi-axial tracking mechanism for a group of photovoltaic (PV) modules, which combines the features of the classical platform and string configurations. For the daily movement (corresponding to the primary axis), the sun tracking is performed as in the case of a PV platform, while the elevation movement (around the secondary axis, which is referenced to the primary one) is transmitted similar to the case of a string of PV modules. The sun tracking is conducted by an open-loop control strategy, based on a predefined step-by-step algorithm, which was designed so that to capture as much as possible incident solar radiation with a minimum energy consumption for achieving the orientation. The modeling, simulation and optimization of the solar tracker is performed by using the virtual prototyping package ADAMS.

Key words. PV module, tracking mechanism, multi-body system, open-loop control, optimization.

1. Introduction

The research in the field of renewable energy systems is a worldwide priority, because they provide viable alternatives to a series of major issues that humanity is facing today: the limited and polluting character of the fossil fuels, the global warming, or the greenhouse effect. The solar energy is the most important source of renewable energy, which can be converted into electric or thermal energy. The method of converting solar radiation into electricity is well known: the photovoltaic (PV) effect. The PV conversion efficiency depends on the quality and type of solar cells, their temperature, and the amount of received solar radiation.

Solar trackers can be added to the PV systems in order to capture an increased amount of solar energy, thus improving the energetic efficiency (from 20% up to 50%) [1-3]. According to the relative movements in the Sun-Earth astronomical system, two groups of solar trackers can be defined: mono-axial (which are used to adjust the daily or altitudinal position of the PV module), and bi-axial (which are able to adjust the both daily and elevation angles, thus assuring a more accurate orientation of the PV module). The solar trackers are actuated by linear or rotary actuators, which are controlled through various strategies, based on use of predefined tracking algorithms (open-loop control) or photo-sensors (closed-loop) [4-6].

The solar trackers can be systematized according to the PV modules placement scheme, as follows: tracking mechanisms for stand-alone PV modules, tracking mechanisms for PV strings, and tracking mechanisms for PV platforms. This paper proposes an innovative design/configuration of bi-axial tracking mechanism, which combines the features of the classical platform and string setups, meaning that the PV modules are disposed on stand-alone strings that in their turn are mounted on a common platform. The orientation of the PV string platforms opens a research area insufficiently explored since now, in the scientific literature being mostly addressed the classical solutions mentioned above.

In order to identify the type of mechanism that is most appropriate for the orientation of the string platform, the four basic bi-axial solar trackers (depending on the orientation and relative positioning of the two revolute axes) were considered: polar (equatorial), pseudo-polar(-equatorial), azimuthal, and pseudo-azimuthal [7]. Given their functional and constructive characteristics, it was determined that the pseudo-azimuthal mechanism is the most appropriate for the string platform design. The pseudo-azimuthal mechanism (Figure 1, a), which is derived from the classical azimuthal system (Figure 1, b), has the primary revolute axis (for the daily movement - 1) positioned on horizontal direction, while in the azimuthal system this axis is vertically disposed. Thus, a more stable structure is obtained. In both designs, the same positioning of the secondary revolute axis (for the elevation movement - 2) is used.

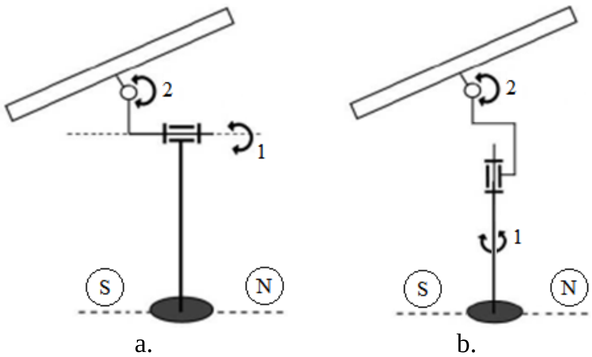


Fig. 1. The schematics of the pseudo-azimuthal (a), and azimuthal (b) tracking mechanisms.

The research is conducted in two stages: firstly, the innovative design for bi-axial pseudo-azimuthal tracking mechanism is described, starting from a basic solution that subsequently supports certain modifications (derived variants); secondly, the modeling, simulation and optimization of the bi-axial tracking mechanism is carried out by using the virtual prototyping environment ADAMS of MSC Software.

2. The Proposed Design

In the proposed tracking mechanism, the primary axis (which is fixed with respect to the ground) is that of the daily movement, while the secondary axis (which is referenced to the primary one) corresponds to the elevation movement. The bi-axial tracking mechanism, which is shown in Figure 2, contains two subsystems (kinematic loops), one for each of the two degrees of mobility (i.e. the daily and elevation movements).

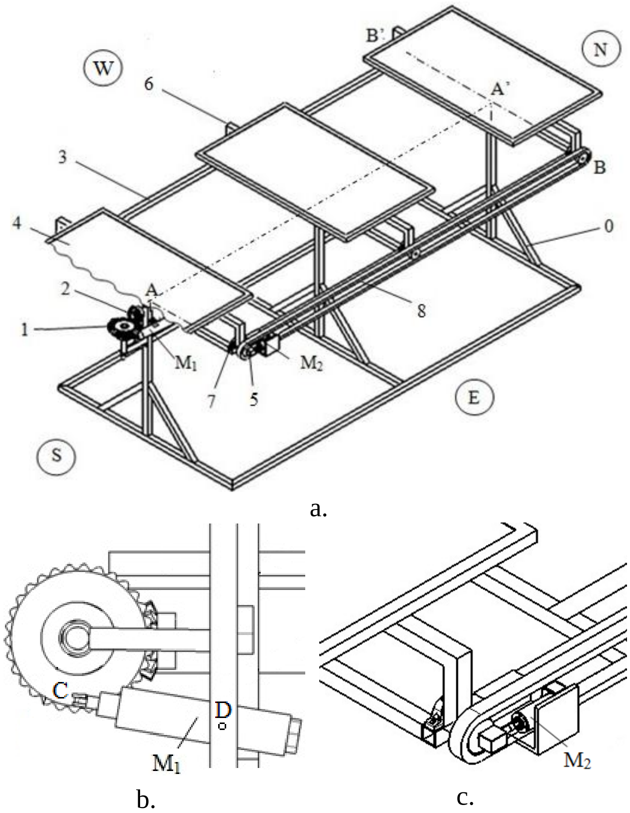
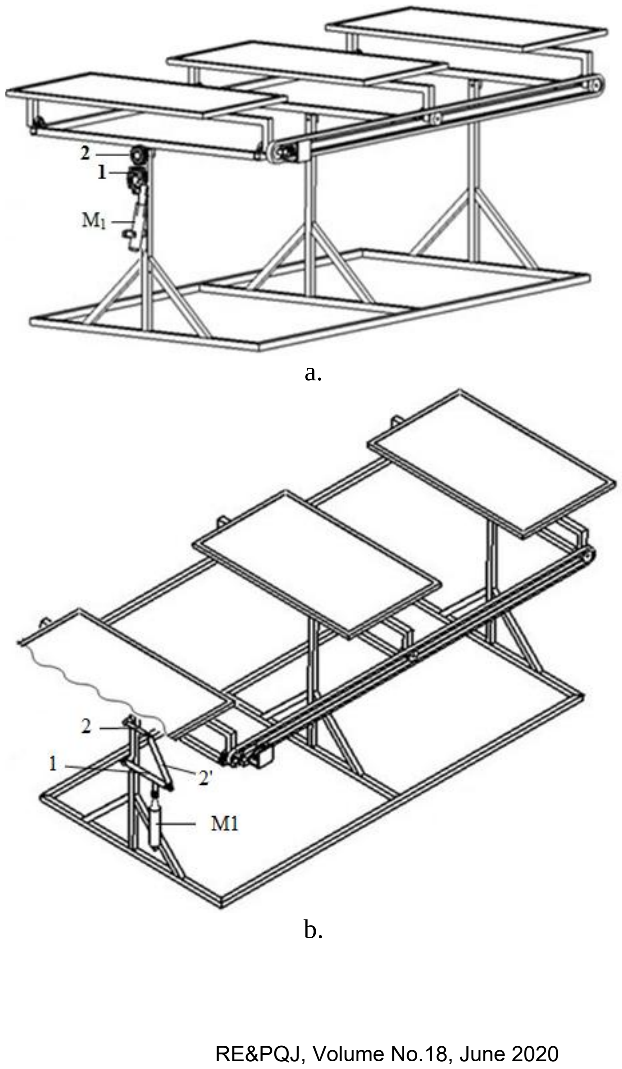


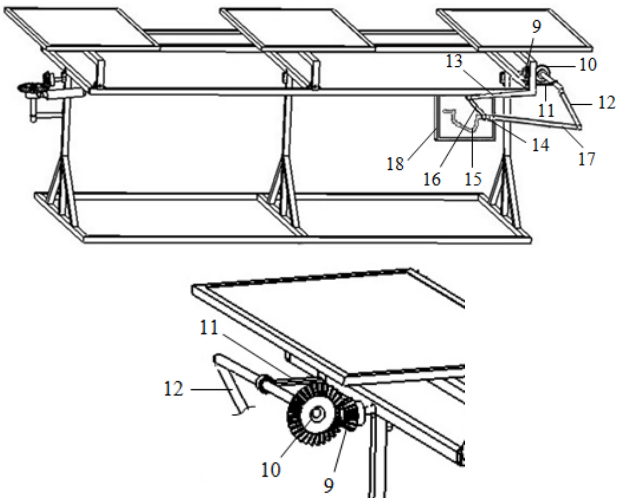
Fig. 2. The bi-axial tracking mechanism for PV string platform.

The daily movement subsystem assures the simultaneous orientation of the PV modules from East (E) to West (W), using as driving element a linear actuator (M_1), the revolute movement (around the primary axis AA') being transmitted to the platform by means of a bevel gear. The driving bevel wheel (1) is connected to the piston of the linear actuator, the piston head being eccentrically disposed relative to the revolute axis of the wheel. The driven bevel wheel is fixedly connected to the revolute axle of the platform frame (3). The two bevel wheels and the linear actuator housing are hinged on the fixed support structure (0). The bevel gear assures two main functions: it amplifies the angular stroke of the platform (acting as a speed multiplier), thus allowing to use a small size linear actuator; it assures the self-blocking of the mechanism in the stationary positions (between actuatings), which is also important when external perturbations (such as wind) occur, through the use of a screw-nut transmission.

The subsystem for the elevation movement assures the simultaneous rotation of the PV modules around the secondary axes BB'. The actuating element is a rotary motor (M_2), whose rotor is connected to a worm gear (5), the driving wheel being coupled to the revolute axle of the first PV module (4). The worm gear ensures both movement irreversibility and amplification, thus allowing using a low power rotary motor. The PV modules are arranged on their own frames (6), which are connected by bearings (7) to the common platform (3). The elevation movement is transmitted to all the string modules by means of a homokinetic belt transmission (8).

Afterwards, the basic solution shown in Figure 2 was changed with the purpose to obtain several derived variants, thus proving the versatility - adaptability of the proposed design, as follows (Figure 3): (a) the use of a cylindrical gear instead of the conical gear for the subsystem of the diurnal movement; (b) the use of a linkage-based motion amplifier instead of the bevel gear for the subsystem of the diurnal movement; (c) the use of a single actuating source (that of the diurnal movement) for controlling the both degrees of freedom of the bi-axial tracking mechanism. All these variants/designs are subject of a recently granted patent [8].





c.

Fig. 3. Derived designs of the bi-axial pseudo-azimuthal tracking mechanism.

In the following, the study is focused on the basic design of the bi-axial pseudo-azimuthal tracking mechanism (shown in Figure 2), the detailed structure of the derived solutions being depicted in reference [8]. The bi-axial mechanism with a single actuating source (Figure 3, c) will be addressed separately in a future work, considering its potential to increase the economic efficiency of the PV system by minimizing the number of motor sources.

3. Modelling, Simulation and Optimization in Virtual Environment

In this section, the modelling, simulation and optimization of the proposed bi-axial pseudo-azimuthal tracking mechanism is carried out through the use of a virtual prototyping platform based on the MBS (Multi-Body Systems) software environment ADAMS (Automatic Dynamic Analysis of Mechanical Systems) of MSC.

The CAD (Computer Aided Design) software solution CATIA (Computer Aided Three-dimensional Interactive Application) was used for conceiving the 3D solid model of the bi-axial tracking system, which contains the bodies/parts mentioned in Figure 2. The solid model was then transferred for the dynamic analysis and optimization into ADAMS by using the CATProduct file format, via ADAMS/Exchange interface. Further, ADAMS/View (the general pre-processing module from the ADAMS package) was used to design the multi-body system model of the mechanical device (including the modelling of the connections between bodies), as shown in Figure 2.

The arrangement of the linear actuator for the daily movement (in terms of global coordinates of the joints on the adjacent bodies - the sustaining pillar and the driving wheel of the bevel gear) was determined by an optimal parametric design process carried out in ADAMS, similarly to the algorithm described in reference [1]. The optimization was configured in the following way:

- design variables - the global coordinates (X, Y, Z) of the connection points (C and D - see Figure 2, b) of the actuator;
- design objective - the power consumed by the linear actuator for performing the imposed movement (tracking) law;
- optimization goal - the minimization of the root mean square (RMS) of the power consumption during simulation;
- design constraints - performing the angular field for the daily movement of the platform (from East to West) with respect to the minimum and maximum lengths of the actuator (when retracted and extended, respectively), so that to avoid the self-blocking of the tracking mechanism (it should be mentioned that the subsystem is sized so that a MecVel L02-FCM linear actuator to be used, with the minimum length of 650 mm, and the stroke of 300 mm).

The OPTDES-SQP (Sequential Quadratic Programming) algorithm from the OptDes code of Design Synthesis, which is one of the algorithms provided with ADAMS/View, was used in the optimization process. The design variables (which are defined by initial - standard values and range limits) are perturbed in the negative direction from the standard value, then again in the positive direction using finite differencing between the perturbed results to compute the gradient (i.e. centered differencing). The optimal design of the mechanism (in terms of linear actuator arrangement) is thus obtained, being found in a configuration that requires a minimum power (so energy) consumption to achieve the movement, and without violating the specified design constraints.

The control system, which is based on the schematic block diagram shown in Figure 4 (for the both movements of the bi-axial mechanism - daily and elevation), was conceived by using the control facilities provided by ADAMS/View Controls Toolkit, with the purpose to establish the motor force/torque applied by the two actuators (linear actuator M_1, and rotary actuator M_2), which actually control the daily and elevation positions (angles) of the PV modules.

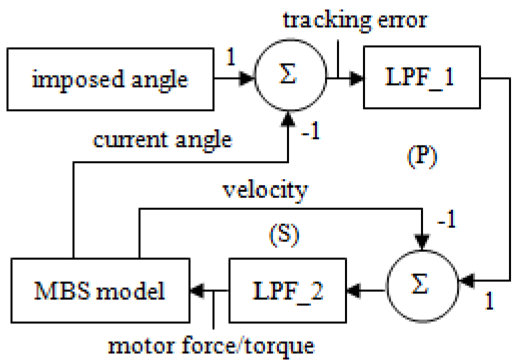


Fig. 4. The control system block diagram.

In the both subsystems (daily and elevation movements), low-pass filters (LPF) have been used to control the movement in accordance with a predefined tracking algorithm (program). Two-loop cascade control schemes have been selected for better tracking accuracy and stability, the primary (P) loop controlling the angular position of the PV platform/modules, while the secondary

(S) loop is used to control the linear or angular velocity of the actuating element. In the MBS model of the mechanical device, the time functions for the motor force (developed by the linear actuator M_1 - for the daily movement) and the motor torque (generated by the rotary motor M_2 - for the elevation movement) are defined by calling/referring the outputs from the LPF controller blocks.

For creating the control system diagram, as shown in Figure 4, the following blocks from ADAMS/View Controls Toolkit have been used:

- Input-Signal Function Block - to model the imposed tracking laws (for the daily and elevation angles of the PV modules) as independent external time functions;
- Input Function Block - to model the current (measured) values of the daily and elevation angles of the PV modules, as well as the corresponding angular velocities with which the two movements are performed, as measures returned (computed) by the MBS model;
- Summing Junction Block - to model the tracking errors by subtracting the outputs from the input function blocks specified above (i.e. the current/measured value of the daily angle is subtracted from its imposed value, thus resulting the tracking error for the daily motion);
- Low-Pass Filter Block - to create the s-domain (Laplace domain) representation of basic linear transfer functions (i.e. the controllers), the filter coefficients being specified as ADAMS/View scalar real values (it should be mentioned that any of these values can be parametrized with an ADAMS/View real design variable to quickly study the effect of varying the bandwidth of the associated block, thus allowing the tuning/optimization of the controller).

The optimization of the position and velocity controllers starts from the transfer function of the low-pass filter, which is defined by the Laplace transform, as follows:

$$\frac{Y(s)}{X(s)} = \frac{K}{\tau s + 1}, \tag{1}$$

where X(s) is the input signal, Y(s) - the output signal, K - the amplification factor of the controller, τ - the time constant of the response (the time in which the system response reaches 1-1/e of the final value, where e is the Euler's number).

Thus, the optimization of the controller aims to determine the optimum value of the amplification factor, which is treated as a design variable, so that the tracking error (the difference between the imposed and measured values - the output of the Summing Junction Block in Figure 4), whose root mean square (RMS) during simulation is treated as a design objective, to be minimal (i.e. the optimization goal). The optimal design of the position and velocity controllers was carried out with the same optimizer/algorithm used for the optimization of the mechanical device (namely, OPTDES-SQP with Centered differencing), but in this case there are no design constraints.

The sun tracking can be performed with a continuous (without brakes) movement, from sunrise to sunset, or by a stepping (step-by-step) movement. Although the continuous tracking would ensure the conditions to capture the maximum available solar radiation, by keeping the angle of incidence to zero (thus, the incident solar radiation equals the amount of direct radiation), in practice, the step-by-step tracking is frequently used (even if the energetic efficiency of the PV system will be lower), because in this way the issues that may arise in the case of continuous tracking are avoided, such as: the dynamic behaviour of the system under the action of non-stationary disturbances (e.g. wind); the need for very high transmission ratios, because the speed with which the continuous orientation would be achieved is very low; the risk of overheating the modules, which would cause a substantial decrease in their efficiency.

Considering the above mentioned, for the study presented in this paper it will be considered that the both movements (daily and elevation) of the bi-axial solar tracker occur in steps. The step-by-step tracking program (which is transposed - implemented in the control system model shown in Figure 4 by the Input-Signal Function Block that models the imposed daily and elevation angles) was established by using an analytic algorithm based on the Melíß's empirical model for estimating the amount of solar radiation [9]. Previous researches have shown that this model is suitable for the climate conditions in the Brașov area [10-12]. The incident solar radiation (R_I) is determined by the following equation:

$$R_I = R_D \cdot \cos i, \tag{2}$$

where R_D is the amount of direct solar radiation (given by the Melíß's empirical model), and i - the angle of incidence (the angle between the sunray and the line perpendicular to the PV module surface), which is computed in correlation with the daily & elevation angles of the PV modules and the corresponding solar/sunray angles for the pseudo-azimuthal system [13].

The bi-axial step-by-step tracking program was established in an optimal parametric design process (with a similar approach to that used for the optimization of the mechanical device and the control system, respectively), which is configured in the following way:

- design variables - the starting position (at sunrise) of the PV system (i.e. the initial values of the daily and elevation angles), the number of tracking steps, the timing table (the time intervals at which the tracking steps are performed), and the tracking step sizes;
- design objective - the energetic efficiency of the bi-axial tracking system, expressing the energy gain obtained by tracking the sun relative to the fixed equivalent PV system, also considering the energy consumed to perform the bi-axial orientation;
- optimization goal - the maximization of the energetic efficiency of the bi-axial tracking system;
- design constraints - the last tracking step (for both daily and elevation movements) must be done / finished before the sunset; the tracking laws are symmetrical relative to the solar noon position.

The energetic efficiency of the bi-axial tracking system was analytically modelled by the following equation:

$$\varepsilon = \frac{E_T - E_F - E_C}{E_F} \cdot 100[\%] , \qquad (3)$$

where E_T is the amount of energy produced by the PV system with bi-axial tracking, E_F - the amount of energy produced by the equivalent fixed (without tracking) system, E_C - the energy consumed for performing the bi-axial orientation. The energy produced (E_T or E_F, by case) is computed depending on the amount of incident solar radiation, the active area of the PV modules and their conversion yield, while the energy consumed for tracking results by integrating the power consumption curve [7].

The mode in which a movement/tracking step was defined is depicted in Figure 5, where t_{k1} / t_{k2} is the starting / ending time of the tracking step, while a_{k1} / a_{k2} are the corresponding angles (daily and elevation, by case) of the PV modules. The differences between the values of the angle and those of the time interval in which the step is performed define the tracking step size ($\Delta a_k = a_{k2} - a_{k1}$) and duration ($\Delta t_k = t_{k2} - t_{k1}$). The initial position/angle from a tracking step (k) is actually the final position from the previous step (k-1), while the final position (after the step is performed) becomes initial position for the next step (k+1), and so on. The scheme shown in Figure 5 covers the both cases regarding the variation of the daily and elevation angle, that is, its increase (dash line) or its decrease (solid line).

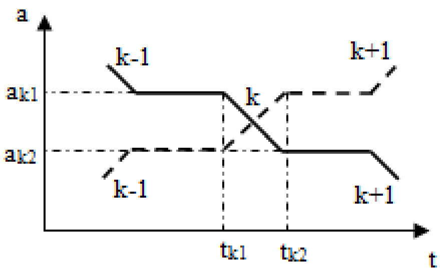


Fig. 5. The configuration of the tracking steps.

The both daily and elevation movements are simultaneously considered in the optimal design of the tracking program, which aims to capture as much incident radiation as possible, but with a minimum number of actuatings (tracking steps). In order to simplify the optimization process, it was considered that all tracking steps for the daily movement have the same size (Δa) and duration (Δt). Thus, noting with a_0 the initial value of the daily angle (in the starting position, at sunrise, facing East), the angular movement domain will be $a \in [a_0, -a_0]$, with the total size "$2 \cdot a_0$", and the steps size (Δa) will result by dividing the total size by the number of tracking steps.

The reference position against which the values of the daily angle of the PV modules are expressed is that from the solar noon position (when the daily angle is null), positive in the morning - facing East. The value of the elevation angle is null when the PV platform/modules are arranged horizontally, positive facing South.

4. Results and Conclusions

For this paper, the numerical simulations were carried out by considering the longest day of the year, June 21 (the summer solstice), and the Brașov geographic area, with the following input data: latitude angle, φ = 45.5°; declination angle, δ = 23.45°; sunrise time, t_r = 4.26; sunset time, t_s = 19.74. The sunrise and sunset times are expressed in solar time, the declination angle being established by the approximate equation of Cooper [14]. The energy conversion system contains 3 PV modules, whose characteristics correspond to a Helios Energy Europe (HEE) module, as follows: active area, S = 1.7 m^2; conversion yield (which is the ratio between the electrical power of the PV module and its area) in standard test conditions, η = 15%.

With the purpose to determine the optimum tracking program, several combinations of values of the number of steps for the daily and elevation movements were performed. The results revealed that the optimum tracking case for the input data mentioned in the previous paragraph is that with 6 tracking steps for the daily movement (to which is obviously added the return run to the initial position, which occurs immediately after sunset) and 2 steps for the elevation movement. The two tracking laws are presented in Figures 6 and 7, alongside with the corresponding variations of the solar angles, the energy consumption curves for performing the tracking being ones shown in Figure 8. Other important results, which prove the viability/usefulness of the proposed bi-axial tracking system, are shown in Figures 9-11, as a comparative analysis between the bi-axial tracking system and the equivalent fixed system.

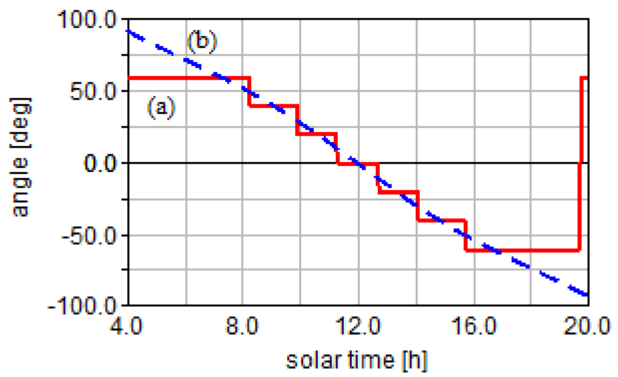


Fig. 6. The daily angle: (a) PV modules, (b) sunray.

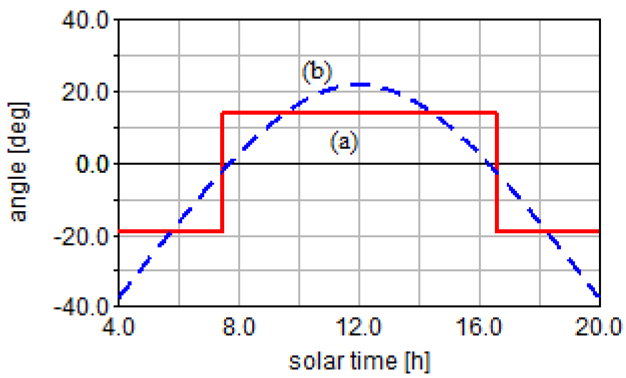


Fig. 7. The elevation angle: (a) PV modules, (b) sunray.

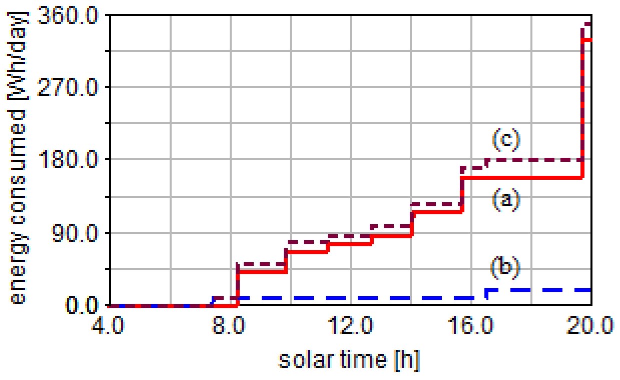


Fig. 8. The energy consumption: (a) daily motion, (b) elevation motion, (c) total consumption.

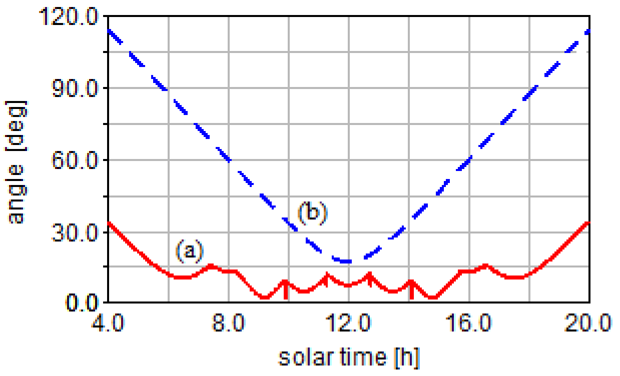


Fig. 9. The angle of incidence: (a) bi-axial PV system, (b) fixed PV system

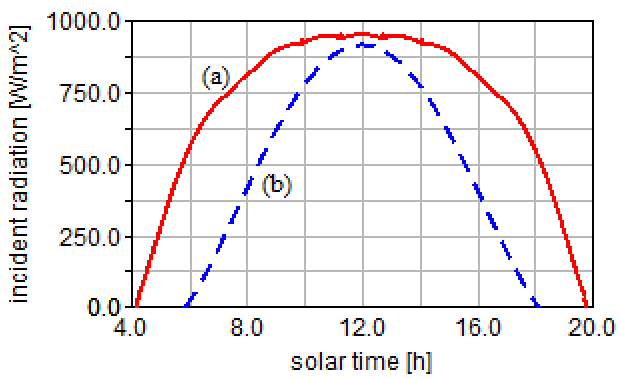


Fig. 10. The incident radiation: (a) bi-axial PV system, (b) fixed PV system.

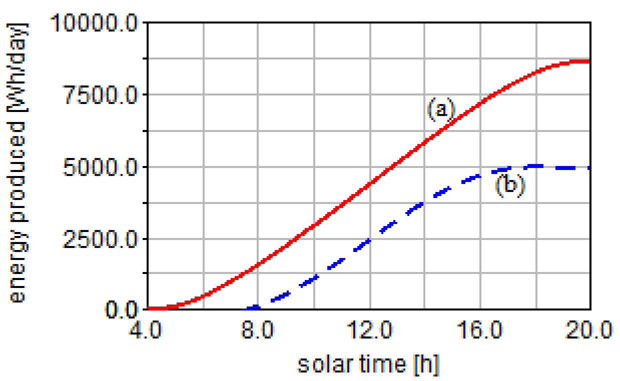


Fig. 11. The energy produced: (a) bi-axial PV system, (b) fixed PV system.

Concluding, the proposed bi-axial solar tracker, which combines the features of the classical platform and string configurations, has the following advantages: possibility to orient medium and large platforms of strings of PV modules; reducing the cost of the system by minimizing the number of motor sources relative to the classical solution of individual modules; the gears interleaved in the daily and elevation movement subsystems act as stroke multipliers and power reducers, thus allowing to use low size/power actuators. By the way in which the bi-axial solar tracker is designed, the energy gain (by reference to the equivalent fixed system) is reflected in values that prove a high efficiency (not only for the representative day considered as an example in the work, but for the whole year), thus justifying the usefulness of the proposed solution, which will be implemented and tested under real operating conditions (this is expected as a direction for further research).

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