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A STUDY ON THE SUN TRACKING MECHANISMS USED FOR THE PHOTOVOLTAIC SYSTEMS

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Abstract: *A major problem of nowadays society is the continuous growth of electricity consumption, simultaneously with the decrease in the fossil fuels resources. A solution is represented by the systems of converting solar energy into electrical energy (i.e. the photovoltaic systems). The work deals with an overview on the tracking mechanisms that can be used for increasing the energetic efficiency of the photovoltaic systems. On these grounds, a case study has been developed, considering a dual-axis equatorial tracking mechanism. The energetic efficiency of the photovoltaic system equipped with the proposed solar tracker was evaluated by modeling & simulating the virtual prototype, in mechatronic concept.*

Key words: *photovoltaic system, tracking mechanism, virtual prototype.*

1. Introduction

The method of converting solar radiation into electricity is well known, namely the photovoltaic (PV) effect, the conversion efficiency depending on the quality and type of PV cells, their temperature, and the amount of received solar radiation. In order to capture the maximum amount of incoming solar radiation, tracking mechanisms (also called solar/sun trackers) can be added to the PV panels, thus increasing the energetic efficiency of the PV system (from 20% up to 50%) [1-3].

The tracking principle of PV modules is based on the data referring to the position of the sun on the celestial vault. To ensure the greatest possible efficiency of solar energy conversion into electricity, the sunlight should fall normally on the surface of the receiver so that the system might periodically change the position so as to keep the relationship between sunlight and the module [5].

In designing the tracking systems, the two rotation movements in the Earth - Sun system should be considered: daily movement (diurnal) and annual precession movement (seasonal) [8, 9]. Thus, two basic types of tracking mechanisms can be systematized: mono-axis, and dual-axis. The mono-axis mechanisms are frequently used for the diurnal movement, the tilt angle of the rotation axis corresponding to the latitude of the location. The dual-axis tracking mechanisms combine the two movements (diurnal and seasonal), thus enabling a very precise tracking throughout the year, without being necessary any positioning adjustments [10].

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In the case of dual-axis tracking, there are three basic types of systems, according to how the axes are located and how the two movements are entered into the system: azimuthal systems - they have not the axes of rotation aligned with the axes according to which the two relative rotations determining the trajectories of the sun on the celestial vault take place (the daily motion is made by rotating the module around the vertical axis), thus requiring the continuous correlation of the two motions; equatorial systems - the axes of rotation are arranged so as to be maintained parallel to the polar axis of the earth, respectively to the axis of rotation which determines the seasonal variation of the sun on the celestial vault; pseudo-equatorial systems - these have an axis parallel to the axis of rotation which causes seasonal variation of the sun position on the celestial vault, and with the axis for the diurnal orientation oscillating.

From the point of view of the control technique, closed-loop systems with photo-sensors are frequently used. The sensors determine the position of the sun and send electrical signals to the controller, which drives the motor to track the sun. However, the sensor based orientation may generate errors in detecting the current position of the sun under variable weather conditions.

The alternative is represented by the open-loop control systems, which are based on mathematical algorithms that can ensure the predefined parameters for motors, depending on the position of the sun on the celestial vault. This position can be precisely established as it is a function of the solar angles that, in their turn, can be calculated for each geographic area. By using this control method, depending on the predefined parameters, the errors introduced by sensors can be avoided [11].

Another solution is to incorporate a sun position sensor in order to automatically verify and calibrate the control system. Furthermore, the tracking system can be adjusted so that it might ensure the maximum of the generated energy. Such hybrid control systems are made up of a combination of open-circuit tracking strategies, based on the movements of the sun, and closed-circuit control strategies, using a feed-back dynamic controller.

The keyword when designing the photovoltaic tracking systems is energy efficiency: energy gain obtained by tracking versus energy consumption to carry out the tracking (for feeding the driving motors/actuators). A photovoltaic system with tracking is energetically efficient if the following condition is met: $\varepsilon = E_T - (E_F + E_C) >> 0$, where E_T represents the amount of electrical energy produced by the PV system with tracking, E_F is the amount of energy produced by the equivalent fixed system (without tracking), and E_C defines the amount of energy that is consumed to orient the module.

Under these conditions, the strategies for optimizing the tracking systems aim to maximize the efficiency ε, by optimizing the mechanical & control devices of the tracking system, as well as the tracking law, having as objective to minimize the energy consumption for tracking (E_C), at the same time as maximizing the absorption of incident solar radiation (E_T).

2. Conceptual Design of the Solar Trackers

The structural synthesis of the tracking mechanisms is performed using a method based on the MBS (Multi-Body Systems) theory. Defining the tracking mechanisms as multi-body systems consists in identifying the bodies and the constraints imposed on them [4], [6-7]. With a view to benchmarking the tracking systems and choosing the fundamental solutions for further studies, techniques specific to product design were applied: multi-criteria analysis and morphological analysis.

The multi-criteria analysis of the tracking systems was based on the following steps: establishing the variants to be analyzed in accordance with the structural systematization performed; establishing assessment criteria; determining weighting coefficients for each criterion; granting importance score; calculating the product between the importance scores and the weighting coefficients. As tracking systems assessment criteria the following were considered: tracking accuracy, range of movement, system complexity, system design, manufacturing possibility.

Further on, the final solutions were established based on the morphological analysis which was conducted in the following stages: establishing all the requirements (parameters, functions, attributes) that the solution of the problem has to fulfill; inventorying possible variations of achievement or ways in which each requirement can be met; describing combinatorial all possible variations, making up a morphological table; proceeding to the 'clear' description of the variations, obtained according to the numerical combinations in the table; proceeding to a first elimination of solutions (e.g. ordinary solutions are eliminated); proceeding to a second elimination of solutions (incompatible, absurd, disadvantageous solutions etc. are eliminated); choosing the solution out of the remaining ones (taking also into account other elements, or even randomly).

The actuation of the system (usually electrical) to achieve the necessary movements can be done by rotary or linear actuator, by reasons of simplification of the solution, the actuated element being directly the module or its support. If the driving source is of a rotary type, the system obtained is more compact, since it acts directly on the module/support coupling, but the constructive solution of the coupling becomes more complicated; moreover, the advantage of this solution is that it can perform high angular strokes.

On the other hand, actuation by linear actuator in which the active element of the actuator (piston) generally acts directly on the element in rotation (module or support) has the advantage of simplifying the design of the rotational couplings, but a disadvantage appears that, in order to achieve high angular amplitudes, it is necessary to have a long stroke linear actuator.

3. Case Study

On the grounds of the assertions made in the previous chapters, a case study was performed, considering the dual-axis equatorial sun tracker shown in Figure 1. The virtual prototyping platform used for the simulation of the proposed tracking mechanism consists of the following software solutions: CAD - CATIA (for the solid modeling of the system); MBS - ADAMS (for developing the mechanical device model); DFC - EASY5 and ADAMS/Controls (for the control system design, and the co-simulation in mechatronic concept).

The dual-axis tracking mechanism contains 7 bodies, as follows: 1 - the system base; 2 - the intermediary support that rotates with respect to the system base (joint A) in order to generate the daily motion; 3 - the PV panel (including the frame), which rotates relative to the intermediary support (joint B) for generating the elevation motion; 4 & 5 - the cylinder & piston of the linear actuator used to drive the daily motion (the actuator is disposed between the intermediary support and the lateral fixed pillar; 6 & 7 - the cylinder & piston of the linear actuator used to drive the elevation motion (the actuator is disposed between the panel frame and the central fixed pillar).

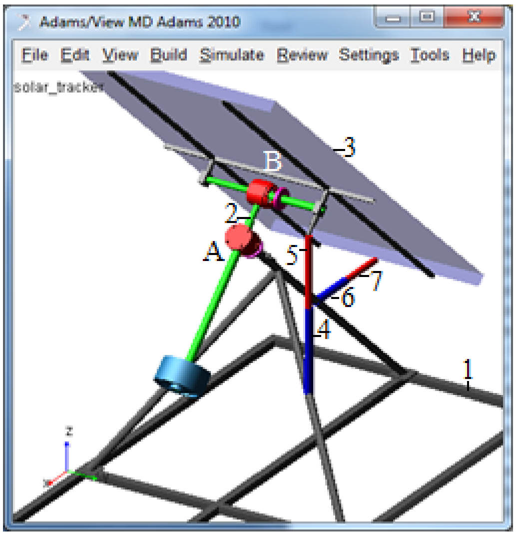

Fig. 1. *Dual-axis equatorial tracker*

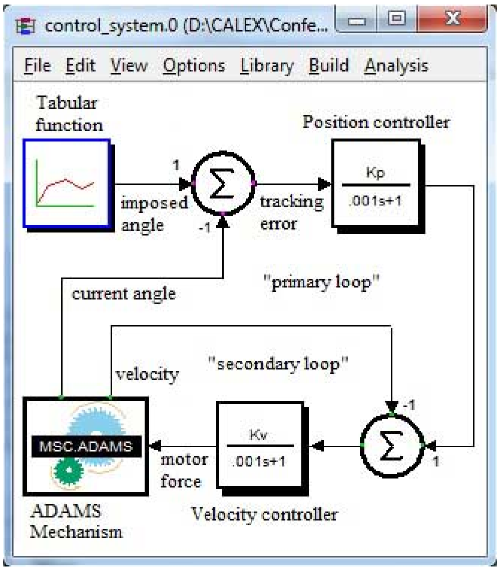

Fig. 2. *The control system model*

For the control system of the tracking mechanism, a two-loop cascade configuration was selected (for the both driving actuators). The controlled parameter in the main (external) loop is the daily/elevation angle of the PV module, while in the secondary (internal) loop the linear velocity in the actuator is controlled. Thus, an improved control of the main variable is insured, which is less affected by perturbations [2].

Under these terms, the control system block diagram was developed by using the DFC (Design for Control) software solution EASY5, as shown in Figure 2 (such a model was separately realized for the two motions of the PV system - daily & elevation). Tabular function block is used for modeling the imposed time-history variation of the daily/elevation angle (i.e. the reference signals).

Low-pass filters were selected for the position and velocity controllers, the modeling of the filter in EASY5 being performed by using the First-Order Lag block, in the format of the time constant. The tuning of the controllers consists in determining the optimal values of the amplification factors (K_P & K_V).

The communication between the two main components of the mechatronic tracking system (the mechanical device, and the control system) is assured through the input & output plants. The daily and elevation angles of the PV module represent the input state variables in the mechanical model, while the outputs transmitted to the controller are the motor forces developed by the linear actuators. The daily angle is measured in the revolute joint between the intermediary support and the fixed pillar, while the elevation angle is measured in the revolute joint between the PV module frame and the intermediary support.

The PV module can be continuously rotated during day-light, or can be in-steps driven (step-by-step), usually by rotation in equal steps, every hour. The maximum amount of incident solar radiation is obtained for the continuous tracking, but in this case the motor operating time is higher (this negatively influencing the system reliability, including the motor wear).

The main idea proposed by the strategy for the optimization of the motion law is to maximize the energy obtained by the step-by-step tracking, in order to absorb an amount of solar energy as close as possible to the maximum case (continuous tracking), but with a lower energy consumption for carrying out the tracking. Actually, optimization is based on the reduction of the angular domains of the rotation axes and of the number of motor actuations, without affecting considerably the incidence of the solar radiation.

The numerical simulations were performed on the basis of input data that are specific to the Braşov geographic area, on the summer solstice day; the values of the input parameters are the following: $\varphi = 45.5°$, $\delta = 23.45°$, $T \in [4.26, 19.74]$ (solar time, between sunrise and sunset). In this study, it was considered that the angular domain for the diurnal motion is $\beta^* \in [-80°, +80°]$; the actuation is done in 11 steps. The module is kept fixed in the morning (4.26-6.91) and in the evening (17.01-22.00); in the end, the module returns to the initial position/sunrise with continuous (without brakes) motion. As regards the elevation motion, the module remains in the position that is specific to the summer solstice ($\gamma^* = \varphi - \delta = 22.05°$) in the time interval 9.01-14.91, and for the rest, in order to increase the incident radiation, it is additionally tilted by 11.05° ($\gamma^* = 11°$).

In these terms, the daily and elevation tracking laws are shown in Figure 3, the two angles being defined/measured with respect to the initial position of the PV module at sunrise (in other words, the null values in the diagrams shown in Figure 3 correspond to $\beta^* = -80°$, and $\gamma^* = 22.05°$).

For these motion laws, the incident solar radiation is the one shown in Figure 4 (curve “a”), to which it corresponds the amount of electrical energy produced by the module E_T = 1755 Wh/day; if the PV module is kept fixed ($\beta^* = 0°$, $\gamma^* = 22.05°$), the corresponding result will be E_F = 1231 Wh/day (curve “b”), and respectively $E_{T\max}$ = 1784 Wh/day for continuous tracking (null incidence angle).

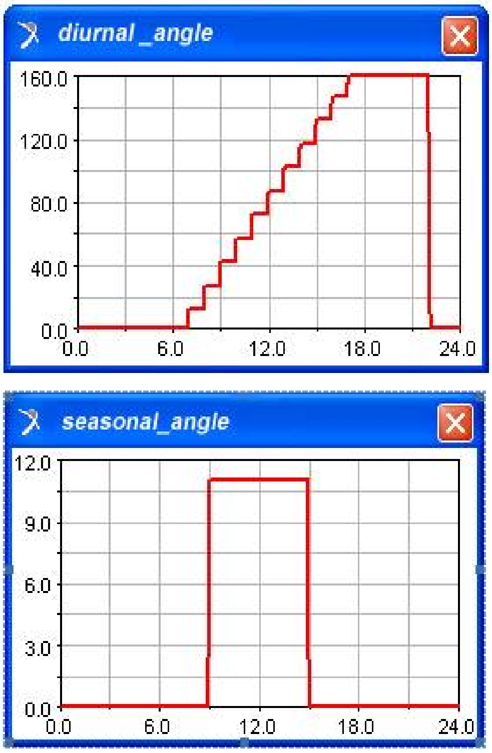

Fig. 3. *The daily & elevation motion laws*

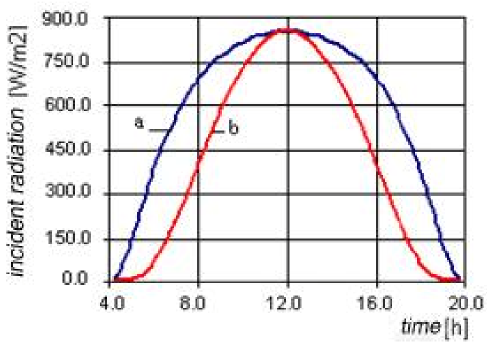

Fig. 4. *The incident radiation with (a) / without (b) tracking*

The computation of the amount of energy produced was done taking into account a PV module having an active area of 1.26 m^2, and the conversion efficiency (yield) of 15%.

For the step-by-step tracking, which is configured in accordance with the tracking laws shown in Figure 3, the total energy consumption for performing the daily and elevation motions is $E_C \approx 57$ Wh/day (see Figure 5). Thus, the energy balance of the tracking system was performed, $\varepsilon = E_T - (E_F + E_C) = 1755 - (1231 + 57) = 467$ Wh/day, which proves that the proposed tracking system is energetically efficient, the energy gain obtained by tracking the sun being of about 38% as compared to the fixed equivalent photovoltaic system.

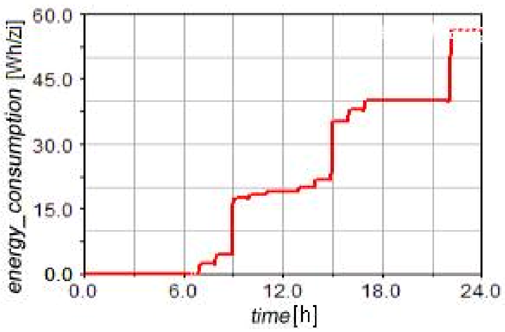

Fig. 5. *The energy consumption for performing the step-by-step tracking*

The results obtained demonstrate the viability of the optimization algorithm proposed, which is based both on the optimization of the mechanical structure of the tracking mechanism, and on the optimization of the module motion law.

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