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SIMULATION OF A DUAL-AXIS TRACKING SYSTEM FOR PV MODULES

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Abstract: *In this paper, a mechatronic tracking system used for increasing the energetic efficiency of the photovoltaic (PV) modules is designed and simulated. The tracking system is approached in the concurrent engineering concept, integrating the mechanical device and the control system at the virtual prototype level. The virtual prototype is a control loop composed by the multi-body (MBS) mechanical model connected with the dynamic model of the actuators and with the controller model. For controlling the tracking mechanism, an opened-loop system is used, which is based on predefined parameters for the motors, depending on the astronomic movements of the Sun - Earth system.*

Key words: *tracking mechanism, virtual prototyping, efficiency.*

1. Introduction

The theme of the paper belongs to a very important field: renewable sources for energy production - increasing the efficiency of the photovoltaic conversion. The researches in this field represent a priority at international level because provides viable alternatives to a series of major problems that humanity is facing: the limited and pollutant character of the fossil fuels, global warming or the greenhouse effect.

The solar energy conversion is one of the most addressed topics in the field of renewable energy systems. The present-day techniques allow converting the solar radiation in two basic forms of energy: thermal and electric energy. The technical solution for converting the solar energy in electricity is well-known: the photovoltaic (PV) conversion.

The degree of use of the solar radiation can be maximized by use of mechanical systems for the orientation of the PV modules in accordance with the paths of the Sun. The tracking systems are mechanical systems that integrate mechanics, electronics, and information technology. These mechanisms are driven by rotary motors or linear actuators, which are controlled in order to ensure the optimal positioning of the module relatively to the Sun position on the sky dome. The orientation of the PV modules may increase the efficiency of the conversion system from 20% up to 50% [2], [5], [6], [9], [10].

The PV system with tracking is efficient if the following condition is achieved:

$$\varepsilon = (E_T - E_F) - E_C >> 0, \qquad (1)$$

in which E_T is the electric energy produced by the PV module with tracking, E_F - the

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energy produced by the same module without tracking (fixed), and E_C - the energy consumption for orienting the PV module. In the current conditions, the maximization of the efficiency parameter ε, by the optimization of the tracking system, became an important challenge in the modern research and technology.

In the design process of the tracking systems, the solar radiation represents the main input data. Interacting with atmospheric phenomena involving reflection, scattering, and absorption of radiation, the quantity of solar energy that reaches the Earth's surface is reduced in intensity. The total solar radiation received at ground level includes two main components: direct solar radiation and diffuse radiation.

The solar radiation can be measured using traditional instruments, or can be digitally recorded with a data acquisition system. In addition, different models were developed for estimating the solar radiation [3]. The traditional Angstrom's linear approach is based on measurements of sunshine duration, while relatively new methods are based on artificial neural networks (ANN) [8].

The orientation principle of the PV modules is based on the input data referring to the position of the Sun on the sky dome. For the highest conversion efficiency, the sunrays have to fall normal on the receiver surface so the system must periodically modify its position in order to maintain this relation between the sunrays and the PV module. The positions of the Sun on its path along the year represent input data for the tracking systems design.

Two basic types of tracking systems can be identified: single-axis and dual-axis. The single-axis systems spin on their axis to track the Sun, facing East in the morning and West in the afternoon. The tilt angle of this axis equals the latitude angle of the loco because this axis has to be always parallel with the polar axis. In consequence, this type of system requires a seasonal tilt angle adjustment. The dual-axis systems combine two motions, so that they are able to follow very precisely the Sun path along the period of one year.

Depending on the relative position of the revolute axes, there are two types of dual-axis systems (Figure 1): polar (a), and azimuthal (b). For the polar trackers, there are two independent motions, because the daily motion is made rotating the PV module around the polar axis. For the azimuthal trackers, the main motion is made by rotating the PV module around the vertical axis, so that it is necessary to continuously combine the vertical rotation with an elevation motion around the horizontal axis.

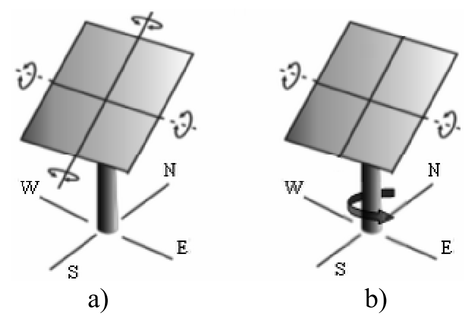

Fig. 1. *Basic types of solar trackers*

Regarding the control process, closed loop systems with photo sensors are traditionally used. The photo sensors are responsible for discrimination of the Sun position and for sending electrical signals, proportional with the error, to the controller, which actuates the motors to track the Sun. Although, the orientation based on the Sun detecting sensors, may introduce errors in detection of real Sun position for variable weather conditions. The alternative consists in the opened loop systems, which are based on mathematic algorithms/programs that may provide predefined parameters for the motors, depending on the Sun positions on the sky dome [1], [7]. These positions can be precisely determined because they are functions of the solar angles that can be calculated for any local area [4]. In this way, the errors introduced by the use of the sensors may be avoided.

From the controller point of view, different control strategies are used, such as classical techniques as PID algorithm or more advanced strategy such as fuzzy logic controller (FLC). An evolution of the fuzzy control concept is the fuzzy logic neural controller (FNLC), which allows the PV system to learn control rules. A more complex controller incorporates the advantages of two alternate design techniques, namely the deadbeat regulator - for quick, rough control, and the LOG/LTR regulator - for soft final tracking.

In these terms, the aim of this paper is to design and analyze a dual-axis polar tracking system, with two motions: the daily motion (from East to West), and the elevation motion (depending on the season). No less important is the design & simulation instrument, which is based on the testing in virtual environment. This kind of approach is based on the design of the detailed digital models and the use of these in virtual experiments, by reproducing with the computer of the real phenomena. An important advantage of this process consists of the possibility to develop measurements in any point or zone and for any type of the parameter (motion, force, energy) that is not always possible to the experimental testing on the physical models (the missing of the adequate sensors, high temperatures etc.).

The virtual prototyping platform includes the following software products: CAD (Computer Aided Design) - CATIA, for creating the geometric model of the mechanical device, which contains data about the mass & inertia properties of the parts; MBS (Multi-Body Systems) - ADAMS, for analyzing, optimizing, and simulating the mechanical system; DFC (Design for Control) - EASY5, for designing the control system. The tracking system is approached in mechatronic concept, by integrating the mechanical device and the control system at the virtual prototype level.

2. Virtual Prototype of the System

For identifying accurate and efficient mechanical configurations suitable for tracking systems, a structural synthesis method based on the MBS theory has been developed. The conceptual design can be performed in the following stages: identifying all possible graphs, by considering the space motion of the system, the type of joints, the number of bodies, and the degree of mobility; selecting the graphs that are admitting supplementary conditions imposed by the specific utilization field; transforming the selected graphs into mechanisms by mentioning the fixed body and the function of the other bodies, identifying the distinct graphs versions based on the preceding particularizations, transforming these graphs versions into mechanisms by mentioning the types of geometric constraints (ex. revolute, translational).

In this way, a collection of possible structural schemes have been obtained. In order to select the structural solution for study, we applied specific techniques for product design such as multi-criteria analysis and morphological analysis. The multi-criteria analysis was performed using the following steps: selecting the possible variants in accordance with the structural synthesis; establishing the evaluation criteria and the weight coefficient for each criterion (the FRISCO formula); granting the importance note to a criterion and computing the product between the importance note and the weight coefficient in the consequences matrix.

The evaluation criteria of the solutions were referring to the tracking precision, the amplitude of the motion, the complexity of the system, the possibility for manufacturing and implementation. The final solution has been established based on the morphological analysis, the description of possible solutions being conducted by combinatorial procedures that associates the requirements to be met (parameters, functions, attributes). In this way, there is described the morphological table, which eliminates the irrational constructive or incompatible solutions.

Using this conceptual design method, we established the solution for the tracking system in study, which is a polar dual-axis mechanism, the basic scheme being shown in Figure 1a. The revolute axis of the daily motion is fixed and parallel with the polar axis. The both motions are directly driven by rotary motors (type MAXON - DX). The motion is transmitted from the output shafts of the motors by using worm gears; these irreversible transmissions assure the blocking of the system in the stationary positions.

The MBS model of the mechanism, developed in ADAMS/View, it is designed so that it has three parts, as follows (Figure 2): base/sustaining frame (1), on which there is disposed the support of the motor and the fixed axle of the revolute joint for the daily motion - A; intermediary element (2), which includes the mobile parts of the joint A, and the fixed part of the joint for the seasonal motion - B; support part (3), which contains the axle of the seasonal motion, the panel frame, and the PV module. The dynamic model takes into consideration the mass forces, the reaction in joints, and the joint frictions. For developing the constructive solution of the tracking system, we used the CAD software CATIA, the geometry transfer from CATIA to ADAMS being performed by using the STEP file format.

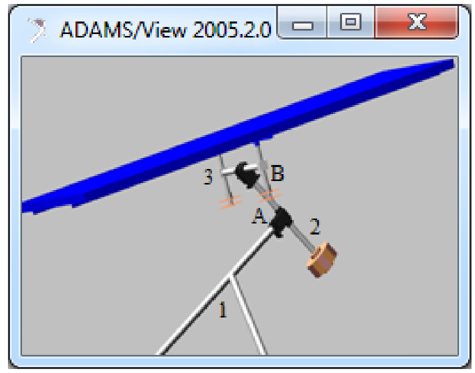

Fig. 2. *MBS model of the polar system*

The tracking mechanism is equilibrated (balanced) by using a system of counterweights, which are dimensioned and disposed in order to obtain the mass centers of the moving structures closed-by the revolution axes. In this way, the motor torqueses for orienting the photovoltaic module in the both directions are minimized, and this has positive effect on the energy consumption for tracking the Sun path.

The solar tracker is an automated system, which has as task the orientation of the PV module (i.e. the effecter) on the imposed trajectory. The design problem can be formulated in the following way: designing a control system which allows the displacement of the effecter on the imposed trajectory. The control system of the solar tracker was designed in the concurrent engineering concept, using ADAMS/Controls and EASY5.

For connecting the mechanical model and the control system, the input and output plants have been defined. The motor (control) torques represents the input parameters in the mechanical model, while the outputs transmitted to the controllers are the daily and seasonal angles. For the input variables, the run-time functions are 0.0 during each step of the simulation, because the control torques will get their values from the control system.

For the output state variables, the run-time functions return the angles about the motion axes (see Figure 2): daily angle (joint A) - the rotational displacement of one coordinate system marker attached to the intermediary element (part no. 2) about the motion-axis of another marker attached to the sustaining frame (part no. 1); seasonal angle (joint B) - the rotational displacement of one coordinate system marker attached to the support part of the panel (part no. 3) about the motion-axis of another marker attached to the intermediary element (part no. 2).

The next step is facilitating the exporting of the ADAMS plant files for the control application. The Plant Inputs refer the input state variables (daily & seasonal angles), while the Plant Outputs refer the output state variables (daily & seasonal motor torques). The input and output information are saved in a specific file for EASY5 (*.inf). ADAMS/Controls also generates a command file (*.cmd) and a dataset file (*.adm) that are used during the simulation in ADAMS/View and ADAMS/Solver. With these files, the control system was created in EASY5, in order to complete the interactive communication between the mechanical and actuating - control systems. For example, in Figure 3 there is shown the control system diagram for the daily motion (the diagram for the seasonal motion is similar).

From the controller point of view, for obtaining reduced transitory period and small errors, we used PID controllers, for both motions. The tuning of the controllers was made by performing a Monte Carlo analysis in ADAMS/Insight. This method is based on the generation of multiple trials to determine the expected values of a random variable. In our case, the variables used in study are the proportional, derivative and integral terms, while the objective is to minimize the tracking error.

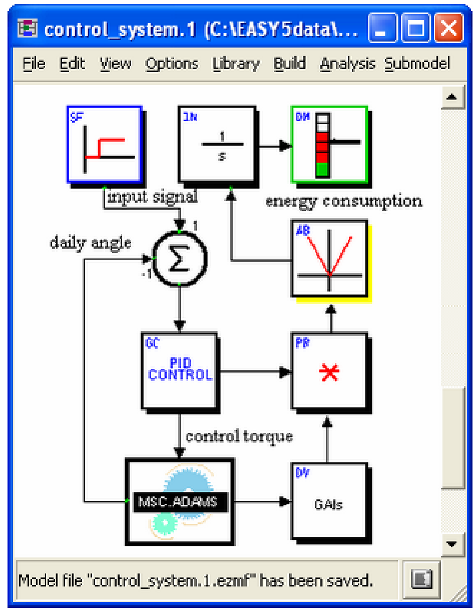

Fig. 3. *Control system diagram*

In the mechatronical model, ADAMS accepts the control torques from EASY5 and integrates the mechanical model in response to them. At the same time, ADAMS provides the current daily & seasonal angles for EASY5 to integrate the control system model.

3. Designing the Control Law

The energy produced by the PV module ($E_{T/F}$) depends on the quantity of incident solar radiation (R_I), the active surface (S) and the conversion efficiency of the module (η):

$$E_{T/F} = \int R_I \cdot S \cdot \eta. \tag{2}$$

The incident radiation, which is normal to the module, is given by:

$$R_I = R_D \cdot \cos i, \tag{3}$$

where R_D is the direct terrestrial radiation, and i - the angle of incidence.

The direct radiation can be experimentally measured, or empirically established. For this paper, we have used experimental data for the solar radiation, which were measured by using the local meteorological station [3]. The angle of incidence is determined from the scalar product of the sunray vector and the normal vector on module:

$$i = \cos^{-1}(\cos\beta \cdot \cos\beta^* \cdot \cos(\gamma - \gamma^*) + \sin\beta \cdot \sin\beta^*), \quad (4)$$

$$\beta = \sin^{-1}(\cos\delta \cdot \sin\omega), \quad (5)$$

$$\gamma = \sin^{-1}\left(\frac{\cos\alpha \cdot \cos\psi}{\cos\beta}\right), \quad (6)$$

$$\psi = (\sin\omega)\cos^{-1}\left(\frac{\sin\alpha \cdot \sin\varphi - \sin\delta}{\cos\alpha \cdot \cos\varphi}\right), \quad (7)$$

where β and γ are the diurnal and seasonal angles of the sunray, β^* and γ^* - the daily and seasonal angles of the module, ψ - the azimuth angle, δ - the solar declination, φ - the location latitude, ω - the solar hour angle, α - the solar altitude angle. The daily angle of the module has the value $\beta^* = 0$ at the solar-noon, being positive in the morning, and negative in the afternoon. The seasonal angle, γ^*, is null when the module is horizontally disposed, being positive for the module facing South.

It has been demonstrated that for every month there is one day whose irradiation is equal to the monthly average: it is the day in which the declination equals the mean declination of the month. Due to this consideration, a noticeable facilitation is introduced in the computing calculation, considering just the mean days of each month instead of the 365 days of the year. Our paper presents the exemplification for the summer solstice day (June, 21), considering the Braşov geographic area, with the following specific data: the location latitude, $\varphi = 45.5°$; the solar declination, $\delta = 23.45°$; the seasonal angle, $\gamma^* = 22.05°$; the solar time, $T \in [4.26, 19.74]$. The average values (for the last five years) of the direct solar radiation during the day are shown in Figure 4; this diagram can be considered as a meteorological prognosis for study.

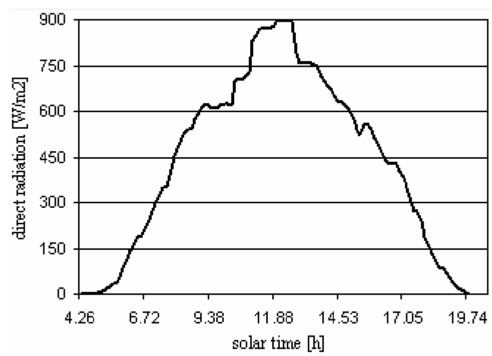

Fig. 4. *Direct solar radiation*

The PV module can be rotated, from the East/sunshine position ($\beta^* = 90°$) to the West/sunset position ($\beta^* = -90°$), without brakes during the day-light, or can be discontinuously driven (step-by-step motion), usually by rotating the panel with equal steps at every hour. Obviously, the maximum incident solar radiation is obtained for the continuous motion, when it is possible to have null values for the angle of incidence during the day-light. As we can see in Figure 4, the direct radiation has small values in the limit positions (close-by the sunshine and sunset, respectively), and for this reason it is not efficient to track the Sun in these areas.

In these terms, our strategy for developing the tracking law intends to identify the optimum field for the daily motion of the PV module, considering the continuous tracking, without brakes. In the next stage, the step-by-step tracking strategies will be developed, in order to avoid the disadvantages of the continuous orientation (there are necessary transmissions with high ratios; the behavior of the system in terms of occurrence of external perturbations).

For identifying the optimum angular field of the daily motion, we have considered the correlation between the motion amplitude and the solar time, for obtaining symmetric revolute motions relative to the solar noon position ($\beta^* = 0$). The analysis has been performed for the following tracking cases: (a) $\beta^* \in [+90^o, -90^o]$, $T \in [4.26, 19.74]$ - the maximum motion field; (b) $\beta^* \in [+75^o, -75^o]$, $T \in [5.55, 18.45]$; (c) $\beta^* \in [+60^o, -60^o]$, $T \in [6.84, 17.16]$; (d) $\beta^* \in [+45^o, -45^o]$, $T \in [8.13, 15.87]$; (e) $\beta^* \in [+30^o, -30^o]$, $T \in [9.42, 14.58]$; (f) $\beta^* \in [+15^o, -15^o]$, $T \in [10.71, 13.29]$; (g) $\beta^* = 0$, $T \in [4.26, 19.74]$ - the fixed/non-tracked system.

The computations were performed considering the above presented relations (2-7) and the experimental data for the direct radiation (see Figure 4). In this way, we obtained the quantity of electric energy produced by the PV system. Afterwards, the energy consumption for realizing the motion laws was determined by using the virtual prototype of the tracking system. For the energy consumption, there is also considered the return of the tracking mechanism in the initial position (East) after the sunset. In this way, the energy balance was performed, the results being systematized in Figure 5 (the energy gain is computed relative to the fixed module case). Analyzing these results, we consider that the optimum field for the daily motion of the PV module, in the summer solstice day, is $\beta^* \in [+60^o, -60^o]$.

Afterwards, in the optimal angular field, we have evaluated - analyzed six tracking cases, depending on the number of steps (in consequence, the step dimension - $\Delta\beta^*$): 12 steps ($\Delta\beta^* = 10°$), 10 steps ($\Delta\beta^* = 12°$), 8 steps ($\Delta\beta^* = 15°$), 6 steps ($\Delta\beta^* = 20°$), 4 steps ($\Delta\beta^* = 30°$), 2 steps ($\Delta\beta^* = 60°$). In these terms, the results for the step-by-step tracking cases are shown in Figure 6.

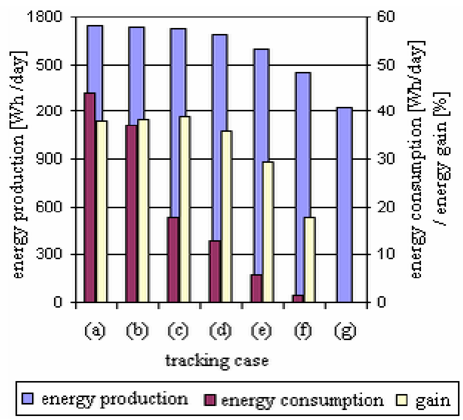

Fig. 5. *Energy balance for the continuous tracking*

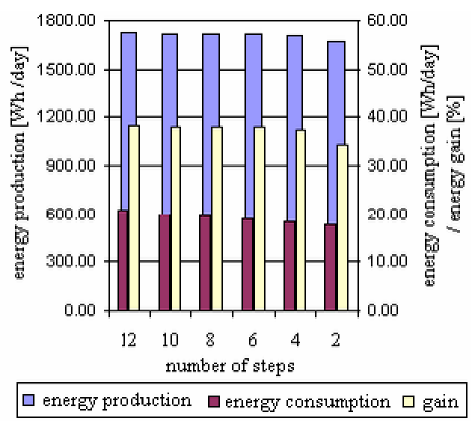

Fig. 6. *Energy balance for the step-by-step tracking cases*

By using the above-presented algorithm for configuring the step-by-step orientation, we obtained values closed-by the continuous tracking case, and this demonstrates the viability of the adopted optimization strategy. Similar studies were performed for different periods/seasons, obtaining in this way the optimal motion law during the year.

4. Final Conclusions

The simulations prove the importance of the virtual prototyping in the design process of the tracking systems, having as main advantage the possibility of performing virtual measurements for any parameter, in any point or area. Another significant advantage brought by the virtual prototyping is the simplicity of the procedures with a reduced testing time and small cost relative to the physical (hardware) prototyping.

Using the virtual prototyping, we are able to optimize the mechanical structure of t he tracking system, choose the appropriate actuators, design the optimal controller, optimize the motion law, and perform the energy balance of the photovoltaic system, without developing expensive hardware prototypes.

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