DYNAMIC ANALYSIS OF THE PHOTOVOLTAIC TRACKING SYSTEMS IN MECHATRONIC CONCEPT

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Abstract: The paper presents researches in the field of increasing the efficiency of the photovoltaic systems. The idea is to design a tracking system that changes the position of the photovoltaic panel in order to maximize the solar radiation degree of use. The tracking system is approached in mechatronic concept, integrating the control system in the mechanical model. The analysis is made using a virtual prototyping platform that includes the following software: CATIA, ADAMS/View & Controls and MATLAB/Simulink. The behavior of the tracking system is evaluated from energetic efficiency point of view.

Keywords: solar tracker, control system, dynamics, virtual prototype, energy balance.

1. INTRODUCTION

The solar energy conversion is one of the most addressed topics in the fields of renewable energy systems. The technical solution for converting the solar energy in electricity is well-known: the photovoltaic systems. The efficiency of the photovoltaic systems depends on the degree of use and conversion of the solar radiation, and this can be increased by using tracking systems, whose aim is to change the position of the photovoltaic panel correlated to the sun position. Basically, the tracking systems are mechanical devices (i.e. mechanisms), driven by rotary motors or linear actuators. According to the scientific literature, the orientation of the photovoltaic panels may increase the efficiency of the conversion system up to 50% [1, 7].

Determining the real behavior of the tracking systems is a priority in the design stage since the emergence of the computer graphic simulation. Important publications reveal a growing interest on analysis methods for multi-body systems (MBS) that may facilitate the self-formulating algorithms, having as main goal the reducing of the processing time in order to make possible real-time simulation [4, 6]. In the last decade, a new type of studies was defined through the utilization of the MBS software: Virtual Prototyping. This technology consists mainly in conceiving a detailed model and using it in a virtual experiment, in a similar way with the real case. One of the most important advantages of this kind of simulation is the possibility to perform virtual measurements in any point and/or area of the system and for any parameter (motion, force, energy etc.). This is not always possible in the real cases due to the lack of space for transducers placement or lack of appropriate transducers.

Basically, the virtual prototyping platform includes CAD, MBS, FEA and C&C software solutions [2]. The CAD (Computer Aided Design) environment is used to create the 3D geometric model of the system, which contains information about the mass & inertia properties of the parts. The MBS (Multi-Body Systems) software is used for analyzing, optimizing and simulating the tracking mechanism. The FEA (Finite Element Analysis) software is used for modeling flexible components, which allows capturing inertial and compliance effects during simulation, and predict loads with greater accuracy, therefore achieving more realistic results. The C&C (Command & Control) software is used for developing the control system of the mechatronic product, in concurrent engineering concept (integrating the control system in the mechanical model of the tracking system).

The tracking system is efficient if the following condition is achieved: $\varepsilon = \Delta E_P - E_T >> 0$, in which $\Delta E_P = E_{PO} - E_{PF}$ is the difference among the electric energy produced by the photovoltaic panel with tracking (E_{PO}), and the same panel without tracking/fixed (E_{PF}), and E_T represents the energy that is consumed for tracking the panel. In the current conditions, the maximization of the parameter ε, through the optimization of the tracking system, became an important provocation in the modern research and technology. The high importance of this direction is confirmed by publications, scientific events, and research projects, in which this problematic is situated in prime how much even the development of a big number of companies that produce tracking systems and components.

In these terms, our paper presents researches in the field of increasing the efficiency of the solar energy conversion in electric energy by using a mechatronic tracking system, with two degrees of freedom. The key word of the design is the energetically efficiency; using the tracking system, the photovoltaic panel follows the sun and increase the collected energy, but the driving actuators consume a part of this energy. The strategy involves designing an optimal tracking system, which intends to minimize the actuating torques/forces that are needed for tracking the sun movements. The optimization problem uses the dynamic model of the electrical and mechanical structure and computes the geometrical parameters of the tracking mechanism. This design strategy is possible by developing the virtual prototype of the tracking system, which is a complex dynamical model. In fact, the virtual prototype of the tracking system is a control loop composed by the multi-body mechanical model connected with the dynamic model of the actuators and with the controller dynamical model. The study was made by using a virtual prototyping platform, which integrates the following software solutions: CAD – CATIA, MBS – ADAMS/View, C&C – ADAMS/Controls and MATLAB/Simulink.

2. DESIGN OF THE TRACKING SYSTEM

The orientation principle of the photovoltaic panels is based on the input data referring to the position of the sun on the sky dome [3]. For the highest conversion efficiency, the sunrays have to fall normal on the receiver so the system must periodically modify its position in order to maintain this relation between the sunrays and the panel. The positions of the Sun on its path along the year represent an input data in designing the solar trackers, so the geometrical relationship between the Earth and the Sun has to be considered. The Earth describes along the year a rotational motion following an elliptical path around the sun. During one day, the Earth also spins around its own axis describing a complete rotation, which generates the sunrises and the sunsets. The variation of the altitude of the sun on the celestial sphere during one year is determined by the precession motion, responsible for a declination of the Earth axis in consideration with the plane of the elliptic yearly path; this motion generates the seasons because of the alternative exposure of the northern and southern hemisphere to the sunrays.

Consequently, for the design process of the tracking systems, there are taken into consideration two rotational motions: the daily motion, and the yearly precession motion. In these conditions, there are two fundamental ways to track the sun, by one axis or by two axes; this fact determines two types of tracking mechanisms [2, 7]: single axis trackers, and dual-axis trackers. The single-axis tracking systems pivot 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 for this type of single axis tracker is necessary a seasonal tilt angle adjustment. The two-axis tracking systems combine two rotational motions, so that they are able to follow very precisely the sun path along the period of one year; that's why dual axis tracking systems are more efficient than the single one.

For this paper, we taken into consideration a dual-axis tracking systems, which has two independent motions (daily motion and seasonal motion), whose structural model is shown in figure 1. In our design, the main motion (i.e. the daily motion) is directly driven by a rotary motor that is able to develop an angular displacement up to 180 degrees, and for the elevation motion a hydraulic linear actuator, which rotates the panel around a parallel with East - West axis, is used. The detailed model of the tracking system, shown in figure 2, is designed so that it has five parts, which are connected one with other, respectively to ground, using the following geometric constraints: base (1) fixed on the ground; intermediary support (2) mounted on the base - revolute joint (B); hydraulic cylinder (4) to base - revolute joint (E); piston (5) to intermediary support - revolute joint (C); cylinder to piston - translational joint (D); motor fixed on the intermediary support; panel (3) to motor (and on the intermediary support) - revolute joint (A).

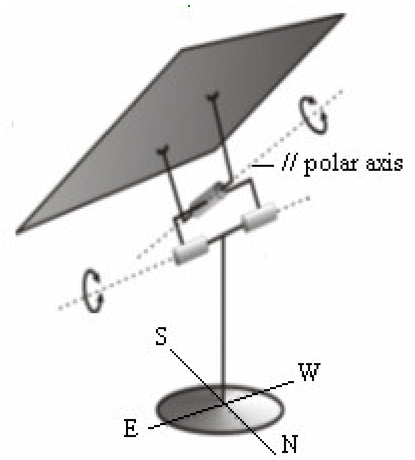


Fig. 1

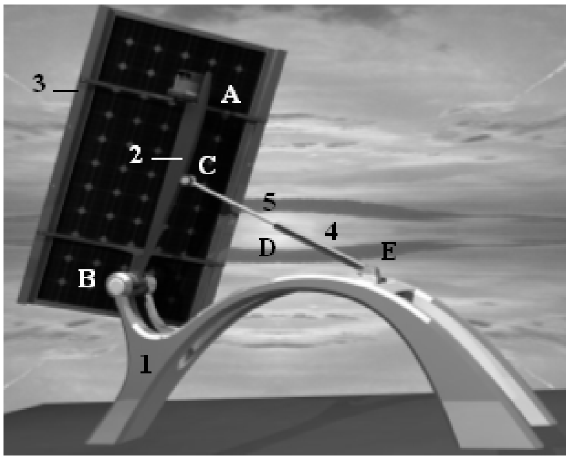


Fig. 2

The keyword in the design process of the tracking systems is the energetically efficiency: using the tracking system, the photovoltaic panel follows the sun and increase the collected energy, but the driving actuators consume a part of this energy. Consequently, in this paper, the design strategy is made in two steps, for minimizing the power consumption (i.e. the factor E_T) and maximizing the solar radiation absorption (E_{PO}), as follows: designing the optimal dual-axis tracking mechanism, which intends to minimize the actuating forces that are needed for tracking the sun movements, the optimization problem using the dynamic model of the electrical and mechanical structure and computing the geometrical parameters of the tracking mechanism; designing the optimal control low, by balancing the mechatronical system tracking error with the command signal, in order to minimize the electrical energy consumption of the motors/actuators.

3. OPTIMIZING THE TRACKING SYSTEM

Using the MBS environment ADAMS, the dynamic optimization of the tracking system is made with the following steps: parameterizing the virtual model, defining the design variables, defining the design objectives & constraints for optimization, performing design studies, and optimizing the model on the basis of the main design variables. The parameterization of the tracking mechanism is made using the points that define the structural model, in fact the locations of the geometric constraints. The parameterization simplifies changes to model because it helps to automatically resize, relocate and orient objects. In this way, relationships into the model are created, so that when a point is changed, any other objects (ex. bodies, joints) that depend on it will be updated. Design variables represent elements that allow creating independent parameters and tie modeling objects to them. In our case, the global coordinates of the design points (see fig. 2) define the design variables. In addition, using design variables, design studies can be performed. The design study represents a set of simulations that help to adjust a parameter for measuring its effect on the dynamic performance of the tracking system. As results, we can identify the main design variables, with great influence on the tracking system behavior.

The optimization problem is described as a problem to minimize the objective functions over a selection of design variables, while satisfying various constraints on the design and state variables of the system. The objective functions are numerical representations of the tracking system efficiency, the optimum values of these functions corresponding to the best possible design. In our case, the minimization of the energy consumption for orienting the panel in both daily and elevation directions is the design objective. The power consumption depends on the motor torque (the daily motion) & force (the elevation motion) generated by the driving elements, and the angular & linear velocities, which are determined having in view the motion law of the panel. The motion law is established having in view is to obtain as much as possible incident radiation with minimum energy consumption for tracking the panel. The photovoltaic panel can be rotated 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 (incoming energy) is obtained for the continuous motion, but in this case the operating time of the motors (i.e. the energy consumption) is high.

The key idea for optimizing the motion law is to maximize the energy gained through the step-by-step orientation, for absorbing a quantity of solar energy closed by the ideal case (continuous orientation), and to minimize the energy consumption for realizing this discontinuous orientation. The electric energy produced by the PV panel depends on the quantity of incident solar radiation (normal to panel), which is given by the relation:

$$G_I = G_D \cdot \cos i, \tag{1}$$

where G_D is the direct terrestrial radiation, and i - the angle of incidence. The direct radiation is empirical established, using the next equation [5]:

$$G_D = G_0 \exp\left(-\frac{T_R}{0.9 + 9.4 \cdot \sin\alpha}\right), \tag{2}$$

$$G_0 = \overline{G}_0 \cdot (1 + 0.0334 \cos x),\ x = 0.9856^\circ \cdot n - 2.72^\circ,\ \alpha = \sin^{-1}(\sin\delta \cdot \sin\varphi + \cos\delta \cdot \cos\varphi \cdot \cos\omega),\ \omega = 15^\circ \cdot (12 - T), \tag{3}$$

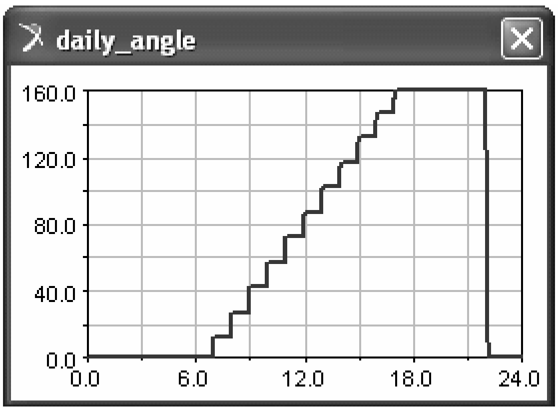
where G_0 is the extraterrestrial radiation, $\overline{G}_0$ - the solar constant (1367 W/m^2), n - the day number during a year, T_R - the distortion factor, which depends on the month and the geographic region, α - the solar altitude angle, δ - the solar declination, φ - the latitude angle, ω - the solar hour angle, and T- the local solar time. The angle of incidence is determined from the scalar product of the sun's ray vector and the normal vector on panel [3]:

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

$$\beta = \sin^{-1}(\cos\delta \cdot \sin\omega),\ \gamma = \sin^{-1}\left(\frac{\cos\alpha \cdot \cos\psi}{\cos\beta}\right),\ \psi = (\mathrm{sgn}\,\omega)\cos^{-1}\left(\frac{\sin\alpha \cdot \sin\varphi - \sin\delta}{\cos\alpha \cdot \cos\varphi}\right), \tag{5}$$

in which β and γ are the diurnal & seasonal angles of the sun's rays in the polar system, β* and γ* - the daily & elevation angles of the panel, and the ψ - the azimuth angle. The numeric simulations were performed considering the Braşov area, in the summer solstice day (φ=45.5°, δ=23.45°, n=172, T∈[4.26, 19.74], T_R=4.2).

Having in view to minimize the energy consumption for orientation, we propose a solution in which the orientation is made in steps, as shown in figure 3. The angular field for the daily motion is β*∈[-80°, +80°], the operating time for a step being 0.1 h. For decreasing the number of actuating operations of the motor, the panel is fixed maintained in the morning (4.26-6.91) and in the evening (17.01-22.00). Afterwards, the panel comes back in the initial position (-80º), with continuous motion in 0.2 h. Regarding the elevation motion, the panel remains in the specific position for the summer solstice (γ* = φ - δ = 22.05º) in the time period 9.01-14.91; excepting this period, for increasing the incident radiation, the panel is supplementary inclined with 11.05º (γ* = 11º). The operating time of the actuator is 0.1 h, for each actuating. In figure 3, the angles are measured relative to the initial position of the panel, in the east/sunrise (-80º for the daily motion, and 11º for the elevation motion).



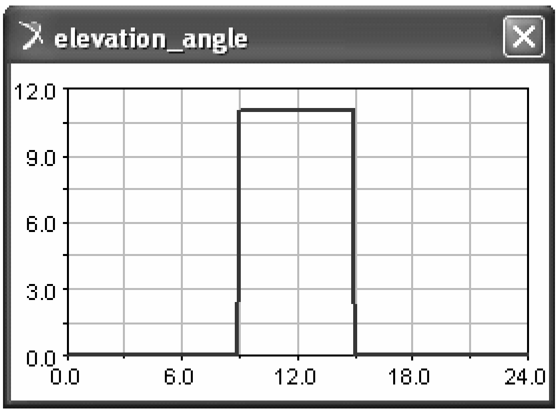


Fig. 3

In this way, we obtain the variation of the incident radiation during the summer solstice day (fig. 4). At the same time, we present the incident radiation obtained in the case of the fixed panel, considering the solar noon position (β^* = 0°, and γ^* = 22.05°). Afterwards, considering the active surface and the panel's efficiency [8], we obtain the energy produced by panel: panel with tracking - 1755 J; fixed panel - 1231 J (for comparing, the maximum incident radiation that can be obtained through the continuous orientation is 1784 J, so that the energy obtained with our solution is close-by the ideal case). Therefore, we obtain an energy contribution of 42.5 % by tracking the panel, but a part from this energy is consumed for driving the motors.

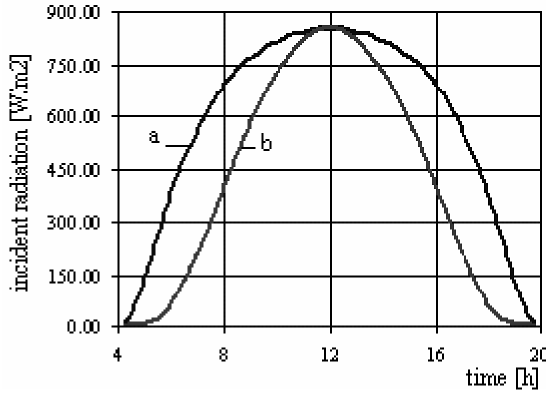


Fig. 4

4. CONTROLLING THE TRACKING SYSTEM

For computing the energy consumption, it is necessary to determine, for beginning, the motor torque and force that generate the prescribed behavior. These dynamic characteristics have been established by developing the control system of the tracking system, using ADAMS/Controls and MATLAB/Simulink. ADAMS/Controls is a plug-in to ADAMS/View that allows integrating motion simulation and controlling system design in the virtual model. The motor torque and the motor force represent the input parameters in the mechanical model of the tracking system; the outputs, which will be transmitted to the controller, are the daily and elevation angles of the panel. ADAMS/Controls and MATLAB/Simulink communicate by passing state variables back and forth.

For the input state variables, the run-time functions are 0.0 during each step of the simulation, because the motor torque & force will get their values from the control system. The run-time functions for the input variables are defined using a specific ADAMS function that returns the value of the given variable, as follows: VARVAL (control torque) and VARVAL(control force). For the output state variables, the run-time functions return the angles about the revolution axes, as follows: daily angle - AZ(panel.MAR_1,support.MAR_2), which returns the rotational displacement of one coordinate system marker attached to panel about the Z-axis of another marker attached to support; elevation angle - AX(support.MAR_3,base.MAR_4), which returns the rotational displacement of one coordinate system attached to support about the X-axis of another marker attached to base.

The next step is for exporting the ADAMS plant files for the control application. The Plant Input refers the input state variables, and the Plant Output refers the output state variables. The input and output information are saved in a specific file for MATLAB (*.m). ADAMS also generates a command file (*.cmd) and a dataset file (*.adm) that are used during simulation. With these files, the control system block (fig. 5) was created in MATLAB/Simulink, in order to complete the link between the control and mechanical systems. In this model, "beta.mat" and "gama.mat" represent the databases with the time-history variations of the daily and elevation positions/angles, according to figure 3. The mechatronic tracking system is a nonlinear system that is controlled using two PID controllers (one for each motion). For configuring the controllers (determining the proportional, integral and derivative parameters), we used the following performance indices: overshot - 10%; settling time - 10 sec. The phase margin and the gain margin have been established for obtaining a robust controller.

ADAMS accepts the control torque & force from MATLAB and integrates the mechanical model in response to them. At the same time, ADAMS provides the current daily & elevation angles for MATLAB to integrate the control system model. As result of the controlling process, we have obtained the time-history variations of the input state variables. Multiplying these functions with the angular & linear velocities, we obtained the power consumption for the both motions. Afterwards, integrating power consumption curves in absolute values, the total energy consumption (i.e. the mechanical work) for tracking the photovoltaic panel is obtained, $E_T \approx 57$ J (fig. 6). With this value, we performed the energetic balance, as follows: $\varepsilon = (E_{PO} - E_{PF}) - E_T = (1755 - 1231) - 57 = 467$ J; this means that the tracking system is efficient from energy balance point of view (the energy contribution obtained by using the tracking system is approx. 38%, relative to the fixed panel case).

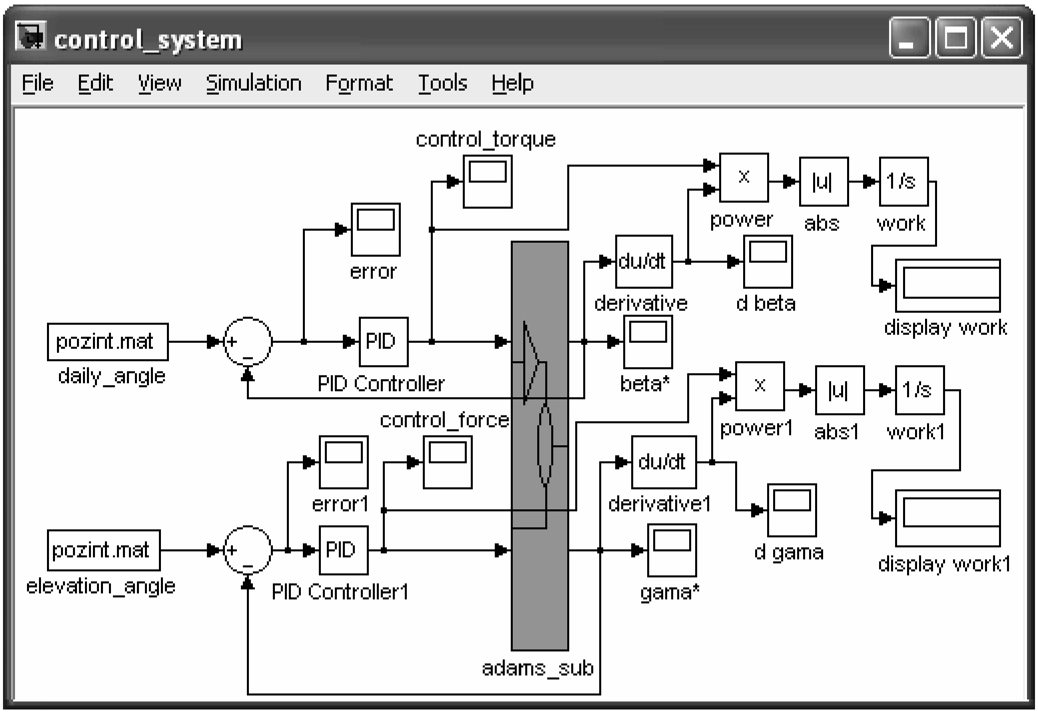


Fig. 5

The application from paper is a relevant example regarding the implementation of the virtual prototyping tools in the design process of the solar tracking systems. One of the most important advantages of this kind of simulation is the possibility to perform virtual measurements in any point or area of the tracking system, and for any parameter (motion, force, energy). In this way, the behavioral performance predictions are obtained much earlier in the design cycle of the tracking systems, thereby allowing more effective and cost efficient design changes and reducing overall risk substantially.

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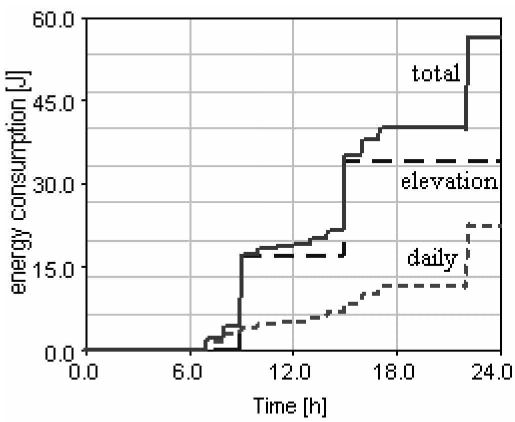

Fig. 6

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