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Designing the tracking system for a string of photovoltaic modules

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Abstract. This paper presents the virtual prototype of the mono-axis tracking system used for improving the efficiency of a string of photovoltaic modules. The solar tracker simultaneously changes the daily position of the modules, using a linear actuator that drives a rack-pinion mechanism. The key in optimizing the tracking system is to maximize the received solar radiation and to minimize the energy consumption for tracking. The virtual prototype is developed using a digital platform which integrates the following software solutions: CATIA - for the solid modeling of the components, ADAMS - for developing the mechanical model in MBS (Multi-Body Systems) concept, and MATLAB/Simulink - for the control system design.

Keywords: photovoltaic module, string, tracking mechanism, mechatronic system, virtual prototype.

1. Introduction

The increase of the emissions of carbon dioxide, responsible for the global warming and for the green-house effect, may have devastating consequences on the environment. The solution is the clean renewable energy sources, the solar energy conversion being one of the most addressed topics in the field. The photovoltaic (PV) systems convert solar energy into electric energy, their efficiency depending on the degree of use and conversion of the solar radiation. The degree of use of the solar radiation can be maximized by use of tracking systems, which are mechatronic devices that integrate mechanics, electronics, and information technology. There are two basic types of tracking systems: mono-axis and dual-axis. The mono-axis systems spins on their axis to track the Sun, facing east in the morning and west in the afternoon; this type of tracker needs a seasonal tilt angle adjustment. The dual-axis systems follow the Sun more precisely due to the combination of the daily and seasonal motions; they are more efficient than the mono-axis, but have the disadvantage of a higher price owed to their extra mechanical and electrical parts.

Considering energetic and economic aspects, we have determined that for the Bra□ov area the mono-axis tracking system is more efficient than a dual-axis system (the energetic gain through the seasonal motion does not justify the cost with this orientation) [1]. Consequently, in this paper we analyze and simulate a mono-axis system which changes the daily orientation of a string of PV module. The design is made by developing the virtual prototype of the tracking system, which is a control loop composed by the multi-body mechanical model connected with the dynamic model of the actuator (including the control system). The approach is made in the concurrent engineering concept, by integrating the mechanical device and the control system at the virtual prototype level.

2. Designing the MBS Mechanical Model

The literature presents different solutions of tracking systems [2-4], but a general approaching for the conceptual design and the structural synthesis of these mechanisms is missing. Thus rises the necessity of a unitary modelling method of mechanisms, and the proposed method is based on the Multi-Body Systems (MBS) theory. In the MBS concept, a mechanical system is defined as a collection of bodies with

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translational and rotational motions, linked by simple or composite joints [5]. The structural design of the tracking systems consists in the following stages: identifying all possible graphs, taking into account the type of joints, the number of bodies, and the degree of mobility of the multi-body system; 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.

In the structural synthesis of the tracking mechanisms, there can be considered general criteria, for example the degree of mobility (M=1 for the mono-axis trackers, and M=2 for the dual-axis trackers), as well as specific criteria, for example the type of the joint between the base and the input/output body. In this way, a collection of possible structural schemes were obtained. The solution for the system used in the study was selected from the multitude of the structural solutions by using of the multi-criteria analysis. The evaluation criteria of the solutions were referring to the tracking precision, the amplitude of the motion, the possibility of manufacturing and implementation.

The PV string was designed to supply a load for a cabin with three rooms. The number of PV modules was determined taking into account the geographical area of Braşov with its specific climatic conditions. So, the resulted PV string has five modules with an active area of 1.26m^2 and a yield of 15% each. From the previously mentioned stages with their requirements, the tracking system for the PV string has the following characteristics: a mono-axis tracker with the motor source disposed outside the modules (i.e. the motor does not act directly on a module), and transmitting the motion to the modules through a mechanism. The motor source of the tracking system is a linear actuator (1-2), which drives a rack bar (3) in translational motion (fig. 1). For the entire string, the motion is transmitted to the PV module by a pinion (4), which is rigidly connected to the module frame (5), through the gear joint. The PV module rotates around a support (6), the tilt angle being the position angle of the revolute axis A-A'. The cylinder (1) and the support (6) are rigidly connected to their corresponding pillars (7, 8). The rack-pinion gear is a speed reducer with the transmission ratio of 17/1.The direction of transmission is not reversible due to a screw-nut mechanism which is integrated in the actuator. The solid model of the mechanism was realized using CAD software (CATIA), the geometry being transferred to the MBS environment ADAMS through the STEP file format.

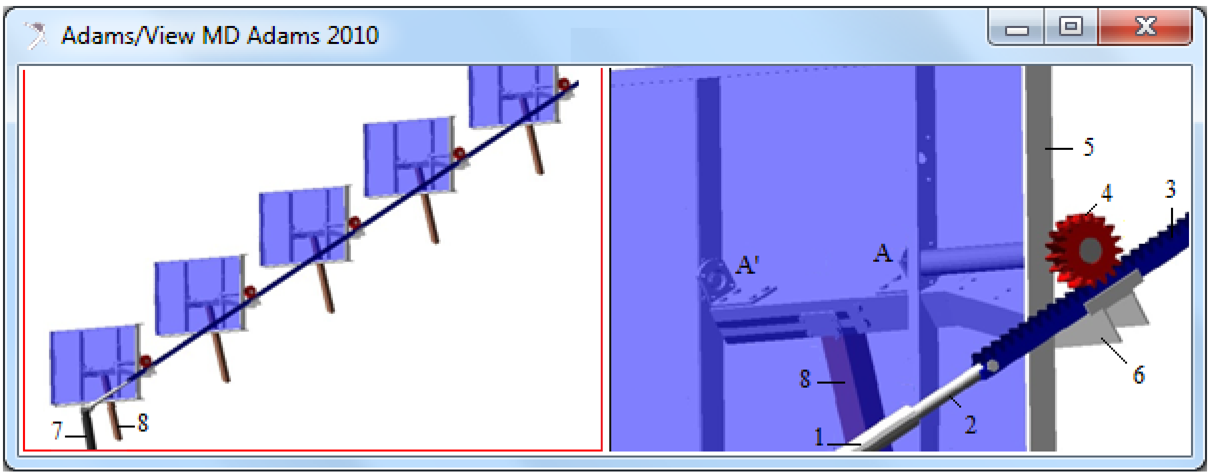

Fig. 1: The tracking mechanism for the PV string (ADAMS).

3. Designing the Control System

The solar tracker is an automated system, which has as task the simultaneous orientation of the PV modules on the imposed trajectory. For this paper, we have selected an opened-loop control system, which is based on an algorithm that provides predefined parameters for the actuator, depending on the Sun positions on the sky dome. For connecting the mechanical model and the control system, the input and output parameters have been defined in the MBS model (ADAMS), using a set of state variables. The motor force which is applied by the linear actuator represents the input parameter in the mechanical model. The force level is computed by the control system, based on the error between the actual daily position of the PV system and the imposed position. The primary output parameter is the daily angle of the modules, the state variable being defined by a run-time function that returns the rotational displacement of one marker attached to module about the motion axis of another marker attached to support (in the revolute joint A, see figure 1).

For improving the control system performance, we have designed a cascade control, using the linear velocity of the actuator as secondary output parameter. Cascade control uses the output of the primary (outer) controller to manipulate the set-point of the secondary (inner) controller as if it were the final control element. This is more complex than a single-loop control, but it provides important benefits such as the ability to address multiple disturbances to the process and to improve set-point response performance. The selection of the linear velocity of the actuator as secondary output parameter was based on the specific requirements for cascade control: secondary loop process dynamics is faster as primary loop dynamics; secondary loop has influence over the primary loop being measured and controllable. The state variable for the secondary output is defined by the linear velocity along the motion axis in the translational joint between piston and cylinder (see figure 1). In these terms, the basic scheme of the cascade control is shown in figure 2 (OC - outer controller, IC - inner controller).

The outer and inner controllers have been modelled as first-order lags. These are low-pass filters, which can be made by connecting in series a resistor with a capacitor. The filter passes low-frequency signals but attenuates signals with frequencies higher than the cut-off frequency. Using the Laplace transform, the transfer function of the controller has the form:

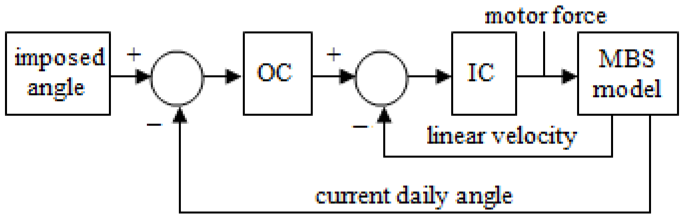

Fig. 2: The cascade control system.

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

where: X(s) - the input signal, Y(s) - the output, τ - the time constant of the response, K - the amplification.

The time constant represents the time it takes the system's response to reach 1-1/e ≈ 63,2% of its final value, where "e" is the mathematical constant. The cut-off frequency is related to the constant time,

$$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi\tau}, \tag{2}$$

where R is the value of the resistor, and C is the value of the capacitor. For both filters, we considered that the time constant value is τ=0.001 seconds, obtaining the cut-off frequency f_c≈159 Hertz; this corresponds to the angular frequency ω=1000 radians per second. In other words there is a low pass filter (the outer controller) which is cascaded into another filter (the inner controller) with the same cut-off frequency. In these terms, the motor force will be:

$$F = K_2[K_1(\beta_i - \beta_c) - v_a], \tag{3}$$

where β_i is the imposed daily angle, β_c - the current/measured daily angle, v_a - the linear velocity of the actuator, K_1 - the amplification of the outer controller, and K_2 - the amplification of the inner controller.

The next step is facilitating the exporting of the ADAMS plant files for the control application, using the ADAMS/Control interface. The input and output information are saved in a specific file for MATLAB (*.m); the export also generates a command file (*.cmd) and a dataset file (*.adm) that are used during simulation. With these files, the control system diagram was created in MATLAB/Simulink (fig. 3), based on the cascade control scheme shown in figure 2. The "mat" block represents the database with the imposed position (daily angle) of the modules. ADAMS Mechanism block is based on the information in the "m" file.

The tuning of the controllers, in order to establish the optimal values of amplification factors K_1 and K_2, is performed through root locus method with the help of the MATLAB/Simulink software. The roots of the controllers transfer functions lead to the description of system`s behaviour in time domain depending on their position. Through the synthesis of the control system, the positions of the transfer functions roots are determined depending on the desired imposed conditions. In our case, the variables used in study are the amplification factors of the controllers, while the design objective is to minimize the tracking error.

First there were determined the polynomial roots of the transfer functions (zeros and poles). The system`s behaviour is examined through the influence of these roots. So, if the grade of the polynomial from the nominator is increased, the system has a faster response and a higher frequency band, but a higher override. By adding an extra pole, the system has a slow response with a smaller frequency band, but with a smaller override. Using this method, the following values of the amplification factors have been obtained: $K_1 = 4843$, $K_2 = 4835$.

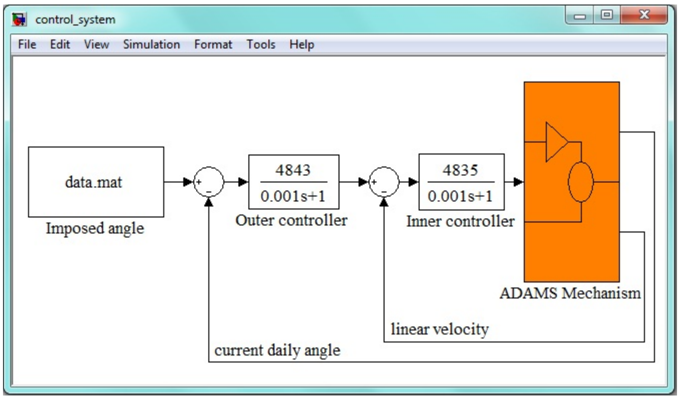

Fig. 3: The block diagram of the control system (MATLAB).

4. Results and Conclusions

The main task in designing the tracking system is to maximize the energetic gain by increasing the solar input and minimizing the energy consumption for tracking. The PV modules can be rotated without brakes during the day-light, or can be discontinuously driven (step-by-step). The maximum incident radiation can be obtained for the continuous motion, but in this case the operating time of the actuator is high, and there are necessary large transmission ratios. In these conditions, we used a step-by-step tracking strategy, which was developed considering the correlation between the optimal field for the daily motion and the number of the steps. The idea is to minimize the angular motion field and the number of steps without significantly affecting the incoming solar radiation.

The energy produced by the PV string depends on the quantity of incident solar radiation, the conversion efficiency, and the number of modules [6]. The incident radiation, which is normal to the active surface, depends on the direct terrestrial radiation and the angle of incidence. The direct radiation is empirical established using the Melißʼs model [7], depending on the extraterrestrial radiation, the medium solar constant, the day number during a year, the distortion factor, the solar altitude angle, the solar declination, the latitude angle, the solar hour angle, and the local solar time. The incidence angle is determined from the scalar product of the Sun's ray vector and the normal vector on module, depending on the tilt angle and the daily angle of the modules. For the mono-axis tracking system in study, the tilt angle is kept fixed throughout the year at the value $\gamma^*=44^0$ [1]. The angular field and the number of steps for the daily motion is established in accordance with the methdology presented in [6].

The paper presents the exemplification for the summer solstice day, for which the optimal angular field of the daily motion is $\beta^*\in[60°, -60°]$ (positive values in the morning, negative values in the afternoon, and $\beta^*=0°$ in the solar noon), the orientation being done in 10 steps. The return of the system in the initial position is made after sunset, with continuous motion. With these data, the imposed motion law of the PV string is shown in figure 4; the data from this diagram (time and angle) were imported in the control system model (see figure 3 - "data.mat" block). As result of the co-simulation performed with MATLAB/Simulink and ADAMS, in figure 5 there is shown the time-history variation of the linear velocity of the actuator, while the necessary motor force is shown in figure 6. With these values, the power consumption can be obtained, and then, by integrating the power curve in absolute value, the energy consumption for realizing the tracking will result, $E_C\approx63$ Wh/day (fig. 7).

Finally, considering the energy production of the PV string with tracking (E_T) and the energy produced by the same string without tracking - fixed (E_F), the energetic balance can be performed. For the fixed string, the modules are kept fixed throughout the day in the solar noon position ($\beta^*=0°$). As was mentioned, the energy produced by the PV string depends on the quantity of incident solar radiation, the active surface and the conversion yield of the modules. Considering a string with five modules, each having the active surface of 1.26 m^2 and the conversion yield 15%, the efficiency of the tracking system (ε) can be expressed in the following way: $\varepsilon = E_T - (E_F + E_C) = 9581 - (6119 + 63) = 3399$ Wh/day, representing an energetic gain of

55.6 % relative to the fixed string, which demonstrates the viability of the tracking strategy. In addition, the root mean square of the tracking error is very small (≈0.0001), and this validates the control system design.

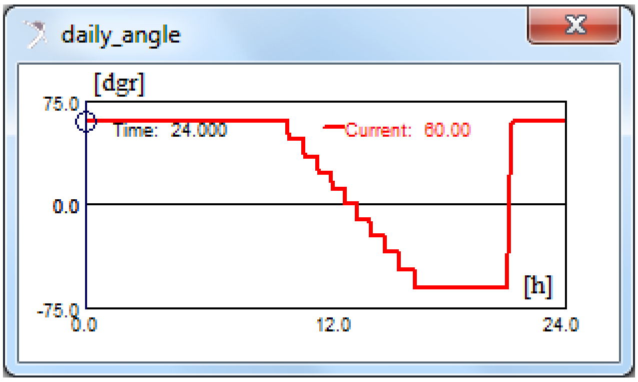

Fig 4: The imposed motion law (daily angle).

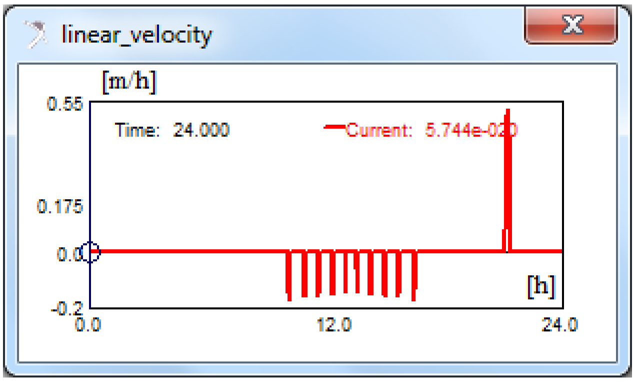

Fig 5: The linear velocity of the actuator.

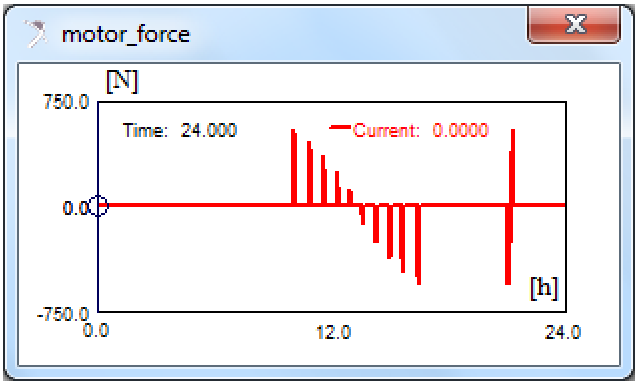

Fig. 6: The motor force.

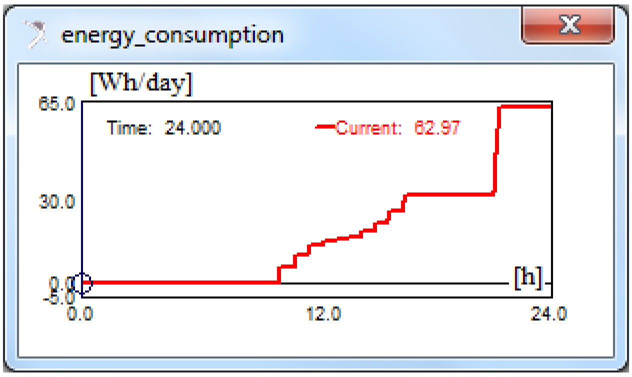

Fig 7: The energy consumption for tracking.

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 prototype (traditional method). The future research will add more climatic parameters to the simulations as well as the implementation and testing of the tracking system in real environment. More, there will be compared the data sets achieved by measurements with the virtual prototype analysis.

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