Mono-Objective Optimization of a Photovoltaic Tracking System with LPF Controllers

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Abstract. The work deals with the optimal design of a single-axis solar tracker, which is used to adjust the daily position of a photovoltaic system in order to capture as much as possible solar radiation. The two main components of the solar tracker (the mechanical device and the control system) have been coupled (integrated) in the concurrent engineering concept. For assuring high stability and robustness, the control system is a cascaded two-loop employing LPF (Low-Pass Filter) controllers. The controlled parameter in the main (external) loop is the daily angle of the photovoltaic platform, while in the secondary (internal) loop the linear velocity in the driving actuator is monitored. The mono-objective optimization problem is described in the following way: to minimize the difference between the imposed and current daily angle (thus preserving a high energetic efficiency of the tracking system), considering the controllers' gains as independent design parameters.

Introduction

The energetic efficiency of the photovoltaic (PV) panels depends on the degree of use and conversion of the solar radiation [1, 2]. To increase the solar input, solar trackers are frequently used, the energetic efficiency of the PV panels equipped with tracking systems being higher (with 20% -50% during the year) relative to the equivalent static PV panels (without tracking) [3-8].

The tracking systems contain mechanisms actuated by motor sources (rotary or linear actuators), which are controlled to ensure the optimal position of the PV panel. Depending on the number of degrees of freedom, two basic types of tracking systems can be systematized: single-axis trackers (they are frequently used for the diurnal motion of the PV panel, from East to West), and bi-axis trackers (for the diurnal and elevation motions).

For the bi-axis systems, in relation with the relative position of the revolute axes, different configurations of tracking mechanisms can be obtained, such as polar tracking systems (where the revolute axis of the diurnal movement is parallel with the polar axis), or azimuthal systems (where the axis of the diurnal rotation is disposed in vertical direction). Additional types of bi-axis systems can be obtained from the basic types, for example the pseudo-azimuthal system, which is derived from the azimuthal system, having the main/daily rotational axis positioned on the horizontal (North-South). Due to its stability, the main application of this system is for the photovoltaic platforms, meaning more PV panels installed (disposed) on common structure/frame.

It was proven that for Brașov geographical area a mono-axis solar tracker is more suited than a bi-axis tracker because the energy gain brought by the bi-axis system does not justify the added cost of the seasonal orientation [9]. Under these terms, the work deals with the modeling and simulation of the single-axis version of a pseudo-azimuthal tracking system, which is used to adjust the daily position of a PV platform. The study is focused on the optimal design of the control device, intending to minimize the tracking errors, in other words the solar radiation losses due to the positioning deviations of the PV platform induced by the controller design. The simulations have been performed by using the virtual prototype of the solar tracker, which integrates the MBS (Multi-Body System) model of the mechanical device and the DFC (Design for Control) model of the control system.

Tracking Mechanism Design

As mentioned, the single-axis version of a pseudo-azimuthal solar tracker is used to adjust the daily motion (from East to West) of the PV platform, which contains three panels (in-line arrangement), the active surface being 5.04 m^2 (1.68 m^2 per panel). The virtual model of the tracking mechanism, which was developed by using the MBS (Multi-Body System) software package ADAMS, is shown in figure 1. The tracking system is actuated by a linear actuator, the motion being transmitted to the platform by a belt transmission (Poly-V grooved belt system), which acts as a stroke amplifier (with 1:2 transmission ratio), thus allowing to use an actuator with small dimension (power). The belt system was created by using ADAMS/Machinery, which is incorporated in to the ADAMS/View preprocessing environment.

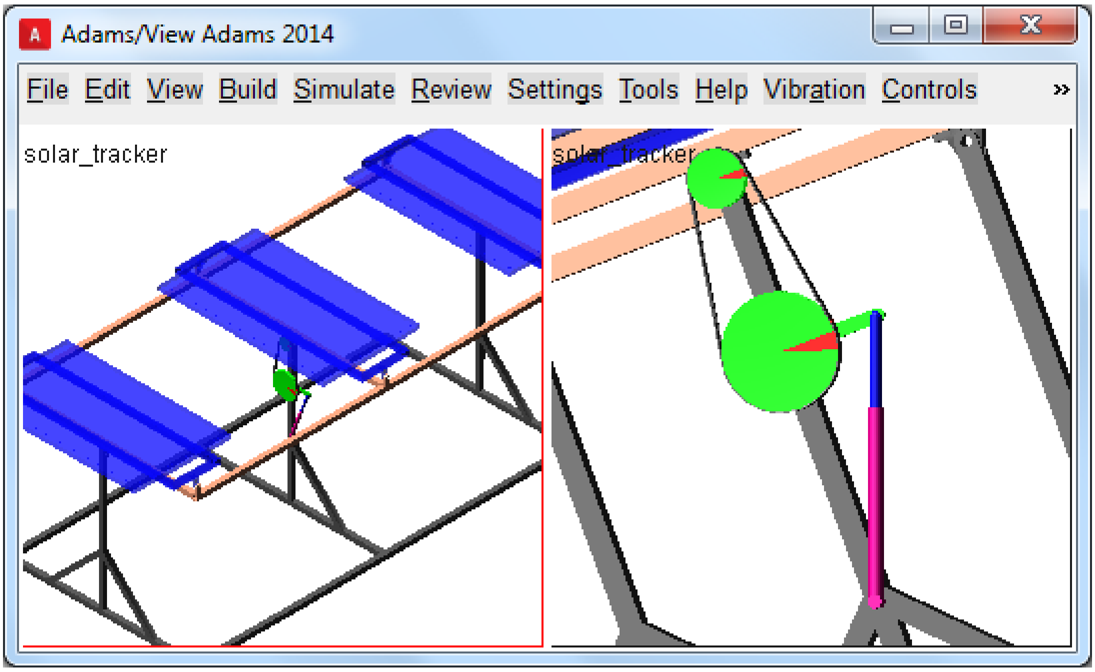

Fig. 1. The MBS model of the mono-axis solar tracker.

The actuator is connected by spherical joints to the adjacent parts (the middle fixed pillar, and the link extension of the driving pulley). The supporting frame of the PV panels is connected to the three pillars (front, middle and rear) through revolute joints (bearings). The driving pulley (driver) of the belt transmission rotates relative to the middle pillar, while the driven pulley (follower) is rigidly connected to the supporting frame (the PV platform). The whole PV platform (including the panels and the supporting frame) weighs around 240 kg.

The optimal design of the mechanical device, intending to minimize the motor force developed by the linear actuator (and in this way, the power/energy consumption for performing the tracking), was conducted in a similar way with the study presented in [10]. The global coordinate of the design points in which the spherical connections of the actuator are located have been used as independent design variables for the optimization process.

The PV platform can be rotated from sunshine (East) to sunset (West) without brakes during the day-light, or can be discontinuously driven (step-by-step motion), the maximum angular field for the daily motion being of 180º (±90º relative to the noon position). The continuous tracking allows obtaining the optimal incidence, but it also generates some problems, such as the long operation time of the system, the need to perform very large transmission ratios (the tracking velocity being very low), or the behavior of the system under the action of non-stationary external perturbations (such as wind) whose effect can be amplified if the system is in motion.

On the other hand, the solar radiation has small values in the limit positions (at sunshine and sunset), and for this reason it is not efficient to track the sun in these areas (the radiation gain does not justify the energy consumption for tracking). The optimal design of the motion law was approached in [6], considering an algorithm based on the mathematical modeling of the incident solar radiation. The design variables in the optimization process of the motion law for the step-by-step tracking refer to the angular field of the daily motion, the number of steps, and the actuating timetable, data which depends on the day of the year for which the simulation is performed.

The numerical simulations in this paper have been performed considering the summer solstice day (June, 21), the corresponding tracking law being defined by the following data (see fig. 2): the angular domain of the daily motion – $\varepsilon \in [+60°, -60°]$ (ε - the daily angle, which is null at noon), the number of tracking steps - 8 (in other words, the motion step size is $\Delta\varepsilon=15°$), the actuating times (in local time) - 8.21, 9.53, 10.76, 11.75, 12.79, 13.78, 15.01, 16.33. After sunset, the system returns to its initial position, with continuous (without brakes) motion.

The tracking law is used as input in the optimization process of the control system for the pseudo-azimuthal tracking mechanism, the daily angle being measured in the revolute joint between the PV platform and the middle pillar.

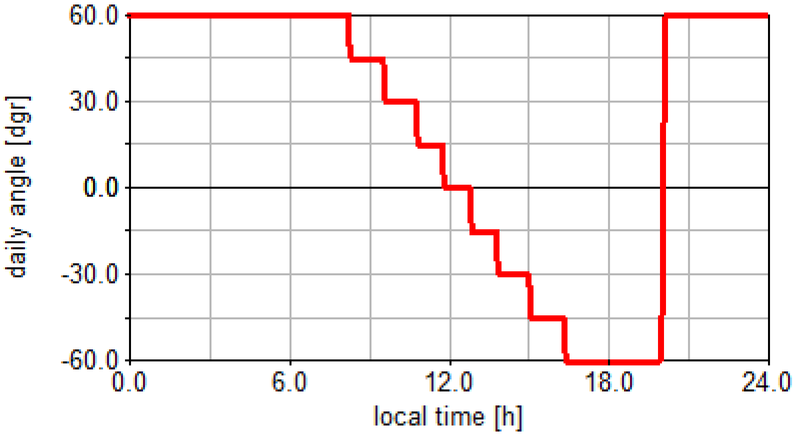

Fig. 2. The tracking (control) law.

Optimal Design of the Control Device

The solar tracker in study is a mechatronic system that integrates the mechanical device (shown in fig. 1) and the controlled operating device. The control system is developed in the concept of the concurrent engineering, through the integration with the MBS model at the virtual prototype level [11]. In this respect, the virtual prototyping platform integrates a DFC (Design for Control) software solution - EASY5, which exchanges information with the MBS software - ADAMS.

Regarding the control system, the literature presents a series of schemes, with one or more loops [12-14]. For the present work, a control system with two loops, in cascade configuration, has been selected. The monitored/controlled parameter in the main (external) loop is the daily angle of the photovoltaic platform, while in the secondary (internal) loop the linear velocity in the driving actuator is controlled. In this configuration, the main variable is controlled by adjusting the reference of the secondary variable. Thus, an improved control of the main variable is insured, which is less affected by perturbations. This type of control system has resulted from testing various configurations, reaching the conclusion that it represents the minimum needed, from complexity point of view, which ensures resolving the control problem of the considered solar tracker.

The communication (data transfer) between the MBS and DFC models is assured by the input and output variables (plants). As input plant (in the MBS model), the control force in the linear actuator is used, while the daily angle of the PV platform and the linear velocity in actuator are used as output plants (in a 2-loop cascade configuration). The input variable takes the value from the DFC model, while the output variables are created by using specific ADAMS/View functions, namely “Angle about Axis” (for the daily angle), and “Velocity along Axis” (for the linear velocity).

The data transfer between ADAMS and EASY5 is assured by using ADAMS/Controls, which is a plug-in that manages the files used during the co-simulation, as follows: I/O plants file (inf), ADAMS/View command file (cmd), and ADAMS/Solver dataset file (adm). The I/O plants file is used in EASY5 for configuring the ADAMS Mechanism extension block.

Under these terms, the control system model is shown in figure 3, where the Tabular Function block is used to model the imposed control law (i.e. the reference signal), in terms of time-history variation of the daily angle (see fig. 2). The block provides a table as a function of time, linear interpolation being used between the time points. For performance and cost reasons, low-pass filters (LPF) are used for the position and velocity controllers, whose modeling in EASY5 was carried out by using first-order lag transfer functions, in time constant format.

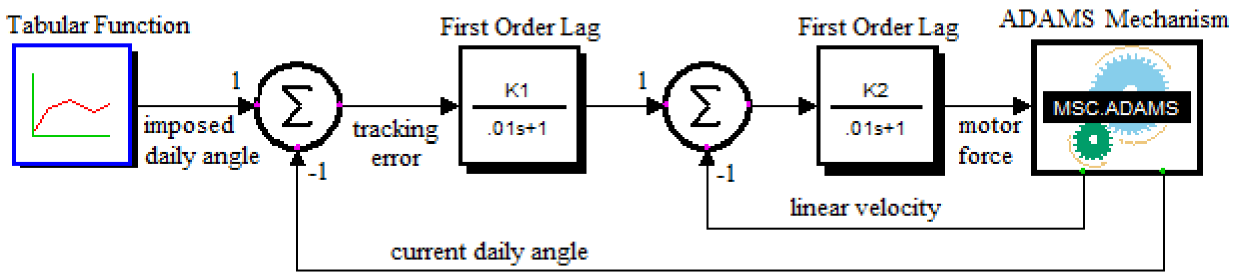

Fig. 3. The control system with 2-loop cascade configuration.

Designing the position and velocity controllers consists in determining the optimum values of the gain factors for the primary (outer) and secondary (inner) control loops (K_1 and K_2). The optimization procedure is similar with the one used to optimize the mechanical device of the tracking system [10]. To access the parametric optimization procedure, it is necessary that the control system model from figure 3 to be transferred in ADAMS. The model is exported from the EASY5 interface through the ESL (External System Library) format, specifying the system parameters that will be identified in ADAMS as design parameters. Once imported in ADAMS, in the form of a general state equation (GSE), the parameterized model of the control system, connected to the MBS model of the mechanical device, becomes available for optimization.

The tracking error is considered as objective function, the optimization goal being to minimize the root mean square (RMS) during simulation (fig. 4), which is a measure of the magnitude of the tracking error varying quantity. The function (F) is explicitly defined in the control system model (see fig. 3) as difference between the imposed (ε^i) and current (ε^c) values of the daily angle,

$$F = \varepsilon^i - \varepsilon^c , \; F_{RMS} = \sqrt{\frac{F_1^2 + F_2^2 + \ldots + F_n^2}{n}} , \qquad (1)$$

where the set of values $\{F_1, F_2, \ldots, F_n\}$ depends on the simulation time interval ($t \in [0, 24]$ hours), and the time increment (0.01 hours).

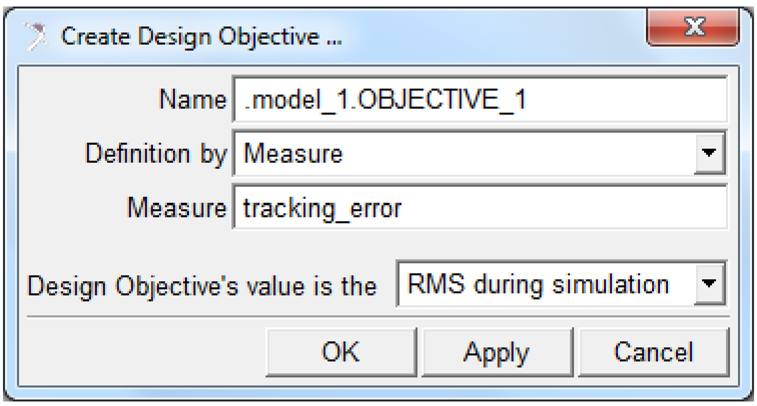

Fig. 4. The modeling of the objective function.

The imposed daily angle is given by the tracking (control) law shown in figure 2 (which is transposed into the Tabular Function of Time block in figure 3), while the current angle is defined in the MBS model of the solar tracker by using the ADAMS/View function AZ(platform.MARKER_1, pillar.MARKER_2), where AZ means Angle about Z-axis (the local motion axis). This function measures the relative motion between the two coordinate system markers placed in the revolute joint that connects the platform frame to the middle sustaining pillar.

As independent variables for optimization there have been considered the amplification factors of the position (K_1) and velocity (K_2) controllers, for which the variation fields have been defined in the range $K_{1,2} \in [1, 10^4]$. The OptDes-GRG (Generalized Reduced Gradient) algorithm was used in the optimization process, thus obtaining the optimum values of the design variables, as follows: K_1=3400, K_2=1800. The tracking error during simulation is very small (fig. 5), the root mean square being of 10^{-6} order, which proves the viability/utility of the optimization process. Insignificant variations occur during the tracking steps, in the stationary positions the steady-state errors being practically null, which ensure optimal sunray incidence. For comparison, in the initial control design, considering the standard values of the amplification factors $K_{1,2}$=100, there was obtained F_{RMS}=0.8727. The improvement brought by the optimal design of the controllers is a considerable one, proving the usefulness of the proposed/adopted optimization algorithm.

Another important result of the dynamic analysis is the energy consumption for performing the tracking (fig. 6), which was obtained by integrating the power consumption curve in absolute value. The small energy consumption ($E_c \cong 113$ Wh/day, while in the initial design the consumption is higher by about 6%, mainly due to the signal overshoots - see figure 5), which is a cumulative effect of the optimal design of the mechanical and control devices of the solar tracker, has a beneficial contribution on the energetic efficiency of the PV system, which will be addressed in a future work.

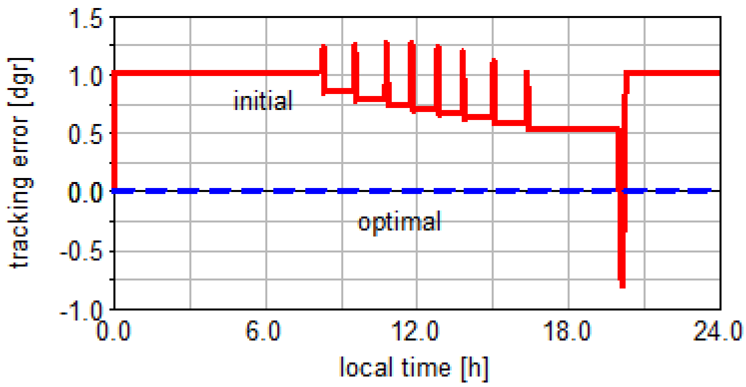

Fig. 5. The tracking error before and after optimization.

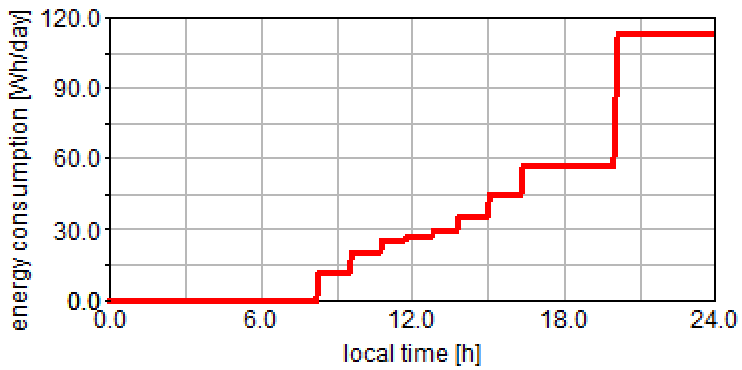

Fig. 6. The energy consumption for performing the tracking.

Final Remarks

The above presented virtual prototype of the solar tracker, connected with the optimization program of the motion (control) law, allows to evaluate several tracking strategies (in terms of motion angular domain, number of motion steps, operating/actuating timing table), in order to increase the energetic efficiency of the PV system, by maximizing the incident solar radiation, minimizing the energy consumption for performing the tracking, and minimizing the tracking (positioning) errors of the PV platform.

Future researches in the field will be focused on improving the solar radiation model (by modeling the diffuse component), evaluating more complex control strategies, approaching the tracking system in bi-axial variant (by adding the elevation motion of the platform), manufacturing and implementing the physical prototype of the solar tracker. The control system circuit board will be realized by using a technique based on photoresist material and ultraviolet light [15].

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