OPTIMAL DESIGN OF THE CONTROLLER FOR A PHOTOVOLTAIC TRACKING SYSTEM USING PARAMETRIC TECHNIQUES

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Keywords: photovoltaic system, tracking mechanism, controller synthesis, design of experiments.

Abstract: The paper is approaching the field of increasing the efficiency of the photovoltaic modules by using solar tracking systems. The main task in optimizing the tracking systems is to maximize the energetic gain by increasing the solar input, and minimizing the energy consumption for tracking. The tracking system is approached in mechatronic concept, by developing the virtual prototype, which is a control loop composed by the multi-body mechanical model connected with the dynamic model of the actuators, and with the controller model. The paper is focused on the optimal design of the PID controller for a PV tracking system, by using the optimization capabilities of the virtual prototyping environment ADAMS of MSC Software, based on DOE (Design of Experiments) parametric technique.

1. INTRODUCTION

The solar energy conversion is one of the most addressed topics in the fields 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 efficiency of the PV systems depends on the degree of use and conversion of the solar radiation. The energy balance refers to the surface that absorbs the incoming radiation and to the balance between energy inflow and energy outflow.

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. Basically the tracking systems are mechatronic 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 PV module relatively to the Sun position on the sky dome. The orientation of the photovoltaic modules may increase the efficiency of the conversion system from 20% up to 50% [2-4].

A photovoltaic module with tracking is efficient if the quantity of electric energy produced by system is substantially greater than the sum of the energy produced by the same module without tracking (fixed) and the energy consumption for tracking. Therefore, the main task in optimizing the tracking systems is to maximize the energetic gain by increasing the solar input, and minimizing the energy consumption for realizing the motion law. For achieving the energetic efficiency condition, all the components of the tracking system (the mechanical device, the actuators, the control system & the controller) are important, as well as their integration. No less important, there are the economical aspects, concerning the cost of the product (which includes the design cost), the reliability, and the pay-back period.

In the last years, we have developed a lot of studies concerning the optimization of the PV tracking systems, considering with priority the mechanical structure and the motion law of the PV modules, for azimuthal, equatorial and pseudo-equatorial tracking systems. The basic objective of this paper is to improve the behavior of the solar trackers from the control system point of view, through the optimal design of the controller. The mechanism was previously optimized from geometric and motion point of view, the tracking strategy aiming to optimize the angular field of the motion and the actuating time for the step-by-step orientation [1].

2. DESIGNING THE TRACKING SYSTEM

The orientation principle of the PV modules is based on the input data referring to the position of the Sun on the sky dome, and for this reason in the design process of the tracking systems two rotational motions are considered: the daily motion and the yearly precession motion. Consequently, there are two basic types of solar trackers: single-axis and dual-axis systems. The single-axis trackers 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, for this type of systems there is necessary a seasonal tilt angle adjustment.

The dual-axis trackers combine two motions, so that they are able to follow very precisely the Sun along the year. Depending on the relative position of the revolute axes, there are three types of dual-axis tracking systems: polar, pseudo-polar, and azimuthal. For the polar trackers, there are two independent motions, because the daily motion is made rotating the PV panel around the fixed polar axis. The pseudo-polar tracking system is derived from the polar one, by reversing the rotations order (thus, the fixed axis is for the elevation motion); in this way diurnal adjustment of the elevation angle is necessary (and not just seasonal) to ensure the optimal positioning of the daily motion axis. For the azimuthal trackers, the main motion is made by rotating the PV panel around the vertical axis, so that it is necessary to continuously combine the vertical rotation with an elevation motion around the horizontal axis.

For this paper, the tracking system in study is a pseudo-equatorial mechanism, with two degrees of freedom, corresponding to the daily and elevation motions. For the both motions, the driving element is a linear actuator, at which the revolute motion developed by the DC motor is transformed in linear motion between the actuator’s components by a screw-nut mechanism. The multi-body dynamic model of the tracking mechanism (fig. 1), which was developed by using the MBS environment ADAMS of MSC Software, includes the actuating motors, the bodies (with mass & inertia properties), the geometric constraints between parts, and the external & internal forces (including the friction forces and the reactions in joints). The PV module is mounted on a support, which rotates around a horizontal axis for generating the elevation. The daily motion is made by rotating the module relative to the support. The linear actuators act between support and module (for the daily motion), respectively between pillar and support (for elevation)

Regarding the controller, different solutions are used / presented in literature, such as classical PID techniques, or more advanced fuzzy logic controllers - FLC [6]. In the synthesis of a control system, the main problem is not only the selection of the controller, but also the tuning of the specific parameters, to verify certain given specifications for the controlled process. From this point of view, because three gains will tune a PID system, the design process involved is easy to describe, while the design of a fuzzy rule-based system is more complex, involving input selection, membership function definition, and rule definition.

The control system of the solar tracker in study was designed in the concurrent engineering concept. For connecting the mechanical model and the control system, the input and output plants have been defined. The motor (control) forces developed by the linear actuators represent the input parameters in the mechanical model, while the outputs transmitted to the controllers are the daily and elevation angles of the PV module. From economic and functional reasons, we have used PID (Proportional Integral Derivative) controllers, for the both motions. This controller attempts to correct the error between a measured process variable and a desired set-point by calculating and then outputting a corrective action that can adjust the process accordingly.

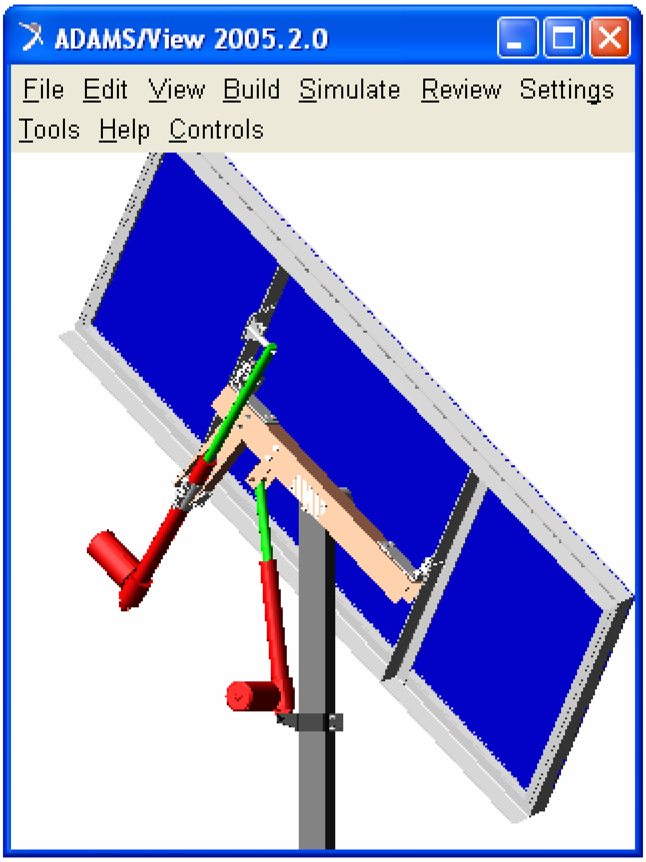

Fig. 1. The MBS model of the tracking system

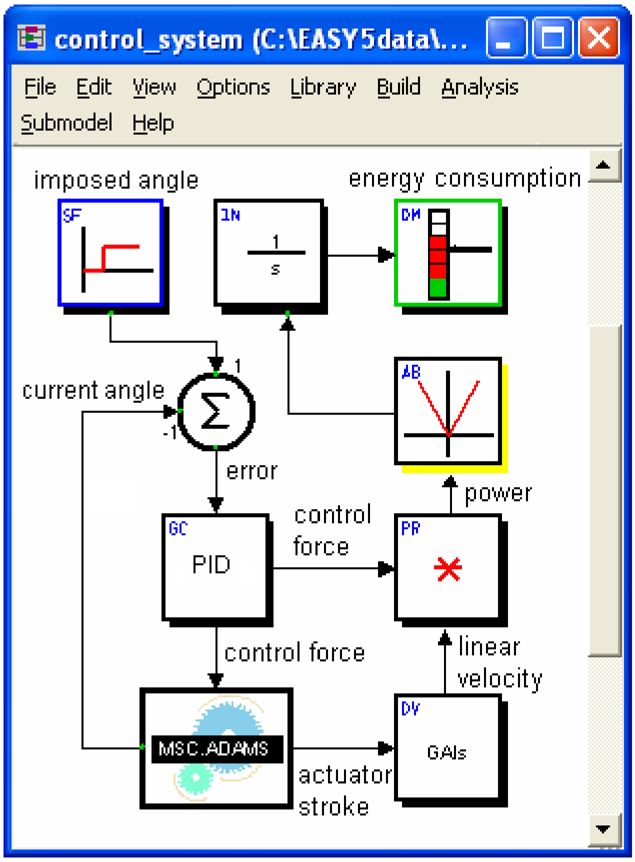

Fig. 2. The control system for the daily motion

The input & output plants have been modeled by using the specific module ADAMS/Controls. For the input variables, the run-time functions are 0.0 during each step of the simulation, because the control forces will get their values from the control system. For the output state variables, the run-time functions return the angles about the motion axes. The input and output information are saved in a specific file (*.inf), ADAMS/Controls generating also a command file (*.cmd) and a dataset file (*.adm) that are used during the simulation. With these files, the control system was created by using the DFC (Design for Control) software solution EASY5 of MSC Software, in order to complete the interactive communication between the mechanical and actuating-control systems. As instant, in figure 2 there is shown the control system diagram for the daily motion, the diagram for the elevation motion being similar.

The energy consumption for realizing the imposed motion law, which is necessary for performing the energy balance of the tracking system, is obtained by integrating ("IN" block) the power consumption curve in absolute value ("AB" block). The power consumption depends on the control force as well as the linear velocity in the specific driving actuator, by their product ("PR" block). The control error is defined as difference between the imposed motion law / angle ("SF" block) and the current angle realized by the tracking mechanism. The MSC.ADAMS block represents the mechanical device model (shown in figure 1), and it was created based on the information from the "inf" file.

The PV module can be rotated without brakes during the day-light, or can be discontinuously driven (step-by-step motion), usually by rotating the module with equal steps at every hour. Obviously, the maximum incident solar radiation is obtained for the continuous motion, but in this case the operating time of the system/motor is high. In our vision, the strategy for optimizing the motion law of the tracking system aims to reduce the angular field for the daily motion (the main motion of the system) and the number of actuating operations, without significantly affecting the incoming solar energy, and to minimize the energy consumption for realizing the tracking. The detailed algorithm for optimizing the motion law was presented in [1], leading to the optimal variations of the daily (β*) and elevation angles (γ*), in different periods / days during the year. For example, the motions laws corresponding to the summer solstice day (June, 21) are shown in figure 3.

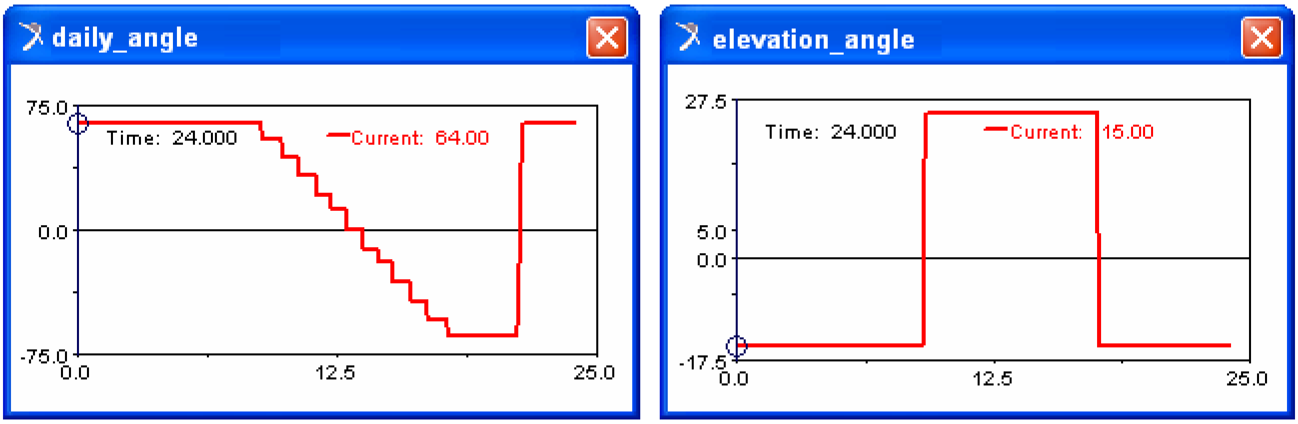

Fig. 3. The motion (control) laws in the summer solstice day

3. THE OPTIMIZATION STRATEGY

As we previously said, the paper is focused on the optimal design of the PID controllers for the above-described tracking system. There are several methods for tuning a PID loop. The most effective methods generally involve the development of some form of process model, and then choosing P, I and D based on the dynamic model parameters. In our research, the tuning of the PID controller is made by using the optimization capabilities of the virtual prototyping technique. For performing this study, we used ADAMS/Insight, part of the MSC.ADAMS suite of software, which is a powerful design of experiments software. ADAMS/Insight allows designing sophisticated experiments for measuring the performance of the mechanical/mechatronic system. It also provides a collection of statistical tools for analyzing the results of the experiments so that we can better understand how to refine and improve the system.

Design of experiments (DOE), also called experimental design, is a collection of procedures and statistical tools for planning experiments and analyzing the results, which can be performed for identifying the effects of varying several design variables simultaneously, having as goal to identify which variables and combinations of variables most affect the behavior of the mechanical system. In the paper, DOE technique was applied to determine the optimal values of the tuning parameters of the PID controller, in order to assure the imposed performance indexes of the system (the settling time, the overshoot, and the steady-state error).

Experimental design was performed in five steps: modeling the purpose of the experiment, in this case the minimization of the tracking error; choosing the set of factors for the tracking system that we are investigating (i.e. the tuning parameters of the controller); determining the values for each factor, and planning a set of trials in which we vary the factor values from one trial to another; executing the runs and recording the performance of the system at each run; analyzing the changes in performance across the runs. The runs are described by the design matrix, which has a column for each factor and a row for each run. The matrix entries are the levels for each factor per run.

The control system model is one in figure 2, for which the control block model of the PID controller is shown in figure 4. The derivative state for input to the PID block is consistent with the proportional state. The PID block automatically creates the integrated state of the proportional input for use as the integrated input. In these terms, we used an implicit differential equation (DIFF) to get the time derivative, as follows: error_derivative → DIF1(.tracker.DIFF_1), where DIFF_1 = DIF(.tracker.DIFF_1) - error, “tracker” being the model name. Afterwards, the ADAMS/View model of the solar tracker, shown in figure 1, has been exported in ADAMS/Insight for creating the experiment.

The first step required for creating the designed experiment is to select the factors to include in the design matrix (the proportional, integral and derivative terms). We select factors from the Candidates list, and then promote them to the Inclusions list (fig. 5). Promoting candidates to inclusions causes them to become part of the design matrix. After promoting the factors, we defined parameters for them in the factor form, as follows: the abbreviation, the nominal / initial value (see figure 4), and the value range (i.e. the list of numeric values).

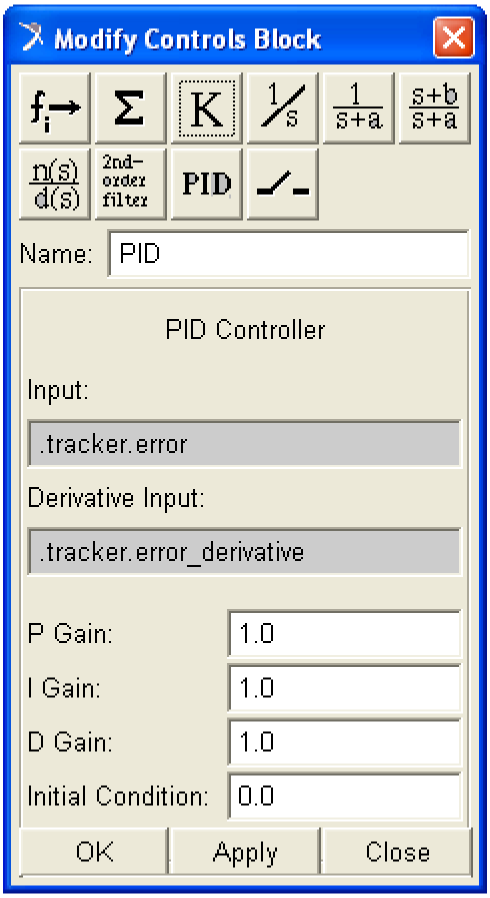

Fig. 4. The controller model

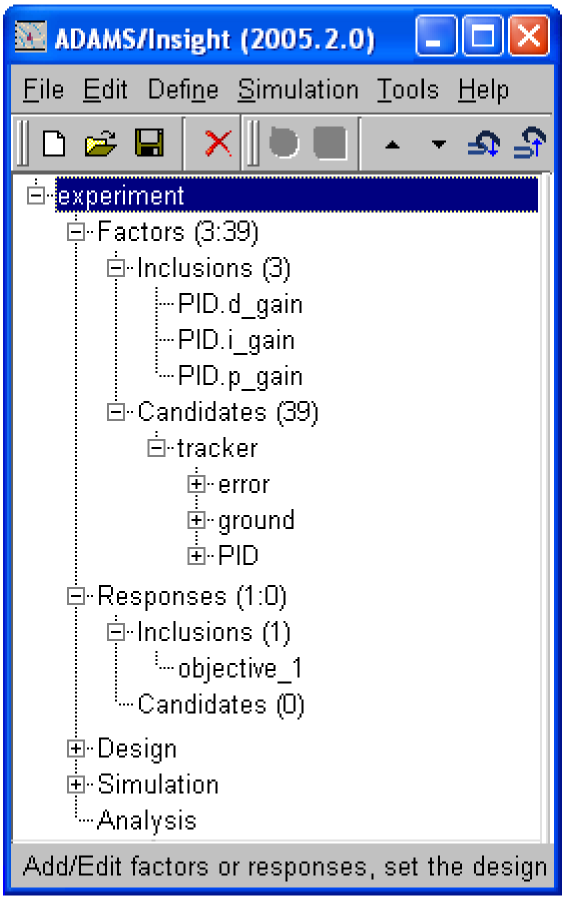

Fig. 5. The factors & response for DOE

After promoting and modifying the factors, the next step is to promote the responses for the experiment. The specific parameters in the response form refer to the desired target, or the approximate lower and upper limits, as well as the operation in the optimization form (e.g. minimize, maximize, less/greater then or equal). In our case, the response (objective_1) refers to the tracking error, the design objective’s value being the root mean square (RMS) during simulation (fig. 6), which is a statistical measure of the magnitude of a varying quantity. The optimization goal is to minimize the design objective (i.e. the tracking error).

The next step is to set the design objective and design type for the experiment, mainly the investigation strategy, and the DOE design type. For the tracking system in study, we used DOE Screening strategy of full-factorial type. This method identifies the factors and combinations of factors that most affect the behavior of the system (how much each factor contributes to the response), picking only high and low values of the setting range.

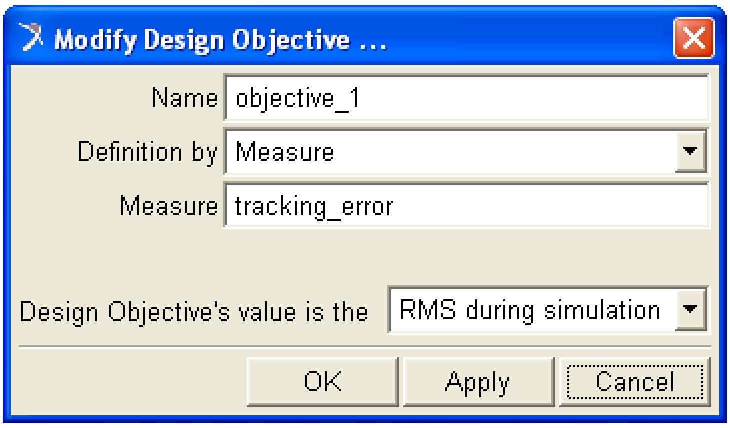

Fig. 6. The design objective

The full factorial algorithm is the most comprehensive of the design types and uses all of the possible combinations of levels for the factors. The total number of runs is m^n, where m is the number of levels and n is the number of factors (in our case, $n=3$ - the tuning factors of the PID controller).

After configuring the investigation strategy, we have created the design space and the work space. The design space is a matrix with the rows representing the run and the columns representing the factor settings; the settings are in a normalized representation. The work space (fig. 7) is a matrix with the rows indicating the runs and the columns identifying the factor settings (f_1: the proportional gain - P, f_2: the integral gain - I, f_3: the derivative gain - D) and resulting response values (r_1). For each trial defined in this matrix, a simulation will be performed; after ADAMS/View completes the trials, the simulation results appear in the design matrix as shown in figure 7 - column “r_1”.

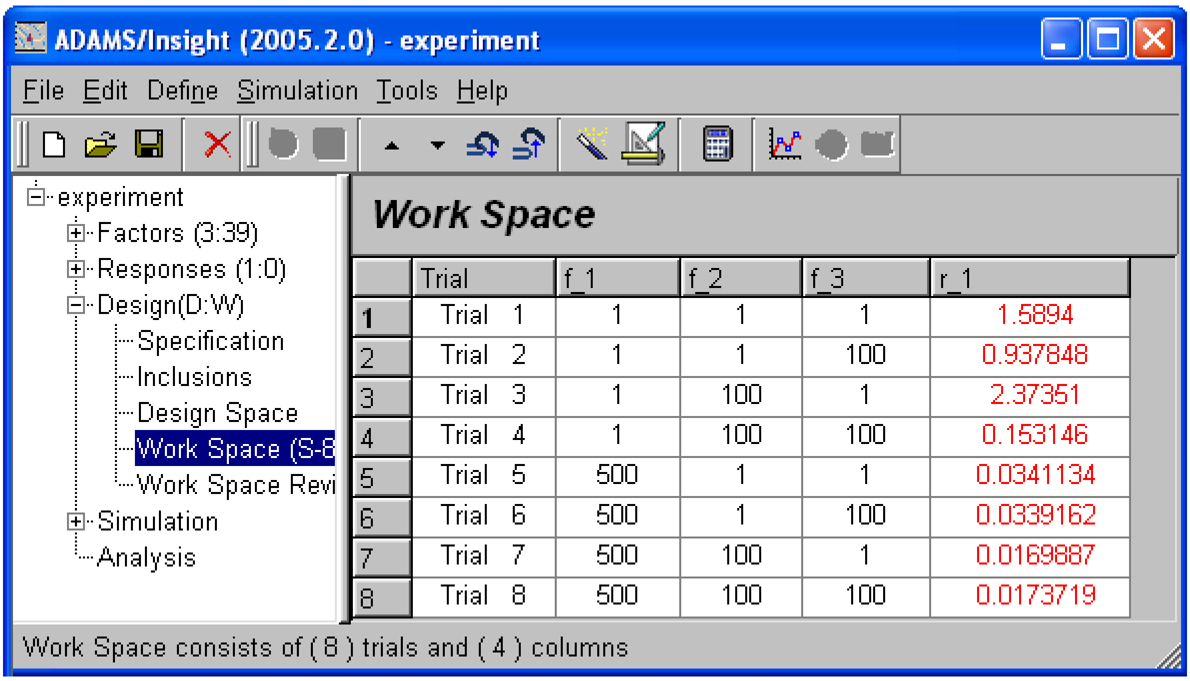

Fig. 7. The work space of the experimental design

In the final step, the effective optimization of the tracking system / PID controller has been performed by updating design objective (response) settings. Using ADAMS/Insight, single-objective and multi-objective optimization can be performed. In our case, because there is only one response, a single-objective optimization is performed. In this case, ADAMS/Insight adjusts the factors to try and meet the objective of the single response, and it computes a cost for the objective based on the difference between the response value and the target value (so a lower cost is better than a higher cost). During optimization, ADAMS/Insight automatically adjusts the factor values so that the resulting response comes as closely as possible to the specified target value.

The method used to solve the optimization problem is OptDes GRG (Generalized Reduced Gradient), which is a conventional gradient-based optimizer (generally more robust than others). The solver settings refer to the relative tolerance for convergence, the maximum number of steps (iterations) to perform, the relative amount to perturb variables during differencing, and the method for computing derivatives using finite differences. As differencing method we have selected Forward, which perturb above the nominal value only, and use the slope as the derivative. The optimization form is shown in figure 8, where we can identify the optimal values of the factors after running the optimization, as follows: P=453.12, I=12.779, D=76.54. These values, which assure the minimum cost for the objective, are then transferred to the controller model (fig. 4) for performing the simulation, considering the previously presented motion laws (fig. 3) and control system block diagram (fig. 2). The simulation goal was to obtain the energy consumption for realizing the tracking law (fig. 9), resulting in this way the total consumption $E_C \approx$ 32 Wh/day.

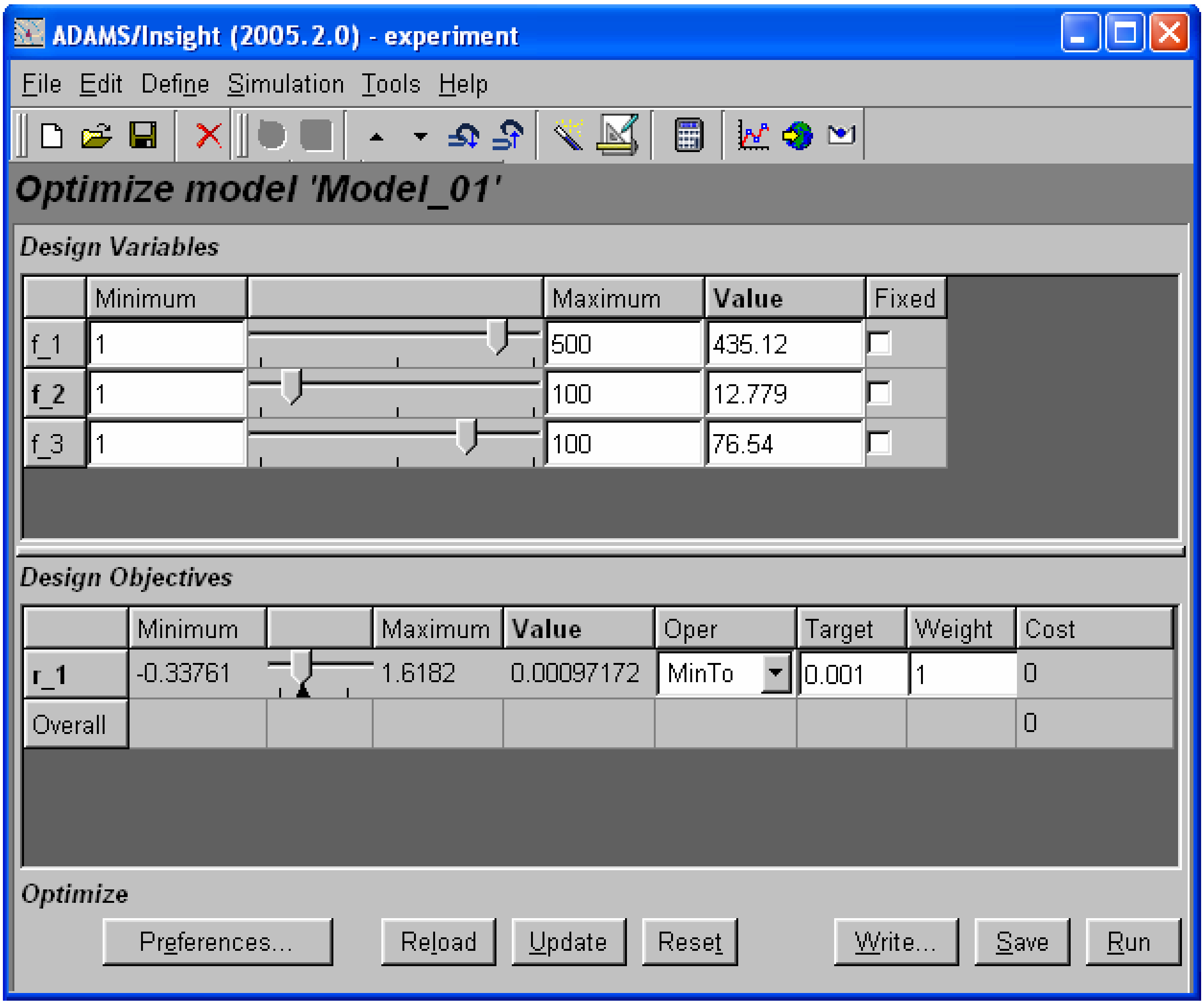

Fig. 8. The optimization window

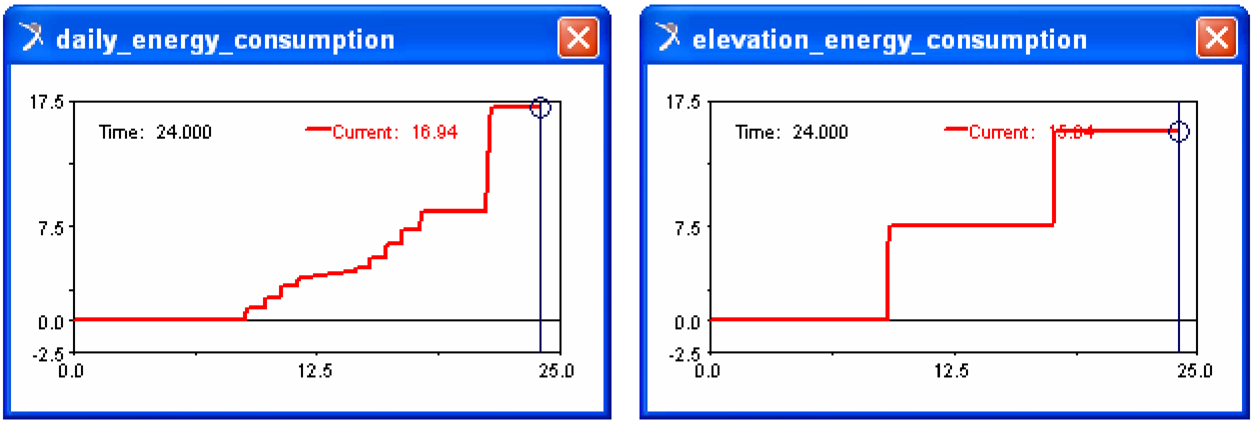

Fig. 9. The energy consumption for realizing the motion (control) laws

In these terms, the incident solar radiation curve was obtained by using the Melißʼs model [5], to which it corresponds the quantity of electric energy produced by the PV module E_T = 1874 Wh/day. Meanwhile, if the PV module would be kept fixed (β^* = 0°, γ^* = 22.05°) it would result E_F = 1231 Wh/day. The quantity of electric energy was computed considering a module with the active surface of 1.26 m^2, and the conversion efficiency of 15%. Thereby the energetic balance was achieved, $E_T - (E_F + E_C) = 1874 - (1231 + 32) = 611$ Wh/day. This demonstrates that the designed tracking system is energetic efficient, the energy contribution obtained through tracking with adequate motion laws being nearly 50% relative to the fixed PV module, and this denotes the viability of the proposed design.

4. FINAL CONCLUSIONS

The optimal design of the controller by considering the entire mechatronic system allows obtaining valuable and realistic results, which are important for the physical implementation. Such results allow evaluating and optimizing the dynamic behaviour of the tracking system in a fraction of both the time and cost required with traditional build-and-test approaches (by developing expensive physical prototypes).

The application is a relevant example regarding the implementation of the virtual prototyping tools in the design process of the PV 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, we are much better equipped to manage the risks inherent in the product development cycle. Connecting the control system and the mechanical device at the virtual prototype level, the physical testing process is greatly simplified, and the risk of the control law being poorly matched to the real system can be eliminated.

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