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Modelling and Simulation of a Hydraulically Operated Solar Tracker

C. Alexandru[1]

[1] Department of Product Design, Mechatronics and Environment
Transilvania University of Brașov
29 Eroilor Bvd., 500036 Brașov (Romania)
E-mail: calex@unitbv.ro

Abstract. The work deals with the design of the hydraulically operated solar tracker used for a photovoltaic (PV) platform. The tracking mechanism is a dual-axis, azimuthal type, the primary axis, that of the daily/diurnal movement, being positioned vertically, which provides a high stability of the entire structure. The actuation in both movement subsystems (daily and elevation) is achieved by using linear actuators, in the subsystem for the daily movement a stroke amplification mechanism being interspersed between the actuator and the rotating part of the support pillar, which constitutes an element of novelty/originality regarding the mechanical device of the solar tracker. The sun tracking is conducted by an open-loop control strategy, based on a predefined step-by-step algorithm, which was designed so that to capture as much as possible incident solar radiation with a minimum energy consumption for achieving the orientation. The modeling and simulation of the solar tracker is carried out in mechatronic concept, by using the virtual prototyping solutions ADAMS (for the mechanical device model) and EASY5 (for the control system model) of MSC Software.

Key words. PV platform, tracking mechanism, open-loop control, simulation.

1. Introduction

The research in the field of renewable energy systems is a worldwide priority, because they provide viable alternatives to a series of major issues that humanity is facing today: the limited and polluting character of the fossil fuels, the global warming, or the greenhouse effect. The solar energy is the most important source of renewable energy, which can be converted into electric or thermal energy. The method of converting solar radiation into electricity is well known: the photovoltaic (PV) effect. The PV conversion efficiency depends on the quality and type of solar cells, their temperature, and the amount of received solar radiation.

Solar trackers can be added to the PV systems in order to capture an increased amount of solar energy, thus improving the energetic efficiency of the system (from 20% up to 50%) [1-5]. According to the relative movements in the Sun-Earth astronomical system, two groups of solar trackers can be defined: mono-axis (which are used to adjust the daily or altitudinal position of the PV module), and dual-axis (which are able to adjust the both daily and elevation angles, thus assuring a more accurate orientation of the PV module). The solar trackers are actuated by linear or rotary actuators, which are controlled through various strategies, based on use of photo-sensors or predefined tracking algorithms [6-9].

The solar trackers can be systematized according to the PV modules placement scheme, as follows: tracking mechanisms for stand-alone PV modules, tracking mechanisms for PV strings, tracking mechanisms for PV platforms, and tracking mechanisms for PV string platforms [10]. This paper deals with the modelling and simulation of the dual-axis tracking mechanism used for a PV platform. Several studies have shown that for such a configuration the type of system that lends itself best is the azimuthal one (considering the high stability that such a system ensures). The modeling and simulation of the azimuthal tracking mechanism is carried out by using the virtual prototyping solutions ADAMS (for designing the mechanical device model) and EASY5 (for designing the control system model), the two models being integrated in mechatronic concept [11].

2. Solar Tracker Design

In the proposed system, the primary axis (which is fixed with respect to the ground, being arranged vertically in the azimuthal setup) is that of the daily movement, while the secondary axis (which is referenced to the primary one, in a horizontal arrangement) corresponds to the elevation movement. The schematic model of the azimuthal tracking mechanism is that shown in Figure 1, where: N - North, S - South, 1 - daily movement, 2 - elevation movement.

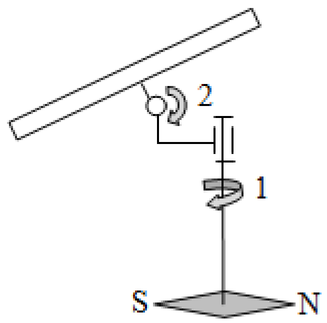

Fig. 1. Schematic model of the azimuthal tracking system.

The dual-axis tracking mechanism, whose mechanical device model conceived with ADAMS software package is shown in Figure 2, contains two subsystems, one for each of the two degrees of mobility (i.e. the daily and elevation movements). The actuation in each of the two subsystems is carried out with hydraulic linear actuators (it was decided to use this type of motors due to considerations related to the required mechanical power, given that the mass in motion is relatively large).

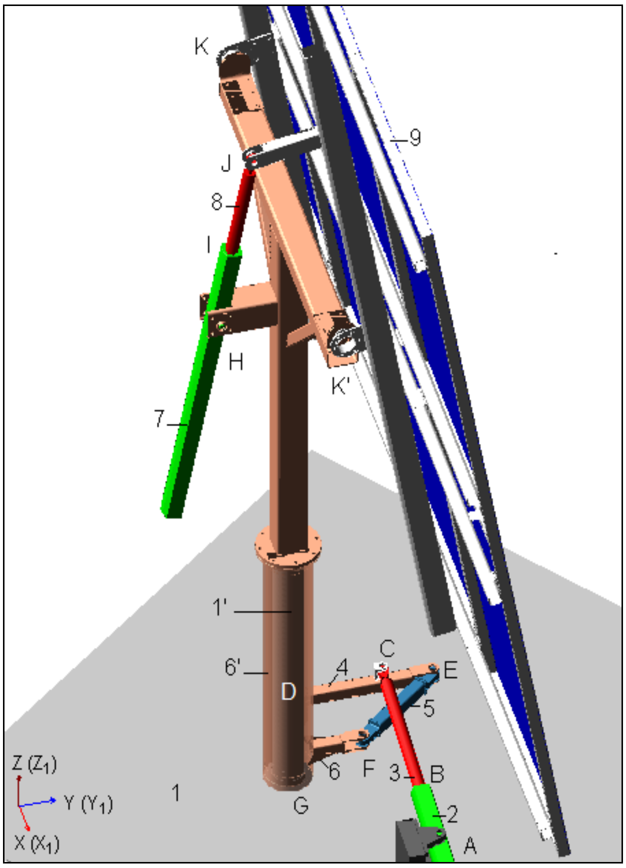

Fig. 2. The mechanical device model of the dual-axis tracking mechanism (ADAMS).

In the design of the dual-axis tracking mechanism, it was started from the requirement to use the same type of linear actuator (namely, ELERO ATON-2, compressed size - 1275 mm, maximum stroke - 600 mm) for both movements (although the angular ranges that must be ensured are significantly different). More precisely, there was the problem of using the type of linear actuator used for elevation movement also in the case of daily movement (where the angular movement range is significantly higher).

With the purpose to meet this requirement, in the daily movement subsystem a stroke amplification mechanism (which is a four-bar mechanism) was interspersed between the actuator piston and the rotating part of the sustaining pillar. The use of this mechanism also allows avoiding possible self-locking positions of the system, which could have occurred if the actuator piston had acted directly on the rotating part of the support pillar, due to the low values of the transmission angle (or in other words, the large values of the complement of this angle, i.e. the pressure angle).

In the case of the elevation movement subsystem, through which the position of the PV platform is adjusted according to the altitudinal position of the sun depending on the season of the year, the implemented actuating solution is a classic one, where the actuator piston acts (is connected) directly on the platform frame, without the need for the use of intermediate/additional elements. Obviously, this is the simplest solution for transmitting the movement, the risk of self-locking in the elevation movement subsystem being very low, considering the value of the angular movement range, between the specific altitudinal positions of the summer and winter solstices (in the geographical area of Brașov, this range is about 45°).

In these terms, the mechanical device of the dual-axis solar tracker is defined by the following components (for notations, see Figure 2):

- bodies (parts): 1 - the fixed base of the system (which is common part with the lower part of the sustaining pillar - 1’); 2, 3 - the cylinder (housing) & piston of the linear actuator for the daily movement; 4, 5, 6 - the elements of the four-bar mechanism used to amplify the actuator stroke in the diurnal movement subsystem (the rocker 6 is rigidly connected to the rotating part of the sustaining pillar - 6’); 7, 8 - the cylinder (housing) & piston of the linear actuator for the elevation movement; 9 - the platform frame;
- joints (the connections between bodies): A - revolute joint (adjacent bodies 2/1); B - cylindrical joint (adjacent bodies 3/2); C - revolute joint (adjacent bodies 4/3); D - revolute joint (adjacent bodies 4/1’); E - revolute joint (adjacent bodies 4/5), F - revolute joint (adjacent bodies 5/6), G - revolute joint (adjacent bodies 6-6’/1-1’); H - revolute joint (adjacent bodies 7/6’); I - cylindrical joint (adjacent bodies 8/7); J - revolute joint (adjacent bodies 9/8); K-K’ - revolute joints (adjacent bodies 9/6’), one of them being passive from a kinematic point of view.

The control system block diagram used in the two subsystems is the one shown in Figure 3 (according to the notations of the parameters in this figure, the model corresponds to the daily movement control system of the solar tracker, the control system for the elevation movement being a similar one from the point of view of the specific components and respectively of the connection scheme between the components), its design being carried out by using the DFC (Design for Control) software solution EASY5.

The control system model conceived in EASY5 communicates with the mechanical device model conceived in ADAMS through the input (I) and output (O) parameters. The I/O plants are defined at the level of the ADAMS interface block (named ADAMS Mechanism in Figure 3) using ADAMS/Controls, which is a plug-in to ADAMS/View (the general pre-processing/modelling interface from the ADAMS software package) that allows the easy integration of mechanical system simulation with control system design [12].

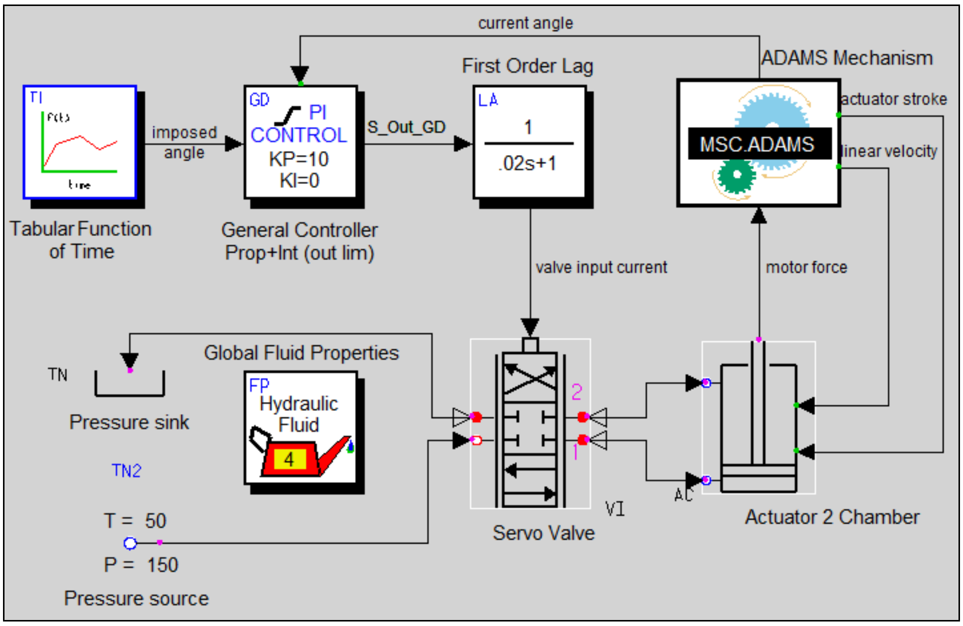

Fig. 3. The control system model corresponding to one of the two movements of the tracking system (EASY5).

The input parameter in the mechanical device model (which is generated by the control system) is represented by the driving/motor force developed by the hydraulic actuator, while the output parameters refer to the position angle (as the case may be, daily or elevation) of the PV platform, the stroke and the linear velocity in the corresponding actuator. The so defined system is one of SIMO (Single-Input Multi-Output) type, whose simplified/schematic model is shown in Figure 4, which is designed with the aim of ensuring high precision and robustness characteristics, considering that the system needs to have very good orientation accuracy, so that there are no losses of incident radiation due to undesirable tracking errors (these represents the differences between the imposed and the current/measured positions of the platform, in terms of daily and elevation angles, by case), including when the system is subjected to non-stationary external disturbances (e.g. wind).

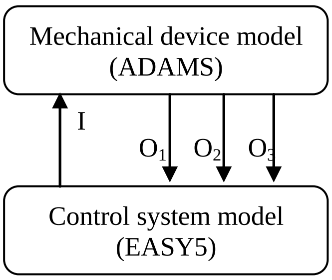

Fig. 4. Input & output plants in the SIMO system: I - motor force, O_1 - position angle, O_2 - actuator stroke, O_3 - linear velocity.

The four parameters per tracking movement (diurnal and elevation, respectively) that define the input & output plants are modelled at the level of the mechanical device of the solar tracker (therefore, in ADAMS), by using some state variables, as follows:

- motor force - the run-time function is set to zero, because its current value is to be generated within the EASY5 control system;
- position angle - the run-time function is expressed by the predefined function AZ (Angle About Z), which returns the angle in the rotational joint G between the rotating and fixed parts of the support pillar (the case of the diurnal angle), and respectively in the rotational joint K between the platform frame and the rotating part of the pillar (the case of the elevation angle);
- actuator stroke - the run-time function is expressed by the predefined function DM (Distance Magnitude), which returns the relative linear displacement between coordinate system markers applied to the actuator housing and piston;
- linear velocity - the run-time function is expressed by the predefined function VR (Velocity Along Line-of-Sight), which returns the relative velocity to one coordinate system marker attached to actuator piston from another marker attached to actuator housing.

In the block diagram of the control system model shown in Figure 3, the following components can be found (the standard names and notations from EASY5 are used) [13]:

- Tabular functions of time (T1) - provides a table as a function of time, which is used for defining the time variation law of the daily or elevation angle, as the case may be (i.e. the imposed tracking program); the law is defined by pairs of time - angle values, linear interpolation being used between these points;
- General Controller Prop+Int_out lim (GD) - models a PI (Proportional + Integral) controller with output limits, which is defined by the following parameters (see the controller model in Figure 5): primary inputs - proportional control gain (GKP), feedback gain (GKF), integration control gain (GKI), derivative limiter gain (GKL), upper/lower limit of output (AMA/AMI); connected inputs - controller input, representing the imposed daily or elevation angle (i.e. T1 block output), controller feedback (i.e. current/measured daily or elevation angle); primary variable - controller output; states - integrated error signal (ERI); transfer function:
  S_Out = ERI + GKP · [REF - GKF · S_Feedback], where:

d(ERI) / dt = GKI · [(REF - GKF · S_Feedback) - GKL · (S_Out - AMA)] when S_Out > AMA,
d(ERI) / dt = GKI· [(REF - GKF · S_Feedback) when AMI < S_Out < AMA:,
d(ERI) / dt = GKI · [(REF - GKF · S_Feedback) - GKL · (S_Out - AMI)] when S_Out < AMI,
as the case may be.

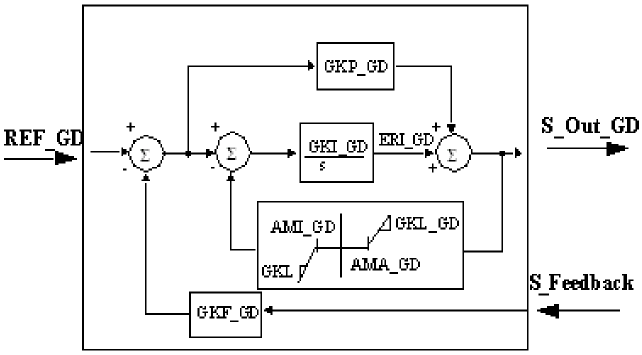

Fig. 5. Schematic model of the PI controller [13].

- First Order Lag (LA) - models a continuous first order lag continuous transfer function, using the time constant format, which is defined by the following parameters: primary inputs - amplification factor /gain (GAI), time constant (TC); connected inputs (S_In) - general controller output (S_Out_GD, as noted in Figure 5); primary state (output quantity) - valve input current; transfer function: d[S_Out]/dt=(GAI*S_In - S_Out)/TC;
- Servo Valve (VI) - models a symmetric, 4-way electrohydraulic servo valve, which is designed to connect to actuator and hydraulic motor components (connect from the OUT ports on VI to the IN ports on the actuators); the connectivity is made in resistive mode, meaning there is no distinct pressure associated with the valve (pressure information comes from the connected components);
- Pressure sink/source (TN/TN2) - models a tank, inlet, exit or fluid sink/source reservoir whose primary function is to provide pressure and temperature boundary conditions for the hydraulic model; primary inputs - tank or source pressure, fluid temperature in tank; connected inputs - loop identifier; ported variables - fluid temperature, pressure, pressure derivative;
- Actuator 2 Chamber (AC) - models a two-sided actuator that consists of a stationary or moveable housing, a movable piston and a fluid chamber on each side of the piston; the nomenclature for the chambers are "Ext" for the chamber that will cause the piston to extend (motion in the positive direction) if its pressure is increased, and "Ret" for the chamber that will cause the piston to retract (motion in the negative direction) when its pressure is increased; primary inputs - piston area facing extend/retract chamber, extend/retract chamber volume at piston position equals "0", viscous damping force coefficient (piston to housing), direction positive external force causes piston to move, additional external force on piston; secondary inputs - vapour pressure of fluid, leakage modelled during steady state analysis, laminar leakage coefficient across piston, additional heat generated internally in the extend/retract chamber fluid; connected inputs - fluid temperature (extend/retract), mass flow (extend/retract), loop identifier (extend/retract), piston position, piston velocity;
- ADAMS Mechanism (AD) - provides the interface link to the MSC.ADAMS model (which contains the mechanical device of the solar tracker, shown in Figure 1), according to the connections scheme depicted in Figure 3; connected inputs - motor force developed by the linear actuator; extension inputs - animation mode - 0/1 (animation off/on), output interval - time between animation data points, ADAMS solver - 1/2 (Fortran/C++), communication mode - 1/2 (pipes/TCP IP); variables - diurnal angle, actuator stroke (piston position), linear velocity; execution mode (configure ADAMS block) - co-simulation (run the combined model from EASY5 using the EASY5 solver to integrate the EASY5 equations and the ADAMS solver to integrate the ADAMS equations; the two solvers exchange input and output data at a rate determined by the communication interval parameter);
- Global Fluid Properties (FP) - defines fluid properties, global function definitions and the desired set of units for the model (metric or English).

The control system defined in this way is an open-loop one, in which the sun tracking is carried out by using a predefined orientation program, based on the relative positions in the sun-earth astronomical system. The design of the dual-axis tracking program and the simulation results obtained on one of the representative days of the year are presented in the next section of the work.

3. Simulation Results

The orientation of the PV modules through open-loop control strategies (such as the strategy used in this work) is carried out either with continuous movement or with in-steps movement (step-by-step). Even if the precision (accuracy) of the in-steps tracking is lower than that of the continuous tracking, the step-by-step orientation is frequently used in practice, mainly from considerations related to the action of non-stationary external factors (such as wind or snow) to which the PV system may frequently be subjected.

In this work, the predefined bi-axial tracking program is a step-by-step type, for both movements (daily and elevation). The tracking program was designed so that to capture as much as possible incident solar radiation with a minimum number of actuatings (tracking steps). The algorithm based on which the bi-axial tracking program was designed for the proposed azimuthal solar tracker is similar to the one used in [14], [15]. The algorithm integrates the Melißʼs empirical model [16], which is used for estimating the amount of incident solar energy captured by the PV platform (this model was the one chosen because it is close to the climatic conditions in the Brașov area).

The both daily and elevation movements were simultaneously considered in the optimal design algorithm of the bi-axial tracking program (in the azimuthal system, the two movements are interconnected, considering the arrangement of the rotation axes), in which the maximization of the energetic efficiency of the PV system is the design objective, while the design variables are represented by the daily and elevation angles of the modules, as well as the actuating times. The energetic efficiency was defined as energy intake brought by dual-axis tracking relative to the case of the equivalent fixed PV system while also considering the energy consumed to achieve the orientation.

The year was divided into several intervals, depending on the variation of the angle of declination in the geographical area of Brașov, the bi-axial tracking program being determined for each of these intervals (the same tracking program is used on all days of an interval). The results presented in this work correspond to the tracking program for the interval N∈[73–87] in which the spring/vernal equinox (March 21 - N=81) is found, the numerical simulations being carried out for this very day (which is a representative one).

The corresponding bi-axial tracking program is presented in Table I, where: ψ/α - the daily/elevation angle of the PV platform, Δψ/Δα - the movement step size, and t - the actuation time (expressed in local time), when the movement step is started/initiated. The last step in the diurnal movement law corresponds to the return of the PV platform to its initial position, after the sunset. With these values, the graphical shapes of the daily and elevation angles of the PV platform are those shown in Figure 6.

Table I. The dual-axis tracking program for the spring equinox.

DIURNAL MOVEMENT		ELEVATION MOVEMENT	
ψ∈[76, -76]°		α∈[15, 44]°	
t	Δψ	t	Δα
8.60	23°	8.30	13°
10.27	25°	10.05	16°
11.67	28°	14.55	-16°
12.93	28°	16.30	-13°
14.33	25°		
16.00	23°		
18.52	-152°		

The daily angle is zero when the PV platform is in the noon position, the maximum variation range of the angle being defined between the positions in which the platform is facing East (ψ = 90°) and West (ψ = -90°) respectively. On the day of the spring equinox, for the considered geographical area, it is not necessary/useful to cover the entire angular range of 180° for reasons related to the reduced input of incident radiation at the extremes of the maximum range, considering also the energy consumption for orientation (this is why the movement range obtained after the optimal design process of the tracking program is of 152°, and not of 180°).

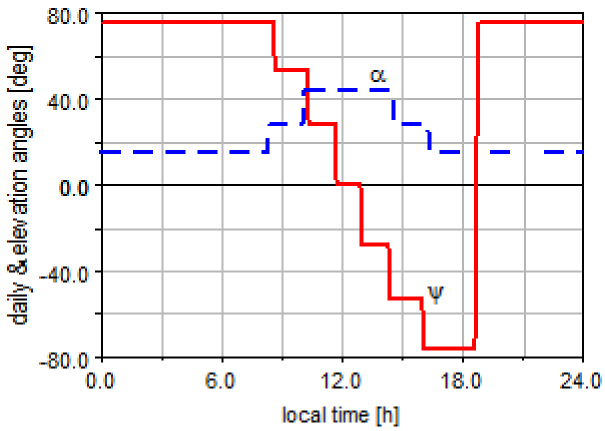

Fig. 6. The time variations of the PV platform angles for the spring equinox.

The elevation angle is zero when the PV platform is vertically (this is the recommended position in strong wind conditions), while on cloudy days it is recommended to bring the platform horizontally (α = 90°), to capture the maximum of diffuse solar radiation (excluding such atmospheric conditions, on the day of the spring equinox, in the initial position the PV platform is tilted by 15°). The so-defined dual-axis tracking program was implemented in the control system model conceived in EASY5 (see Figure 3) as a tabular function of time, through the T1 component/block.

Through the co-simulation in ADAMS and EASY5 of the mechatronic model of the tracking system, a series of specific results were obtained, some of which are shown in Figure 7, as follows: the incident radiation curve, the energy produced by the PV platform, the energy consumed for performing the bi-axial tracking (d - for the diurnal motion, e - for the elevation motion, t - total energy consumption). In order to evaluate the energy efficiency of the proposed tracking system, the first two diagrams in Figure 7 also show results that correspond to the case of the fixed equivalent system (without tracking), in which case the platform is positioned in the noon position (ψ = 0°), tilted with the elevation angle α = 45° degrees (as average optimal value per year). The curves corresponding to the PV system equipped with the proposed dual-axis tracking mechanism are marked with I, and those specific to the fixed equivalent PV system are marked with II.

The amount of electricity produced by the PV platform (with and without tracking) was obtained by integrating the incident radiation curves, and considering the conversion efficiency of the PV modules (14%), as well as the active surface of the platform (8 modules × 1.638 m^2 = 13.104 m^2). The PV modules considered in the computation are of HHE (Helios Energy Europe) type (such modules are already used in various practical applications at the Transilvania University of Brașov).

The following numerical values are extracted from the previously presented diagrams: energy produced by the PV system with bi-axial tracking: E_{PT} = 13863.88 Wh/day; energy produced by the fixed PV system (without tracking): E_{PF} = 10305.65 Wh/day, energy consumed for performing the bi-axial tracking: E_C = 67.08 Wh/day. The supplementary energy obtained by tracking the sun path is obtained in the following way: $\varepsilon = E_{PT} - (E_{PF} + E_C)$ = 13863.88 – (10305.65 + 67.08) = 3491.15 Wh/day, representing an effective energy gain (reported to the fixed PV system) of 33.87%. Such computations were performed for all intervals during the year, the average annual energy gain being of 38.71%, thus justifying the use of the proposed dual-axis azimuthal tracking mechanism.

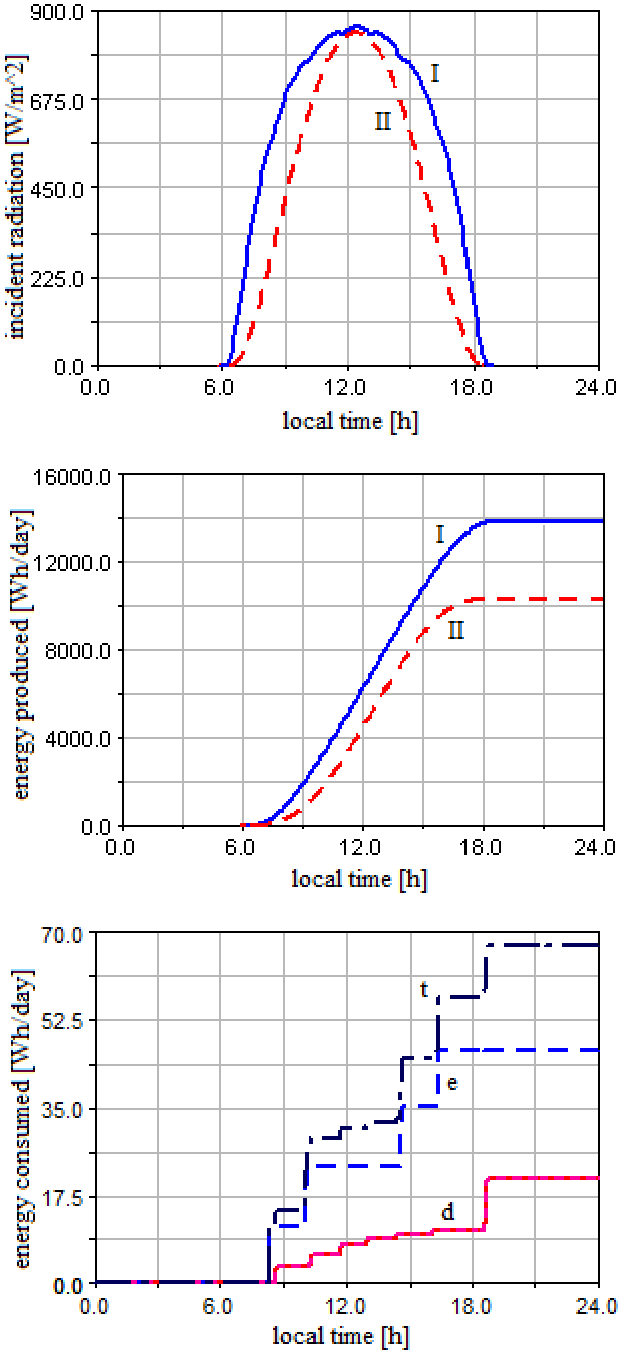

Fig. 7. Results of the simulation in a virtual prototyping environment for the spring equinox day.

4. Conclusions

The application presented in this paper is an edifying example of the possibilities offered by virtual prototyping in the optimal design of PV tracking systems. The proposed dual-axis solar tracker has several important advantages, such as the ability to orient medium and large PV platforms, reducing the cost by minimizing the number of motor sources relative to the classical solution of individual modules, ensuring very good tracking accuracy while proving high stability and robustness performance. By the way in which the proposed dual-axis solar tracker is designed, the energy gain (by reference to the equivalent fixed system) is maintained to values that prove its usefulness/viability.

References

[1] C. Alexandru, M. Comșiț, “Virtual prototyping of the solar tracking systems”, Renewable Energy and Power Quality Journal (2007), Vol. 1, nr. 5, pp. 105-110.

[2] C. Alexandru, C. Pozna, “The optimization of the tracking mechanism used for a group of PV panels”, Renewable Energy and Power Quality Journal (2009), Vol. 1, nr. 7, pp. 245-249.

[3] S. Seme, B. Stumberger and M. Hadziselimovic, “A novel prediction algorithm for solar angles using second derivative of the energy for photovoltaic sun tracking purposes”, Solar Energy (2016), Vol. 137, pp. 201-211.

[4] S.A. Sharaf Eldin, M.S. Abd-Elhady, H.A. Kandil, “Feasibility of solar tracking systems for PV panels in hot and cold regions”, Renewable Energy (2016), Vol. 85, pp. 228-233.

[5] R. Singh, S. Kumar, A. Gehlot and R. Pachauri, “An imperative role of sun trackers in photovoltaic technology: A review”, Renewable & Sustainable Energy Reviews (2018), Vol. 82(3), pp. 3263-3278.

[6] C. Alexandru, “A novel open-loop tracking strategy for photovoltaic systems”, The Scientific World Journal (2013), Vol. 2013, pp. 205396(1-12).

[7] M.E.H.Chowdhury, A. Khandakar, B.M. Hossain, R. Abouhasera, “A low-cost closed-loop solar tracking system based on the sun position algorithm”,. Journal of Sensors (2019), Vol. 2019, pp. 3681031 (1-11).

[8] D.A. Flores-Hernández, S. Palomino-Resendiz, N. Lozada-Castilloc and A. Luviano-Juárez, “Mechatronic design and implementation of a two axes sun tracking photovoltaic system driven by a robotic sensor”, Mechatronics (2017), Vol. 47, pp. 148-159.

[9] Z. Mi, J. Chen, N. Chen, Y. Bai, R. Fu and H. Liu, “Open-loop solar tracking strategy for high concentrating photovoltaic systems using variable tracking frequency”, Energy Conversion and Management (2016), Vol. 117, pp. 142-149.

[10] C. Alexandru, “Optimal design of the dual-axis tracking system used for a PV string platform”, Journal of Renewable and Sustainable Energy (2019), Vol. 11(4), pp. 043501(1-14).

[11] C. Alexandru and C. Pozna, “Dynamic modeling and control of the windshield wiper mechanisms”, WSEAS Transactions on Systems (2009), Vol. 8(7), pp. 825-834.

[12] *** Getting Started Using ADAMS/Controls, MSC.Software, 2005

[13] *** EASY5 Guide, MSC.Software, 2005.

[14] C. Alexandru, “Optimization of the bi-axial tracking system for a photovoltaic platform”, Energies (2021), Vol. 14(3), pp. 535(1-30).

[15] C. Alexandru, “Innovative bi-axial tracking mechanism for PV modules”, Renewable Energy and Power Quality Journal (2020), Vol. 18, pp. 184-189.

[16] M. Meliß, Regenerative Energiequellen: Praktikum, Springer (1997).