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THE ENERGY BALANCE OF A PV STRING EQUIPPED WITH SOLAR TRACKER

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Abstract—The paper puts forward a photovoltaic (PV) string equipped with solar tracker. This is a dual-axis tracking system, with two degrees of freedom, which correspond to the daily and seasonal (elevation) motions. A rotary motor drives the daily motion, while for the seasonal orientation there is used a linear actuator. The daily motion is transmitted to all the modules of the string with a multi-parallelogram mechanism, which also assures the frame for transmitting the seasonal motion. The main objective of the research is to increase the energetic efficiency of the PV system, by maximizing the rate of incident solar radiation with minimum energy consumption for performing the tracking. The study is approached by developing the virtual prototype (dynamic model) of the solar tracker, which integrates the multi-body mechanical device (developed in ADAMS) and the control system (designed in EASY5), in mechatronic concept.

Keywords—energy balance, photovoltaic string, simulation, solar tracker.

I. INTRODUCTION

THE increasing of the CO_2 emissions and the depletion of the fossil fuel resources require strong and active measures to be taken. The solution consists of using renewable energy sources (such as sun, wind or water). The sun is an extremely powerful energy source, and solar radiation is by far the largest source of energy received by the Earth. However, only a very small fraction of this freely available energy is exploited through direct means for human use.

The present-day techniques allow converting the solar radiation in two basic forms of energy: thermal and electric energy. The technical solution used for converting the solar energy in electricity is well-known: the photovoltaic panels (PV). The implementation of the PV arrays (system of modules that function as a single electricity-producing unit) appeared as a necessity for the development of large systems for producing electric energy based on the solar energy [1], [2].

The efficiency of the photovoltaic system depends on the degree of use and conversion of the solar radiation [3]–[5]. When performing the energy balance on a photovoltaic panel, reference is done to the surface that absorbs the incoming radiation and to the balance between energy inflow and energy outflow. There are two ways for maximizing the rate of useful energy: optimizing the conversion to the absorber level, and decreasing the losses by properly choosing the absorber materials; increasing the incident radiation rate by using mechanical tracking systems, which allow the maximum degree of solar radiation collecting [6]–[9]. The orientation of the photovoltaic panels, in order to intercept the maximum amount of solar radiation that reaches the ground level, may increase the efficiency of the solar conversion system up to 50% [10]–[16].

Basically, there are two solutions for developing the PV arrays with tracking (depending on the existence/or not of a common frame - sustaining structure): PV platforms, where the modules are mounted on a common frame (modules with the same sustaining structure), the orientation being realized simultaneously by the orientation of the entire platform; array of individual modules, where the modules are separately mounted on individual sustaining structures.

For the PV array, the orientation can be realized in two ways: tracking independently each module of the array (module with own tracking system - self motor source); simultaneous tracking of all modules of the array, or tracking for groups of modules, by using single driving (actuating) source, which transmits the motion to the all modules of the array/group. The second solution even is more complex by constructive aspects (needs the design of the mechanisms suitable for transmission of the power from the driving source) ensures theoretically a greater energetic & economic efficiency because of the minimization of the driving sources in the array.

The design strategy proposed by this paper, having as goal to increase the efficiency of the PV arrays, involves the following aspects: designing the dual-axis tracking mechanism for a string configuration of PV modules, with single motor source for each motion (the daily motion and the seasonal motion); designing the optimal motion (control) law of the tracking mechanism. The goal is to obtain as much as possible solar radiation with minimum energy consumption.

II. Tracking System Design

For the design process of the tracking systems, the two rotational motions in the Earth - Sun system (the daily motion, and the yearly precession motion) should be considered. Consequently, there are two fundamental types of solar trackers: single-axis, 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 solar tracker is necessary a seasonal tilt angle adjustment.

The two-axis tracking systems follow combine two rotational motions, so that they are able to follow very precisely the Sun path along the period of one year. That is why dual-axis tracking systems are more efficient than the single one (but also more expensive).

The application in paper is made for a string configuration array (PV modules that are disposed in line), using a dual-axis tracking mechanism, with two degrees of freedom, which correspond to the daily and seasonal motions. For each motion, there is a motor source, which is placed (mounted) on the structure of the first PV module in the string (with other words, the motor source directly drives the first module). The actuating source for the daily motion is a rotary motor, while the seasonal (elevation) motion is performed with a linear actuator. The daily motion is transmitted to the other modules of the string with a multi-parallelogram mechanism, which assures identical positioning angles for all modules (there is the same motion for the input and output elements in a parallelogram mechanism).

The structural model of the tracking mechanism for the daily motion is shown in Fig. 1. The representation is made in the motion plan (Π), which is normal to the polar axis. Each module rotates around its own support, which oscillates relative to the sustaining pillar for adjusting the elevation angle. The multi-parallelogram mechanism assures the frame for transmitting the elevation motion (this paper is focused on the daily motion of the PV panels).

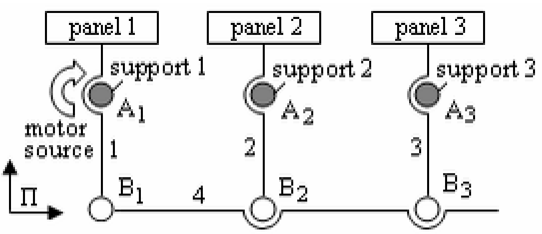

Fig. 1. The structural model of the tracking mechanism for the daily motion.

For simulating the behavior of the tracking mechanism, the dynamic model has been developed in mechatronic concept by using a virtual prototyping platform [17]–[19], which includes the following software solutions: CATIA - to create the solid model, which contains information about the mass & inertia properties of the rigid parts, ADAMS/View - to model the mechanical device of the tracking system, and EASY5 - to model the control system. The geometric model of the tracking mechanism was transferred from CATIA to ADAMS/View using the STEP file format (via the ADAMS/Exchange interface); then the model was assembled by using the specific geometric constraints. In this way, the virtual model of the tracking system is shown in Fig. 2, while Fig. 3 presents the detail with the driving (actuating) sources.

Fig. 2. The virtual prototype of the PV string with dual-axis tracking system.

Fig. 3. The driving sources of the dual-axis solar tracker.

The dynamic model of the tracking system takes into consideration the mass forces, the reaction in joints, and the joint frictions. For blocking the system in the stationary positions between actuatings, when the motors are stopped, the model contains two irreversible transmissions: worm gearbox, for the rotary motor, and screw-nut mechanism, for the linear actuator. In this way, there is no energy consumption in the stationary positions.

III. Control System Design

The control process of the tracking mechanism was approached in the concurrent engineering concept, by integrating the electronic control system and the mechanical device at the virtual prototype level. In fact, the virtual prototype is a control loop composed by the MBS mechanical model connected with the dynamic model of the motors, and with the controller dynamical model. Thus, the physical testing process is greatly simplified, and the risk of the control law being poorly matched to the real system is eliminated. For this study, the control system of the mechatronic solar tracker was modeled using the DFC (Design for Control) software solution EASY5, the data transfer between the mechanical device and the control system being managed through the ADAMS/Controls interface [20].

For connecting the mechanical model (ADAMS/View) and the control system (EASY5), the input & output parameters were defined. The control torque developed by the rotary motor (for the daily motion), and the control force developed by the linear actuator (for the seasonal motion) represent the input parameters in the mechanical model. The outputs transmitted to the controller are the daily and seasonal (elevation) angles, which are measured on the first module in the string.

For the input state variables, the run-time functions are 0.0 during each step of the simulation, because the control 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 [21]: VARVAL(variable). For the output state variables, the run-time functions return the angles about the motion axes, as follows: daily_angle - AZ(module_1.MAR_1, support_1.MAR_2), which returns the rotational displacement of one coordinate system marker attached to module about the Z-axis of another marker attached to support; elevation_angle - AZ(support_1.MAR_3, pillar_1.MAR_4), which returns the rotational displacement of one marker attached to support about the Z-axis of another marker attached to pillar.

The next step is facilitating the exporting of the ADAMS plant files for the control application. The input and output information are saved in a specific file for EASY5 (*.inf). ADAMS/Controls also generates a command file (*.cmd) and a dataset file (*.adm) that are used during simulation [22]. With these files, the control system was created in EASY5, the block diagram for the daily motion being represented in Fig. 4 (a similar model was developed for the seasonal motion).

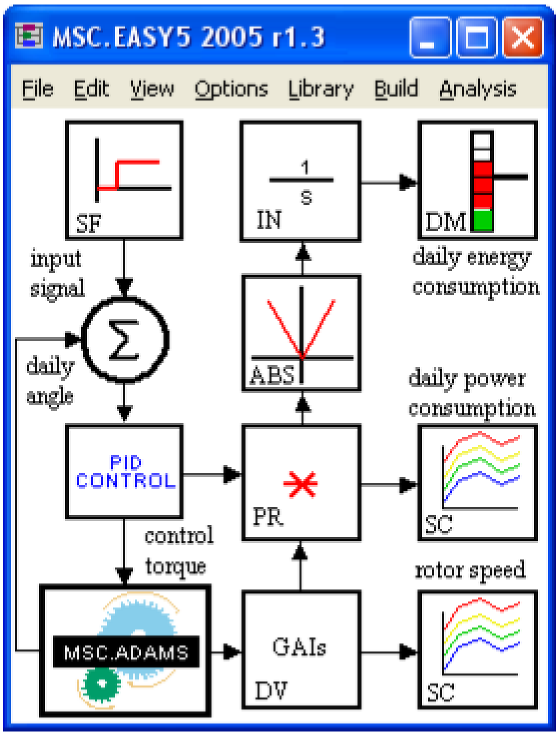

Fig. 4. The control system block diagram for the daily motion.

In these models, the input function generators represent the databases for the daily and seasonal (elevation) angles, which model the imposed motion (tracking) laws.

From the control device point of view, for obtaining reduced transitory period and small errors, PID controllers have been used (for the both motion). The controller tuning (aiming to obtain the proportional - P, Integral - I, and derivative - D terms) was performed in an optimal design process with Matrix Algebra Tool (MAT), the model being transferred to MAT by using the EMX file format. The design objective refers to the minimization of the tracking error (the difference between the imposed and current daily angle).

In MAT, the “minimize_v” function was used to perform the optimization. MAT will repeatedly call the function as it performs the minimization procedure. The function will set the tracking error appropriately and returns the error in the simulation, defined as the sum of the squares of the differences between the simulation and desired values. In this way, the values of the proportional (P), integral (I) and derivative (D) terms will result in a simulation that meets the design requirements.

In the mechatronic model, ADAMS accepts the control torque & force from EASY5 and integrates the mechanical model in response to them. At the same time, ADAMS provides the current daily & seasonal angles for EASY5 to integrate the control system model. This model is used in the next section for the optimal design of the motion (control) law.

IV. MOTION LAW DESIGN

The PV modules can be rotated without brakes during the day-light, or can be discontinuously driven (step-by-step motion). Obviously, the maximum incident solar radiation is obtained for the continuous motion in the entire angular field (from -90° at sunrise, to +90° at sunset), but in this case the operating time of the motors is high. In paper, the strategy for optimizing the motion law of the tracking system aims to reduce the angular field of the daily motion and the operating time of the motor source, without significantly affecting the incoming solar energy, and with minimum energy consumption. This strategy involves the identification of the optimal angular field, as well as the optimal actuating timing (for the step-by-step motion).

The energy produced by the PV array depends on the quantity of incident solar radiation, the module efficiency, and the number of modules. 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 established by using the Meliss's empirical model [4], depending on the extraterrestrial radiation, the medium solar constant, the turbidity factor (atmosphere clarity), the solar altitude angle, the solar declination, the latitude angle, the solar hour angle, and the 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 diurnal and seasonal angles of the Sun's rays, the daily and elevation angles of the module, and the azimuth angle. In this way, there is possible to estimate the incident radiation in every day during the entire year, for different locations, and tracking strategies. The paper presents the exemplification for the summer solstice day, which is a relevant situation for evaluating the energetic efficiency. The numeric simulations were performed considering the Braşov geographic area, with the following input data: the location latitude, φ=45.633 North; the location longitude: 25.583 East; the solar declination, δ=23.45°; the day number, n=172; the local time from sunshine to sunset, $T \in [5.579, 21.059]$; the elevation angle of the modules: γ^*=24.5° (the seasonal/elevation motion is not taken into consideration in this study).

For identifying the optimal motion field, the correlation between the motion amplitude and the local time was considered, with the aim to obtain symmetric revolute motions relative to the noon position (β^*=0, T=13.319). The analysis was performed for the following tracking cases: (a) $\beta^* \in [+90°, -90°]$, $T \in [5.579, 21.059]$ - the maximum motion interval; (b) $\beta^* \in [+75°, -75°]$, $T \in [6.869, 19.769]$; (c) $\beta^* \in [+60°, -60°]$, $T \in [8.159, 18.479]$; (d) $\beta^* \in [+45°, -45°]$, $T \in [9.449, 17.189]$; (e) $\beta^* \in [+30°, -30°]$, $T \in [10.739, 15.899]$; (f) $\beta^* \in [+15°, -15°]$, $T \in [12.029, 14.609]$; (g) β^*=0, $T \in [5.579, 21.059]$ - the fixed (non-tracked) photovoltaic array.

In this study, the modules are rotated without brakes (continuous orientation). As result, the incident solar radiation curves for the considered tracking cases are shown in Fig. 5. Integrating these curves, and taking into account the number of modules in the PV string (the study is performed for a string with five PV modules), the active surface of the modules (1.26 m^2 for each module) and the conversion efficiency of the modules (15%), the energy produced by the PV string was obtained.

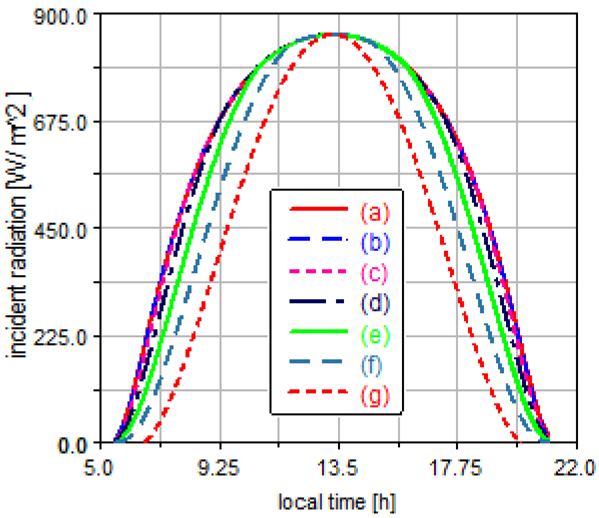

Fig. 5. The incident radiation curves.

Afterwards, the energy consumption for realizing the motion laws has been determined by using the virtual prototype of the tracking system (see sections II & III of the paper). For the energy consumption, there is also considered the return of the tracking mechanism in the initial position (east/sunshine) after the sunset. In this way, the energy balance was performed, the results being systematized in TABLE I (the energy gain is computed relative to the fixed PV string case). There are the following notations: E_T / E_F - the energy produced by the PV string with / without tracking (fixed); E_C - the energy consumption for performing the tracking.

Analyzing these results, the optimal motion domain (with the best ratio between the energy gain and the operating time of the motor) can be identified, as follows: (c) $\beta^* \in [+60°, -60°]$.

TABLE I
THE ENERGY BALANCE FOR THE TRACKING CASES

Case	E_T / E_F [Wh/day]	E_C [Wh/day]	Energy gain [%]	Operating time [h]
(a)	8704.39	88.17	40.02	15.48
(b)	8697.01	66.61	40.25	12.9
(c)	8632.22	40.58	39.62	10.32
(d)	8428.10	25.53	36.55	7.74
(e)	7994.53	11.68	29.73	5.16
(f)	7248.03	2.97	17.74	2.58
(g)	6153.63	-	-	-

Afterwards, in the optimal angular domain, different step-by-step tracking strategies were evaluated. The objective is to minimize the operating time, which is important for the durability and reliability performance of the tracking system. In these terms, six tracking cases were developed - analyzed, depending on the number of steps (in consequence, the step dimension - $\Delta\beta^*$) for realizing the optimal angular field: 12 steps ($\Delta\beta^*=10°$), 10 steps ($\Delta\beta^*=12°$), 8 steps ($\Delta\beta^*=15°$), 6 steps ($\Delta\beta^*=20°$), 4 steps ($\Delta\beta^*=30°$), 2 steps ($\Delta\beta^*=60°$). In each case, the angular velocity for the motion steps is 10 degrees per minute.

One of the most important problems in the step-by-step tracking is to identify the optimal actuating timing, in which the motion step has to be performed. In paper, the solution to this problem is obtained by developing an algorithm based on the following phases:

(1) the optimal angular field has been segmented into the intermediary positions, depending on the step dimension for each case (e.g. for 4 steps there are the following positions: $\beta^* = \{\pm 60°, \pm 30°, 0°\}$), and the incident radiation curves have been consecutively obtained considering the module fixed in these positions during the day-light;

(2) analyzing these curves, the moment in which the value of the incident solar radiation for a certain position "k" become smaller than the value in the next position "k+1" can be identified; in this moment, the motion step is performed;

(3) the analysis continues with the next pair of positions "k+1" and "k+2", and so on.

For example, in Fig. 6 there are presented the diagrams for the 4-steps tracking case. Because there is a symmetrical motion relative to the noon position (T=13.319 - local time), the actuating moments are also symmetrically disposed (I-IV, II-III). The motion (tracking) law obtained in this way is shown in Fig. 7.

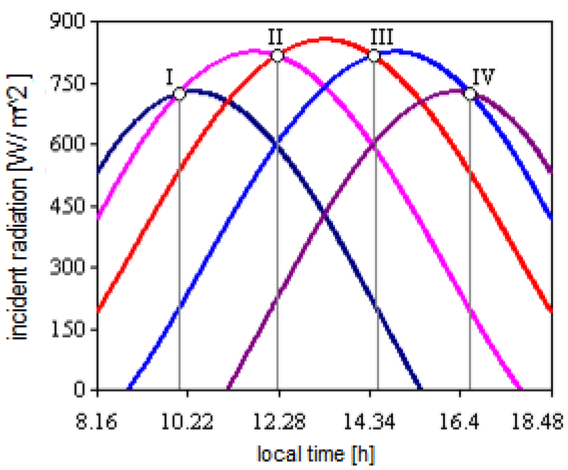

Fig. 6. The determination of the optimal actuating timing.

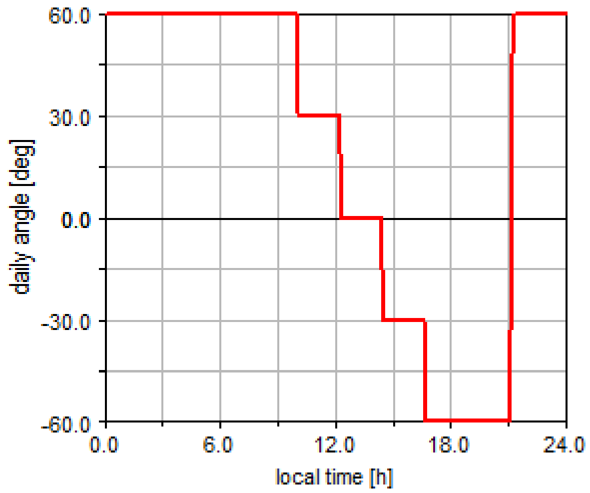

Fig. 7. The motion law for 4-steps tracking case.

For the considered step-by-step tracking cases, the results of the energy balance are systematized in TABLE II. The energy gain is computed relative to the fixed PV string case, while the efficiency parameter ε_{STEP} is determined as relative value to the efficiency for the continuous tracking case (with the corresponding values from TABLE I - case c).

TABLE II
THE ENERGY BALANCE FOR THE IN-STEPS TRACKING CASES

Steps	E_T [Wh/day]	E_C [Wh/day]	Energy gain [%]	ε_{STEP} [%]
12	8602.34	47.80	39.02	98.48
10	8598.62	45.98	38.99	98.40
8	8591.77	44.79	38.89	98.17
6	8576.96	43.69	38.67	97.61
4	8534.59	41.93	38.01	95.94
2	8354.84	40.60	35.11	88.62

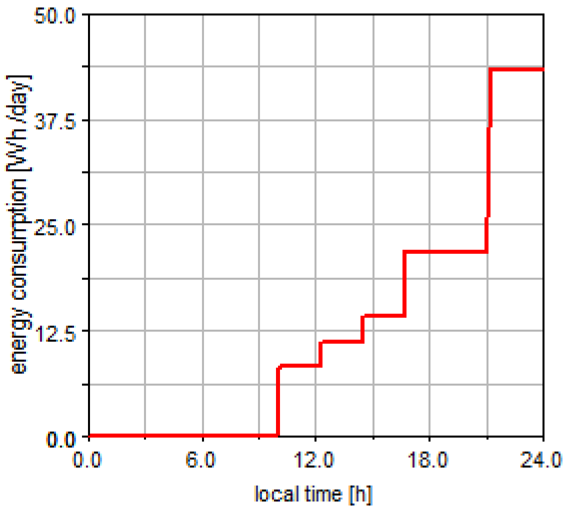

Fig. 8. The energy consumption for the 4-steps tracking case.

Therefore, by using the above-presented algorithm for configuring the step-by-step orientation, there are obtained values close to that of the ideal case (continuous orientation, without brakes), and this demonstrates the viability (utility) of the adopted optimization strategy. As can see, the energy consumptions for realizing the step-by-step motion laws are greater than the energy consumption for the continuous motion, and this because of the over-shootings that appear when the motor is turned-on/off.

For example, Fig. 8 shows the time-history variation of the energy consumption for the 4-steps tracking case, which is obtained by integrating the power consumption curve in absolute value.

V. Final Remarks

The application is a relevant example regarding the implementation of the virtual prototyping tools in the design process of the tracking systems. One of the most important advantages of this kind of analysis - simulation is the possibility to perform virtual measurements in any point or area of the tracking mechanism, and for any parameter (motion, force, energy).

At the same time, integrating the electronic control system and the mechanical device of the tracking mechanism at the virtual prototype level (i.e. the modeling in mechatronic concept), the physical testing process is greatly simplified, and the risk of the control law being poorly matched to the real photovoltaic tracking system is eliminated.

The optimization strategy based-on the minimization of the angular domain for the daily motion and the minimization of the number of actuating operations (i.e. tracking steps) leads to an efficient photovoltaic system, without developing expensive hardware (physical) prototypes. 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.

Considering the algorithm of the product design development, the virtual prototyping precedes the manufacturing and implementation stage. Based on the simulation and optimization results (some of them have been presented in this paper), the embodiment design of the solar tracker has been recently finished, and the technical documentation for manufacturing has been elaborated. The physical prototype of the tracking system is about to be developed, and it will be implemented in the Green Energy Independent Campus (GENIUS) from the *Transilvania* University of Braşov, creating a real perspective for the research in the field. This will allow a relevant comparison between the virtual prototype analysis and the data achieved by measurements.

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