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STRATEGY FOR OPTIMIZING THE MOTION LAW OF THE PHOTOVOLTAIC TRACKING SYSTEMS CONSIDERING THE ENERGY BALANCE

Cătălin Alexandru
University "Transilvania" of Braşov
29 Bd. Eroilor, 500036 Braşov
Romania

ABSTRACT
In this paper, we propose a strategy for optimizing the tracking systems, which is based on the design of the optimal motion law for obtaining as much as possible incident radiation with minimum consumption for driving the system. The optimization is made by reducing the angular field of the panel without significantly affecting the incoming solar energy. The key idea is to determine the optimum angular field in which the system is efficient from energetic point of view. This strategy is possible by developing the virtual prototype of the tracking system, using specific software solutions, as follows: ADAMS - for developing the mechanical model, EASY5 - for designing the control system.
Keywords: tracking system, virtual prototype, optimal motion law, energetic efficiency.

1. PROBLEM STATEMENT
The technical solution for converting the solar energy in electricity is well-known: the photovoltaic (PV) systems. The energetic efficiency of these systems depends on the degree of use of the solar radiation, which can be maximized by use of mechanical systems for the orientation of the panels in accordance with the Sun path. Basically, the tracking systems are mechanical systems (i.e. mechanisms) driven by rotary motors or linear actuators, which are controlled in order to ensure the optimal positioning of the panel relatively to the Sun position on the sky dome. The key word for the design process of the tracking systems is the energetic efficiency: using the tracking system, the PV panel follows the sun and increase the collected energy, but the driving motors/actuators consume a part of this energy.
In this paper, we propose a strategy for optimizing the tracking systems, which is based on the design of the optimal motion law for obtaining as much as possible incident radiation with minimum consumption for driving the system. In fact, the optimization is made by reducing the revolution angular field of the panel, without significantly affecting the incoming solar energy. The key idea is to determine the optimum angular field in which the system is efficient from energetic point of view. This strategy is possible by developing the virtual prototype of the tracking system, which is a control loop composed by the multibody mechanical model connected with the dynamic model of the motors/actuators and with the controller model. The virtual prototyping platform integrates specific software solutions, in the concurrent engineering concept: ADAMS - for developing the mechanical model, and EASY5 - for designing the control system of the tracking mechanism.
The application is made for a single-axis tracking mechanism, which tracks the daily motion of the Sun, facing East in the morning and West in the afternoon. The tilt angle of the revolute axis equals the latitude angle of the location because this axis is parallel with the polar axis. The geometric optimization of the tracking mechanism, which has been performed in [1], uses the dynamic model of the mechanical structure, and computes the geometrical parameters of the tracking mechanism (the global coordinates of the design points), intending to minimize the power consumption that is needed for tracking the Sun path.

2. DEVELOPING THE VIRTUAL PROTOTYPE

The objective for this paper is to optimize the motion law for a single-axis tracking system, at which the daily motion is driven by a linear actuator (fig. 1). The dynamic model of the tracking system, which has been developed using the MBS environment ADAMS/View, includes the actuating motor, the bodies (with mass & inertia properties), the geometric constraints between parts, and the external & internal forces. The panel is mounted on a support, which rotates around a horizontal axis for the manually adjustment of the seasonal tilt angle. The daily motion is made by rotating the panel relative to the support, the linear actuator acting between the intermediary support and the panel. The solution for system used in the study was selected from the multitude of the structural solution by using of the Multi Criteria Analysis. The evaluation criteria were referring to the tracking precision, the amplitude of the motion, the complexity of the system, design and easy manufacturing and implementation.

For simulating the real behaviour of the tracking system, in order to obtain more realistic results, we have developed the control system, in the concurrent engineering concept, using ADAMS/Controls and EASY5 of MSC Software. For connecting the mechanical model and the control system, the input & output parameters have been defined. The control force developed by the linear actuator represents the input parameter in the mechanical model. The output, which is transmitted to the controller, is the daily angle of the photovoltaic panel.

For the input state variable, the run-time function is 0.0 during each step of the simulation, because the control force will get the values from the control system. The run-time function for the input variable is defined using a specific ADAMS function, namely VARVAL [4], which returns the value of the given variable. For the output state variable, the run-time function defines the angle about the revolute axis (i.e. the daily angle), as follows: AX (panel.MAR_1, support.MAR_2); this function returns the rotational displacement of one marker attached to panel about the X-axis of another marker attached to support.

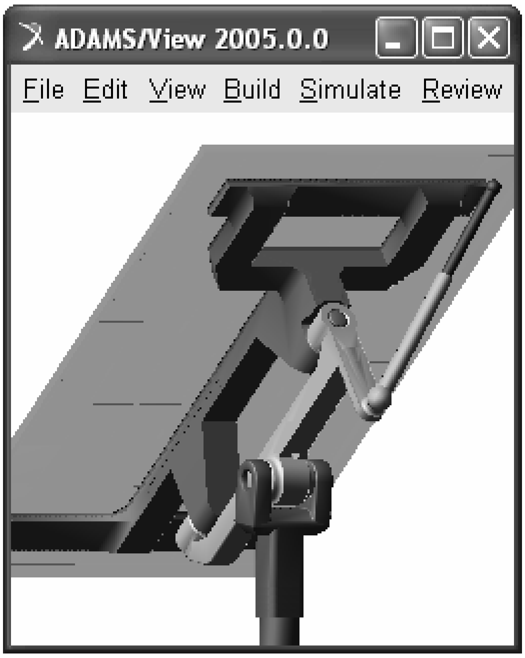

Figure 1. The virtual prototype of the system.

The next step is to export the ADAMS plant files for the control application. The input and output data are saved in a specific file for EASY5 (*.inf); ADAMS also generates a command file (*.cmd) and a dataset file (*.adm) that are used during simulation [4]. In the mechatronic model, ADAMS accepts the control force from EASY5 and integrates the mechanical model in response to this. At the same time, ADAMS provides the current daily angle for EASY5 to integrate the control system.

For controlling the tracking system, in order to obtain reduced transitory period and small errors, we used a PID controller. The specific parameters of the controller have been established having in view the following conditions: the increasing of the proportional term generates the decreasing of the transitory period from the dynamic response of the system, and of the position error, respectively; the integral term generates a class of dynamic responses and attenuates the error history.

3. RESULTS AND CONCLUSIONS

The key idea for optimizing the motion law of the PV panel is to maximize the energy gained through orientation with minimum energy consumption for driving the system. The photovoltaic panel can be rotated without brakes during the day-light, or can be discontinuously driven (step-by-step motion), usually by rotating the panel with equal steps at every hour. Obviously, the maximum incoming radiation is obtained for the continuous orientation of the panel/system, facing east in the morning and west in the afternoon, in the entire angular field, $\beta^* \in [-90^\circ, +90^\circ]$, but in this case the operating time of the motor, and consequently the energy consumption, is high (β^* is the daily angle of the panel, the neutral value $\beta^*=0$ corresponding to the solar noon position, when the local time is T=12.00).

The tracking cases have been formulated using optimal algorithms based on the angular field of the daily motion. These algorithms have been developed considering the correlation between the maximum amplitude of the motion and the operating time of the motor, aiming to the minimization of the energy consumption for tracking the Sun. In fact, the optimization is made by reducing the angular field of the revolute axis without significantly affecting the incoming energy. The idea is to determine the optimum angular field for the daily motion in which the system absorbs a quantity of solar radiation closed-by the ideal case that corresponds with the maximum angular field.

For realizing the energy balance, the first step is to compute the electric energy produced by the photovoltaic panel. The outgoing energy depends on the quantity of incident radiation on the photovoltaic panel, as well as the active surface and the panel's efficiency. The incident radiation, which is normal to the panel, depends on the direct terrestrial radiation, and the angle of incidence (i.e. the angle between the Sun's ray vector and the normal vector on panel). The direct radiation is empirical established, using the relation presented in [2], taking into consideration 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 solar local time.

The incidence angle is determined from the scalar product of the Sun's ray vector and the normal vector on panel, depending on the diurnal and seasonal angles of the Sun's rays, the daily and elevation angles of the panel, and the azimuth angle [3]. In these terms, we are able to estimate the incident radiation in every day during a year, for different locations, and tracking strategies. Our paper presents the exemplification for the summer solstice path of the Sun, which is a relevant situation for comparing the tracking strategies based on the angular field of the daily motion. The numeric simulations have been made considering the Braşov geographic area, with the following input data: the location latitude, φ=45.5º; the solar declination, δ=23.45°; the day number during the year, n=172; the local solar time, $T \in [4.26, 19.74]$; the distortion factor, T_R=4.2 [2].

The comparative analysis has been made for the different angular fields of the daily motion, which are compared with the results corresponding to the maximum angular field, $\beta^* \in [-90^o, +90^o]$, and with the fixed panel case in the solar noon position ($\beta^*=0$) during the day-light, respectively. The angular fields, which decrease with 30º (±15º) for each tracking case, and the intervals for the solar hour angle, have been established for obtaining symmetric revolute motion, relative to the solar noon position. For the considered tracking cases, between the sunrise/sunset time and the lower/upper time limit of the interval, the system remains in the position that corresponds with the minimum/maximum value of the daily angle, for example $\beta^*=-60^o$ for $T \in [4.26, 6.84]$, and $\beta^*=60^o$ for $T \in [17.16, 19.74]$, respectively, for the tracking case in which the angular field is 120º ($\beta^* \in [-60^o, +60^o]$).

In this way, the incident radiation for the considered angular fields has been obtained. Integrating the incident radiation curves, and taking into account the active surface and the panel's efficiency, we have obtained the energy (mechanical work) produced by the photovoltaic panel. In the second step, the energy consumptions for realizing the considered angular fields have been evaluated through the dynamic analysis of the virtual mechatronic model, which has been described in the section 2. The energy (mechanical work) consumptions for the considered tracking cases have been obtained by integrating the power consumption curves.

Afterwards, the energy balance for the considered cases has been performed, $\varepsilon = (E_{PT} - E_{PF}) - E_C$, in which E_{PT} is the quantity of electric energy produced by the PV panel with tracking, E_{PF} - the energy produced by the same panel without tracking (fixed), and E_C - the energy that is consumed for moving the system, the final results being systematized in the table 1. The energetic efficiency is computed considering the energy gain relative to the fixed panel case. In addition, for identifying the optimum angular field, we have taken into consideration the operating time of the motor. This parameter is very important for the system's reliability, including the motor's wearing. In these conditions, we consider that the optimum angular field for the daily motion of the PV panel is $\beta^* \in [-60^o, +60^o]$.

For the graphic comparison of the results, in the diagrams from figure 2 there are presented the time-history variations of the incident solar radiation [W/m^2], as well as the electric energy / mechanical work [J] produced in the extreme situations (maximum angular field - a, fixed panel - b), and in the optimum case - the adopted solution (c). On the other hand, in figure 3 there are the power [Nm/h] & energy / mechanical work [J] consumption curves, for the maximum angular field (a), and the optimum case (c), respectively.

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 simulation is the possibility to perform virtual measurements in any point or area of the tracking system, and for any parameter.

Table 1. The evaluation of the energetic efficiency of the PV system.

Tracking case - β* [º]	E_{PT} / E_{PF} [J]	E_C [J]	Efficiency [%]	Operating time [h]
[-90, +90]	1740.879	17.352	40.041	15.48
[-75, +75]	1739.401	12.861	40.286	12.9
[-60, +60]	1726.443	8.676	39.573	10.32
[-45, +45]	1685.621	5.082	36.549	7.74
[-30, +30]	1598.907	2.325	29.727	5.16
[-15, +15]	1449.606	0.591	17.737	2.58
0 (fixed)	1230.726	-	-	-

The optimization based-on the identification of the optimum angular field for the daily motion leads to an efficient tracking system, without developing expensive hardware prototypes. In this way, the behavioral performance predictions are obtained much earlier in the design cycle, thereby allowing more effective and cost efficient design changes and reducing overall risk.

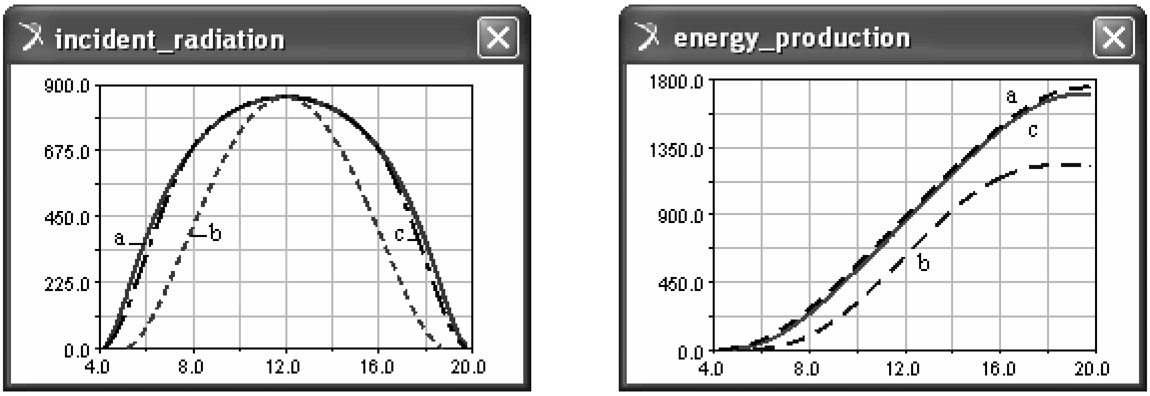

Figure 2. The incident radiation & the energy (mechanical work) produced by the PV system.

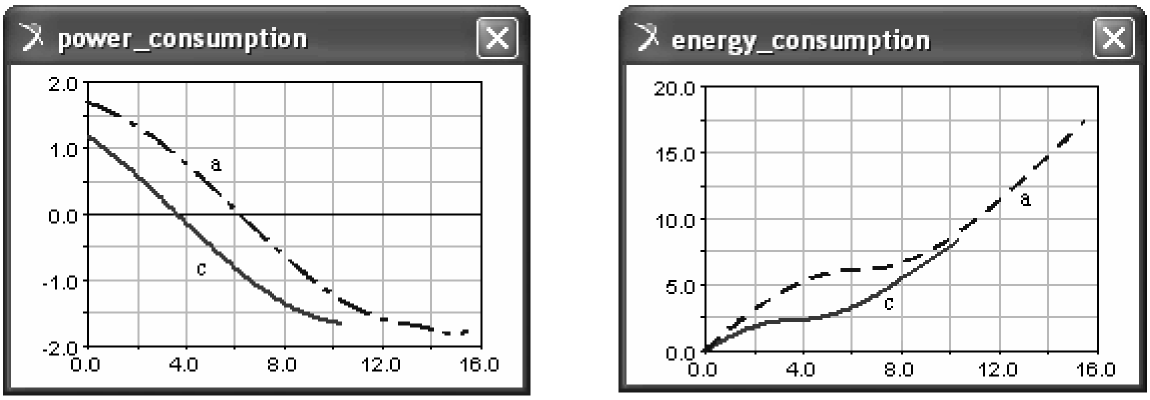

Figure 3. The power & energy (mechanical work) consumption for realizing the motion law.

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