Design and optimization of a photovoltaic system with tracking mechanism

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Abstract: One important problem of today's society is the continuous growing demand of electric energy versus the constant drop of the fossil fuels. The conversion of the solar energy in electric energy is one of the most addressed topics in the field of renewable energy systems. In this paper it is selected for presentation the pseudo-polar tracking mechanism for a photovoltaic module. After the mechanical description, the paper continues with the optimization process achieved according to specific design variables and motion laws. After the interpretation of results, the tracking system proves to be energetic efficient.

Keywords: photovoltaics, tracking mechanism, optimization, efficiency.

1. Introduction

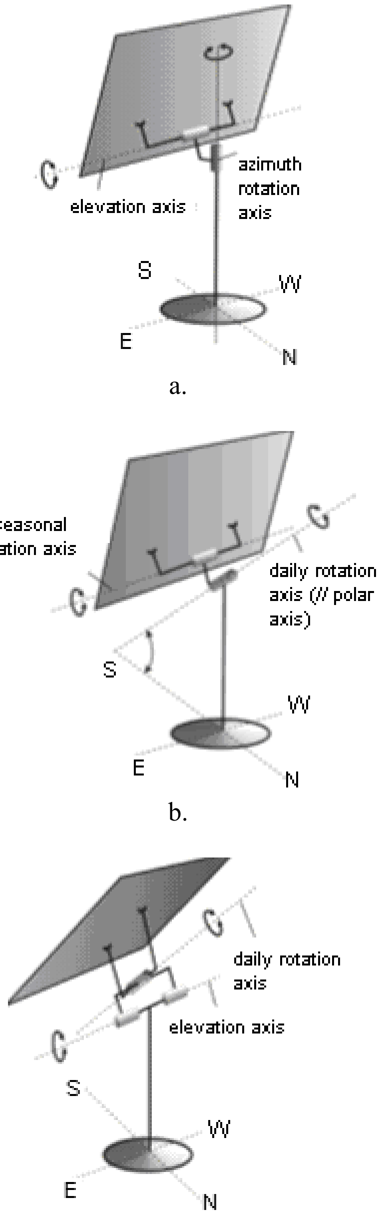
Although the Sun is the biggest energy source available, the society makes the most use of fossil fuels and radioactive substances as energy sources. Their usage is not only harmful to the environment, but also to the global security, since these are limited and found only in specific areas of the Earth. A domain that helps developing the renewable energy sources is the conversion of solar energy ino electrical energy with the help of photovoltaic (PV) systems. The radiation emitted by the Sun is altered by some atmospheric phenomena, such as scattering, absortion and reflection, diminishing its intensity. The global solar radiation that reaches the ground level is formed of diffuse and direct solar radiation. The amount of energy received by Earth each hour equals the energy that mankind consumes in a year.

The PV conversion can be improved by the use of tracking mechanisms, which are mechatronic systems that assure the optimal positioning of the PV module relative to the Sun position on the sky dome [1-8]. The systematization of tracking systems is based on the data regarding the Sun-Earth relative position. Taking into consideration that, in order to obtain the most efficient conversion system, it is necessary that the sunrays fall normal to the surface of the photovoltaic (PV) module. Considering the two motions of the Earth (the daily rotation and the yearly / seasonal rotations), two fundamental types of tracking mechanisms can be systematized: mono-axis and dual-axis tracking mechanisms.

The mechanisms from the first category are used for performing the daily rotation, the tilt angle of the rotation axis, parallel with the polar axis, corresponds with the latitude of the location; therefore, for these systems it is necessary a seasonal adjustment of the rotation axis tilt. Dual-axis tracking mechanisms combine the two movements (daily and seasonal), so they allow a very precise orientation during the whole year, without the need of manual position adjustments.

In the case of dual-axis solar tracker, there can be distinguished three types of systems, depending on the manner in which the axes are located and the way the two motions are introduced in the system:

- azimuth orientation systems (fig. 1, a) - the systems that do not have the orientation axes aligned with the axes according to which the two relative rotations, that determine the Sun`s trajectories on the sky dome, take place, thus requiring the correlation of the movements throughout the day;
- polar orientation systems (fig. 1, b) - systems with the axes disposed in such way that they will maintain their parallelism with the Earth`s polar axis and, respectively, the rotational axis which maintains the seasonal variation of Sun`s position on the sky;
- pseudo-polar orientation systems (fig. 1, c) - systems with one axis parallel with the axis which determines the seasonal variation of Sun`s position on the sky and the second axis, for the daily rotation is oscillating.



a.

b.

c.

Figure 1. Basic types of tracking systems.

The system's driving source (usually, electrical) of the required motions can be achieved through rotative motor, or through linear actuator, for simplifying the solution, the driven element being the module or its stand. If the motor drive is rotative, the resulted system is more compact, because it is driven directly in the rotation joint of the module/stand, but the joint's constructive structure becomes complicated. Also, this solution has the advantage of achieving higher angular stroke, eliminating the risk of mechanism self-blocking. On the other hand, the drive through linear actuator, at which the actuator's active element (the piston) usually acts directly on the element involved in the rotation movement (the module or the stand), has the advantage of simplifying the joint's constructive solution (through which the orientation of the two axes is achieved). But – besides the fact that the solution is not anymore so compact – appears the disadvantage of requiring an actuator with large linear stroke for executing large angular amplitudes, while also presenting the mechanism self-blocking risk. In this case, the problem can be solved through intercalation of a stroke amplifying mechanism, but, in this way, the kinematic and constructive solution becomes complicated, also increasing the price of the system.

In these conditions, the following can be formulated: for daily rotation it is preferred the drive through rotative motor, because the angular stroke (the amplitude) to be achieved is high (theoreticaly, 180°); for seasonal rotation (elevation) both types of drives cand be used because the angular stroke is smaller (maximum 47° for Braşov local area).

2. Design and optimization of tracking mechanism

The conceptual design for obtaining suitable tracking mechanisms was made by using a structural synthesis method based on Multi-Body Systems (MBS) theory, according to which a mechanical system is defined as a collection of bodies with large translational and rotational motions, linked by simple or composite joints.

The structural design consists in the following stages [3]: identifying all possible graphs, taking into account the space motion of the system, the type of joints, the number of bodies, and the degree of mobility of the multibody system; selecting the graphs that are admitting supplementary conditions imposed by the specific utilization field; transforming the selected graphs into mechanisms by mentioning the fixed body and the function of the other bodies, identifying the distinct graphs versions based on the preceding particularizations, transforming these graphs versions into mechanisms by mentioning the types of geometric constraints (ex. revolute joint - R, or translational joint - T). The graphs of the multibody system are defined as features based on modules, considering the number of bodies and the relationships between them (ex. R, T, R-R, R-T, RR-RR, RR-RT and so on).

In the structural synthesis, there can be taken considered general criteria, for example the degree of mobility of the mechanism (M=1 for mono-axis trackers, and M=2 for dual-axis trackers), the number of bodies, and the motion space (S=6 in the general spatial case), as well as specific criteria, for example the type of the joint between the base and the input/output body. In this way, the structural synthesis method was applied and a collection of possible structural schemes were obtained.

In order to select the tracking mechanism for study, specific techniques for product design, such as multi-criteria analysis and morphological analysis [4], have been applied. The multi-criteria analysis has been performed using the following steps: selecting the possible variants in accordance with the structural synthesis; establishing the evaluation criteria and the weight coefficient for each criterion (the FRISCO formula); granting the importance note to a criterion and computing the product between the importance note and the weight coefficient in the consequences matrix.

The evaluation criteria of the solutions were referring to the tracking precision, the amplitude of the motion, the complexity of the system, the possibility for manufacturing and implementation. The final solution has been established based on the morphological analysis, the description of possible solutions being conducted by combinatorial procedures that associates the requirements to be met (parameters, functions, attributes). In this way, there is described the morphological table, which eliminates the irrational constructive or incompatible solutions.

In the conditions mentioned in chapter 1, for considerations regarding the simplicity of motion control, there are preferred solutions where the motions are independent - unlinked, requirement at which respond the polar and pseudo-polar tracking systems (see figure 1, b, c). In these terms and using the above-presented conceptual design method, the solution for the photovoltaic tracking mechanism in study has been established. This is a pseudo-polar tracking system, with the virtual prototype presented in figure 2. The digital model has been realized by using the MBS (Multi-Body Systems) environment ADAMS of MSC Software.

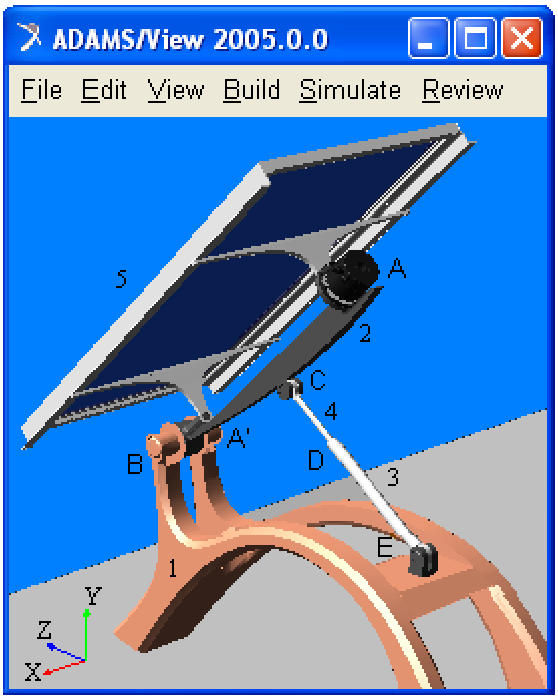


Figure 2. Virtual prototype of the pseudo-polar tracking system (MBS ADAMS).

The actuating for daily orientation is made through a rotative motor, meanwhile for generating the elevation rotation is used a linear actuator. The system contains five bodies: the system's base - 1; the intermediary stand - 2, which rotates relatively at basis (joint B) to generate the elevation motion, and on which the motor and the fixed part of joint A for the daily rotation are positioned; the cylinder - 3 and actuator's piston - 4, linked through translational joint (D) and, respectively, at the adjoining elements through revolute joints (E, C); body 5 which includes the photovoltaic module and its frame.

The key word in designing the photovoltaic tracking systems is energetic efficiency: obtained energy contribution through tracking vs. energy consumption for tracking achievement (while supplying the driving motors/actuators). A PV tracking system is efficient if the following condition is fulfilled: $\varepsilon = E_T - (E_F + E_C) >> 0$, where E_T represents the quantity of electric energy generated by the module with tracking mechanism, E_F represents the quantity generated by the same module without tracking (fixed), and E_C defines the quantity of energy consumed for moving the module.

In these conditions, the tracking systems` optimization strategy targets the maximization of efficiency ε, on one hand by improving the mechanical structure of the system, and on the other hand by optimizing the motion law. It has as purpose to minimize the energy consumption for tracking (E_C), simultaneously with the maximization of solar energy absorption (E_T).

The optimization of the tracking system`s mechanical model, by using the MBS ADAMS environment, was achieved following the stages [9]: model`s parametrization, defining the design variables, defining the optimized objective functions and design constraints, the execution of parametric design studies and experiments design to identify main design variables (with significant influence on the system`s behaviour), the system`s proper optimization regarding the main variables. There were used two ways for the parametrization of tracking systems: parametrization by the points that define the mechanism`s structural scheme (in this case, joints locations – see figure 2) and, respectively, the parametrization by expressions, which define the relations between various objects from the model (the expression, that defines the value of a parameter specific to an object, is modified when a value interviening in the expression changes). Through parametrization, relations are created between the model`s objects, so that when an object changes, the other objects depending on it adapt automatically.

Design variables allow the defininition of independent parameters in the model, on which other objects are linked. In the case of tracking systems, the design variables were considered the global coordinates of mechanism`s significant points. Further more, by using design variables there can be made parametric analysis, in this case parametric and experiments design. Parametric design consists in recognizing the objective function sensibility at individual alteration of design variables, allowing which variables have a major influence on the system`s behaviour. The experiments design consists in establishing the design`s sensibilities and resistance points through simultaneously change of design variables.

The objective function is a numeric representation of quality, efficiency or system price, its optimization maximizing or minimizing it, according to case. Examples can be execution time, energy requirements, total material cost etc. The objective function, named also functional cost or performance index, is a numeric quantification which distinguishes (evaluates) the possible design variants. The optimization study improves, if possible, the objective function without breaking design constraints. The constraints are „boundaries” that directly or indirectly eliminate the unacceptable system design, taking the form of additional objects in designing tracking systems. Unsually, a constraint involves simulation results, but the following can be also considered: various sizes, mases or other parameters that depend on the mechanism structure. The optimization problem consists of establishing design variable for which the best system behaviour is obtained and described through the objective function, respecting the required design constraints.

In the case of tracking systems, the optimization objective is to minimize the consumed energy during tracking. The energy consumption can be obtained by integrating the curves representing the power consumed to orientate the system, which depends on the motor forces and/or torques generated by the motor sources (rotative motors or linear actuators) and on their angular/linear speeds. These parameters are determined taking into consideration the motion law imposed to the module (orientation system), which is established so that a maximum incident solar radiation is obtained, with a minimum consumption for tracking.

The PV module can be continuously rotated during a light-day, or it can be moved in steps (step-by-step), usually rotating it with an equal number of steps every hour. Obviously, the quantity of maximum incident solar radiation is achieved through perpetual tracking, but in this case the motor operating time is large (fact with a negative impact on system`s reliability). The main idea proposed by the movement law optimization is to maximize the energy obtained by step-by-step tracking, in order to absorbe a solar energy quantity approaching the maximum case (continuous tracking), but with reduced orientation energy consumption. Actually, the optimization is based on diminishing the angular motion fields and the number of actuating operations without significantly altering the solar radiation.

The dual-axis pseudo-equatorial tracking mechanism from figure 2 was chosen in order to exemplify the described optimization algorithm, considering as objective the minimization of the energy consumption for tracking.

3. Results and Conclusions

The geometrical optimization of the chosen system (see figure 2) is made distinctly on the two rotations, in the specific kinematic chains. In the daily rotation kinematic chain were considered three design variables, in this case the module-motor joint: $X_A \rightarrow$ DV_1, $Y_A \rightarrow$ DV_2, $Z_A \rightarrow$ DV_3. In addition, to maintain the rotation axis orientation the following expressions were used: $X_{A'} = X_A$, $Y_{A'} = (DV\_2 - (Z_{A'} - DV\_3) \cdot \tan \gamma^*)$, where γ^* is the module`s elevation angle. For elevation motion, the kinematic chain BCDE is considered, which is symmetricaly disposed in YZ vertical-longitudinal plane, thus resulting six design variables: $Y_B \rightarrow$ DV_4, $Z_B \rightarrow$ DV_5, $Y_C \rightarrow$ DV_6, $Z_C \rightarrow$ DV_7, $Y_E \rightarrow$ DV_8, $Z_E \rightarrow$ DV_9. Also, the location and orientation of the translation joint (between the actuator`s elements) were parameterized through expressions, like: LOC_RELATIVE_TO({0, 0, 0}, POINT_D), respectively ORI_ALONG_AXIS (POINT_E, POINT_C, "Z"). In addition, in the kinematic chain of the elevation motion, a design constraint was introduced for limitating the presure angle, the maximum accepted value being 65°.

The objective function, for both motions, is represented by the energy consumption needed for achieving the imposed module trajectory, a step-by-step movement. The numeric simulations were made using entry data specific for the Braşov local area, in the summer solstice day. In this study (which targets the optimization regarding joints` locations) the angular field for daily motion is $\beta^* \in [-80°, +80°]$; the motion is made in 11 steps, with an operating time for each step of 0.1 h. The photovoltaic module is kept fixed in the morning (4.26-6.91) and evening (17.01-22.00). Finally, the photovoltaic module returns at its initial position/sunrise (-80°) with continuous motion in 0.2 h.

Regarding the elevation motion, the photovoltaic module remains in the position specific to summer solstice day ($\gamma^* = \varphi - \delta = 22.05°$) in the time interval 9.01-14.91, and to maximize the incident solar radiation it is additionaly tilted by 11.05° ($\gamma^* = 11°$), the operating time of the linear actuator being 0.1 h for each manoeuvre.

The motion laws obtained in the previous described conditions are presented in figures 3 and 4, the daily and elevation angles being defined relative to the initial position of the system.

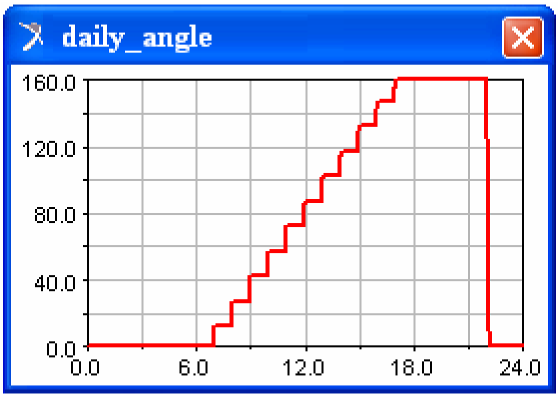


Figure 3. Motion law for the daily orientation.

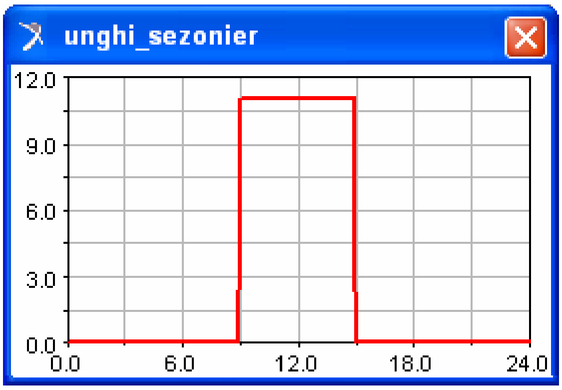


Figure 4. Motion law for the elevation orientation.

For these motion laws, the incident solar radiation, which was obtained by using the Meliß's model [5], is shown in figure 5 (curve "a"), to which it corresponds the quantity of electric energy produced by the PV module E_T = 1755 Wh/day. Meanwhile, if the module would be kept fixed ($\beta^* = 0°$, $\gamma^* = 22.05°$) it would result E_F = 1231 Wh/day (the radiation curve "b" in figure 5), and for continuous orientation (null incidence angle) it would be obtained $E_{T\ max}$ = 1784 Wh/day. So, the electric energy quantity generated through module step orientation is very close to the ideal case (continuous motion). The quantity of electric energy was computed considering a module with active surface of 1.26 m^2 and conversion efficiency of 15%.

Throughout the performed parametric design studies, the influence of each design variable on the energy consumption required for orientation was determined, regarding the motion laws from figures 3 and 4. From the results presented in table 1, the main design variables are drawn as follows: DV_1 and DV_2 for daily motion, respectively DV_4, DV_6 and DV_7 for elevation motion. The others are secondary variables, neglected in the optimization process, which was performed using the algorithm GRG (Generalized Reduced Gradient) of OPTDES.

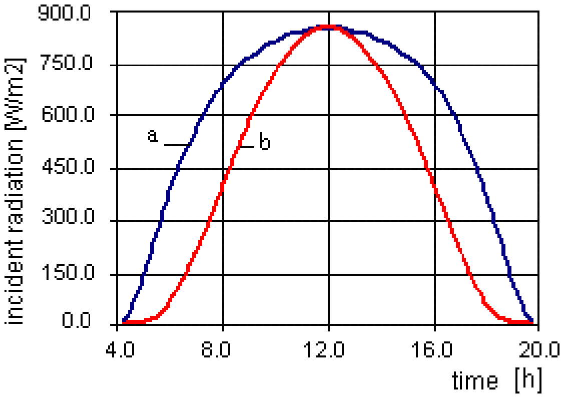


Figure 5. Incident solar radiation for the tracked (curve "a") and fixed PV module (curve "b").

Table 1. Results of the design studies.

Design variables	Value field [m]	Energy consumption [Wh/day]
DV_1	[-0.328, -0.128]	[173.02, 78.67]
DV_2	[0.385, 0.585]	[114.65, 138.84]
DV_3	[-0.649, -0.449]	[127.52, 124.60]
DV_4	[0.048, 0.248]	[119.08, 133.66]
DV_5	[0.311, 0.511]	[121.29, 129.06]
DV_6	[0.185, 0.385]	[139.92, 117.31]
DV_7	[-0.294, -0.094]	[117.14, 135.54]
DV_8	[-0.122, 0.078]	[122.14, 131.45]
DV_9	[-0.741, -0.541]	[128.85, 122.38]

Thus, the optimum variant for tracking system was obtained, at which the total energy consumption for orientation is $E_C \approx 57$ Wh/day, thereby the energetic balance was achieved, $\varepsilon = E_T - (E_F + E_C) = 1755 - (1231 + 57) = 467$ Wh/day. This demonstrates that the designed tracking system is energetic efficient, the energy contribution obtained through tracking with adequate motion laws being nearly 38% relative to the fixed PV module.

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