Design of the Mechatronic Systems Used for Improving the Efficiency of the Solar Energy Conversion Devices

Cătălin Alexandru

***Abstract*—The article deals the design and simulation of the mechatronic tracking systems that can be used for increasing the energy efficiency (i.e. the energy output) of the photovoltaic modules, by improving the capture rate of the incident solar radiation (which is normal to the module surface). Firstly, the classification of the solar tracking mechanism is performed by considering several criteria, such as the number of degrees of freedom, the working mode, the number of modules and their layout. Secondly, the design (analysis and optimization) algorithm is depicted by using three specific mechanical models: kinematic, dynamic, and inverse dynamic. Finally, a case study is developed, by considering the bi-axial tracking system used for a photovoltaic platform, whose behavior is simulated in a virtual prototyping environment.**

***Index Terms*—Photovoltaic module, tracking mechanism, mechatronic system, simulation.**

I. 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 solar energy is the most important source of renewable energy. The advantages of solar energy are not only the low impact on the environment, but also the benefits of stability and security as avoiding the problems associated with the use of fossil and nuclear fuels.

The sunray passes a straight line from the Sun to the Earth. At the entrance to the atmosphere of the Earth, some of the light is scattered, another is absorbed by the atmosphere, and part of it gets to the ground. The solar radiation on the Earth's surface consists of direct and diffuse radiation. The direct radiation is the part of the solar radiation that touches the Earth without being reflected. On the other hand, the diffuse radiation represents the part of the sunlight that touches the surface of the Earth after being dispersed by the molecules and particles in the atmosphere.

The current technical solutions can convert the solar energy into electric or thermal energy. The method of converting solar radiation into electricity is well known: the photovoltaic (PV) effect. The photovoltaic module is made up of several cells (typically made of silicon - monocrystalline, polycrystalline, or amorphous), which are connected in series and/or in parallel. The conversion efficiency of the PV system depends on the quality and type of solar cells, their temperature, and the amount of received solar radiation [1]-[3].

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C. Alexandru is with the Product Design, Mechatronics and Environment Department, Transilvania University of Braşov, 500036 Braşov, Romania (e-mail: calex@unitbv.ro).

A feasible solution to increase the efficiency of photovoltaic systems, which is addressed in this work, consists of the use of solar tracking mechanisms, the maximum solar energy collection rate being obtained when the solar radiation is normal on the surface of the receiver [4].

II. Tracking Systems Systematization

According to the number of degrees of freedom, in correlation with the two movements from the Earth-Sun astronomical system, the solar tracking mechanisms may be mono-axial and bi-axial [5]-[9].

The mono-axial tracking systems (with one degree of freedom) are frequently used to perform the diurnal movement, the seasonal position being fixed at an optimal angle predefined for the specific location, called elevation angle. These systems have the advantage of low cost due to lower number of elements (including in terms of the number of actuating sources), but they have the disadvantage of lower energy efficiency than bi-axial tracking systems.

The bi-axial tracking mechanisms (with two degrees of freedom) provide a precise positioning of the PV module by performing the both movements in the Earth-Sun system: the diurnal movement (corresponding to the rotation of the Earth around its own axis) and the altitudinal/elevation movement (corresponding to the rotation of the Earth around the Sun).

Considering the working (operation) mode, two fundamental types of solar tracking systems can be identified: passive and active. The operation of passive systems is based on the thermal expansion of a Freon-based fluid from one corner of the system to the other because of the heat sensitivity of the working fluid.

The active tracking systems are mechatronic devices, based on electrically actuated positioning devices, which include actuators (rotary or linear), speed reducers, and various types of mechanisms. The orientation of the PV modules by active tracking mechanisms can increase the efficiency of the conversion system with values between 20% and 50% relative to the equivalent fixed system (without tracking) [10]-[13].

Depending on the number of PV modules and their layout, the tracking systems can be classified in the following way: tracking systems for individual modules - the modules are individually mounted on supporting frames and driven by their own motor sources; tracking systems for strings - the modules are individually mounted, but oriented simultaneously from the same motor source (mono-axial systems) / sources (bi-axial systems); tracking systems for platforms - the modules are mounted on the same supporting frame (platform), being oriented simultaneously by rotating the platform from its motor source(s); tracking systems for

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string platforms - the modules are mounted on individual strings, which are in turn arranged on a common platform.

For this paper, the study is developed by considering the bi-axial tracking mechanism of a PV platform. The behavior of the solar tracker is simulated by using the virtual prototyping software solutions ADAMS (for the mechanical device design) and EASY5 (for the control system design) of MSC.Software.

III. Tracking Systems Design Algorithm

The analysis and optimization algorithm of the solar tracking mechanisms is based on the development/approach of three specific mechanical models, as shown in Fig. 1: kinematic, dynamic, and inverse dynamic.

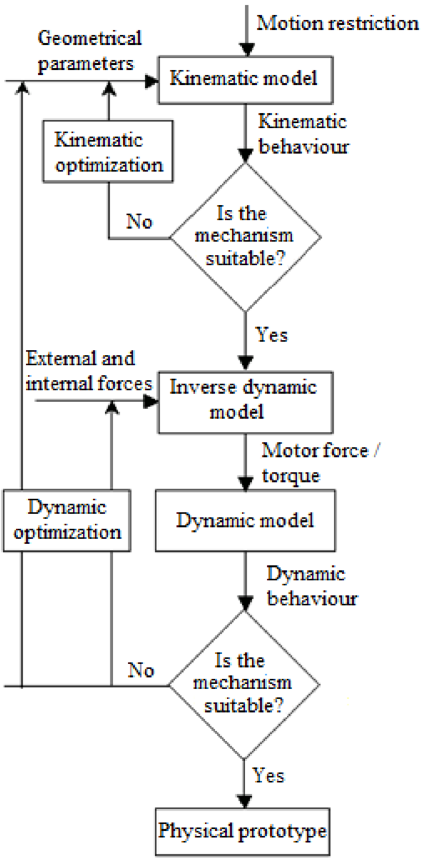


Fig. 1. The design algorithm of the tracking systems.

The input data in the kinematic analysis are the assembled configuration of the tracking mechanism (bodies and joints) and the motion restrictions that replicate the actuating elements, while the outputs are represented by the motion states of the elements/bodies (linear or angular positions, velocities and accelerations).

The dynamic analysis considers the assembled configuration of the solar tracker and the force / torque loads (external and internal), the behavior of the mechanism under the forces action and the reaction states being the unknowns to be determined.

The inputs in the inverse dynamic analysis are the same as in dynamics, but with the actuating elements as in kinematics (motion restrictions), the purpose (output) of this analysis being to determine the motor forces and/or torques that are applied by the actuating sources in order to generate the kinematically prescribed behavior.

The type of analysis that can be performed on a specific model depends on the number of degrees of freedom (DOF), which defines the number of independent/uncontrolled movements (in other words, the number of movements that take place under the forces action), as follows: DOF = 0 → kinematics and inverse dynamics, DOF > 0 → dynamics. This parameter, which provides a quantitative assessment of tracking system structure (topology), can be computed by using the Gruebler count, $DOF = 6\cdot n - \Sigma(r + r_m)$, where n is the number of moving parts (bodies), r - the number of geometric restrictions in joints (which constraint the relative motions between bodies), and r_m - the number of motion restrictions

As the complexity and competitiveness of product development increases, the design and manufacturing times must be reduced, conditions in which the development and testing of physical prototypes become major impediments. The design process based on simulation and virtual prototyping offers a viable and efficient alternative from this point of view. Virtual prototyping allows evaluating the system functionality from early design phases, and offers the possibility of multi-functional optimization so that to achieve an optimal balance between performance, safety, durability, and cost.

Generally, a virtual prototyping platform integrates the following software solutions (Fig. 3): CAD (Computer Aided Design), MBS (Multi-Body Systems), FEA (Finite Element Analysis) and DFC (Design for Control). The CAD software is used to create the 3D-solid model of the tracking system, which offers information about the mass and inertial properties of the bodies. The MBS software, which is the central component of the virtual prototyping platform, is used to simulate and optimize the behavior of the system. The FEA software is used to model the flexible components and to evaluate the stress and deformability states. The DFC software is used to model the control/command device for the mechatronic systems, such as the active tracking systems for PV modules.

The simulation algorithm of the tracking systems involves the following steps:

- within MBS environment (for this study, ADAMS): modeling the mechanical device (bodies, joints, actuating elements and others, by case); analyzing the MBS model; modeling the inputs and outputs plants;
- within DFC environment (in this case, EASY5): modeling the control system block diagram, configuring the MBS interface block, designing the control element (i.e. the controller), simulating the mechatronic system.

In this way, the mechanical and control devices are integrated at the virtual prototype level, as shown in Fig. 2, thus making possible the co-simulation (testing in parallel) of the two models (MBS and DFC), and minimizing or even eliminating the risk that the motion law (imposed through the control system) not to be respected/followed accurately by the mechanical device. The so defined co-simulation generates a closed loop, where the input and output plants in/from the MBS (ADAMS) and DFC (EASY5) models affect each other. The communication between the two models is managed by using ADAMS/Controls, which is a plug-in to ADAMS/View - the general preprocessing interface from ADAMS software package [14].

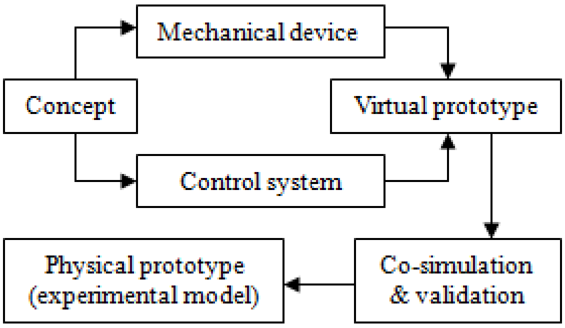


Fig. 2. Co-simulation scheme of the mechatronic systems.

IV. Case Study

In this paper, the previously presented design algorithm was applied for the bi-axial (DOF=2) tracking system that equips a PV platform, the schematic model of the mechanism being shown in Fig. 3. The elevation movement is performed by rotating the platform/modules (2) along with its supporting element (1) relative to the fixed pillar (0), around the primary axis (A) that is horizontally directed (East - West), while the diurnal movement occurs by rotating the platform relative to the supporting element, around a variable secondary axis (B), which is referenced to the primary one.

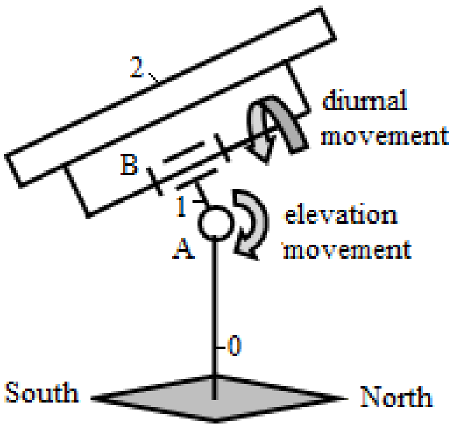


Fig. 3. The schematic model of the bi-axial tracking system.

The so-defined tracking mechanism (which is called pseudo-polar) offers a very good stability of the structure, allowing a large number of PV modules to be placed on the platform, in various configurations (layout modes).

The virtual prototype of this type of tracking system (conceived in ADAMS/View) is shown in Fig. 4. The driving element for the elevation movement is a linear actuator, while the diurnal movement is driven by a rotary motor. The piston (4) of the linear actuator acts on the supporting frame (1), while the cylinder (3) is connected to the fixed pillar (0). The rotary motor for the diurnal movement is placed / mounted on the supporting element, the rotor being connected to the platform frame through two-way couplings. The solid (geometric) model of the solar tracker was conceived by using the CAD software environment CATIA of Dassault Systems, and it was then imported in ADAMS through the CATProduct file format, via the general transfer (export - import) interface from ADAMS software package (namely, ADAMS/Exchange).

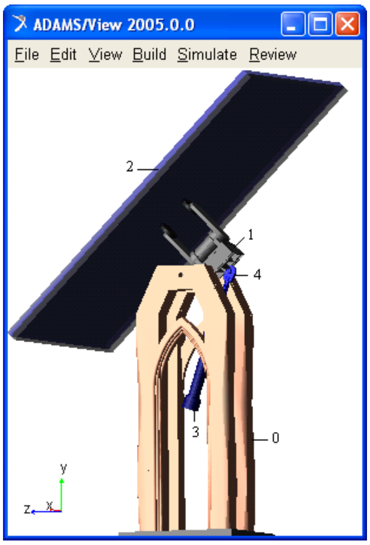


Fig. 4. The virtual prototype of the bi-axial solar tracker.

The input and output control plants, which assure the communication between the mechanical (MBS) and control (DFC) devices / models, were defined in accordance with the connection scheme shown in Fig. 5.

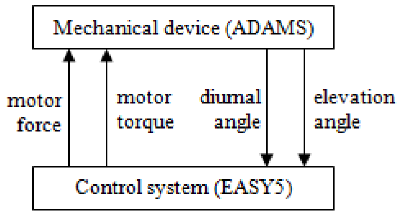


Fig. 5. The input and output control plants.

In the MBS model of the mechanical device, the two input state variables, representing the motor torque developed by the rotary actuator (for the diurnal movement) and the motor force generated by the linear actuator (for the elevation movement), were modeled by null values during the entire simulation interval, because these variables will receive the necessary signals (values) from the control application.

For the output state variables, the time functions return the diurnal and elevation angles of the PV platform, which are measured in the specific revolute joints, as follows (for notations, see Fig. 3): A - the elevation movement, B - the diurnal movement. These functions were modeled in ADAMS/View Function Builder, by using the predefined function AZ(To_Marker, From_Marker), which returns the rotational motion (angle) between the joint coordinate systems on the adjacent bodies (the platform and the supporting element - for the diurnal movement, the supporting element and the fixed pillar - for the elevation movement).

Based on the previously defined input and output state variables, the control diagram block of the bi-axial tracking mechanism was conceived in EASY5. For example, figure 6 shows the control system model for the diurnal movement of the PV platform (the control system model for the elevation movement is similar to that of the diurnal movement).

In the control system model, the tracking error represents the difference between the imposed and measured values of the diurnal angle, the minimization of this error being the goal for the optimal design of the controller, which is a control loop feedback mechanism (PID) that applies a correction based on proportional (P), integral (I), and derivative (D) terms. The controller tuning, which intends to determine the optimal values of the three terms in correlation with the control problem was conducted by following the procedure presented in [7].

Stepwise (step-by-step) tracking, which is commonly implemented in practical applications, was considered for the both rotations (movements) of the PV system. The imposed tracking laws, which control the diurnal (β) and elevation (γ) angles of the PV platform, were configured by using an original algorithm, which integrates an analytical model for estimating the amount of incident solar radiation, in a similar way with the study presented in [15], aiming to maximize the input of solar radiation obtained by tracking the sun path, with a minimum energy consumption to achieve the orientation of the PV platform.

For the diurnal movement, the numerical simulations from this work were performed for the longest daylight of the year, namely the summer solstice day - June 21 (local sunrise time - 5.466, local sunset time - 21.183). The step-by-step tracking law is that shown in Fig. 7, the diurnal angle varying in the range $\beta \in [80°, -80°]$. It is assumed that the diurnal angle is positive in the morning and negative in the afternoon, relative to the noon reference position (when β=0°). The tracking steps are performed according to the following actuation timings: 8.144, 9.444, 10.619, 11.694, 12.769, 13.869, 14.944, 16.019, 17.194, and 18.494 (in local time). The PV system returns into the initial position after sunset, with continuous motion (without breaks). In this simulation, the elevation position of the PV platform is fixed at γ=24.5° (the optimal value for the summer season).

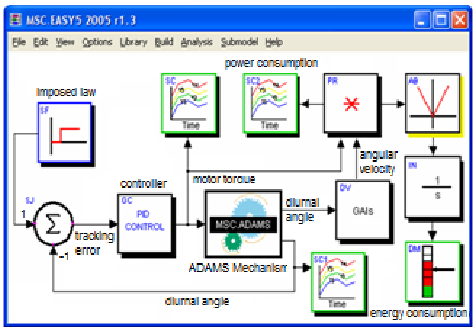


Fig. 6. The control system block diagram for the diurnal movement.

The dynamic analysis carried out by the co-simulation achieved with ADAMS and EASY5 offers important results for evaluating the performance of the tracking system , some of which being presented in figure 8. The system loading is accomplished by the mass and inertial forces of the moving parts. In order to balance the effect of these forces in the stationary positions of the tracking system (between actuatings), it was necessary to introduce into the virtual model a resistant torque (or resistant force for the elevation motion), which ensures the blocking of the system without the need for the driving motor to remain running (turned on). These resistant forces simulate, in fact, the effect of the irreversible transmissions that are integrated into the real motors/actuators.

Thus, the motor torque for the diurnal movement (Fig. 8.c) was obtained as the difference between the necessary torque (Fig. 8.a), when the motor has to keep the platform in the stationary positions (as if there is no irreversible transmission), and the resistant torque (Fig. 8.b). For the motor torque obtained in this way, the corresponding power consumption for performing the tracking law is that presented in Fig. 8.d.

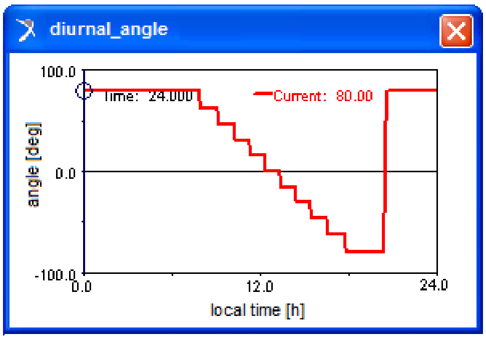
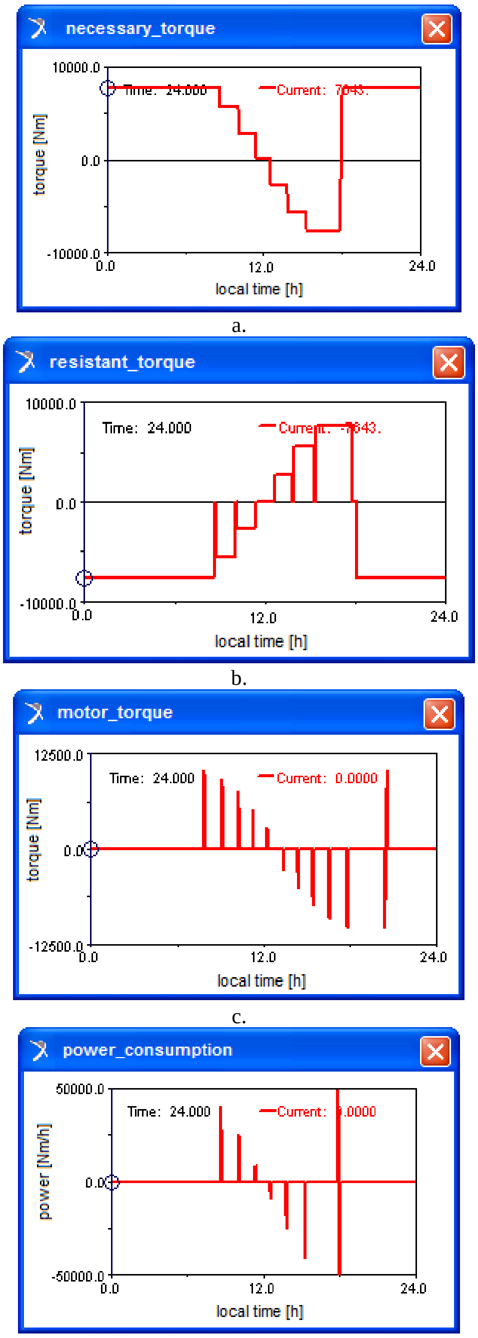


Fig. 7. The step-by-step tracking law.



d.

Fig. 8. Results of the dynamic simulation.

Furthermore, it is approached the case in which a non-stationary load, represented by a wind gust, was applied on the PV system (supplementary to the mass and inertial forces). The wind speed was set to 30 m/s, corresponding to a pressure of 1.73 kN/m^2, and consequently a wind force of 40 kN (the platform surface is about 23 m^2), which was applied during the second movement step from the stepping tracking law shown in Fig. 7.

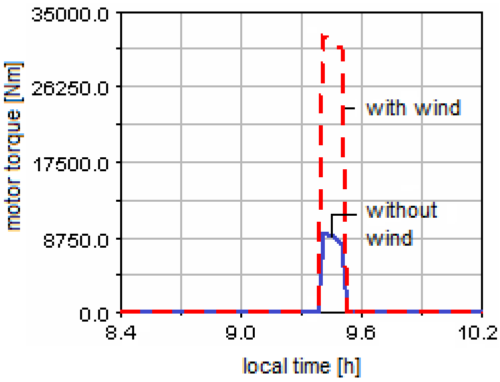


Fig. 9. The motor torque in the presence of wind action.

Considering that the wind acts on half of the platform (the worst case), the additional torque generated by the wind will be of 22.7 kNm. When the wind acts as a resistant force (in opposite direction to the PV system movement), the wind action is compensated by the motor, which has to generate a higher power (motor torque) for performing the motion step, as can be seen in Fig. 9.

V. CONCLUSIONS

The purpose of this study was to emphasize the importance of the testing in virtual prototyping environment, given that the alternative for identifying the optimal solution would have been the development and testing of experimental models, which is an expensive and time consuming process. An important advantage of the testing in virtual prototyping environment consists in the ability to make measurements that are actually very difficult to be performed on experimental models. The results obtained through the simulations in virtual environment prove the high performance of the proposed tracking system, which is already implemented in the solar park of the Transilvania University of Brașov.

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Cătălin Alexandru was born in Cetăţeni, Romania, 1967. He recived his bachelor (1991), the PhD (1998), the PhD supervisor (2009) in mechanical engineering at Transilvania University of Brașov, Romania.

He is currently a professor at Transilvania University of Brașov, Romania, in the product design, mechatronics and environment department. He published over 150 scientific articles, part of them in prestigious ISI-rated journals (such as Mechanism and Machine Theory, Applied Mathematical Modelling, Journal of Renewable and Sustainable Energy, The Scientific World Journal, Proceedings of the Institution of Mechanical Engineers - Part C: Journal of Mechanical Engineering Science). He owns 3 patents. He participated at numerous international conferences in Romania and abroad (England, Scotland, Portugal, Spain, France, Germany, Austria, Italy, and others). Research interests in mechanical & mechatronic systems, automotive engineering, renewable energy systems, virtual prototyping.

Prof. Alexandru is a member of International University Association for Science and Technology of Romania (UASTRO), and International Federation for the Promotion of Mechanism and Machine Science (IFToMM), editor for the Bulletin of the *Transilvania* University of Brasov: Series I - Engineering Sciences, and reviewer for prestigious ISI-rated journals (Advances in Mechanical Engineering, Applied Mathematical Modelling, Applied Mathematics and Computation, IEEE Transactions on Industrial Informatics, IEEE Transactions on Power Electronics, Journal of Mechanical Science and Technology, Journal of Renewable and Sustainable Energy, Mechanical Sciences, Mechanisms and Machine Theory, Robotics and Autonomous Systems, Solar Energy, Renewable Energy, and others).