ANNALS of the ORADEA UNIVERSITY.
Fascicle of Management and Technological Engineering, Volume VII (XVII), 2008

ASPECTS REGARDING THE MECHATRONIC TRACKING SYSTEMS USED FOR IMPROVING THE PHOTOVOLTAIC CONVERSION

Cătălin ALEXANDRU
University ”Transilvania of Braşov”, Product Design & Robotics Dept., calex@unitbv.ro

Keywords: photovoltaic module, tracking mechanism, control system, virtual prototype, energetic efficiency.

Abstract: The paper presents a lot of aspects regarding the improvement of the solar energy conversion in electricity by using mechatronic tracking systems. The tracking principle is based on the input data referring to the position of the Sun on the sky dome; in this way, the basic types of tracking systems are obtained. Based on the knowledge stage in the domain, the design process of the tracking systems is approached in mechatronic concept, by integrating the electronic control system in the mechanical structure of the solar tracker at the virtual prototype level; the components of the digital prototyping platform are also described.

1. INTRODUCTION

The paper is in the field of the renewable sources for electricity production, which is a priority for the research at the international level. There is a fact that the fossil fuels (ex. gas, oil, coal) there are limited and hand strong pollutants. In the last 15 years, the price of petroleum had tripled and the previsions on the medium term there are not quite encouraging. The increase of the emissions of carbon dioxide, responsible for the global warming and for the greenhouse effect, may have devastating results over the time on the environment. The solution to the previously highlighted problems is the renewable energy, including the energy efficiency, the energy saving, and systems based on clean renewable energy sources. The concept of sustainable development have been enounced for the first time in the year 1987, in the Brundland Commission Report, and subsequent adopted at the political level, so in the Conference for Development and Environment from Rio de Janeiro (1992), the participant countries have undertaken to develop national strategies for sustainable development (The Program Agenda 21).

At the European level there are a series of structures in the field of renewable energy, like The Consultative Council of Research in Photovoltaics, which drafts a series of reports concerning the future projection on the research in the field. One of these reports is the publication: “A Vision for Photovoltaic Technology for 2030 and Beyond” (2004), and the paper is reported to this. There are also a series of research groups with significant results in the implementation of the renewable energy systems like The Delft Institute for Sustainable Energy (The Netherlands), The Energy Research Centre of Netherlands (Netherlands), Frauenhofer Institute for Solar Energy Systems (Germany), Solar Centre Julich (Germany), TEI of Heraklion (Greece), The Renewable Department - ADME (France) etc. In the same effort, there are on the energy market companies with preoccupations in the field of renewable energy like Shell, BP, AmCo, Viessmann etc.

The potential of renewable energy is not uniformly distributed on the entire area of the Earth, and in this sense there are zones more or less favorable for applications in the field. Which is the solution for less favorable areas? A plausible answer might be: the usage at the maximum of the existent potential of the renewable energy concomitant with the minimization of the costs, including the design & testing costs of the conversion systems, so the quantity of produced energy (thermal, or electrical) to justify the financial investment (the paper is in this frame). There is also the possibility to use hybrid systems that combine different types of systems based on the renewable energies, for example the alternative production of electricity, depending on the meteorological conditions, by using photovoltaic modules (solar energy conversion) or wind turbines (wind energy conversion).

The solar energy conversion is one of the most addressed topics in the fields of the renewable energy systems. The Sun is a giant nuclear fusion reactor, and the energy it supplies is enormous; it converts 4 million tones of hydrogen per second in to helium, and it can potentially provide 5.41024J per year equal to 170109 kilowatts, which is the equivalent of about 27.000 times the total amount of energy presently produced from all other sources. However, only a very small fraction of this freely available energy is exploited through direct means for human use. As a result of the atmospheric phenomena involving reflection, scattering, and radiation absorption, the quantity of solar energy that ultimately reaches the Earth's surface is much reduced in intensity as it traverses the atmosphere. Finally, the total solar radiation received at ground level (fig. 1) includes the direct solar radiation (A), and the diffuse radiation (B).

The present - day techniques allow converting the solar radiation in two basic forms of energy: thermal and electric energy [14, 34]. The technical solution used for converting the solar energy in electricity is well-known: the photovoltaic modules (PV); the term comes from Phos (light in Greek), and Volta (the physicist Allesandro Volta). The solar cell is the smallest component of a photovoltaic module. The cell is made from a thin slice of silicone (mono-crystalline, poly-crystalline, or amorphous), which is the most often used semiconductor material.

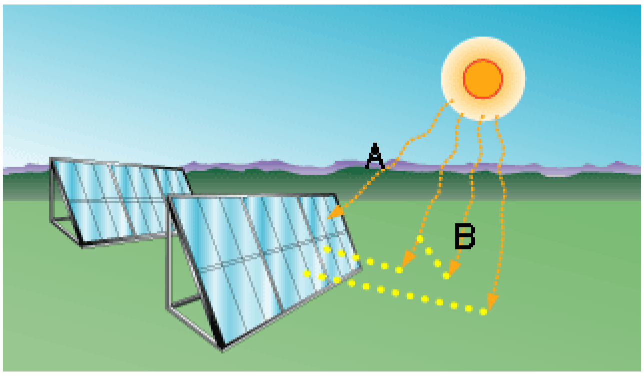


Fig. 1. The main components of the solar radiation

The efficiency of the photovoltaic systems depends on the degree of use and conversion of the solar radiation. When performing the energy balance on a photovoltaic module, reference is done to the surface that absorbs the incoming radiation, and to the balance between energy inflow and energy outflow, $E_u = E_i - E_p$, where: E_u - rate of useful energy leaving the absorber; E_i - rate of optical (short wavelength) radiation incident on absorber; E_p - rate of energy loss from the absorber [14]. According to this relation, there are two ways for maximizing the rate of useful energy (transformed in electricity): 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, the maximum degree of collecting being obtained when the solar radiation is normal on the active surface (this solution is approached in our paper).

Basically, the tracking systems are mechanical devices (i.e. mechanisms), driven by rotary motors and/or linear actuators, which move the photovoltaic module in order to follow the Sun path during the light-day. The orientation of the PV modules may increase the efficiency of the conversion system from 20% up to 50% [1, 5, 8, 9, 19].

2. THE ORIENTATION PRINCIPLE

The tracking principle is based on the input data referring to the position of the Sun on the sky dome. For the highest conversion efficiency, the sunrays have to fall normal on the receiver (i.e. the photovoltaic module) so the system must periodically modify its position in order to maintain this relation between the sunrays and the panel. The positions of the Sun on its path along the year represent an input data in designing the tracking system, so the geometrical relationship between the Earth and the Sun has to be considered. The Earth describes along the year a rotational motion following an elliptical path around the Sun. During one day (24 hours), the Earth also spins around its own axis describing a complete rotation, which generates the sunrises and the sunsets. The variation of the altitude of the Sun on the celestial sphere during one year is determined by the precession motion, responsible for a declination of the Earth axis in consideration with the plane of the elliptic yearly path. This motion generates the seasons because of the alternative exposure of the northern and southern hemisphere to the sunrays trajectory.

Consequently, for the design process of the tracking systems, there are taken into consideration two rotational motions: the daily motion, and the yearly precession motion. In these conditions, there are two fundamental ways to track the Sun, by one axis and by two axes. This fact determines two basic types of tracking mechanisms (fig. 2): single axis solar trackers (a), and dual-axis solar trackers (b). The single-axis 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 location because this axis has to be parallel with the polar axis; in consequence, there is necessary a seasonal tilt angle adjustment.

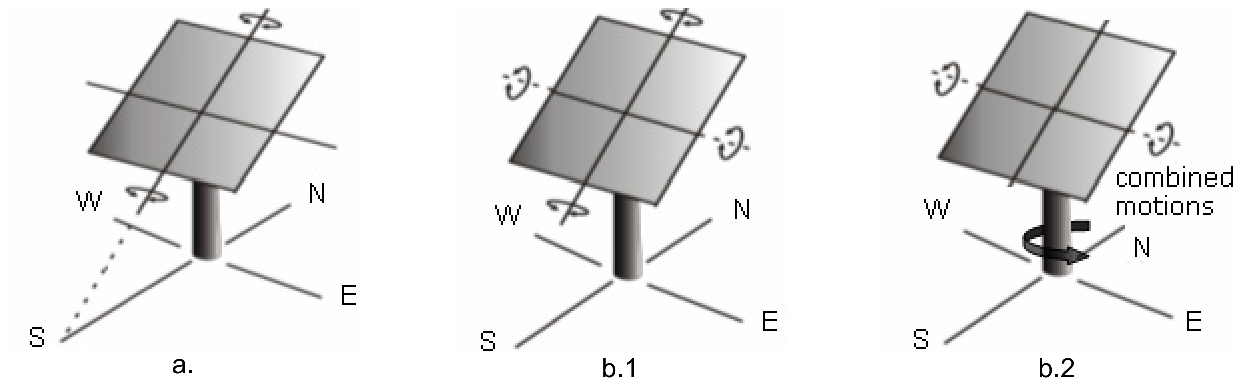


Fig. 2. Basic types of tracking systems

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's why dual axis tracking systems are more efficient than the single one. For the tracking systems based on the scheme b.1, there are two independent motions (daily motion and seasonal motion), and this because the daily motion is made by rotating the panel around the polar axis. At the same time, there are tracking systems that realize the main motion by rotating the panel around the vertical axis - azimuth orientation (b.2); in this case, it is necessary to continuously combine the vertical rotation with an elevation motion, the correlation between these motions increasing the complexity of the control process.

Having in view the operating principle, there are two fundamentals types of tracking systems: passive and active solar trackers. The passive trackers are based on thermal expansion of a Freon - based liquid from one edge of the tracker to another because of the heat sensitive working fluid [11]. The active tracking systems are based on electrically operated positioning drives, which need motors, gearboxes, mechanisms, couplings etc. Usually, the nowadays active solar trackers are based on planar / spatial linkages, gear mechanisms, chain or belt transmissions.

In the design process of the tracking systems, the solar radiation represents the main input data. The solar irradiance can be measured using traditional instruments, or can be digitally recorded with a data acquisition system. Within an EU funded project, a solar radiation atlas was realized for Europe [31]. At the same time, there were developed large meteorological databases, such as METEONORM (http://www.meteonorm.com).

In addition, different models were developed for estimating the solar radiation. The traditional Angstrom's linear approach is based on measurements of sunshine duration, while relatively new methods are based on artificial neural networks - ANN [35]. In reference [30], there are studied four models for estimating the monthly mean solar radiation, including linear Angstrom - Prescot variation, quadratic equation, logarithmic variation, and exponential function; the root mean square error is the principal elements of this comparative analysis. A step by step procedure was developed in [24] for implementing an algorithm to calculate the solar irradiation, using both zenith and azimuth angles to describe sky element's position, for a surface that is tilted to any horizontal and vertical angle. For a similar azimuth system, the mathematic model developed in [2] estimates the hourly and daily radiation incident on planes of three step tracking and hour angle three step tracking. Several simple clear sky and cloudy sky models were tested in reference [7] for evaluating the global solar irradiance under the climate and latitudes of Romania.

Other papers refer to the computation of the yearly energy collection allowed by different tracking strategies. A theoretical analysis of different intervals of intermittent two-axis tracking of the Sun, by a gear mechanism, on the amount of annual energy received by solar panels, has been carried out in [17]; the solar radiation is estimated considering Ashrae assumption (standard sky). Using as input data the location latitude and commonly available values of monthly irradiation, a relation between the latitude of the chosen location and the most suitable tracker is established in [33]. Reference [9] develops an analysis model for comparing the energy capture between fixed tilt angle and solar tracking systems in clear sky and mean sky conditions, using the Moon - Spencer and the Aste models.

Specific software tools were developed in [20] for simulating the energy yield of the PV systems for different tracking cases. A single-axis tracking system is designed in [15] for adjusting the PV module at three specific positions: morning, noon and afternoon; in this way, the optimal stopping daily angle in the morning and afternoon is obtained relative to the solar noon position.

3. THE DESIGN PROCESS OF THE TRACKING SYSTEMS

The modern design process of the PV tracking systems involves conceptual and functional design, command & control, digital mock-up, virtual prototyping, testing and optimization. The conceptual design has as main objective to establish the best product concept (in the given conditions, by performing an efficient management of information picked by the science, technology, economy, market, culture, legislation, policy etc.), using specific design tools, such as multi-criteria analysis and morphologic analysis [22]. The multi-criteria evaluation is for obtaining the most efficient and feasible photovoltaic tracking systems, performing the following steps: establishing the variants and the evaluation criteria; determining the contribution for each criterion (the FRISCO formula is frequently used); applying the contribution notes for each variant; establishing the optimal variants by using the consequences matrix. The morphologic analysis is performed for choosing the solution by taking into consideration the requirements list, which contains aspects regarding the material, form, color, mounting place etc. For describing the solutions, there are used combinatory procedures, which generate the specific morphologic table (the ZWICHY diagram).

The research of the literature reveals the limits of the actual stage in the development of the tracking mechanisms for the PV modules. Since now there are no unitary modelings on structural, kinematical and dynamical aspects in designing the mechanical structure of the solar trackers. At the same time, a general approaching for the conceptual design and the structural synthesis of these mechanisms is missing. Thus rises the necessity of a unitary modeling method of mechanisms, and in our opinion this method is based on the Multi Body Systems theory [13, 32, 36], which may facilitates the self-formulating algorithms, having as main goal the reducing of the processing time for making possible the real-time simulation.

In the structural synthesis based on the MBS theory, the mechanical system is defined as a collection of bodies with large translational and rotational motions, linked by simple or composite joints. In this terms, the structural design involves the following steps [36]: 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 the 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 tracking mechanism (M=1 for the single-axis solar trackers, and M=2 for the dual-axis solar trackers), the number of bodies, and the motion space (S=3 in the planar space, and 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, a collection of possible structural schemes for single/dual-axis tracking mechanisms can be obtained [3, 36].

The analysis algorithm of the tracking systems involves the development of three specific mechanical models: kinematic, inverse dynamic, and dynamic [3]. The kinematic model of the tracking mechanisms contains the rigid parts, which are connected through geometric constraints, and the specific geometric parameters; the input is made using kinematic restrictions that impose the motion of the driving elements (usually, the angular or linear positions). The aim of the kinematic analysis is to evaluate the relative motion between components, and to identify if the tracking system is able to generate the angular fields of the PV module.

The inverse dynamic model includes the kinematic model and, in addition, the external and internal forces & torques. Basically, there are taken in consideration the mass forces, which depend on the geometric model and the material content for each mobile body, the reactions in joints, and the friction forces. In addition, the model can be completed with other external factors, for example the wind or snow action, and so on. The aim of the inverse dynamic analysis is to determine the turning moment and/or the linear force applied by the driving elements in order to generate the kinematically-prescribed behavior of the tracking mechanism.

The dynamic model of the tracking systems includes the components of the inverse dynamic model, but the input is made through the above-determined torques and/or forces. The idea is to obtain the tracking system behavior in real operating conditions. Having in view to evaluate the energetic efficiency of the tracking systems, the main parameters that are taken into consideration in the dynamic optimization of the mechanical structure are the motor torques and/or forces for driving the system. The aim of the optimization process is to minimize these parameters, in fact the power (energy) consumption for moving the PV module.

The active tracking systems are, in fact, controlled systems (i.e. mechatronic systems), which integrates mechanics, electronics, and information technology. Regarding the control process of the tracking systems, in literature, closed loop systems with photo sensors are traditionally used. The photo sensors are responsible for discrimination of the Sun position and for sending electrical signals, proportional with the error, to the controller, which actuates the motors to track the Sun. Many authors have adopted this method as a basis in construction and design of such systems [4, 8, 12, 16]. Although, the orientation based on the Sun detecting sensors, may introduce errors in detection of real Sun position for variable weather conditions (ex. cloudy day).

The alternative consists in the opened loop systems [1, 3, 25], which are based on mathematic algorithms/programs that may provide predefined parameters for the motors, depending on the Sun positions on the sky dome (i.e. the astronomic movements of the Sun - Earth system). These positions can be precisely determined because they are functions of the solar angles that can be calculated for any local area. By using this control technique, based on predefined parameters, the errors introduced by the use of the sensors may be avoided.

Other solution is to incorporate some kind of Sun position sensor to check and calibrate automatically the astronomical control system. In addition, the tracking system can also be adjusted to provide maximum output energy, to self-trim it initially or self correct itself throughout its life [29]. Such hybrid control system, which consists of a combination of opened loop tracking strategies based on solar movement models and closed loop strategies using a dynamic feedback controller, is developed in [27]. The comparative study between a classical open loop tracking strategy and the proposed hybrid one is also presented, considering the energy saving, which implies that the sun is not constantly tracked with the same accuracy, to prevent energy over-consumption by the motors. The tracking mechanism described in [26] is operated by a digital program in the control system, while in the active operation mode the tracker uses the signal of a Sun detecting linear sensor to control the pointing.

From the controller point of view, different control strategies are used [5, 21, 25, 38], such as classical techniques as PID algorithm, or more advanced strategy such as fuzzy logic controller - FLC. In reference [37], whose aim is to design a low cost two-axis solar tracker for obtaining a high precision positioning of the panel, the control-board is able to support different control strategy, PID and FLC; using the error signal, the tracking capacities of the proposed approaches are tested on an experimental prototype. In reference [10], the implementation of a fuzzy logic neural controller (FNLC) in photovoltaic systems has been studied; this controller, which is an evolution of the fuzzy control concept, allows the system to learn control rules. A controller which incorporates the advantages of two alternate design techniques (a deadbeat regulator for quick, rough control, and an LOG/LTR regulator, for soft, final tracking) is presented in [28]; the first one performs approaching the target in a minimum of time; the second one allows a soft approach to the target. The first order Sugeno fuzzy inference system is utilized for modeling and controller design of an azimuth & elevation tracker [6]; in addition, the estimation of the insolation incident is determined by fuzzy IF - THEN rules.

In the typical design of a mechanical system with controls, the mechanical and controls designers work from the same concept, but use different sets of tools. The result is that each designer produces a model for the same problem. Each design is then subject to verification and testing, and the first time the two designs are brought together is during physical prototype testing. If a problem occurs during the interaction between the controls design and the mechanical design, the engineers must refine the control design, the mechanical design, or both, and then go through the entire verification process.

In the concurrent engineering concept (fig. 3), by integrating the control system in the mechanical model at the virtual prototype level, the physical testing process is greatly simplified, and the risk of the control law being poorly matched to the real system is eliminated [18]. In this concept, the command & control (C&C) software directly exchanges information with the MBS software, which is used for developing the mechanical model. The simulation of the mechatronic system involves the following steps [3]:

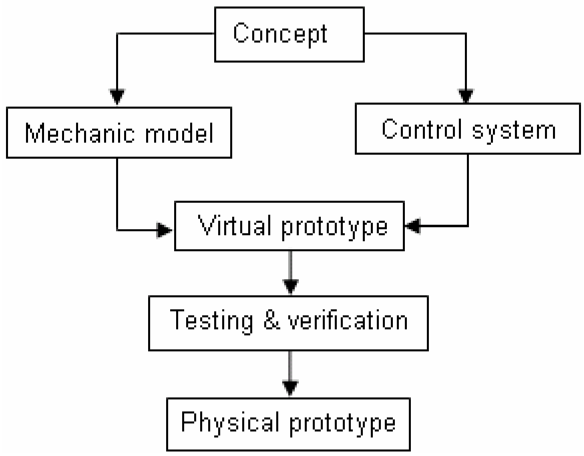


Fig. 3. The concurrent engineering model

- designing the mechanical model (including bodies, joints, forces), and modeling the input and output plants for the control;
- explaining the mechatronic system trajectory, and defining the input reference signal;
- designing the control system block, designing the controller, and simulating the system.

This simulation process creates a closed loop in which the control inputs from the control application affect the MBS simulation, and the MBS outputs affect the control input levels.

Excepting the above-described software solutions (MBS and C&C), the virtual prototyping platform of the tracking systems can includes specific programs for Computer Aided Design (CAD), Finite Element Analysis (FEA), and Product Data Management (PDM). The CAD environment is used to create the geometric model of the system, which contains information about the mass & inertia properties of the rigid parts. The FEA environment is used for modeling flexible components, which allows capturing inertial and compliance effects during simulation, and predict loads with greater accuracy, therefore achieving more realistic results. The PDM technique represents the glue that enables the main components of the virtual prototyping platform to be successful by making all of the up-to-date component data readily available and manageable. In addition, by integrating in the virtual prototyping platform a specific software for designing and simulating photovoltaic systems (PVs), the functionality of the tracking system can be evaluated from energetic and economic balance point of view (the contribution of energy that is obtained by tracking versus the material and energetic costs, including the energy consumed by the motors, and the pay-back period).

One of the most important advantages of this kind of simulation, based on virtual prototyping tools, is the possibility to perform virtual measurements in any point or area of the tracking system, and for any parameter (motion, force, energy). This is not always possible in the real cases due to the lack of space for transducers placement, or lack of appropriate transducers. This helps us to make quick decisions on any design changes without going through expensive prototype building and testing. With virtual prototyping, the behavioral performance predictions of the tracking systems are obtained much earlier in the design cycle, thereby allowing more effective and cost efficient design changes and reducing overall risk substantially.

Concrete steps in this direction have been already made in the “Transilvania” University, in the frame of the Centre Product Design for Sustainable Development (PDSD). The virtual prototyping platform includes the following software solutions (in commercial configuration): CAD - CATIA, MBS - ADAMS, FEA - NASTRAN/PATRAN, C&C - EASY5, PVs - VALENTIN PVSOL, PDM - SMARTEAM. For instant, by using this software platform, in the figure 4 there are presented the virtual prototypes for two dual-axis tracking systems (including the mechanical structure and the control system).

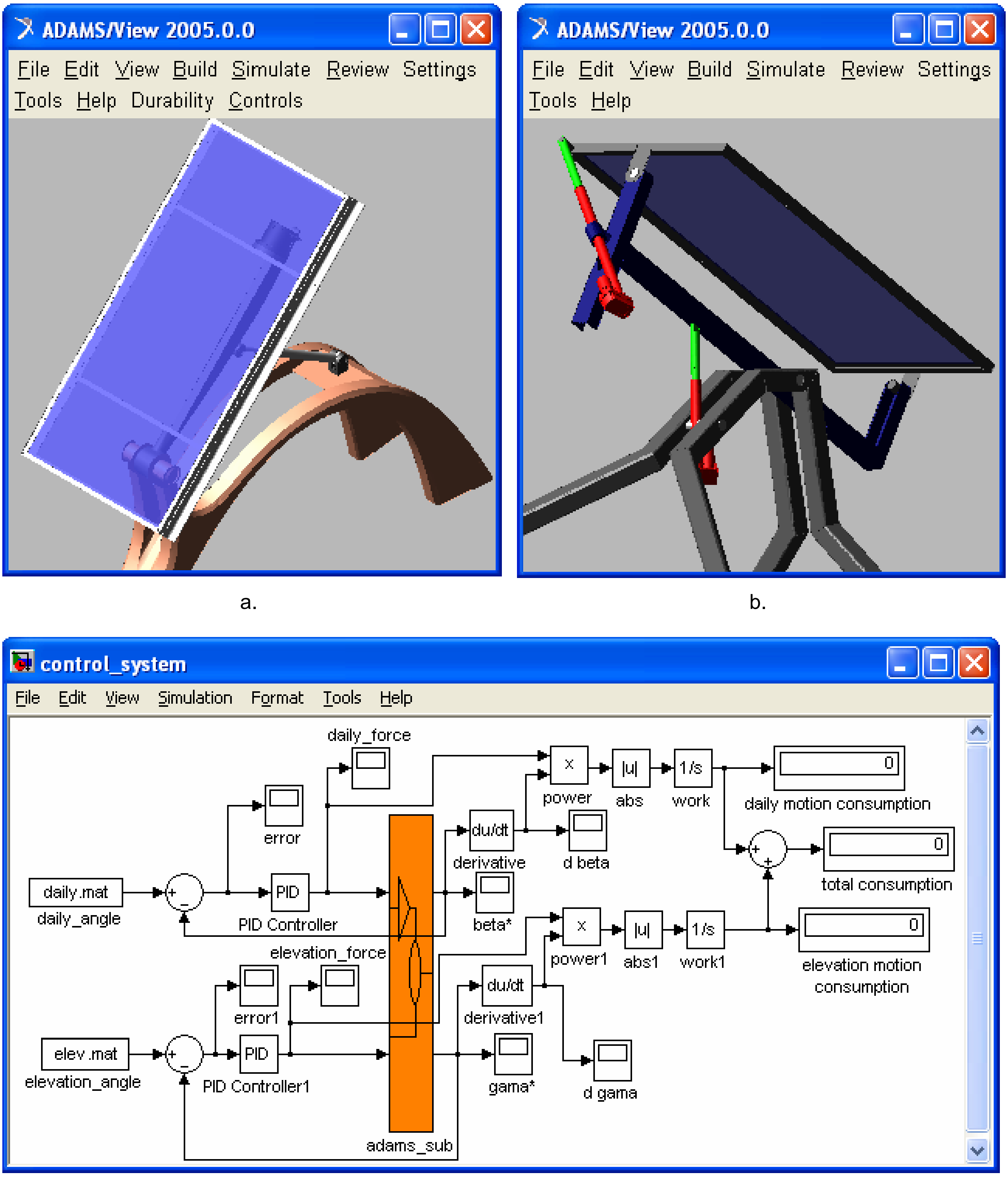
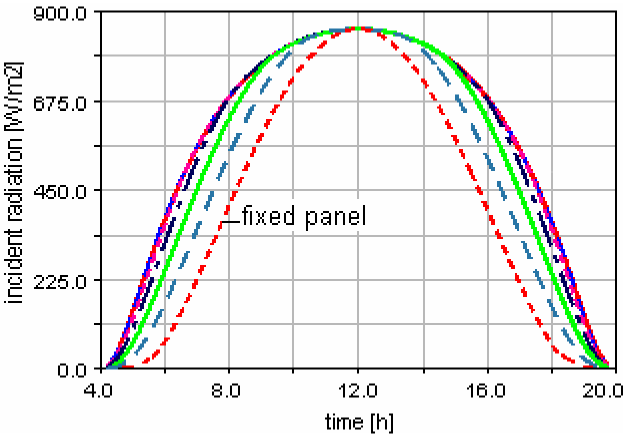


Fig. 4. The virtual prototypes for dual-axis tracking systems

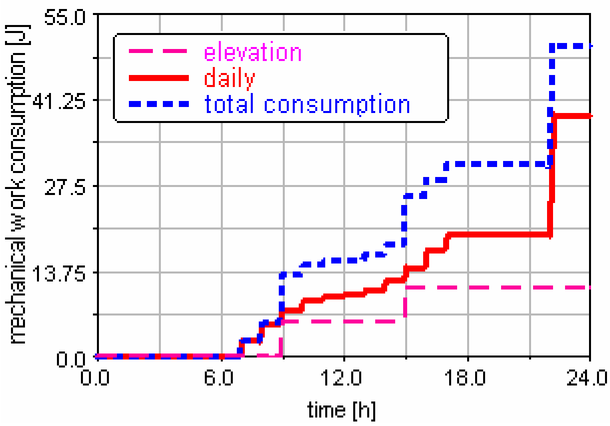
For the dual-axis tracking system shown in figure 4-a there is a rotary motor that directly drives the daily motion, the elevation position being automatically adjusted with a linear actuator that includes a worm gear. The solar tracking system from figure 4-b uses linear actuators with screw-nut mechanisms for driving the daily and the elevation motions. In the both systems/prototypes, the panel is mounted on a support that rotates around the horizontal axis for generating the elevation, and the daily motion is made by rotating the panel relative to the support. At the same time, in figure 4-c there is presented the control system diagram of the tracking systems, in which the “adams_sub” block includes the mechanical model of the tracking mechanism. The connection between the mechanical model and the control system is made by using the specific module ADAMS/Controls.

For these tracking systems, there were performed the kinematic and dynamic analysis & optimization, having as goal to increase the energetic efficiency, by maximizing the absorption of incident solar radiation (in fact the quantity of electric energy produced by the photovoltaic system with tracking), and minimizing the energy (power) consumption for realizing the motion law. The key idea for optimization was to maximize the energy gained through step-by-step tracking strategies, for absorbing a quantity of solar energy closed to the ideal case (continuous orientation), with minimum energy consumption for driving the systems. The tracking strategies were formulated using optimal algorithms based on the number of steps necessary for orientation. These algorithms were developed considering the correlation between the maximum amplitudes of the motion and the number of the tracking steps, aiming to the minimization of the steps number.

In this way, we have obtained a lot of results (motion, force, energy) for evaluating the energetic efficiency of the PV systems with solar trackers. For example, in figure 5 there are presented the following results: a - the incident solar radiation obtained with different tracking strategies (which can be compared with the fixed panel case); b - the mechanical work consumption for realizing the motion law. With such results, the energy & economic balance can be performed without developing expensive hardware prototypes.



a.



b.

Fig. 5. Specific results for evaluating the energetic efficiency of the PV tracking systems

The Romanian Ministry of Education financially supported the publishing of this paper in the frame of the CNCSIS research grant - code 892 / 2007 (A-type).

REFERENCES

[1] Abdallah, S., Nijmeh, S. Two-Axis Sun Tracking with PLC Control. Energy Conversion and Management, Vol. 45 (11), 2004, p. 1931-1939.
[2] Ai, B., Shen, H., Ban, Q. Calculation of the Hourly and Daily Radiation Incident on Three Step Tracking Planes. Energy Conversion and Management, Vol. 44 (12), 2003, p. 1999-2011.
[3] Alexandru, C., Comşiţ, M. The Virtual Prototype of a Complex PV System with Tracking. Proceedings of the 21-st European Photovoltaic Solar Energy Conference, Dresden, 2006, p. 2255-2260.
[4] Akkaya, R., Kulaksiz, A. Microcontroller-Based Stand Alone Photovoltaic Power System for Residential Appliances. Applied Energy, Vol. 78 (4), 2004, p. 419-431.
[5] Al-Mohamad, A. Efficiency Improvements of Photovoltaic Panels using a Sun-Tracking System. Applied Energy, Vol. 79 (3), 2004, p. 345-354.

[6] Alata, M., Al-Nimr, M.A., Qaroush, Y. Developing a Multipurpose Sun Tracking System using Fuzzy Control. Energy Conversion and Management, Vol. 46 (7-8), 2005, p. 1229-1245.
[7] Badescu, V. Verification of Some Very Simple Clear and Cloudy Sky Models to Evaluate Global Solar Irradiance. Solar Energy, Vol. 61 (4), 1997, p. 251-264.
[8] Baltas, P., Tortoreli, M., Russel, P. Evaluation of Power Output for Fixed and Step Tracking Photovoltaics. Solar Energy, Vol. 37 (2), 1986, p. 147-163.
[9] Canova, A., Giaccone, L., Spertino, F. Sun Tracking for Capture Improvement. Proceedings of the 22-nd European Photovoltaic Solar Energy Conference, Milano, 2007, p. 3053-3058.
[10] Chojnacki, J.A. Application of Fuzzy Logic Neural Network Controllers in PV Systems. Proceedings of the 20-th European Photovoltaic Solar Energy Conference, Barcelona, 2005, p. 2269-2272.
[11] Clifford, M.J., Eastwood, D. Design of a Novel Passive Tracker. Solar Energy, Vol.77 (3), 2004, p. 269-280.
[12] Dobon, F., Lugo, A., Monedero, J. First Results of the Tetra-Track System and Control Electronics. Proceedings of the 3-rd World Conference on Photovoltaic Energy, Osaka, 2003, p. 2050-2053.
[13] Garcia de Jalón, J., Bayo, E. Kinematic and Dynamic Simulation of Multibody Systems. Springer-Verlag, New York, 1994.
[14] Goswami, Y., Kreith, F., Kreder, J. Principles of Solar Engineering. Taylor & Francis, Philadelphia, 1999.
[15] Huang, B.J., Sun, F.S. Feasibility Study of One Axis Three Positions Tracking Solar PV. Energy Conversion and Management, Vol. 48 (4), 2007, p. 1273-1280.
[16] Karimov, K., Saqib, M., Akhter, P. A Simple Photovoltaic Tracking System. Solar Energy - Materials and Solar Cells, Vol. 87 (1-4), 2005, p. 49-59.
[17] Koay, C.W., Bari, S. Intermittent Tracking of Flat plate Collectors. Proceedings of the World Renewable Energy Congress - WREC, Kuala Lumpur, Malaysia, 1999, p. 79-82.
[18] Mătieş, V., Mândru, D. Tehnologie şi educație mecatronică. Editura Todesco, Cluj-Napoca, 2001.
[19] Mohring, H.D., Klotz, F., Gabler, H. Energy Yield of PV Tracking Systems. Proceedings of the 21-st European Photovoltaic Solar Energy Conference, Dresden, 2006, p. 2691-2694.
[20] Narvarte, L., Lorenzo, E. Tracking Gains and Ground Cover Ratio. Proceedings of the 22-nd European Photovoltaic Solar Energy Conference, Milano, 2007, p. 3153-3156.
[21] Odeh, S. Design of a Single-Axis Tracking Collector. Proceedings of the 14-th EuroSun Conference, ISES, Freiburg, 2004, p. 527-532.
[22] Pahl, G., Beitz, W. Engineering Desing, Springer - Verlag, London, 1996.
[23] Poulek, V., Libra, M. New Solar Tracker. Solar Energy Materials, Vol. 51 (2), 1998, p. 113-120.
[24] Reda, I., Andreas, A. Solar Position Algorithm for Solar Radiation Applications. Solar Energy, Vol. 76 (5), 2004, p. 577-589.
[25] Roth, P., Georgiev, A., Boudinov, H. Design and Construction of a System for Sun Tracking. Renewable Energy, Vol. 29 (3), 2004, p. 393-402.
[26] Roth, P., Georgiev, A., Boudinov, H. Cheap Two Axis Sun Following Device. Energy Conversion and Management, Vol. 46 (7-8), 2005, p. 1179-1192.
[27] Rubio F.R., Ortega, M., Gordillo F. Application of New Control Strategy for Sun Tracking. Energy Conversion and Management, Vol. 48 (7), 2007, p. 2174-2184.
[28] Rubio, F.R., Aracil, J. Design of a Combined Tracking Control System. Control Engineering Practice, Vol. 5, 1997, p. 23-31.
[29] Sala, G., Pachon, D., Anton, I. Test, Rating and Specification of PV Concentrator Components and Systems. Instituto de Energia Solar, Madrid, 2002.
[30] Salmi, M., Chegaar, M., Mialhe, P. Modeles d'Estimation de l'Irradiation Solaire Globale au Sol. Revue Internationale d'Heliotechnique Energie - Environment, no. 35, 2007, p. 19-24.
[31] Scharmer, K., Greif, J. The European Solar Radiation Atlas, 2000, Ecole des Mines, Paris.
[32] Schiehlen, W.O. Multibody Systems Dynamics: Roots & Perspectives. Multibody Systems Dynamics, Vol. 1 (2), 1997, p. 149-188.
[33] Sorichetti, R., Perpinan, O. PV Solar Tracking Systems Analysis. Proceedings of the 22-nd European Photovoltaic Solar Energy Conference, Milano, 2007, p. 246-252.
[34] Tiwari, G.N. Solar Energy. Alpha Science Int. Ltd., Pangbourne, 2002.
[35] Tymvios, F.S., Jacovides, C.P., Scouteli, C. Comparative Study of Angstrom's and Artificial Neural Networks Methodologies in Estimating Global Solar Radiation. Solar Energy, Vol. 78 (6), 2005, p. 752-762.
[36] Vişa, I., Comşiț, M. Design of the Linkages-type Tracking Mechanisms by using MBS Method. Proceedings of 12-th IFToMM World Congress, Besançon, 2007, p. 582-587.
[37] Yazidi, A., Betin, F., Notton, G. Low Cost Two-Axis Solar Tracker with High Precision Positioning. First International Symposium on Environment Identities and Mediterrance Area, Corte-Ajaccio, 2006, p. 121-126.
[38] Zogbit, R., Laplaze, D. Design and Construction of a Sun Tracker. Solar Energy, Vol. 33 (5), 1984, p. 369-372.