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A review on the sun tracking mechanisms for PV strings

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Abstract. This paper deals with a review on the solar trackers used for increasing the energetic efficiency of the photovoltaic (PV) strings. To begin with, the context from which the utility of the tracking mechanisms emerges is presented. The study continues with the systematization of the PV systems according to the structure that is oriented (i.e. the configuration in which the PV panels are disposed / arranged), presenting also the main advantages and disadvantages of the existing structures. Thus, it is retained as a solution for deepening the research that of the simultaneous orientation of the PV panels arranged in a string-like configuration. Afterwards, the study is focused on the main components that are taken into account in the design process of the tracking systems for PV strings, such as the tracking mode, the evaluation of the solar energy potential (involving the modelling of the solar radiation), the emplacement/disposing scheme of the panels in different array configurations, the mechanical and control devices of the solar trackers.

Keywords: *PV strings, energetic efficiency, mechanical and control devices*

Introduction

The work is the result of a preliminary analysis of necessities that identify the existence of a strategic frame at global level concerning promoting and implementation of the renewable energy systems, the necessity to open the economic environment to interdisciplinary top domains, the existence of direct-indirect customers from the economic and social environments, the development of new/innovative solutions for complex products that are economically and energetically efficient.

In this frame, the study is approaching a theme that belongs to a very important (and topical also) field: renewable sources for energy production - increasing the efficiency of the photovoltaic systems. The researches in this field represent a priority at global level because provides viable alternatives to a series of major problems that humanity is facing: the limited and pollutant character of the fossil fuels, global warming or the greenhouse effect. By promoting of the renewable energy systems, in the spirit of energy saving, the project is in a perfect agreement with the actual effective integration politics of Romania into European Union and respectively is targeting one of the thematic areas stated by the European Frame Program (namely, Energy).

The photovoltaic systems can deliver energy on large-scale to a competitive price, as stated by the European Commission for Energy, in the report "A Vision for Photovoltaic Technology for 2030 and Beyond". The report emphasizes as the development of advanced technologies in the photovoltaic area, and a European strong and competitive industry will support the strategic initiatives concerning to the security and the diversity of the electric energy sources. The realization of the PV arrays (system of panels that function as a single electricity-producing unit) appeared as a necessity for the development of large systems for producing electric energy based-on the solar energy.

PV tracking systems

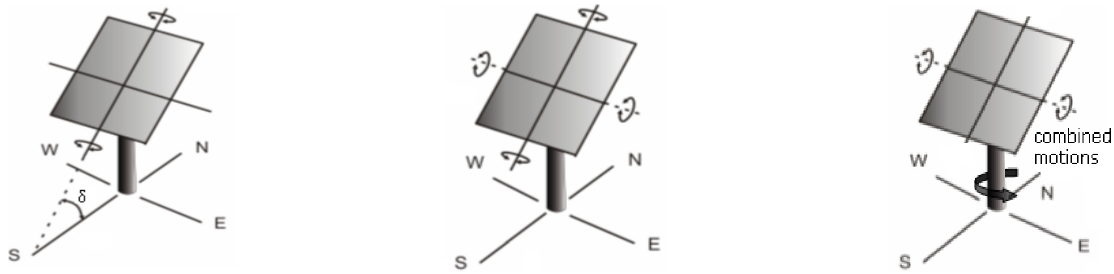
The energetic efficiency of the PV arrays depends on the degree of use of the solar radiation, which can be maximized by use of mechanical systems for the orientation of the panels in accordance with the paths of the Sun. Basically, the tracking systems are mechanical systems with M=1 or M=2 degrees of mobility (corresponding with the number of revolute axes), 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, on the entire period of the day (the diurnal motion, East - West), and also depending on the season (the seasonal/elevation motion).

From energetic point of view, the photovoltaic array with tracking is efficient if the following condition is achieved: $\varepsilon = (E_T - E_F) - E_C >> 0$, where E_T is the electric energy produced by the PV array with tracking, E_F - the energy produced by the equivalent fixed (without tracking) PV array, and E_C - the energy consumption (demand) for tracking the sun. In the current conditions, the maximization of the efficiency parameter ε through the optimal design of the tracking system became an important challenge in the modern research and technology.

Having in view the operating principle, there are two fundamentals types of tracking systems: passive and active 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 [13]. The active trackers are based on electrically operated positioning drives, which need motors, gearboxes, mechanisms, couplings etc. Usually, the nowadays active tracking systems are based on planar or spatial linkages, gear mechanisms, chain or belt transmissions. The orientation of the photovoltaic panels with active solar trackers may increase the efficiency of the conversion system from 20% up to 50% [1, 5, 9, 11, 26].

The tracking principle of the PV panels 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 PV panel) 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, 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 [42]. Consequently, for the design process of the solar trackers, there are taken into account two rotational motions: the daily motion, and the yearly precession motion.

Under these circumstances, there are two fundamental ways to track the sun, by one axis or by two axes, what determines two types of tracking mechanisms (figure 1): mono-axis (a), and dual-axis (b) solar trackers. The mono-axis tracking mechanisms pivot on their axis to track the sun, facing east in the morning and west in the afternoon. The tilt angle of this axis equals the latitude angle of the loco because this axis has to be always parallel with the polar axis. In consequence for this type of single axis tracker is necessary a seasonal tilt angle adjustment. The two-axis tracking systems follow combine two rotational motions, so that they are able to follow very precisely the sun path along the period of one year; that'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 main (daily) motion is made by rotating the panel around the polar axis. At the same time, there are tracking systems that realize the daily motion by rotating the panel around a vertical axis - azimuthal orientation (b.2); in this case, it is necessary to continuously combine the vertical rotation with an elevation motion around the horizontal axis, the corellation between motions increasing the complexity of the control process [26].



a. b.1 b.2

Figure 1. Basic types of tracking systems.

In practice there are two solutions for developing the PV tracked arrays:

I. PV platforms, where the panels are mounted on a common frame (panels with same sustaining structure), orientation being realized simultaneously by the orientation of the entire platform;

II. array of individual panels, where the panels are separately mounted on individual sustaining structures.

The PV platforms, even they have the advantage of a unitary electrical scheme, where the energetic management is safer and more feasible, generate multiple inconvenient concerning the construction, which has to be massive and solid (in the case of a greater number of panels, the assembly platform - sustaining pillar may reach masses in the terms of tones), or integration in the built environment, which may be difficult or even impossible (e.g. it cannot be mounted a platform on a roof because these impose the construction of a foundation). Another major disadvantage of the PV platforms consists in the fact that the efficiency of the system may be smaller because of the close mounting of the panels that may provoke overheating.

The array with individual panels eliminates the disadvantages of the platforms but they need a larger area for mounting (the sustaining structure is not compact as in the case of the platforms), and the disposer of them have to care out of the eventual auto shadings that may appear between the individual panels. For panels with individual supports, the tracking can be realized in two ways:

II.1. tracking independently each panel of the array (panel with own tracking system - self motor source);

II.2. simultaneous tracking of all panels of the array, or tracking for groups of panels, by using single driving source (for single-axis systems, M=1) or two driving sources (for dual-axis systems, M=2), which transmits the motion to the all panels of the array/group (figure 2).

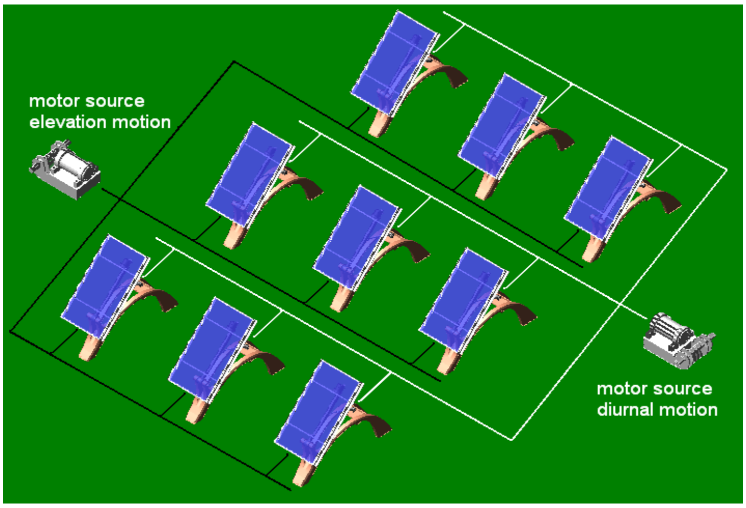


Figure 2. Simultaneous orientation in a PV array.

Obviously, the second solution (II.2), even is more complex by constructive aspects (needs the design of the mechanisms suitable for transmission of the power from the driving source to the panels of the array), ensures theoretically a greater energetic efficiency because of the minimization of the consumers in the array. The orientation of the arrays/groups of panels, with the predicted advantages and the characteristic problems that involves, opens a research area insufficiently explored since now, fact sustained by the literature and practical developments in the field that refer almost entirely to the orientation individual panels. The evaluation of the state of the art in the field is based on the attentive exploration of the literature, considering with priority ISI and BDI journals, proceedings of the conferences organized by recognized international forums, and reference books in the field.

In the design process of the tracking systems, the solar radiation represents the main input data. The total solar radiation received at ground level includes two main components (figure 3): direct solar radiation (A), and diffuse radiation (B). The solar radiation 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 [38]. At the same time, there were developed large meteorological databases, such as Meteonorm (www.meteonorm.com).

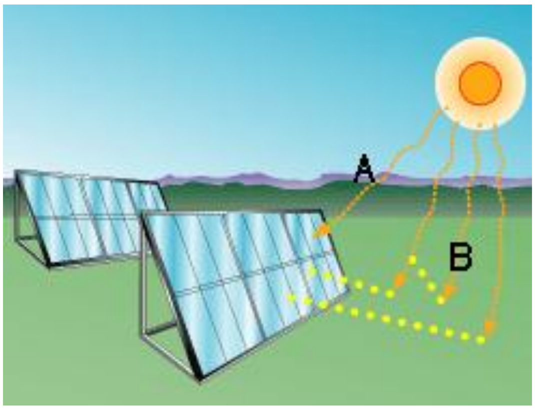


Figure 3. Solar radiation components.

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 [43]. In reference [37], 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 [31] 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 [3] 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 [7] for evaluating the global solar irradiance under the climate and latitudes of Romania.

Other papers in literature 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 flat-plate collectors, has been carried out in [21]; the solar radiation (both direct and diffuse components) 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 chose location and the most suitable solar tracker is established [41]. In reference [11] , there is developed an analysis model for comparing the energy capture between fixed tilt angle and sun tracking systems, in clear sky and mean sky conditions, using the Moon-Spencer and the Aste models. Specific software tools were developed in [27] for simulating the energy yield of PV systems as a function of the ground cover ratio, for different tracking cases. An one axis three position sun tracking PV module is designed in [17] for adjusting the PV position only at three fixed angles (three position tracking): morning, noon and afternoon; in this way , the optimal stopping daily angle in the morning or afternoon, relative to the solar noon position, is obtained. An experimental study was performed in [8] to investigate the effect of using a continuous operation two-axes tracking on the solar energy collected; the energy gain relative to a fixed panel is up to 47%.

As it was previously mentioned, the active tracking systems contain mechanisms (e.g. linkages, gear mechanisms, cam mechanisms, chain or belt transmissions), which are driven by controlled motors & actuators. The research of the literature reveals the limits of the actual stage in the development of the tracking mechanisms (i.e. the mechanical device) for the PV arrays. Since now there are no unitary modelings on structural, kinematical and dynamical aspects in designing the mechanical structure; 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, such as the Multi-Body Systems method [15, 39], which may facilitates the self-formulating algorithms, having as main goal the reducing of the processing time, for making possible the real-time simulation.

a. b.

Figure 4. Constructive solutions of tracking mechanisms for PV strings.

The literature presents some constructive solutions of tracking mechanisms, mainly for individual PV panels [10, 14, 18, 19, 23, 28, 30]. In the case of the arrays/groups of panels there are only summary descriptions of different producers for such systems, for simple topologies (line - string) and single-axis systems (M=1) [47]. For example, the tracking system shown in figure 4.a, produced by SunPower, realizes the diurnal orienting for a line-array, the motion being transmitted with a parallelogram mechanism. The constructive solution from figure 4.b, developed by Energy Innovations, contains a tracking system that adjust the elevation angle (to track the sun altitude) for a string of three sticks of panels (each stick has a proper support); the motion is transmitted with a double four-bar mechanism.

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, 9, 14, 19]. 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), and requires some automatic drivers to point it to the east at the beginning of the day.

The alternative consists in the opened loop systems [1, 2, 32], 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 (the systems are not affected by clouds, irradiance values or other optical circumstances). The astronomical computerized systems require a reference or zero positioning; the reference can be adjusted at the beginning of the operation, but recalibration is required.

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 [36]. 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 [34]. The comparative analysis between a classical open loop tracking strategy and the 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 [33] 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; the position of the sun is calculated, and the pointing errors appearing during its daily work are stored for later analysis.

From the controller point of view, different control strategies are used [5, 28, 32, 46], such as classical techniques as PID algorithm or more advanced strategy such as fuzzy logic controller - FLC. In reference [45], 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 [12], 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 (Linear Quadratic Gaussian with Loop Transfer Recovery) regulator, for soft, final tracking) is presented in [35]; 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 modelling and controller design of an azimuth & elevation tracker [6]; in addition, an estimation of the incident radiation corresponding to the dual-axis tracking system is determined by fuzzy IF-THEN rules.

A specific problem for the photovoltaic arrays consists in the establishing of the emplacement/disposing mode of the panels. Basically, the panels can be arranged in line, in string, or in matrix, the number of panels in a specific emplacement scheme depending on the size of the array / covered area. For this kind of systems, knowing the losses due to self-shadowing among panels is a key issue. Knowing these losses allows optimizing the placement of the panels over the area as well as quantifying the energy production losses; however, there is very little literature about this matter. Such a subject is approached in [29], with the purpose to develop a procedure for calculating the irradiance losses due to self-shadowing among trackers as a function of the position and distance among them. The procedure is divided into three parts: calculating the solar irradiation that reach to one PV panel free of shadows; calculating the shadows produced by one panel over another one, and so the losses of solar radiation are estimated; obtaining the solar irradiation losses in a PV array by composing the shadows over each panel produced by the other ones surrounding it. In this way, so called butterfly graphics (with the percentage of shadowing losses between panels) are obtained, as shown in figure 6. The procedure was applied for the solar park of 6.4 MW installed in Lorca (Murcia - Spain). Reference [22] examines the theoretical aspects associated with the design of azimuth trackers for a PV array, taking into account shadowing between different trackers and back-tracking features, and this tracking alternative is compared with the more conventional fully stationary array approach; the application is made for a 1.4 MW PV plant. Reference [20] shows a simulation model for the sizing of stand-alone solar PV systems with interconnected arrays, which are comparatively less susceptible to shadow problem. The non-tracking (e.g. fixed and tilted) and mono-axis tracking aperture arrays having cross-connected modules of solar cells in a 6×6 modular configuration are considered; finally, a simple cost analysis has also been carried out.

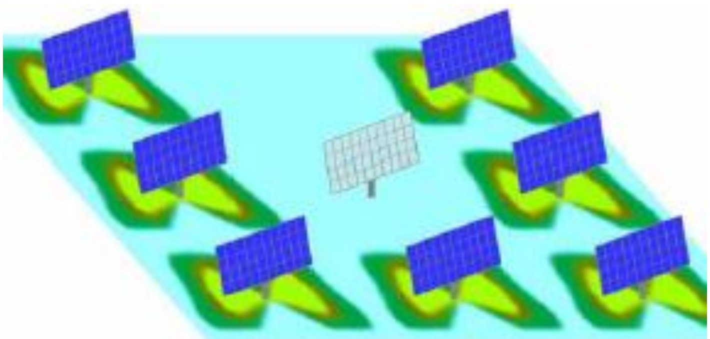


Figure 6. PV panels layout based on butterfly graphics.

Other subject that is insufficient approached in literature is the evaluation of the non-stationary external loads (such as the wind or snow action) on the dynamic behaviour of the tracking system, as well as on the system's components. Some aspects are presented in [40], dealing with the calculation of the wind action, which is modelled by three dimensional-normal forces, on the bearings of a tracking system, the effect of the weight forces being also considered. Specific models for considering the deformability (for bodies and joints) and vibration characteristics of the components are missing in literature, as well as the evaluation of the tracking systems durability.

Final remarks

The background research reveals a series of aspects and hardships in the literature concerning the tracking systems for PV arrays. Based on this study, the following conclusions and recommendations for further research directions were formulated.

In the literature there are no unitary models for the tracking mechanisms of the PV arrays/strings referring to the structural, kinematical and dynamical issues. In the same time, there is no general approach for conceptual design and structural synthesis of these mechanisms. In this regard, a method for the unitary modelling of the tracking mechanisms should be used, and this can be based on the MBS (Multi-Body Systems) theory. On the other hand, the literature mainly addresses tracking solutions for PV panels arranged in simple topologies (line - string), especially for mono-axis systems, with one degree of freedom (for the diurnal or elevation motion). From this point of view, it is desirable a global approach of the array topologies (generally, the matrix topology), considering dual-axis tracking systems, with two degrees of freedom (for the both motions), so as to capture as much solar energy (incident radiation) as possible.

The issue concerning the control of the tracking systems is approached mostly for the tracking systems of the individual panels, using different techniques/methods (such as PID, FNC, FNLC). The research is focused mostly on the quantity of the energy achieved by tracking, but less on the energy consumption (demand) for performing the orientation (consumed by the actuating sources). This is mainly due to the fact that the system is not approached as an integrated assembly (mechanical device - actuating & control device). Thus, it is desirable the integration of the main two components at the virtual prototype level, during the entire design process (i.e. modelling in mechatronic concept), which will allow the simultaneous evaluation of both the energy gain brought by orientation and the energy consumption to achieve the orientation.

The literature presents different models/methods for the evaluation of the radiation potential as input data in the design of the tracking systems (the number of the modules from the array depends on the solar energy potential of the mounting area and respectively of the necessary amount of the energy that has to be provided). In the case of the PV systems equipped with tracking mechanisms, the modelling of the incident solar radiation has to consider the tracking method (i.e. the type of tracking mechanism, equatorial or azimuthal - see figure 1), because this influences the modelling of the incident angle, which is then found in the incident radiation captured by the PV panel.

The layout/arrangement of the PV panels within an array is approached in the literature almost in exclusively from the point of view of avoiding the self-shading. Complementary, this issue should also be approached with the aim to simplify - optimize the solution for transmitting the motion from the actuating source to all the PV panels of the array in order to obtain high efficiency systems. Following this trend, it is desirable a modular approach of the PV array by designing modules of panels with tracking systems, having the possibility to transmit (or receive) the motion to (from) another module, depending on the number of the panels of the PV array.

Finally, another research direction that should be studied more intensively consists in the evaluation of the dynamic behaviour of the tracking systems through compliant models, by considering the deformation and vibration characteristics under FEA (Finite Element Analysis) software environment, within a virtual prototyping platform. Moreover, by the prediction of the product lifecycle, the economic efficiency of the tracking systems can be evaluated more precisely.

References

[1] Abdallah, S. The effect of using sun tracking systems on the voltage-current characteristics and power generation of flat plate photovoltaics. *Energy Conversion and Management*, **45** (11), 2004, pp 1671-1679.

[2] Al-Rousan, N., Isa, N.A.M., Desa, M.K.M. Advances in solar photovoltaic tracking systems: A review. *Renewable & Sustainable Energy Reviews*, **82** (3), 2018, pp 2548-2569.

[3] Al-Garni, H., Awasthi, A., Ramli, M. Optimal design and analysis of grid-connected photovoltaic under different tracking systems using HOMER. *Energy Conversion and Management*, **155**, 2018, pp 42-57.

[4] Alexandru, C. A comparative analysis between the tracking solutions implemented on a photovoltaic string. *Journal of Renewable and Sustainable Energy*, **6** (5), 2014, pp 053130 (1-17).

[5] Alexandru, C. Optimal design of the dual-axis tracking system used for a PV string platform. *Journal of Renewable and Sustainable Energy*, **11** (4), 2019, pp 043501(1-14).

[6] Altuzarra, O., Macho, E., Aginaga, J., Petuya, V. Design of a solar tracking parallel mechanism with low energy consumption. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 2015, **229** (3), pp 566-579.

[7] Bădescu, V. Verification of some very simple clear and cloudy sky models to evaluate global solar irradiance. *Solar Energy*, **61** (4), 1997, pp 251-264.

[8] Bakos, G.C. Design and construction of a two-axis sun tracking system for parabolic trough collector efficiency improvement. *Renewable Energy*, **31** (15), 2006, pp 2411-2421.

[9] Baltas, P., Tortoreli, M., Russel, P. Evaluation of power output for fixed and step tracking photovoltaics. *Solar Energy*, **37** (2), 1986, pp 147-163.

[10] Barkat, B., Mohammedi, B., Bendaas, M.C. Mechanical design of a sun tracking system with two axis for arid areas. *Proceedings of the 6th World Renewable Energy Congress*, Brighton, 2000, pp 825-831.

[11] Chowdhury, M., Khandakar, A., Hossain, B., Abouhasera, R. A low-cost closed-loop solar tracking system based on the sun position algorithm. *Journal of Sensors*, 2019, pp 3681031(1-11).

[12] Çinar, S., Hocaoğlu, F., Orhuna, M. A remotely accessible solar tracker system design. *Journal of Renewable and Sustainable Energy*, 6, nr. 3, 2014, pp 033143(1-12).

[13] Clifford, M.J., Eastwood, D. Design of a novel passive tracker. *Solar Energy*, **77** (3), 2004, pp 269-280.

[14] Engin, M., Engin, D. Optimization controller for mechatronic sun tracking system to improve performance. *Advances in Mechanical Engineering*, 2013, pp 146352(1-9).

[15] Garcia de Jalón, J., Bayo, E. *Kinematic and Dynamic Simulation of Multibody Systems* (New York: Springer-Verlag), 1994.

[16] Garrido, R., Diaz, A. Cascade closed-loop control of solar trackers applied to HCPV systems. *Renewable Energy*, **97**, 2016, pp 689-696.

[17] Huynh, D., Dunnigan, M. Development and comparison of an improved incremental conductance algorithm for tracking the MPP of a solar PV panel. *IEEE Transactions on Sustainable Energy*, **7** (4), 2016, pp 1421-1429.

[18] Kalogirou, S. Design and construction of a one-axis sun-tracking system. *Solar Energy*, **57** (6), 1996, pp 465-469.

[19] Karimov, K., Saqib, M., Akhter, P. A simple photovoltaic tracking system. S*olar Energy - Materials and Solar Cells*, **87** (1-4), 2005, pp 49-59.

[20] Kaushika, N.D., Gautam, N.K., Kaushik, K. Simulation model for sizing of stand-alone solar pv system with interconnected array. *Solar Energy: Materials and Solar Cells*, **85** (4), 2005, pp 499-519.

[21] Koochaki, A., Hosseini, H.S. Application of swarm based optimization algorithms to maximize output energy of photovoltaic panels. *Tehnicki Vjesnik-Technical Gazette*, **23** (6), 2016, pp 1571-1578.

[22] Lorenzo, E., Perez, M., Ezpeleta, A. Design of tracking photovoltaic systems with a single vertical axis. *Progress in Photovoltaics*, **10** (8), 2002, pp 533-543.

[23] Mauro, S., Battezzato, A., Biondi, G., Scarzella, C. Design and test of a parallel kinematic solar tracker. Advances in Mechanical Engineering, **7** (12), 2015, pp 1-16.

[24] Maties, V., Mandru, D. *Tehnologie si Educatie Mecatronica* (Cluj-Napoca: Todesco), 2001.

[25] Meliss, M. *Regenerative Energiequellen: Praktikum* (Berlin: Springer-Verlag), 1997.

[26] Mi, Z., Chen, J., Chen, N., Bai, Y., Fu, R., Liu, H. Open-loop solar tracking strategy for high concentrating photovoltaic systems using variable tracking frequency. *Energy Conversion and Management*, **117**, 2016, pp 142–149.

[27] Narvarte, L., Lorenzo, E. Tracking gains and ground cover ratio. *Proceedings of the 22nd European Photovoltaic Solar Energy Conference*, Milano, 2007, pp 3153-3156.

[28] Odeh, S. Design of a single-axis tracking collector. *Proceedings of the 14th EuroSun Conference*, Freiburg, 2004, pp 527-532.

[29] Perez, P.J., Almonacid, G., Vidal, P.G. Estimation of shading losses in multi-trackers PV systems. *Proceedings of the 22nd European Photovoltaic Solar Energy Conference***,** Milano, 2007, pp 2295-2298.

[30] Poulek, V., Libra, M. New solar tracker. *Solar Energy Materials and Solar Cells*, **51** (2), 1998, pp 113-120.
[31] Reda, I., Andreas, A. Solar position algorithm for solar radiation applications. *Solar Energy*, **76** (5), 2004, pp 577-589.
[32] Roth, P., Georgiev, A., Boudinov, H. Design and construction of a system for sun-tracking. *Renewable Energy*, **29** (3), 2004, pp 393-402.
[33] Roth, P., Georgiev, A., Boudinov, H. Cheap two axis sun following device. *Energy Conversion and Management*, **46** (7-8), 2005, pp 1179-1192.
[34] Rubio F.R., Ortega, M., Gordillo F. Application of new control strategy for sun tracking. *Energy Conversion and Management*, **48** (7), 2007, pp 2174-2184.
[35] Rubio, F.R., Aracil, J. Design of a combined tracking control system. *Control Engineering* Practice, **5** (1), 1997, pp 23-31.
[36] Santhiya, R., Senthilnathan, A., Chinnaiyan, V., Nithya Priya, R. Grid connected multilevel inverter and MPPT for photovoltaic system. *Lecture Notes in Electrical Engineering*, **326**, 2015, pp 201-211.
[37] Salmi, M., Chegaar, M., Mialhe, P. Modeles d'estimation de l'irradiation solaire globale au sol. Revue Internationale d'Heliotechnique Energie - Environment, **35**, 2007, pp 19-24.
[38] Scharmer, K., Greif, J. *The European Solar Radiation Atlas* (Paris: Ecole des Mines), 2000.
[39] Schiehlen, W.O. Multibody systems dynamics: roots & perspectives. *Multibody Systems Dynamics*, **1** (2), 1997, pp 149-188.
[40] Sharan, A.M. Determination of bearing loads due to wind in solar tracking systems. *Journal of Solar Energy Engineering*, **126** (1), 2004, pp 668-670.
[41] Singh, R., Kumar, S., Gehlot, A., Pachauri, R. An imperative role of sun trackers in photovoltaic technology: A review. *Renewable & Sustainable Energy Reviews*, **82** (3), 2018, pp 3263-3278.
[42] Tiwari, G.N. *Solar Energy* (Pangbourne: Alpha Science Int. Ltd.), 2002.
[43] 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*,**78** (6), 2005, pp 752-762.
[44] Vieira, R.G., Guerra, F.K.O.M.V., Vale, M.R.B.G., Araujo, M.M. Comparative performance analysis between static solar panels and single-axis tracking system on a hot climate region near to the equator. *Renewable & Sustainable Energy Reviews*, **64**, 2016, pp 672-681.
[45] Zsiborács, H., Baranyai, N.H., Vincze, A., Háber, I., Weihs, P., Oswald, S., Gützer, C., Pintér, G. Changes of photovoltaic performance as a function of positioning relative to the focus points of a concentrator PV module: Case study. *Applied Sciences*, **9** (16), 2019, pp 3392(1-19).
[46] Yao, Y., Hu, Y., Gao, S., Yang, G., Du, J. A multipurpose dual-axis solar tracker with two tracking strategies. *Renewable Energy*, **72**, 2014, pp 88-98.
[47] *** Websites of tracking systems manufacturers (DegerEnergie, Lorentz GmbH, Power Tracker, Sun Trackers, Solenergy, Sola Traka, Traxle Trackers, Ecoware, Dobon's Technology, Energy Innovations, Wattsun Solar Trackers, SunPower, Bright Light Solar, Solar Motors, Inspira, Solan Mover, Helio Track).