Novel control design algorithm for a PV sun tracking mechanism

A Marcu[1] and C Alexandru[1]

[1]Product Design, Mechatronics and Environment Department, Transilvania University of Braşov, Romania

E-mail: calex@unitbv.ro

Abstract. In this work, a mechatronic solar tracker used for increasing the efficiency of the PV systems is approached in the modern trend of concurrent engineering, the study being focused on the optimal design of the control device, which is a mono-loop system with feedback based on PID controller. The mechanical device of the solar tracker, which corresponds to a dual-axis azimuthal mechanism, is defined as a multi-body system (MBS) those modeling is carried out by using the MBS software environment ADAMS. The control system block diagram is then developed in the DFC (Design for Control) software solution EASY5, the communication (link) between the two models (MBS & DFC) being managed through the input and output control plants. The optimization of the control system aims to determine the optimal values of the tuning factors of the PID controller so that to minimize the tracking accuracy, which is expressed as the difference between the imposed and measured values of the PV panel angles (daily and elevation). A generalized reduced gradient (GRG) algorithm was used to find the optimal design.

1. Introduction

The thematic of the research is now-a-days a priority on global level, because it provides viable alternatives to major problems resulting from the use of fossil resources (oil, gas, coal). The work approaches the increasing of the energetic efficiency of the photovoltaic (PV) systems by maximizing the rate of incident solar radiation (which is the amount of solar energy received on the PV panel surface) through the optimal design of a mechatronic (active) sun tracking mechanism. The study is focused on the optimal design of the control system for a dual-axis tracking mechanism used to adjust the daily and elevation angles of a PV system.

In traditional approaches, the tracking systems design is usually performed by separate examination of the two main components (the mechanical device, and the actuating & control device), based on specific design tools from mechanical engineering (for the mechanical device), and respectively controls engineering (for the actuating & control device). In such approach, the integration of the two components is performed at the physical prototype level, which generates the risk that the control (motion) law applied by the actuating device to be poorly matched by the mechanical device. This fact highlights the need of developing models by which the integrated optimal design of the PV tracking systems to be possible, the energetic efficiency of these systems depending on both mechanical and control designs [1-6].

The main feature of the work refers to the development of a novel control design algorithm, whose implementation requires simultaneous data transfer between three specific models - software solutions

(in this case, ADAMS - Automatic Dynamic Analysis of Mechanical Systems, and EASY5 - Engineering Analysis Systems, both produced by the renowned American company MSC.Software, which is a global leader in simulation software technology), all within a virtual prototyping platform. The virtual prototyping tools provide important benefits in the design, simulation and optimization process of mechanical and mechatronic systems, as pointed out in [7-12].

Through the modeling in mechatronic concept, there is created the frame for approaching the functionality of the entire assembly (including the tracking mechanism, and the actuating & control device), making it possible to assess and optimize the energetic efficiency of the PV tracking system (both in terms of energy gain brought by tracking the sun, and energy consumption for performing the motion).

2. The mechanical device of the solar tracker

As was mentioned, the mechatronic tracking system is composed by two main components: the mechanical device, and the actuating & control device. From the point of view of the mechanical device, the tracking mechanisms can be systematized (grouped) in accordance with the following criteria:

a. the number of degrees of freedom (DOF): mono-axis (which are able to assure only the daily or the elevation motion of the PV system), and dual-axis systems (which allow the PV system to perform the both motions, daily & elevation, thus assuring a better incidence of the sunrays on the PV panel surface, through a more precise positioning of the panel relative to the sun path throughout the daylight);

b. the positioning of the motion axis (axes): equatorial, pseudo-equatorial, azimuthal, and pseudo-azimuthal tracking systems [13].

All these types of tracking mechanisms have specific advantages and disadvantages, as pointed out in [14-19], the selection of the optimal design having to be made in correlation with the number of panels oriented simultaneously, and with the geographic implementation area as well. The mechanical device of the solar tracker used in this study corresponds to a dual-axis tracking mechanism of azimuthal type, those simplified model is shown in figure 1. The 3D geometric model of the solar tracker was designed by using a CAD software solution (CATIA), constituting the basis for the conception of the MBS (Multi-Body System) model, formed by rigid bodies, joints and motion generators, which was developed by using the virtual prototyping environment ADAMS (the world's most widely used multi-body dynamics simulation software).
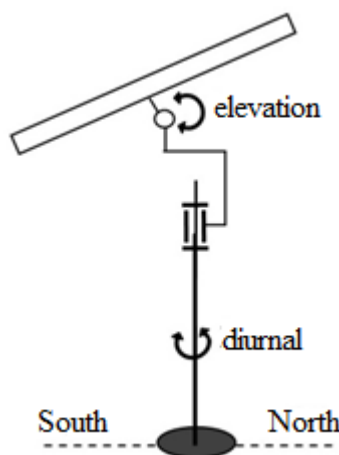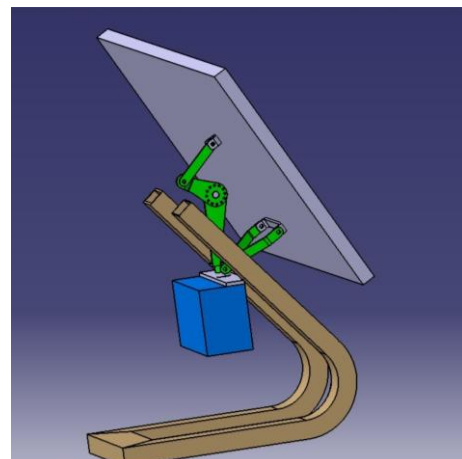

Figure 1. Dual-axis azimuthal system   **Figure 2.** The MBS model of the solar tracker [20]

The detailed description of the mechanical device (i.e. MBS model) of the dual-axis azimuthal tracking system was carried out in [20]. The diurnal (daily) motion of the PV system, in East-West

direction (around the vertical axis), is generated through a worm gear servo-motor, while for elevation, in South-North direction, around the horizontal axis, the motion is transferred from the actuating source to the PV panel through a multi-link planar mechanism. The two servo-motors are installed (mounted) inside a protection box, as can be seen in figure 2.

3. The modeling of the control system

Regarding the control system of the solar trackers, various schemes with one or more loops (contours) (corresponding to the number of monitored / controlled parameters) can be conceived. The one-loop control systems are used to monitor the position of the PV panel (in accordance with the type of tracking mechanism), while in the two-loop schemes, besides the position, a velocity parameter usually occurs. In a more general case, three parameters (position, velocity. and current) can be controlled. Obviously, the one-loop schemes are the simplest, while the multi-loop schemes provide superior dynamic behavior, in terms of stability and robustness [21-25].

For this work, mono-loop control systems have been selected / designed to control both diurnal and altitudinal movement of the azimuthal dual-axis solar tracker, the monitored parameters being the daily and elevation angles of the PV panel.

With the aim to ensure the communication between the mechanical model (ADAMS) and the control system (EASY5), the input and output variables have been defined, as well as the functions by which these variables are called. For the input variable, representing the motor torque developed by the driving actuator, the time function is 0.0, and that is because the variable will receive its value from the control application. Subsequently, this variable was assigned as a function for the motor torque, using the predefined function VARVAL (Variable Value), which returns the value of the state variable. For the output variable, the time function returns the daily or elevation angle of the PV panel, as the case, which was modeled in ADAMS by using the predefined function AZ (Angle about Axis). The coordinate systems used for modeling are positioned in the revolute joints through which the two movements of the PV panel are carried out.

Based on the above mentioned state variables, the input (PINPUT) and output (POUPUT) plants of the controlled process have been defined. These plants are then used to generate the specific files for the DFC application (in this case, EASY5) by using ADAMS/Controls, which is a plug-in to ADAMS that manages the interface (communication) between ADAMS and control applications, such as EASY5, MATLAB or MATRIX$_X$ [26]. The information related to the input and output parameters are stored in a specific file for EASY5 (INF extension), alongside with a command file (CMD extension) and a data file (ADM extension) that are used during the co-simulation process.

With these files, a mono-loop control system was developed in EASY5 (fig. 3), with the following significances of the component blocks:

- RF - Ramp Function Generator, which is used to model the reference/input signal (i.e. the imposed daily or elevation angle, as the case);
- SJ - Summing Junction, which is used to compare the imposed ("1") and current/measured ("-1") signals/angles;
- GC - General Controller, which is used to model the control device, in this case PID (Proportional-Integral-Derivative);
- ADAMS Model - the interface link to the MBS model of the solar tracker (shown in figure 2), which is based on the information from the INF file.

From the point of view of the control element, a robust PID (Proportional-Integral-Derivative) controller was used, which allows to achieve the imposed objectives by changing the transfer function parameters. This type of control loop feedback mechanism assures important benefits, such as: easy practical implementation, low cost, easy tuning (empirical methods based on measurements are frequently used), ability to solve various targets related to stationary error or overshoot, enable multi-loop control, and others [27].
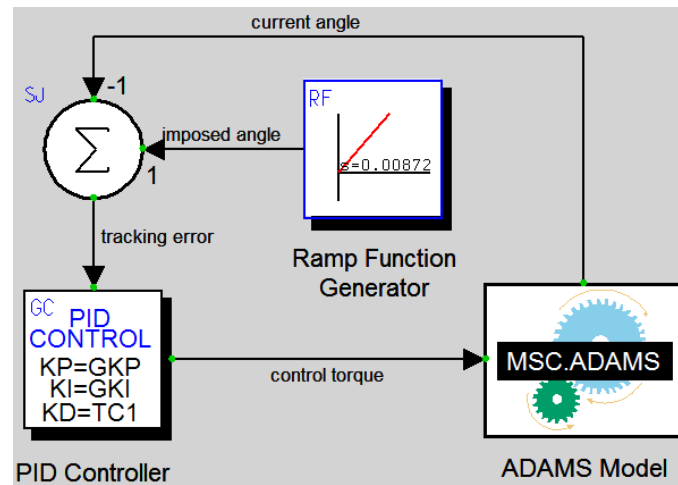
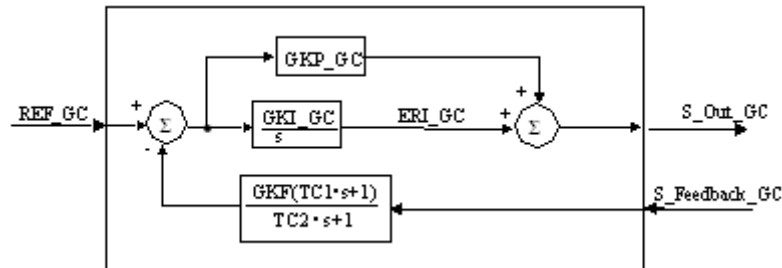**Figure 3.** The DFC model of the mono-loop control system.

Figure 4. The general model of the PID controller [28].

The PID controller block diagram in EASY5 is shown in figure 4, the transfer function, which is used to characterize the relationship between the output and input parameters, having the form [28]:

$$S\_Out\_GC = ERI + GKP \cdot (REF\_GC - FBS \cdot S\_Feedback) \tag{1}$$

where:

$$FBS = \frac{ERV + S\_Feedback \cdot TC1 \cdot GKF}{TC2}, \quad \frac{\mathrm{d}(ERV)}{\mathrm{d}t} = GKF \cdot S\_Feedback - FBS,$$

$$\frac{\mathrm{d}(ERI)}{\mathrm{d}t} = GKI \cdot (REF\_GC - FBS) \tag{2}$$

with the following notations: REF_GC - controller input (namely, the tracking error, in fact the output from the summing junction block - see figure 3); S_Out_GC - controller output (namely, the control/motor torque generated by the servo-motor, which is transmitted to the MBS mechanical model of the solar tracker, in other words the input for the ADAMS interface block in figure 3); GKP - proportional control gain; GKI - integration control gain; TC1 - derivative action time constant (which is used as a lag time constant to calculate an approximate derivative from the error signal); S_Feedback - controller feedback; TC2 - feedback damping time constant (which is used in the feedback line to help prevent an implicit loop); ERI - integrated error signal; ERV - intermediate output; s - Laplace transform.

By neglecting the feedback line of the controller (which is already integrated/implemented in the control system block diagram shown in figure 3), a simplified form of the transfer function of the PID controller is obtained, as follows:

$$\frac{S\_Out\_GC}{REF\_GC} = GKP \cdot \left[1 + \frac{1}{GKI \cdot s} + TC1 \cdot s\right] \tag{3}$$

For the optimization study carried out in this work, the reference/input command (i.e. the imposed daily or elevation angle, by case) corresponds to a ramp signal having the motion amplitude of 30 degrees and the rise time of 60 seconds, which is found in an analytical function of form *0.0087222·time* (in radians). In the control system block diagram shown in figure 3, through the summing junction block, the imposed angle is compared with the corresponding current (measured) angle of the PV panel, the difference between the two values being actually the tracking error. The output from the summing junction block (i.e. the previously defined tracking error) is used as input in the PID controller block, which generates the motor/control torque for the MBS mechanical model of the solar tracker.

The control device tuning, aiming to determine the optimal values of the controller factors with the view to assure the control target (the imposed performance indexes, in terms of accuracy, stability and robustness), is frequently performed by using specific methods from control theory or stability theory (such as root locus or frequential methods). For this paper, the controller tuning is approached by an optimal design technique, which can be also implemented/adapted for the optimization of the mechanical device of the tracking mechanism.

The optimal design of the control system is defined by the following data: independent design variables - the tuning factors of the PID controller (GKP, GKI, TC1); design objective - the tracking error (the difference between the imposed and current/measured daily and elevation angles of the PV panel, as the case); monitored value of the design objective - the root mean square (RMS) during simulation; optimization goal - the minimization of the design objective.
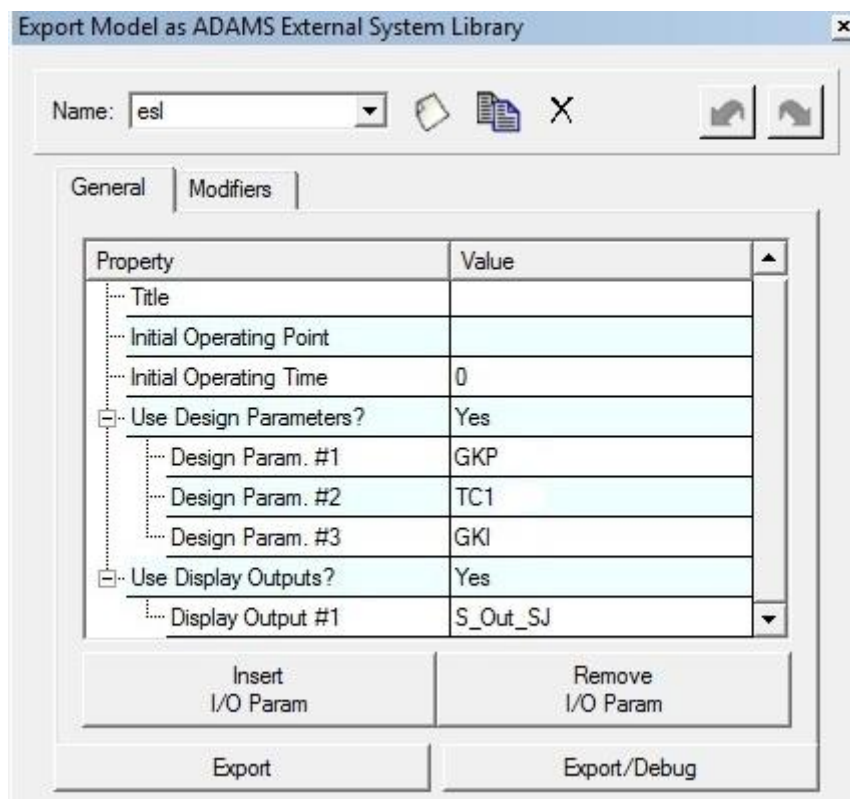

Figure 5. EASY5 to ADAMS model export interface.

In these terms, for having access to the parametric optimization tools integrated in ADAMS, there is necessary to transfer the control system model (shown in figure 3) from EASY5 to ADAMS. This is carried out from the EASY5 export interface (figure 5) by using the ESL (External System Library) format. The three tuning factors of the PID controller (GKP, GKI, TC1) are specified in the Design Parameter field, while the Display Output field is used to define the design objective (i.e. the tracking error, defined as the output from the Summing Junction block - see figure 3). The so defined library is then imported in ADAMS under the form of a general state equation (GSE). Thus, the parameterized model of the control system, coupled with the MBS model of the mechanical device, is prepared for the optimal design process that will be conducted in ADAMS. Each of the three independent design variables is defined by an initial (standard) value and a variation field (in terms of minimum and maximum limits).

The optimization problem of the control system is a mono-objective one (targeting to minimize the root mean square of the tracking error during simulation), without design constraints. A generalized reduced gradient algorithm was used to find the optimal design (namely OPTDES-GRG, which is integrated in ADAMS), the independent design variables (i.e. the tuning factors of the PID controller) being defined by range limits (boundaries). The tracking error can be assimilated with the steady state error from control theory, which defines the difference between the input signal and the value at the output response is going to stabilize. The other parameters used in control theory for evaluating the response of a dynamic system (such as raise time, settling time, and overshoot) are not relevant for the tracking system design due to the low speed with which the motion (tracking) steps are performed, therefore they will not be considered in the optimization process.

4. Results and conclusions

The optimization algorithm uses a minimizer function, which sets the tracking error appropriately and returns the error in the simulation, defined as the sum of the squares of the differences between the imposed and simulation/current angles of the PV panel (daily or elevation, as the case).

As result of the optimization process, the optimal values of the specific factors of the PID controller, which assure minimal tracking errors, have been obtained. In the case of the PID device used to control the elevation motion, the optimal values of GKP (P), GKI (I) and TC1 (D) result in a simulation that meets the design requirements, as follows: $GKP = 5.516 \cdot 10^7$, $GKI = 3.081 \cdot 10^7$, $TC1 = 1.049 \cdot 10^6$. With these values, the time history variation of the tracking error is shown in figure 6, the root mean square during simulation having a very small value ($RMS = 1.2517 \cdot 10^{-7}$). At the same time, the variation of the control torque developed by the actuating/driving motor (which is input in the MBS mechanical model from the control system block diagram shown in figure 3) is presented in figure 7. Similar results (in terms of tracking accuracy) have been obtained in the case of the control system used for the daily motion, thus proving the usefulness (viability) of the proposed optimal design algorithm.
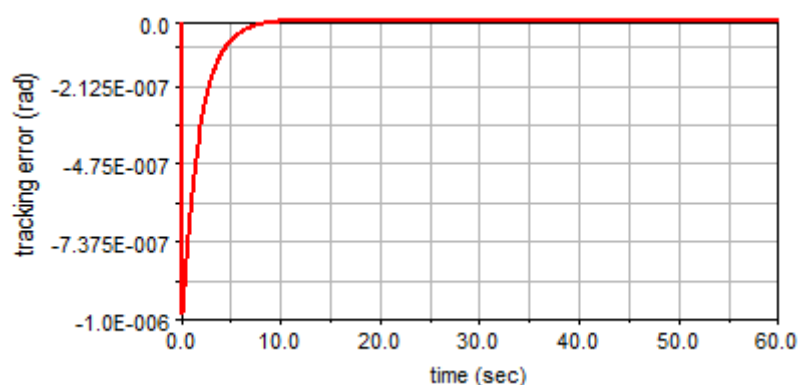

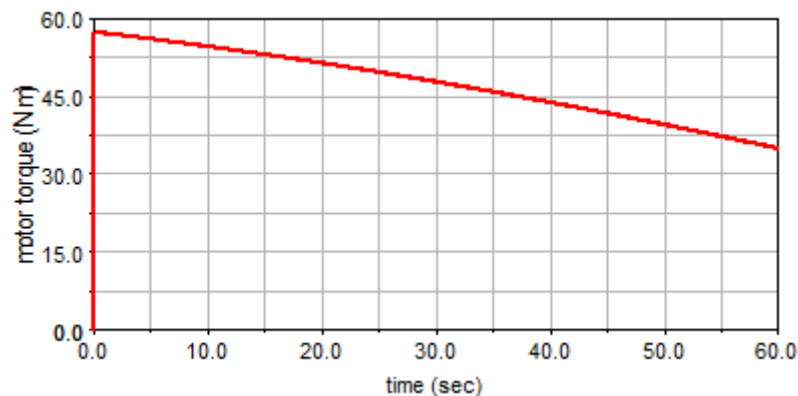**Figure 6.** The time-history variation of the tracking error.

Figure 7. The time-history variation of the motor torque.

By integrating the mechanical device and the control system at the level of the virtual prototype of the solar tracker, the risk that the control law is not followed by the mechanical model is   minimized. The mono-loop control system with PID controller ensures the stability and tracking accuracy of the proposed dual-axis solar tracker. The tracking errors are insignificant, thus maximizing the quantity of incoming solar radiation by an optimal sunray incidence.

In this stage, the PV solar tracker is prepared (ready) for the implementation of an effective in-steps tracking program. The optimal design of the step-by-step tracking laws for the daily and elevation motions, aiming to maximize the incident radiation captured by the PV panel alongside with the minimization of the energy consumption for performing the tracking, will be approached / presented in a future work.

References

[1]   Alexandru C and Comşiţ M 2008 The energy balance of the photovoltaic tracking systems using virtual prototyping platform *Proceedings of the 5th IEEE International Conference on the European Electricity Market EEM 2008* pp 253-258

[2]   Alexandru C and Pozna C 2008 Virtual prototype of a dual-axis tracking system used for photovoltaic panels *Proceedings of the IEEE International Symposium on Industrial Electronics ISIE 2008* pp 1598-1603

[3]   Alexandru C 2009 The design and optimization of a photovoltaic tracking mechanism *Proceedings of the 2nd IEEE International Conference on Power Engineering, Energy and Electrical Drives POWERENG 2009* pp 436-441

[4]   Alexandru C and Tatu I N 2013 Optimal design of the solar tracker used for a photovoltaic string *Journal of Renewable and Sustainable Energy* **5** pp 1-16

[5]   Altuzarra O, Macho E, Aginaga J and Petuya V 2015 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* **229** pp 566-579

[6]   Edgar R, Stachurski Z and Cochard S 2016 Optimisation direct normal insolation of rectangular PV platforms *Solar Energy* **136** pp 166-173

[7]   Alexandru C and Pozna, C 2009 Dynamic modeling and control of the windshield wiper mechanisms *WSEAS Transactions on Systems* **8** pp 825-834

[8]   Alexandru C and Alexandru, P 2010 The virtual prototype of a mechatronic suspension system with active force control *WSEAS Transactions on Systems* **9** pp 927-936

[9]   Alexandru C and Alexandru, P 2011 A comparative analysis between the vehicles' passive and active suspensions *International Journal of Mechanics* **5** pp 371-378

[10]   Alexandru P, Macaveiu D and Alexandru C 2012 Design and simulation of a steering gearbox with variable transmission ratio *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* **226** pp 2538-2548

[11]   Bernard A 2005 Virtual engineering: methods and tools *Journal of Engineering Manufacture* **219** pp 413-421

[12]   Tarniţă D, Catană M and Tarniţă D N 2014 Contributions on the modeling and simulation of the human knee joint with applications to the robotic structures *Mechanisms and Machine Science* **20** pp 283-297

[13]   Alexandru C 2013 A novel open-loop tracking strategy for photovoltaic systems *Scientific World Journal* **2013** pp 1-12

[14]   Flores-Hernández D A, Palomino-Resendiz S, Lozada-Castilloc N and Luviano-Juárez A 2017 Mechatronic design and implementation of a two axes sun tracking photovoltaic system driven by a robotic sensor *Mechatronics* **47** pp 148-159

[15]   Hoffmann F M, Molz R F, Kothe J V, Nara E O B, Pablo L and Tedesco C 2018 Monthly profile analysis based on a two-axis solar tracker proposal for photovoltaic panels *Renewable Energy* **115** pp 750-759

[16]   Ioniţă M and Alexandru C 2012 Dynamic optimization of the tracking system for a pseudo-azimuthal photovoltaic platform *Journal of Renewable and Sustainable Energy* **4** pp 1-15

[17]   Sharaf Eldin S A, Abd-Elhady M S and Kandil H A 2016 Feasibility of solar tracking systems for PV panels in hot and cold regions *Renewable Energy* **85** pp 228-233

[18]   Sinha S and Chandel S S 2016 Analysis of fixed tilt and sun tracking photovoltaic-micro wind based hybrid power systems *Energy Conversion and Management* **115** pp 265-275

[19]   Vieira R G, Guerra F K, Vale M R and Araujo M M 2016 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** pp 672-681

[20]   Marcu A and Alexandru C 2017 Study regarding the solar trackers used for photovoltaic modules *Bulletin of the Transilvania University of Braşov - Series I: Engineering Sciences* **10(59)** pp 53-62

[21]   Çinar S M, Hocaoğlu F O and Orhun M 2014 A remotely accessible solar tracker system design *Journal of Renewable and Sustainable Energy* **6** pp 1-12

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

[23]   Nsengiyumva W, Chen S G, Hu L and Chen X 2018 Recent advancements and challenges in solar tracking systems (STS): A review *Renewable & Sustainable Energy Reviews* **81** pp 250-279

[24]   Roy T K and Mahmud M A 2017 Active power control of three-phase grid-connected solar PV Systems using a robust nonlinear adaptive backstepping approach *Solar Energy* **153** pp 64-76

[25]   Seme S, Stumberger B, Hadziselimovic M 2016 A novel prediction algorithm for solar angles using second derivative of the energy for photovoltaic sun tracking purposes *Solar Energy* **137** pp 201-211

[26]   *** 2010 *Getting Started Using ADAMS/Controls* (MSC.Software Press)

[27]   Sabir M M and Ali T 2016 Optimal PID controller design through swarm intelligence algorithms for sun tracking system *Applied Mathematics and Computation* **274** pp 690-699

[28]   *** 2010 *EASY5 Library User Guides* (MSC.Software Press)