BOND GRAPH MODELING, IMPLANTATION AND PERFORMANCE ANALYSIS OF DUAL-AXIS SOLAR TRACKING SYSTEM

Abd Essalam Badoud

Automatic laboratory of Setif, Electrical engineering department, University of Setif , Algeria

ABSTRACT

The paper presents the modeling, simulation and hardware implementation of solar tracking system using bond graph approach. In this work, the design and development of high-efficiency dual-axis solar tracking system using a new algorithmic technique to accurately track the maximum power point (MPP) of a PV array using bond graph control that is based on programmable logic controllers (PLC). The performance of the solar tracker was analyzed and compared with the static solar panel and the result showed that the solar tracker is better than the static solar panel in terms of voltage, current and power. As a result of the experiment, the power generated by the proposed tracking system has an overall increase of about 51.2% more than the static solar panel in sunny days and about 53% under partially shaded conditions.

KEYWORDS

Modeling, Solar tracking, Implantation, Bond Graph, Mechanical Structure

1. INTRODUCTION

The energy conversion efficiency of commercial solar PV is around 15-19%. Millions of dollars are spent in order to gain a small percentage in energy conversion efficiency. The power generation of solar PV can be increased using sun tracking technology [1]. However, the design of the sun tracker is usually very complicated and expensive. Units are heavy and prone to breakdown and installation is difficult. Generally, the sun tracking systems can be described as mechatronic systems that consist of mechanical subsystem, electrical drives, and information technology [2].

Many theoretical studies have been conducted for the past several decades to show the improvement of PV power generation using 1-axis or 2-axis sun tracking PV [3]-[7]. The authors dealing with the single- and dual-axis tracing systems reported in [3]-[7] an about 20% to 50% increase in the efficiency of the solar energy conversion, when compared to those PV systems without the sun tracking.

The shading effect is considered in tracking the location of the sun. The sunlight was diffused through the interaction of clouds and dusts [8], [9]. The purpose of bond graph solar tracking system is to ensure the sunlight can be focused at one point and it can increase the efficiency of the solar energy system.

This paper presents the design and implementation of a two axis solar-tracking algorithm in order to improve the availability of solar energy and to improve the system's total efficiency. This work is divided into two stages namely, hardware and software development. In hardware development, three light dependent resistors (LDR) were utilized to capture the maximum light source from the sun. For positioning the solar panel two servo motors also were employed to move the solar panel to maximum light source location sensed by the LDRs. As for the software part, the code was constructed by using C programming language. The controller is designed using bond graph approach with the inputs as the solar panel output, LDR sensor output and target being the position of solar panel which yields maximum output from solar panel. This work proposes a simple and effective approach to modeling two axis solar-tracking multi-physics problems using bond graphs, which is not affected by the above limitations.

This paper is divided into two stages, which are hardware and software development. In hardware development, three light dependent resistor (LDR) has been used for capturing maximum light source. Two servo motors have been used to move the solar panel at maximum light source location sensing by LDR. Moreover, the code is constructed using Symbols software and targeted to microcontroller. The efficiency of the system has been tested and compared with static solar panel on several time intervals.

2. BOND GRAPH MODELING

Since the introduction of the bond graph principles, the interest of bond graph was shown as a basis of complex and multidisciplinary system modeling. Researches were also carried out to develop system analysis using the graphic support of bond graph and the concept of causality. Several authors gave an interesting light on the application of this approach in modeling [10]-[12], optimization [13], fault detection and isolation [14], [15] and control of renewable energy systems [16].

Bond graph is a graphical way of modeling physical systems. All these physical systems have in common the conservation laws for mass and energy [17].

The bond graph formalism, created by Paynter [18], is a graphical representation based on power transfer figured by bonds. This approach allows the Modeling of continuous systems as well as the continuous part of hybrid dynamical systems. The constituting elements can be classified into five groups as follows [19]:

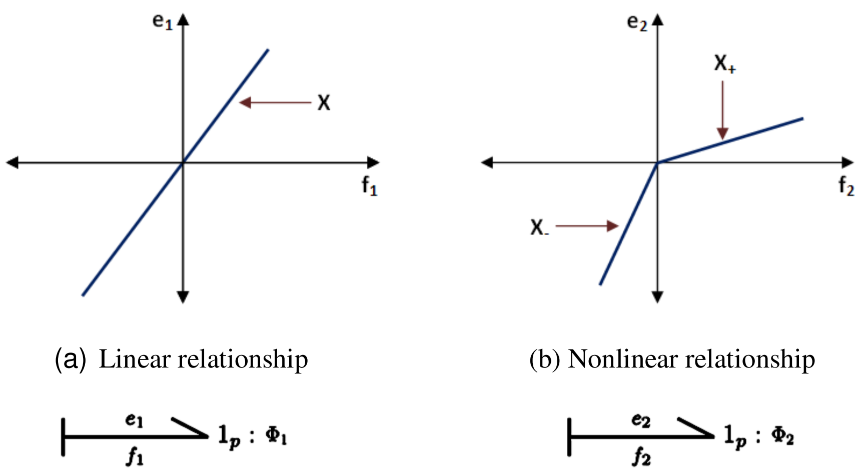
- A group of elements producing energy composed of effort sources Se and flow sources Sf.
- A group of elements storing energy composed of capacitive elements C and inductive elements I (represented by the blocks integral causality and derivative causality).
- A group of elements consuming the energy composed of the resistive elements R.
- A group of switching elements composed of the switches Sw. It's worth noting that an open switch is represented by a zero flow source Sf = 0 and by a zero effort source Se = 0 when it's closed.
- A group of elements distributing energy composed of junctions 0 and 1 as well as transformers TF or gyrators GY. This field is named junction structure.

The bond graph methodology clearly and intuitively starts by considering energy flows between the ports of the (actual and conceptual) components of an engineering system. Physical effects and their interactions are considered initially in a qualitative manner. At further stages of the modeling process, details are specified as necessary so that a mathematical model can be generated and can be evaluated. If properly applied, the bond graph methodology enables one to develop a graphical model that is consistent with the first principle of energy conservation without having the need to start with establishing and reformulating equations [20].

Bond graph models are ideally suited for modeling a nonlinear system. A bond graph model does not assume any linearity constraints. The model hides the complexity of nonlinearity from the user of the model. Once the modeler defines the nonlinear relationship in the model, it is the job of the underlying bond graph software to solve the model. The whole process is transparent to the user of the model.

1-port element is the most basic of the bond graph elements. This element has a single port for energy exchange with its environment. There will be a constitutive equation depicting the relationship between the co-variables of the element bond.

The only constraint on the constitutive equation is that the energy should be conserved as per the underlying physical law of bond graph modeling. Two different relationships between the co-variables (effort and flow) are depicted graphically in figure (1-a) and (1-b). The bond graph model for this relationship is depicted by 1-port elements in figure (1-c) [21].



(a) Linear relationship (b) Nonlinear relationship

(c) 1-port resistor

Figure 1. Relationship between flow and effort for 1-port resistor elements

The constitutive relationship for the 1-port resistor elements are given in equations (1) and (2).It can be seen that the model for both linear and nonlinear behavior look-alike, with the constitutive relationship hiding the difference. It is the job of the solver software to simulate the model differently.

$$e_1 = \phi_1 f_1 \quad (1)$$

$$e_2 = \phi_2 (f_2) \quad (2)$$

$$\text{where, } \begin{cases} \phi_1 = X & \text{always} \\ \phi_2 = X_- & \text{if } f_2 < 0 \\ \phi_2 = X_+ & \text{if } f_2 > 0 \end{cases} \quad (3)$$

This paper addresses the problem of bond graph methodology as a graphical approach for the modeling, simulation and implementation of photovoltaic generating systems.

3. BOND GRAPH METHOD FOR SUN POSITION

In the analysis of the solar tracking system, the intensity of solar radiation is the most basic input parameters. Establishing a suitable model of sun irradiance is essential for the design of the solar tracking system (figure 2).

The sun elevation angle marked as a can be calculated by the following equation, as shown in equation (1):

$$sin(\alpha) = sin(\varphi)\, sin(\sigma) + cos(\varphi)\, cos(\sigma)\, cos(\omega) \qquad (4)$$

φ : local dimension

σ : sun equatorial latitude angle

ω : solar hour angle

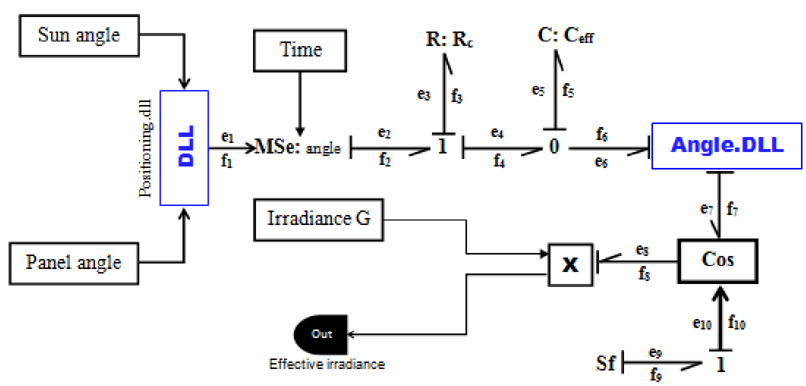


Figure 2. Bond graph model of effective sun irradiance

The solar radiation received by the solar cell array mainly depends on the solar incidence angle θ, while solar incidence angle marked as θ is a function of sun equatorial latitude angle σ, local dimension φ, solar cell array tilt angle β, solar cell array azimuth angle γ and solar hour angle to ω [9]. Their specific relationship can be calculated by the following equation, as shown in equation (2)

$$\begin{aligned} cos(\theta) = {} & sin(\sigma)\left[sin(\varphi)cos(\beta) - cos(\varphi)sin(\beta)cos(\gamma)\right] + sin(\beta)sin(\gamma)cos(\sigma)sin(\omega) \\ & + cos(\sigma)cos(\omega)\left[cos(\varphi)cos(\beta) + sin(\varphi)sin(\beta)cos(\gamma)\right] \end{aligned} \qquad (5)$$

According to this equation, we can get the specific solar incidence angle θ of the solar cell array in any location, season, time and geometric position. After solving the solar elevation angle α and solar incidence angle θ, the solar tracking system can be designed based on this solar model.

4. BOND GRAPH CONTROL STRATEGY OF THE SOLAR TRACKING SYSTEM

A bond graph is perhaps the most physical modeling technique. Skilled bond-graph modelers say that there are many situations in the modeling of complex systems that can be properly understood and analyzed only with this technique [22]. As a bond graph preserves the topological and computational structure (if we use a causal bond graph), it is very convenient for demonstrations of how can modern modeling and simulation tools, which are based on preserving the topology, automatically perform the computational structure during the model compilation.
To implement the accurate control of the solar panels, bond graph control strategy is used to control the motor operations ensuring the control mechanism's fast response time and its adjustability. The bond graph model of the solar tracking controller is shown in figure (3). The signals value of the sunshine strength fed back by the LDR sensor form the input of the controller. bond graph control handles the angle errors of the two stepping motors in the vertical and horizontal axes as the fuzzy control inputs.

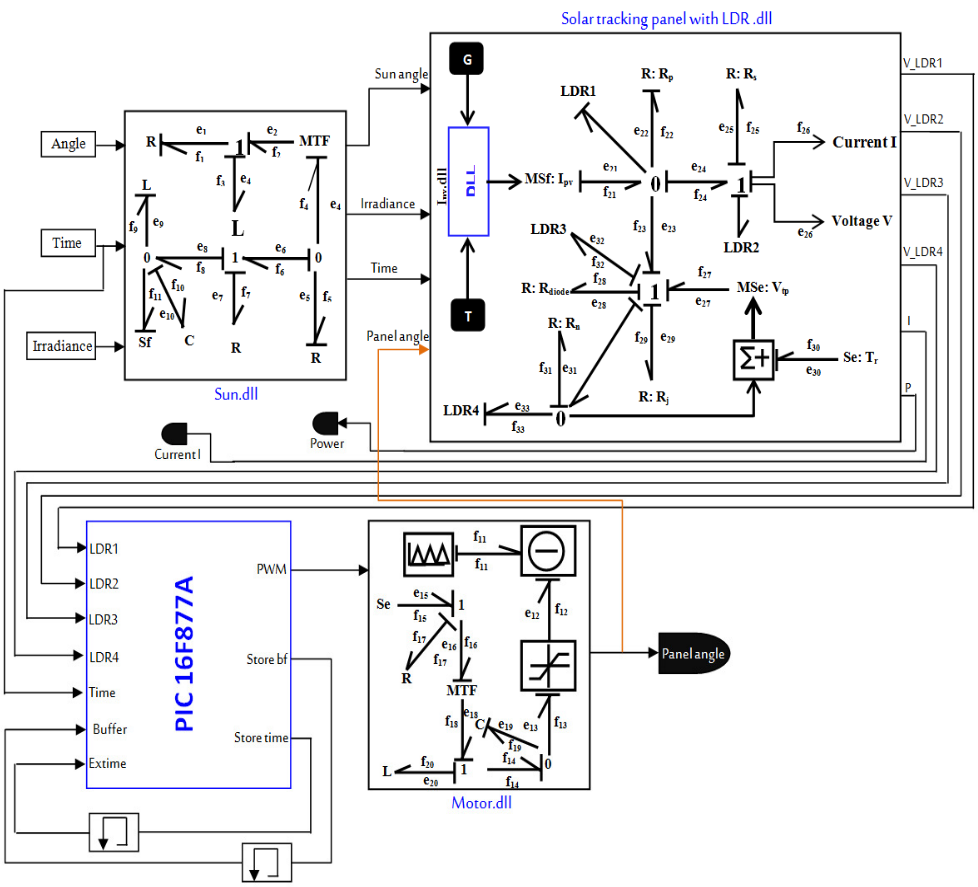


Figure 3. Block diagram of overall system

5. DESIGN AND IMPLEMENTATION

5.1. LDR Sensor Circuitry

The daily motion of the sun from east at dawn to the west at dusk is tracked by the dual axis solar tracking on first axis (axis 1: daily motion, E: East, W: West). The rotation al range of this axis is ±80° with the position of solar noon as the reference position (0°). On the other hand, the seasonal variation of the Sun position is tracked by the dual axis solar tracking via the second axis (axis 2: elevation, N: North, S: South). This axis has ±60° rotation al range for tracking the altitude angle of sun during the different seasons.

To improve the sensor accuracy and sensitivity, use the Light dependent resistors (LDR) as the illumination sensor in this design. The layout of sensors in the controller is shown in figure (4). There are four LDRs are placed in the sensor board's different directions. These sensors are placed on the same plane in four black pipes because sensors are sensitive the ambient light. Among them, sensors 3&4 test east-west direction, sensors 1&2 detection of north-south direction, when the difference between the two sensors exceed a set value, the controller action, driving the corresponding motor to adjust the position of solar panels, which make sure the solar panels and the sunlight is always vertical.

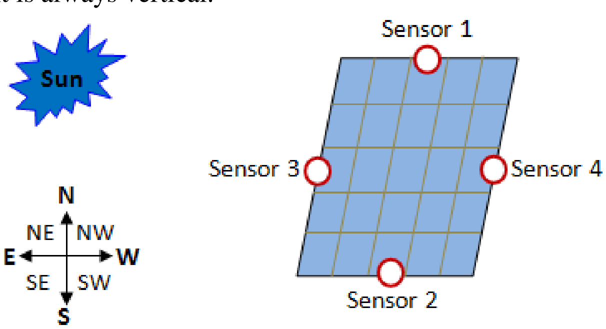


Figure 4. LDR sensors circuitry

The binary character of the new matrix solar sensor suggests a simple digital control of the tracker actuators. Circuit design starts with the truth table, where the input signals are S1, S2, S3 and S4 and the output signals, N, E, S, W, determine the start/stop functions of the N-S and E-W actuators. The truth table, without redundant values, is given in Table 1.

Table 1. Truth table

Inputs				Outputs				Direction
S1	S2	S3	S4	N	S	W	E	
0	0	0	0	0	0	0	0	Stable system
0	0	0	1	0	0	0	1	East
0	0	1	0	0	0	1	0	West
0	0	1	1	0	0	1	1	Stable system
0	1	0	0	0	1	0	0	South
0	1	0	1	0	1	0	1	South-East
0	1	1	0	0	1	1	0	South- West
0	1	1	1	0	1	1	1	South

1	0	0	0	1	0	0	0	North
1	0	0	1	1	0	0	1	North-East
1	0	1	0	1	0	1	0	North-West
1	0	1	1	1	0	1	1	North
1	1	0	0	1	1	0	0	Stable system
1	1	0	1	1	1	0	1	East
1	1	1	0	1	1	1	0	West
1	1	1	1	1	1	1	1	Stable system

The control technique adopted in the proposed dual axis solar tracking is a bond graph approach. The dual axis solar tracking would track the sun's position based on the light intensity received by the photo-sensor.

5.2. Mechanical Structure

After the solar panels and other components were selected, the overall structural design of the solar tracker as seen in figure (5) was modeled using mechanical design software, SolidWorks.

Figure 5. Fabricated design model

The horizontal movement part of the solar tracker comprises:

- A polyethylene T of 63mm is found in the horizontal and vertical mechanical part.
- Bearings of 63/25 whose rolls minimized friction.
- An axis of 25mm which is mounted on the photovoltaic panel that is responsible for the horizontal rotation (north/south direction).
- A pulley integral with the north/south axis generating the torque.
- Support integral with the motor and receiving the motor shaft.

- Axis with gear transmitting the movement of the motor to the pulley.
- A stepper motor 12V and 0.41A and 5W.

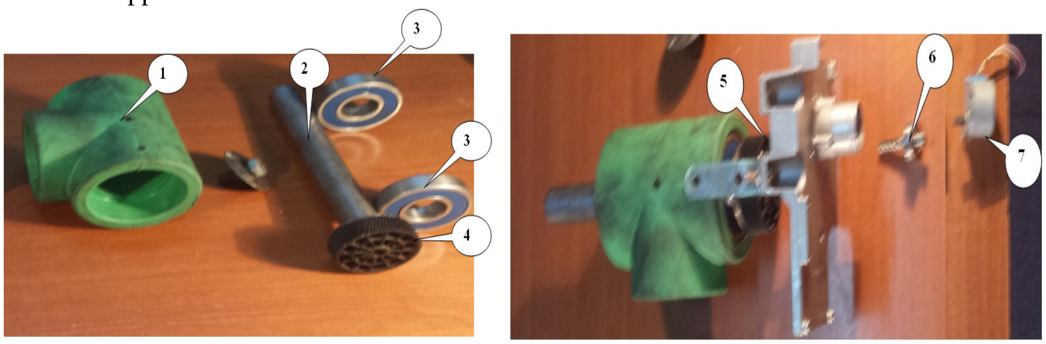


Figure 6. Exploded view of the mechanical assembly of the horizontal axis

The vertical movement part of the solar tracker comprises:

It was the same description of the previous game devices 1-7.

- Polyethylene 63mm ring receiving the axis integral with the polished and the motor and tapered bearing ring is fixed relative to the system.
- The tapered roller 63/25 whose role is to minimize the friction of the vertical part.

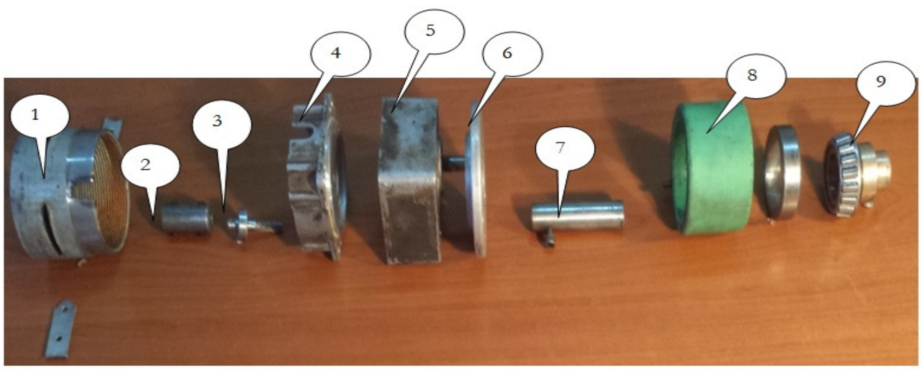


Figure 7. Exploded view of the mechanical assembly of the vertical axis

6. RESULTS AND DISCUSSIONS

The simulation PV module is based on the photowatt PW1650 module, which will also be used during the experiments. Its details are shown in Table 2.

Table 2. The electrical specifications of photowatt PW1650 module at standard test conditions

Maximum power P_{max}	165W
Current peak power I_{mp}	4.8 A
Voltage peak power V_{mp}	34.4 V
Short circuit current I_{sc}	5.1 A

Open circuit voltage V_{oc}	43.2 V
Bypass diodes	4
Number of cells per module	72

The bond graph solar tracking system with two axes was manufactured according to the specific design of automatic laboratory of Setif. Photo of this system are shown in figure (5).

The measurements of the data were taken from a wide area where there was no obstruction that would prevent the tracker from getting the maximum sunlight. The measurement of output voltages and currents were taken at two different days sunny day (03/07/2017) and cloudy day (14/01/2017) from 07:22 until 16:22. The data collected is demonstrated in the graphs below.

- Static solar panel with 5° of angle facing south
- Solar panel with tracking system facing south

6.1. Analysis for a Clear Winter Day

Table 3. Output power variation for January, 14, 2017 from 07:22 to 16:22

Time	**Radiation (W/m2)**		**Energy generation (kWh/hour)**		**Increasing of solar tracking (%)**
	Fixed solar panel	**Solar panel with solar tracking**	**Fixed solar panel**	**Solar panel with solar tracking**	
07:22	64	166	0.08	0.31	
08:22	257	493	0.33	0.73	
09:22	465	648	0.59	0.94	
10:22	609	726	0.77	1.05	
11:22	692	760	0.88	1.25	
12:22	709	764	0.90	1.25	
13:22	657	738	0.83	1.07	
14:22	539	673	0.68	0.97	
15:22	361	542	0.46	0.79	
16:22	139	278	0.18	0.45	
Moy.	449.2	578.8	0.57	0.88	54.38

Figure (8) shows the incident solar energy for a clear day in winter, near the solstice (a very short day in Setif). As it can be seen from the graph, the dual axis tracker receives more radiation than the fixed solar panel. Near the sunrise and the sunset, the tracking advantage has a very large value since the fixed systems do not look toward the sun.

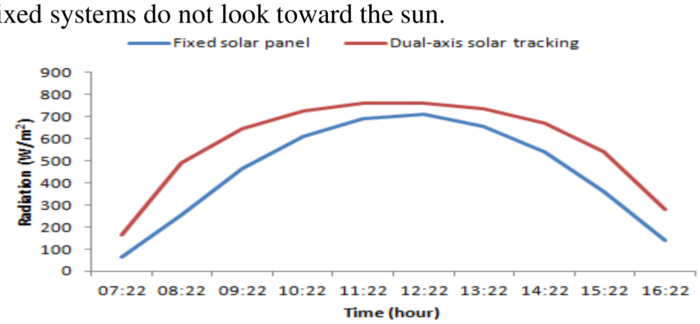


Figure 8. Hourly incident solar energy during a clear winter day in Setif

Figure (9) presents the energy generation of the systems during the clear winter day.

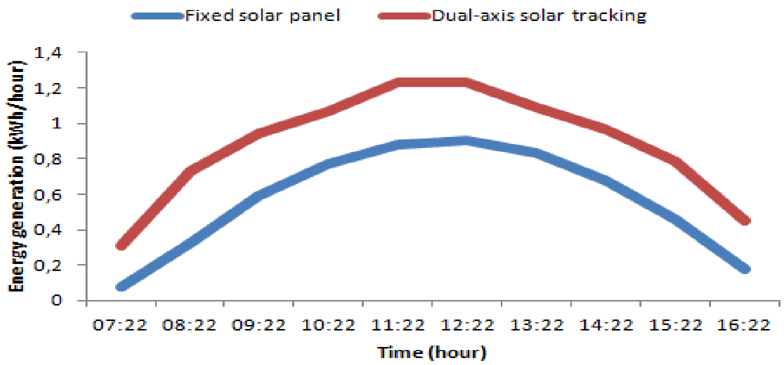


Figure 9. Electricity generation during a clear winter day in Setif

Table 4. Output power variation for July, 03, 2017 from 06:22 to 18:22

Time	Radiation (W/m2)		Energy generation (kWh/hour)		Increasing of solar tracking (%)
	Fixed solar panel	Solar panel with solar tracking	Fixed solar panel	Solar panel with solar tracking	
06:22	82	586	0.12	0.88	
07:22	277	793	0.42	1.20	
08:22	496	906	0.75	1.37	
09:22	694	964	1.05	1.45	
10:22	846	991	1.28	1.49	
11:22	937	1000	1.42	1.50	
12:22	957	1000	1.45	1.50	
13:22	906	994	1.37	1.50	
14:22	786	973	1.19	1.47	
15:22	610	925	0.92	1.39	
16:22	395	828	0.60	1.25	
17:22	179	650	0.27	0.98	
18:22	39	332	0.06	0.50	
Moy.	554.15	841.69	0.84	1.27	51.2

The single-day increase of energy generation is 51.2% in clear days. The overall increase of total energy generation for July 03, 2017 from 06:22 to 18:22, is 53% in Setif.

Figures (10) and (11) demonstrated actual mechanical daily variation of the altitude and azimuth angle which compared with theoretical value calculated from equations (4) and (5).

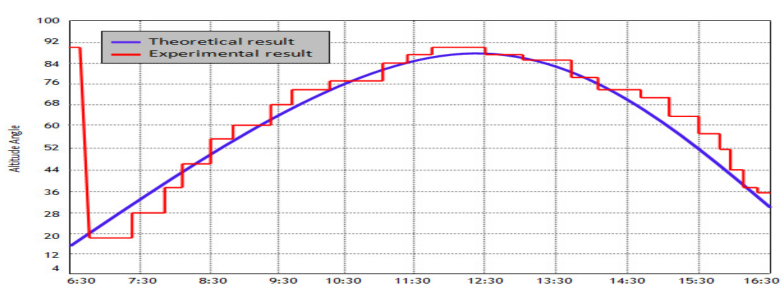


Figure 10. Daliy variation of altitude angle

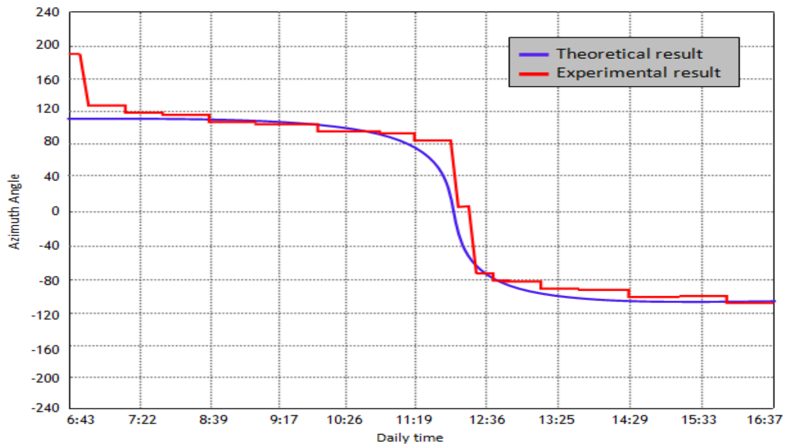


Figure 11. Daliy variation of azimuth angle.

The proposed tracking system could automatically trace position of sun, therefore, the output voltage of the PV panel is maintain higher than the fix-angle system during daily time as shown in figures (8) and (9).

7. CONCLUSION

In this work, we presented a design of a PV solar tracking system. A control algorithm based on the formulas obtained from the modeling analysis was implemented.

The installation cost of bond graph solar tracking PV is about the same as the regular mounting cost of a conventional rooftop PV system, but providing 53% higher PV energy generation efficiency.

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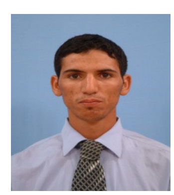

Abd Essalam Badoud was born in Ait Muhli, Algeria; he received the Engineer, Magister and Ph.D. degrees in automatic from the University of Sétif 1, in 2006, 2009 and 2014 respectively. He is member at the Automatic Laboratory of Sétif, currently he is professor at the electrical engineering department, university of Sétif1, Algeria. His main research areas include modeling, control, design and diagnosis for renewable energy and nuclear systems. His is the author of more than 65 papers in journals and conferences.