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Review of dual axis solar tracking and development of its functional model

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Abstract

The use of solar energy is in the upswing due to its environmental friendliness and abundance. That notwithstanding, efficiency remains a major problem in many of the applications. Mitigation is normally in the form of tracking systems. This paper therefore investigates dual axis solar tracking systems from two dimensions. Firstly, a review of extant literature was conducted to draw up a trajectory of where we are in the efficiency map, Therefore it was found that the current efficiency of dual axis tracking configuration is about 35-43%. Secondly, from the above review, a generic functional model of how an efficient and effective tracking system should be is presented. The two components, coevolving, shall be used to inform the design and development of an efficient solar tracker.

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1. Introduction

The use of renewable energy resources in power generation has increased as they are environment friendly and abundant. These resources are alternatives to fossil fuels whose supply is in constant decline. Among renewable resources solar is the most vital resource as it is widely and easily accessible. Hence, the current significant research interest in solar energy resources, especially photovoltaic (PV) systems. Photovoltaic systems convert solar energy into electrical energy with the use of semiconductors. Though the use of PV is commonly associated with low

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conversion rates, years of testing and research have led to improvement of the conversion output of the PV system. Improved solar cells have been developed. Moreover, solar tracking systems have developed and preferred over conventional fixed PV systems. Design methods is a series of technical procedures employed in the generation of new or refining existing engineered systems/products. The use of design methods has the desired effect of bringing rationality and order to the otherwise ill-defined and ill-structured (1) process of systems' generation. Very important to this process is the functionalized approach. In the approach, design problems are conceptualised as Functions and the designed products as Structures. Thus, all design activities are functions. For instance, design objectives are restricted to functional objectives, so are design requirements (or product design specifications), and the functional analysis diagram leading to the morphological chart. Results from the two situations indicate a more organized and focused approach to parameters that bear on the ultimate performance of the product to be designed.

Thus this paper has two dimensions. Firstly; extant literary materials in solar dual axis tracking is reviewed to draw up the efficiency trajectory map. Efficiency map is defined, in this paper, loosely as “answering the question of *where did we start in the efficiency of dual axis trackers and where are we now?*” To that end, a review solar trackers in the last two decades was undertaken and an efficiency-time graph plotted. In the second part, structural arrangement or the embodiment designs of the most highly efficient solar trackers were distilled and a functional model that represents efficient solar trackers built. The model is presented in the form of both an objective tree diagram and functional analysis diagram.

2. Literature review

The first solar tracker was a mechanical system by C. Finster, invented in 1962. Though the Finster solar tracker realized insignificant energy gains, years of testing and research have led to improvement of the conversion output of the PV system and consequently the emergency of different tracking technologies and applications (e.g. concentrator and non-concentrator). In short, improved solar cells have been developed and the use of solar tracking system over the use of conventional fixed PV system has grown. In fixed photovoltaic system the solar receiver (PV module) is in a stationary position facing the true north. However, with mechanical or electro-mechanical systems, the orientation of the collector change continually in reference to the azimuthal directions (east-west) and also in its elevation. This is dependent on the tracker's geometrical capacity.

2.1. Classification of solar tracking system

Mousazadeh et al, (2009) carried a review study, which resulted in the general categorisation of solar tracking systems (2) according to two main typologies, namely, Energy source (i.e. passive, active and manual), and Degree of freedom (i.e. single or dual axis). Passive tracking systems- designate all devices that position solar collectors for optimum capture of energy using mechanical potential and thermal energy principles. Passive systems do not use of electrical energy. Some of the typical mechanical working principles are Shape Memory Alloy (SMA), Thermo-fluids, Mechanical potential system (lever, weight and springs). In Shape Memory Alloy, cylindrical actuators to change the shape the SMA receivers through mirrors until an optimum orientation is achieved (3) Recent developments, among others by Kusekar et al (2015), have seen the use of high pressure fluids to convert the potential energy in the mechanical structure that hold up the PV panel into kinetic energy, which is then used to move the panel toward the sun. (4)

Active tracking systems- use electrical energy as their source. A number of categories exist such as; Electro-optical based tracker, Auxiliary bifacial solar cell and chronological (time and date based) tracker. At some instances, a combination of these different systems may be realised and the resulting system will be referred to as Hybrid. Of all active trackers, electro-optical based-trackers are generally more popular. Mousazadeh et al (2009) reports (2) the use of differential illumination of coupled electro-sensors to generate a differential signal to a controller which then sends a signal to drive the solar system. For improved photosensitivity, the sensor can be mounted on a pyramidal structure (in the *figure 2b outlines* the photo-diode mounted on pyramid) or use of collimator tube might be vital as

it prevent diffuse irradiation from reach the sensors therefore ensuring precise measurement of the position of the sun. Fig.1c is a system made up of four mini- solar module positioned on the North- south and east-west that detect the light intensity, this is system also use the Programmable Logic Controller (PLC) manipulate the two positioning mechanism through two DC motors (5)

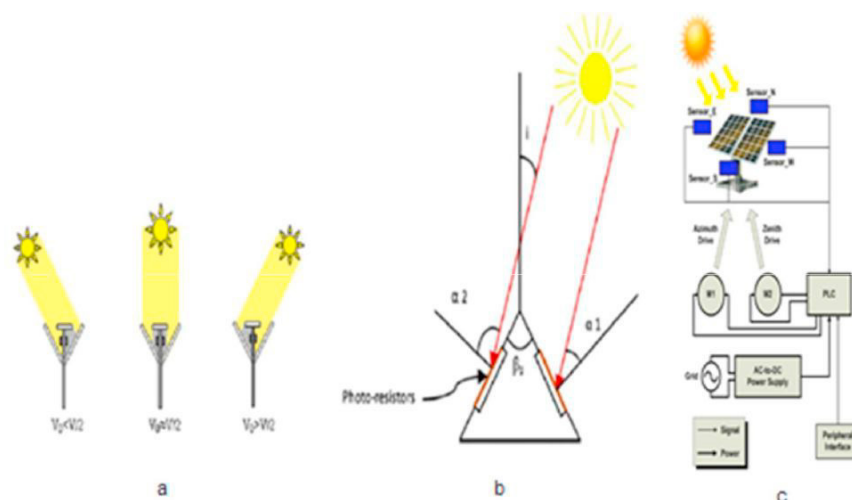


Fig. 1, Different configuration of Photo-sensor used for active tracking mechanism, a b, (6) c (7)

Auxiliary Bifacial Solar cell tracker- In this type of trackers an auxiliary PV cell is used to sense the position of sun and also provide the tracking energy, as it is connected to a permanent magnet DC motor. Both these are fixed to a driving axle of the tracker (8).

Chronological tracker - Uses the geographical and astronomical data to calculate the relative path of the sun for a specified period of time (day and month), with the aid of mathematical formulae and algorithms. To follow the predicted sun's path the system will rotate at constant speed which the sun moves.

Manual tracking system- it is a tracker that is humanly operated and powered. In this method of tracking the operator physically manipulates the position of the collector through a mechanism provided. In some cases this strategy is integrated to an active or passive for secondary axis of dual axis, as a way of reducing complexity implicated by the use of dual axis.

Degree of freedom based typology

Single axis tracking system- These trackers are capacitated to rotate only in one axis in order to position the sun in a desirable orientation for maximum solar energy harvesting. The following are single axis configurations which include; horizontal single axis tracker (HSAT), vertical single axis tracker (VSAT), tilted single axis tracker (TSAT) and polar single axis tracker (PSAT). The nomenclature of these trackers is derived from how the tracker rotates in reference to the surface, that is HSAT's motion is horizontal to ground. The motion in VSAT is vertical to the ground and is aligned to the east to west direction. The axis of TSAT is projected at an angle from the horizontal or vertical. Lastly the PSAT also has a tilted axis which is aligned to the polar star.

Dual axis tracking systems- These system has two degree of freedom which are perpendicular to each other. These tracking devices are generally classified as tip-tilt and the azimuthal-altitude trackers. Dual axis can be deployed for both passive and active tracking strategies.

2. 2. EFFICIENCY TRAJECTORY OF PV OUTPUT DUE TO DUAL AXIS TRACKERS OVER THE PAST TWO DECADE

In 1997 Hoffmann, R., et al. reported an efficiency improve of more than 30% on an open loop active tracker which was evaluated on PV concentrators (9). In 1998 an experimental review of closed loop active tracker, with solar cell used to sensor the position of the sun result in improvement of efficiency 30-50%. The tracking was tested in northern regions of Chile (10). Yousef, H. (1999) (11) developed a tracker that deployed an artificial intelligence approach. A PC based fuzzy logic control, which acquired data through photo-diode to drive motors was engaged, the system increased conversion efficiency of PV system by 50%. A study on performance of different tracking configuration carried out in Germany outlined a 30% increase due to active tracker (12). Dougherty, B. (2001) describes a mobile tracking device with was part of Building Integrated PV testing facility achieved 40% conversion efficiency over fixed (13). A field tested (in Malta) auxiliary PV cell based, roof mounted tracking system recorded a 40% efficiency increase (14). A tracker used in water pumping is reported to efficiency increase of 19-24% (15). Abdallah, S. and Nijmeh, S. (2004) Carried out experimental evaluation on a PLC deployed in a real time based tracking system in Jordan. The authors found a 41.34% increase of efficiency (16). In 2005 Piao, Z.G., et al developed and conducted laboratory test for a time based active tracker, which used a micro-controller and engaged idle mode in gloomy sky conditions. Furthermore a 21% efficiency increase was reported (17). Experimentally tested tracking system in Jordan by Mamlook, et al., (2006) achieved efficiency improvement of 40%. This tracker was a solar mathematical formulae based with a PLC (18). Rubio, F., et al., (2007) developed and experimentally tested a PC controlled through mathematical formulae with PV arrays used as feedback sensors. SCADA used for supervision and monitoring with an application developed in LABVIEW. The system attained a 40% efficiency over fixed PV collector (19).

Chen-Sheng, et al., (2008) repots a 49.2% increase in efficiency due to a system, developed and filed tested in Tibet. The tracker was developed to deploy a Microprocessor as a controller, (time based system with feedback from position sensors). Also it had a poor environment protection (Wind, Vibrations and cloud) and human -machine interface. (20) In 2009 Cemil Sungur recorded 42.6% efficiency improved after experimentally testing a real time based, PLC controlled and DC motor driven tracker in Turkey (21). Barsoum, N. and Vasant, P., (2010) achieved 40% efficiency improvement over fixed through a microcontroller (PIC16F84A), LDRs and DC Motor based tracker (22). A Micro-controller was used for multi-function approach tracking, by Kassem, A. and Hamad M. (2011) achieved a 64% (23). In 2012 Eke, R. and Senturk, A., evaluated a commercial (in Turkey) Pesos SF-40SD dual axis tracking mounted on Mono Crystalline silicon PV and found a 30.79% increase in efficiency. (24). Anusha, K. and Chandra Mohan Reddy,S. (2013) realised a 40% increase due to a system real time based, which deployed Microcontroller (LPC2148) and Stepper Motor (25). Singh, K.P., and Gupta, B., (2014) Experimental (India) Microcontroller (PIC16F877A programmed in DOTNET), Stepper Motor geared (Worm and spur) Infra-red sensor 35-42% (26). In 2015 Ceyda, A.T., and Cenik, Y., (2015) evaluated a microcontroller (PIC16F877A programmed in MPLAB IDE) with linear actuators and potentiometer (feedback sensors) based tracking system at laboratory scale in Turkey. In this study efficiency of 40% was recorded (27). A Microcontroller (Atmega 8), LDRs, DC motor geared and L293D motor driver was also constructed and tested at experimental scale by Shashwati, R. and Tripathi, A.K (2016) and 40% efficiency was realised (28). Akbar, H.S., et al., (2017) developed a microcontroller (Atmega 328), LDRs, DC motors and relays. Through the system efficiency of about 55-30% was recorded (29).

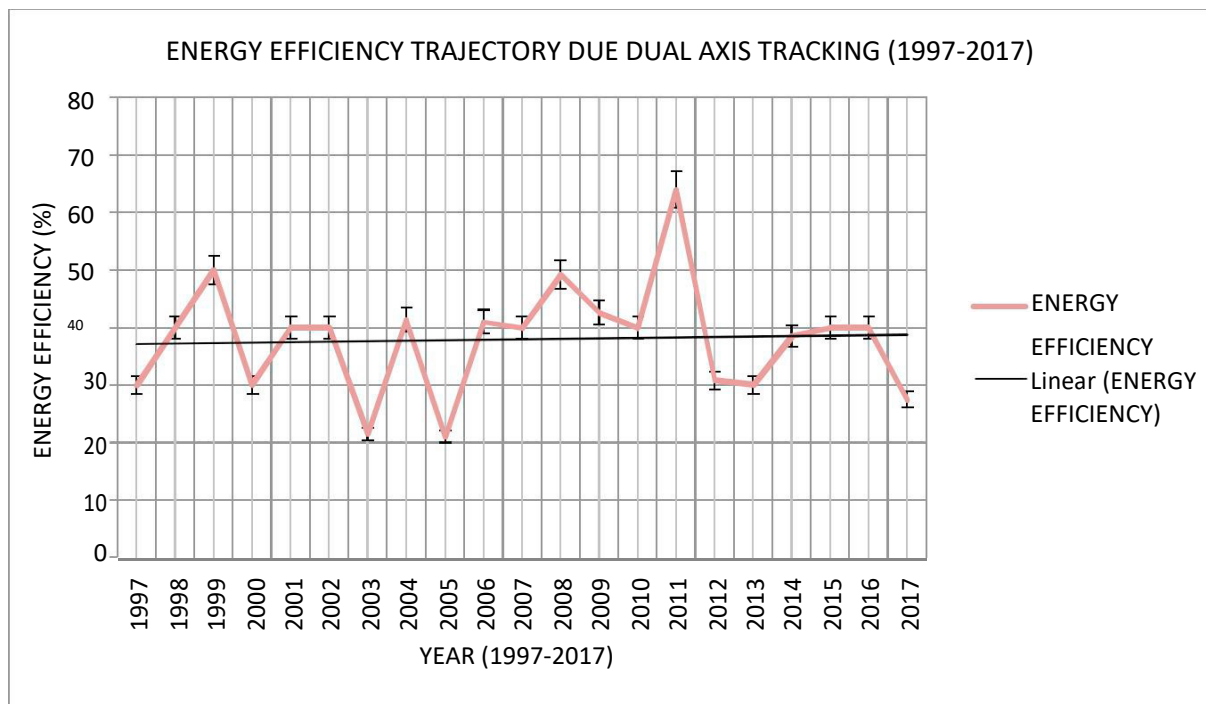


Fig. 2, Dual axis solar tracking system efficiency trajectory map for period of 20 years

The above fig.2 is a trajectory map of energy efficiency due to dual axis tracking systems. Generally the efficiency of PV technology is constant, as it is defined by a linear pattern in the graph. The average efficiency of dual tracking system is estimated to be $38 \pm 5\%$. Therefore a region of 33–43% defines a general point at which the efficiency of dual axis tracking system is that currently.

3.0. Procedure for development of functional model

An overall function of a tracker was identified then broken into its sub-functions, then presented in a solution independent manner. These functions were then translated to a black and transparent boxes to further determine the inputs and output to the process, in terms of energy, material and signal flow of the process. Finally the relation between input and output in a process was studied to aid in identification of functional modules.

4.0. Results and discussion

4.1. Objective tree diagram

Table 1: solar tracking objective tree diagram

Overall objective	functional	Level 1 Sub-functions	Level 2 Sub-functions	Level 3 sub-functions
Tracking position of the sun to maximize the energy received	Measurement of solar radiation on the surface	Determining the position of the sun	1. Measure the precise sun position vector 2. Encoding all measured angles	1. Measure the solar hour angle of the sun 2. Measure the Altitude angle of the sun 1. Correcting of error reading 2. Amplification of measured angles 3. Conversion of measured angle into compatible signals

Tracking motion the position	3.	Decoding the measured angles	1. Accepting the signals of measured angles
			2. Comparing the signal with the reference points of sun position for each time interval.
			3. Signal sent to help generate motion for tracking
		1. Receiving signal of calculated sun position.	
		2. Comparing of current orientation with calculated position of the sun.	
		3. Sending signal to activate release of power to generate the tracking motion	
		1. Power generated form the storage/ generating device.	
		2. Transmission of power to the actuator.	
		3. Actuator converts the input power transmitted into motion.	
		4. Orientation of the solar photovoltaic system changes to be aligned perpendicular to the sun	
2. Calibrate		1. Monitoring the feedback	1. The support platform provide two degree of freedom
			2. Provide a mechanical suspense to maintain the orientation
3. Generating the			1. Measure the orientation of the position
			2. Correcting of error reading
			3. Amplification of measured angles
			4. Conversion of measured angle into readable signal
			5. Comparing the signal with the reference points of sun position for each time interval.
			6. Re-orientation to reduce the tracking errors.
Monitoring the tracking effect (Support functions)	7.	Energy consumption conservation	1. During non-energy production cycle (i.e. at night/ after tracking) switch to uses of other form of energy other than electrical.
			2. When the tracking process reaches high tilt angles during the winter solstice, then turn to the uses of potential energy to return to the summer solstice position to conserve energy.
			3. Recycling of waste energy back into the system.
		4. User's interface	1. Data acquisition
			2. Store data about the performance.
			3. Display data for easy retrieval by the user.
			4. Warning about system malfunction.
		5. Environmental interference/disturbance	1. Measure the potential weather conditions (wind speed, direction, rain, cloud cover) that could disturb the tracking/ damage the tracking device.
			2. Compute the compensation on tracking due to the disturbance.
			3. If the magnitude of weather condition overwhelms the tracking device provide the safety measures.

4. 2. BLACK BOX MODEL

From the black box diagram as illustrated in the Fig. 3, inputs, overall function and output of the process were identified as basis for the constructing the transparent box.

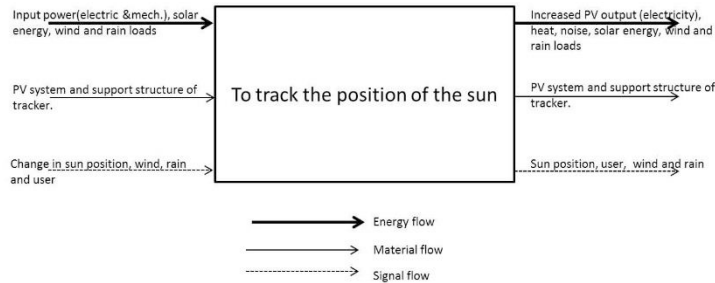


Fig. 3, solar tracking black box model

4. 2. TRANSPARENT BOX

Energy, material and signal flow is presented in diagram, Figure 4 below, the main purpose of identifying the process heuristics module (action), while maintaining a state of independence towards solution. The following are modules which later be translated into physical entities to provide actions identified; Power source (electrical, mechanical), control unit, actuation module, energy recycling module, feedback mechanism, user's interface, positioning mechanism and environmental interference monitoring module (rain and wind protection). Among the identified heuristics module an energy recycling module which not commonly included different designs of solar tracking systems

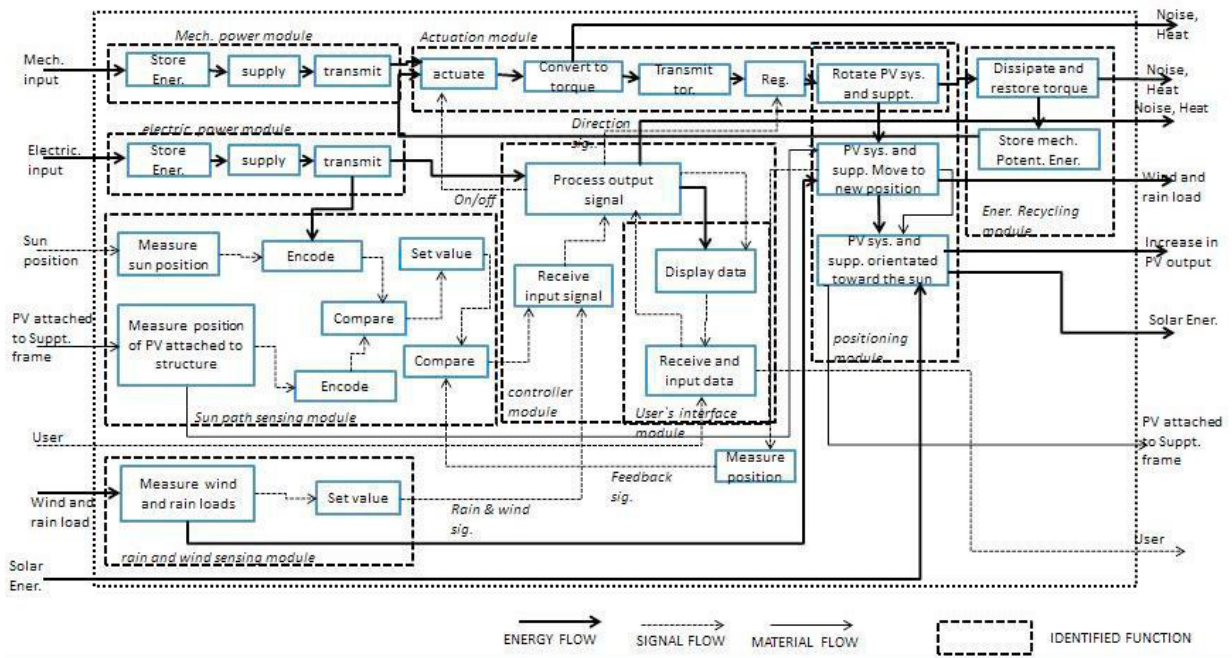


Fig. 4, Flow diagram of a solar tracking system

5. Conclusion

Through this study it can be concluded that dual tracking systems are vital for implementation to PV plants and other solar applications. Though still face with some challenges especially, high cost complexity in regard to design and implement no matter the type of solar tracking (i.e. passive or active). Also it was found that the current (during the period of 1997-2017) efficiency of dual tracking configuration to be about 33–43% on average basis. Furthermore active tracking systems were found to be commonly implemented for dual axis tracking than passive, though they share the same obstacle of complexity and addition expense in terms of utilisation in comparison to single axis tracking configuration. As for passive and active tracker differ with way of deploying the design trade off; the active tracking is based on accuracy while there is consumption of generated energy. As for passive the accuracy of the tracking is limited but it is more energy conservative as it uses other energy form than the generated electricity.

Lastly the Nigel Cross design model (through two first steps of process objective and function) was deployed to aid in establishment of a functional model of solar tracking system through the use of objective tree and functional analysis methods. And some of identified heuristics module developed with aid of the aforementioned methods are not common embedded in solar tracking device; that is the energy recycling module. For future; physical entities will be assigned to the identified functions to develop a tracking device concept and a prototype.

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