

# Comparative Analysis of Mechatronic Designsof aSun-Tracking System for Improved Solar Panel Output and Feasibility

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**ABSTRACT:** The paper presents a comparative analysis of the common mechatronic designs for a sun-tracking system used for increasing the power output from a solar panel. The limited power yield of conventional solar cells remains one of the prime reasons which questions the feasibility and benefits of consuming solar energy. A solar tracker, following a mechatronic structure, can provide the solution to this limitation; however, the level of complexities and resultant power increase are variable. A sun-tracking system can increase the power yield from a solar panel to up to 74%, but this is not the case with all designs. Some of the solar tracking systems only add 8% - 10% to the final power output, but adds a huge and unreasonable cost to the overall system expense. With multiple design solutions in hand, it is important to weigh and compare the cost, complexity, and efficiency of these solutions to match the system design configurations with the project needs and budget.

**Keywords:** sun tracking system, solar tracker for PV panels, microcontroller-based sun-tracking system, FPGA- based sun-tracking system, mechatronic design of solar tracking system.

## INTRODUCTION

Solar energy has emerged as one of the most environment-friendly and long-term solutions for addressing the problem of growing energy demand and limitations of fossil fuels [1,2,3]. However, the acceptance and implementation of photovoltaic cells for solar energy generation still remains underrated particularly because of the low energy output of nearly 19% [4]. This means that a solar input of 1000W would only produce energy of 190W at the user-end. For a requirement of 1000W output, an input of approximately 5260W would be required, thus, demanding a huge solar panel [5]. Great work has been done to

improve the efficiency of the solar cells to increase the power yield; however, it comes at a cost as the advanced photovoltaic cells as nearly twice as expensive as the regular photovoltaic cells [6,7]. This leaves us with the dilemma of whether to spend heavily for increasing the solar energy yield or adjust with the low yield. Fortunately, there is another solution to the problem, which is the design of a "sun-tracking system", which can optimize the voltage yield, without the need of changing the solar cells and panels.

Whenever a design moves from plain electronics to a combination of electronics and mechanical components (moving parts as in the case of a sun-tracking system), it enters the realm of mechatronics[8]. A number of

researchers and engineers [4,9,10] have presented their designs for a sun-tracking system for improved solar output, but lack discussion on comparativeness and competitiveness of the proposed system design. The aim of the paper is to present an improved model of a sun-tracking system, evaluating on the criteria of (i) power output/efficiency, (ii) cost, and (iii) design complexity [11]. This three-dimensional criterion refers to the general considerations of any system design; a system producing high power output might not be feasible because of its high price and design complexity or a very cheap system might not be feasible because of its low efficiency. Only when these three domains are rightly balanced and evaluated, the sustainability and feasibility of a mechatronic system design can be justified. This evaluation defines the very aim and purpose of the present paper on the design analysis of a sun-tracking system.

### THE SUN-TRACKING SYSTEM

Figueiredo et al. (2008) explain that the real problem with the use of solar cells is that the earth is not always in perpendicular position to the sun [4], which is the ideal position for absorbing solar energy and converting it into the power output [12]. As the position of the

earth in relation to the sun changes during the day, the fixed solar panels do not receive adequate sunlight at most part of the day. This problem can be resolved by installing a revolving system, which adjusts the position of the panel in accordance with the sun rays, in to optimize the amount of sunlight received by the photovoltaic cell [13,14]. The use of sun-tracking or solar-tracking systems have shown promising results; for example, Chin and McBride (2013) found out that the use of a solar tracker can increase the potential power output of a photovoltaic plant to up to 40%, which represents a phenomenal growth in energy without the need of changing the material of the cells or increasing their size.

The basic principle of the sun-tracking system for PV cells is that it tracks the position of the sun at different intervals and rotates the solar panel accordingly to achieve a 90°-angle between the sun and the panel [12], as shown in figure 1.

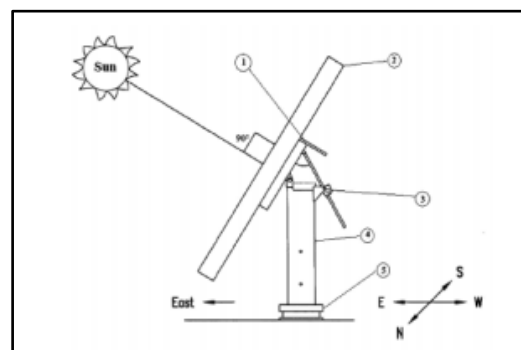


Figure 1: Two-axis equatorial sun tracking system with a tilt angle- perpendicular to the sun [15]

A single-axis sun-tracking system uses a tilted PV panel mount, as shown in figure 2, with a single electric motor that drives the panel's trajectory relative to the sun's position [16]. For a single-axis system, the moment is around the x-axis only, while for a two-axis system, the azimuth position (elevation) of the panel is also adjusted for higher accuracy.

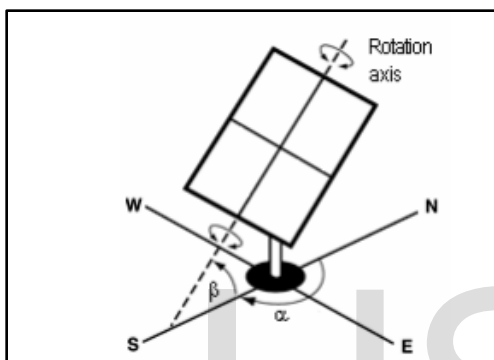


Figure 2: Rotational axis of the sun tracking system

[16]

Earlier built sun-tracking systems were manually fed with the sun's day-to-night position using solar datasheets, also known as 'chronological trackers' [17,18]. However, the recent sun-tracking systems are built using light sensors to track the sun's position and automatically adjust the solar panel without the need of manually feeding sun's position at different times of the day.

### IMPROVING THE SYSTEM DESIGN

The system design comprises of the mechanical structure and moving parts, light

sensors, the control circuitry, and the control algorithm for guiding the solar panel's position. Some of the most popular and common design configuration will be considered for comparison and analysis.

### *Mechanical Structure*

The basic mechanical structure comprises a mounting surface, relays, and motors [19]. Standard aluminium surfaces are commonly used for the mounting purpose and they have shown satisfactory results in a number of projects, thus, leaving the mounting surface material out of the debate. Moving on to relays, they provide protection from unbalanced phase currents, ensuring that the PV cell does not move away from the defined boundaries [4]. In recent practices, mercury switches have been preferred over CM-phase relays for achieving this balance [20,9]. The advantage of the mercury switch is the presence of contained mercury drop, which flows towards the lower position due to gravity. As it touches both the electrodes simultaneously, the circuit closes and the movement of the panel towards that direction is interjected. In this way, the solar panel would not tilt beyond the defined horizontal and vertical boundaries, preventing any damage to the structure of the panel [20]. A

picture of mercury switches and their preferred position for use in the sun-tracking system is shown in figure 3.

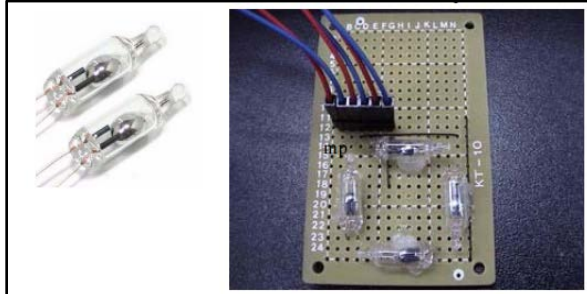


Figure 3: Presentation of mercury switches and their placement in the circuit [20].

The most important mechanical component is the motor, which needs to be programmed and controlled to achieve the desired degree of freedom. Both DC motors and stepper motors can be used for the purpose; however, stepper motors offer more accurate and easy to control movement with defined rotation angles [21]. Elsodany et al. (2011) explain that DC motors provide a continuous spinning rotation, while stepper motors allow more precise positions, as each of its four coils are charged by a signal from the control source. This would also mean that a stepper motor demands more complicated control circuitry and programming logic as compared to the DC motors.

### ***Light Sensors***

Light sensors are used to sense the sunlight and send an output signal accordingly, which

can then be used for positioning the solar panel [22]. For a single-axis design, two light sensors placed normal to each other on the horizontal axis can support PV panel positioning on the horizontal axis. On the other hand, a dual-axis system would require at least four light sensors for detecting light from the eastern, western, southern, and northern directions [23]. The majority of the practitioners have used a two or four sensor design; however, more sensors can be added for additional accuracy, but at the cost of complexity in the design and programming.

Tudorache and Kreindler (2010) used two luminescent diodes of LED type, placed normal to each other such that the signal they generate is correlated with the light intensity applied to the PV panel, as shown in figure 4 [16]. The relative position between the PV panel and sunlight dictates the amount of the sunlight received by each LED. So, depending on this position, one of the LEDs will produce a greater voltage signal than the other, thus, guiding the position of the panel.

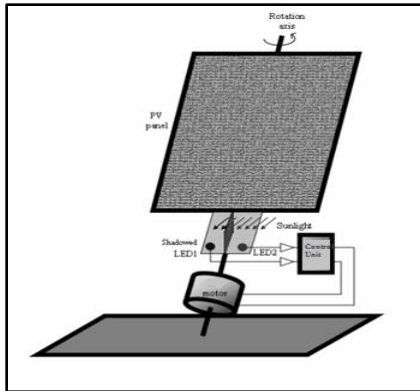


Figure 4: Block diagram of light sensors and motion control [16]

Some problems with LED diodes are narrower scope and weakened sensitivity as compared to the light sensing photoresistors [24,25]. The light dependent resistor (LDR) and CdS sensors are photoresistors and can be used to achieve the same purpose of sensing the sun's light and directing the PV panel's position accordingly, see figure 4. Both the quantity and interface would remain the same, as in the case of LEDs. Another available sensor is of the infrared (IR) sensor, which can further improve the accuracy of light detection; however, can significantly add to the system cost [26].

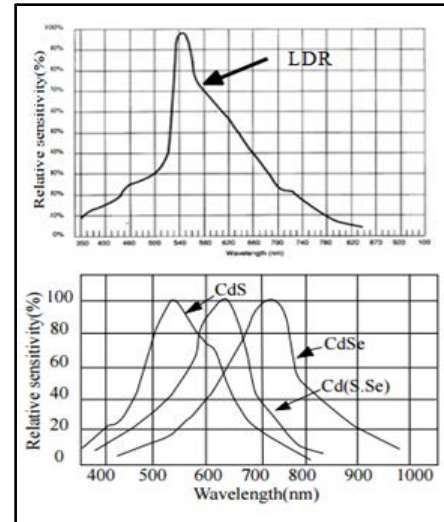


Figure 5: Photoresistors sensitivity slopes [27]

### Control Unit

The control unit serves as the brains of the hardware, which controls the functions and assigns hierarchical tasks to the hardware [28,20]. Commonly, a microcontroller or a field programmable gate array (FPGA) is used to control the entire circuit and ensure that each component is performing the defined task properly [29]. Salem (2013) and Arsalan (2013) used the Microcontroller 8051 along with the analog-to-digital converter to serve as the control unit. The problem with microcontrollers is that, though economical, they face difficulties in dealing with control systems that require high processing and input/output handling speeds [30]. Furthermore, as microcontrollers come with a pre-defined circuitry, there are only a limited number of I/O ports available for operation

[28]. On the contrary, FPGA offers more advanced and flexible solution for constructing the control unit of the sun-tracking system [28]. A sketch of the system architecture with an FPGA controller is presented in figure 6.

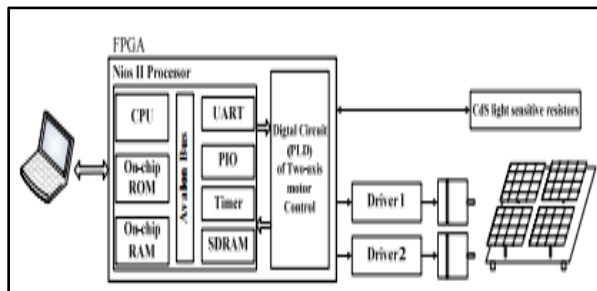


Figure 6: FPGA-based system architecture [9]

While microcontrollers are suitable for a small project with a fixed number of PV panels, the use of FPGA can be handier in projects where there is a probability of change in the number of PV panels, switches, or light detecting sensors [31]. For larger projects with a multiple and varied number of PV panels, a PLC-based control unit can offer a better solution, providing the additional advantage of remote monitoring through SCADA or other control applications [4].

### **Control Algorithm**

The control algorithm is the logic or program that executes the sun tracking procedure and coordinates the movement of the positioning system [32]. After the hardware is selected, it is important to define a logic (program), with which the entire solar positioning system will

run and achieve the desired positioning output. Earlier researchers have used the Perturb & Observe (P&O) technique of maximum power point tracking (MPPT) algorithm [33,34], while contemporary researchers have taken use of the fuzzy logic of the MPPT algorithm [35,31]. The reason for the wide popularity of the MPPT algorithm is that it compares the current power value of the PV with the previous one and sets the PV panel position based on the higher power values.

Al-Diab (2010) used the P&O method to oscillate the position of the PV panel around the MPP. If a given perturbation leads to increase or decrease in the output power of the PV, then the subsequent perturbation is generated in the same (opposite) direction [36,37]. Thus, when the MPP is achieved, the system should stop oscillating so to maintain the position with little disturbance. Chao et al. (2009) further refined the P&O method by using quadratic equations in order to further decrease the oscillations steps to achieve more stable power output. On the contrary, the fuzzy logic demands a more complex logic defining, but offers the benefit of better dealing with input nonlinearities [38,9]. Huang et al. (2009) developed a solar tracker based on the fuzzy logic and found a smoother position maintaining output and reduced power

consumption by the motors as compared to the P&O algorithm. The fuzzy logic operates in three discrete stages; fuzzification, inference, and defuzzification. In the fuzzification stage numerical power output values are changed into linguistic terms, which are used in rule defining. These terms are of (i) negative big [NB], (ii) negative medium [NM], (iii) negative small [NS], (iv) zero [ZE], (v) positive small [PS], (vi) positive medium [PM], (vii) positive big [PB] [35]. The inference stage compares the linguistic input and produces an output stage based on base rules, as shown in figure 7. The final stage of defuzzification converts the linguistic output to a numeric crisp, which guides the motor rotation, thus, setting the position of the solar panel.

Er \ CE	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

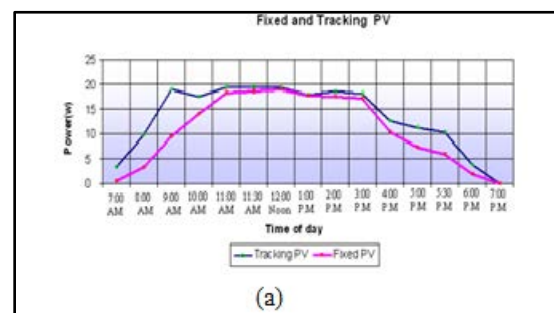
Figure 7: Base rules using in FLC, representing the input and output values of the controller in three dimensions[24]

### FINDINGS

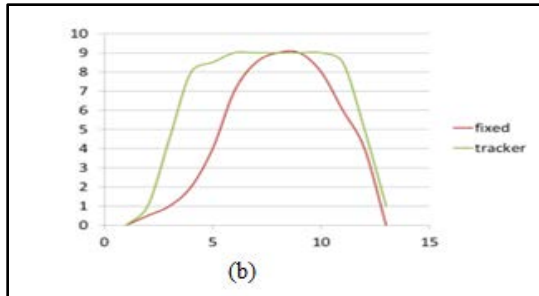
In order to meet the research criterion of power output, the results from various studies are combined and analysed together so to get

a holistic view of the circuit design, and how a change in individual components and algorithms can result in system modification and improvement. The percentage difference between the power output of a fixed PV panel and a PV panel with a solar tracker has been used as the efficiency indicator of the system design.

Zheng et al. (2012) and Hon and Kolte (2013) used the system combination of photoresistors sensors and stepper motors controlled with an FPGA and fuzzy logic algorithm. The power output results of the two studies are presented in figure 8(a) and 8(b) respectively. It can be seen that the power output for tracking PV is greater than the fixed PV for the entire time period, with an average percentage increase of ~67% [39] and 26% [29]. From both the figures it can be seen that the highest efficiency is achieved during the initial time intervals, that is, early in the morning.

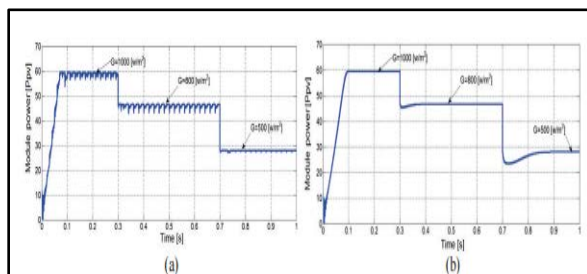


(a)



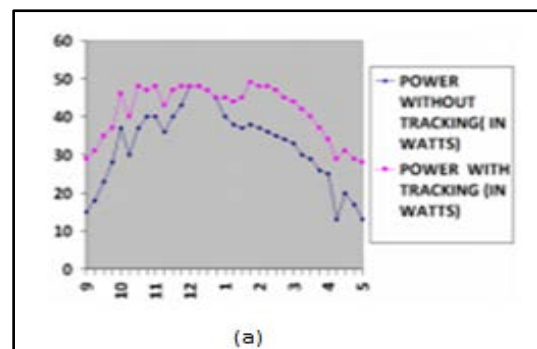
**Figure 8: Power Output Comparison for a fixed PV Panel versus a Sun-Tracking Panel using FPGA and Fuzzy Logic (a) Approximately 67% Power Increase[39] (b) Approximately 26% Power Increase[29]**

Bounechba et al. (2014) compared the P&O algorithm with the fuzzy logic algorithm and found the fuzzy logic produces more stable output and smooth PV power curves as compared to the P&O algorithm as shown in figure 9. A more careful analysis of the PV power curves shows that the power curves for P&O algorithm are in a wave form, where it continuously drops from the peak point and then again reaches the top point, resulting in lower overall power output.



**Figure 9: PV power curves generated by (a) Perturb and Observe algorithm and (b) Fuzzy Logic controller at temperature 25oC and solar irradiance change 1[kW/m2], 0.8[kW/m2] and 0.5 [kW/m2] [35]**

Krishna and Sinha (2013) and Arsalan (2013) used the system combination of a stepper motor and a microcontroller with an LDR based positioning algorithm. The voltage output from the LDR sensor was used as the input to the microcontroller, thus, setting the position of the PV panel. The power outputs of these studies are presented in figure 10(a) and 10(b). In both the studies it was observed that a higher duration of constant power was achieved during that middle of the day, at 47-48W[26] and 22.5W[25]. The average percentage increase in the power output was of ~74% and ~37% respectively. With the microcontroller setting, the tracking solar panel maintains its higher power output during the peak hours, unlike the case with FPGA, where the tracker panel generates slightly lower output during the peak time.





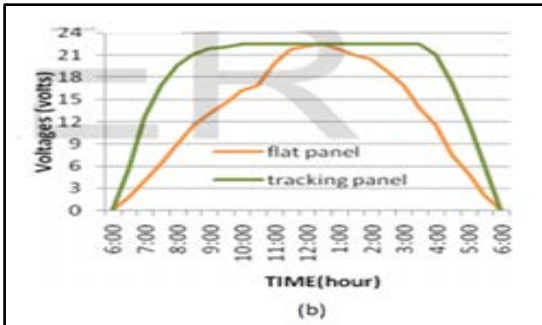


Figure 10: Power Output Comparison for a fixed PV Panel versus a Sun-Tracking Panel using Microcontroller and LDR-based logic (a) Approximately 67% Power Increase [26] (b) Approximately 26% Power Increase [25]

Design cost can be reduced by using dc geared motors instead of stepper motors and using a microcontroller to control the rotation of the motor, as done by Al-Diab (2010) and Iqbal et al. (2015). The dc geared motor has greater torque withholding ability, and therefore, can work with lower RPM for sustaining a position for a greater time interval. The power and current output is presented in figure 11. From these results, it was observed that despite the use of dc geared motors and not the conventional dc motors, there were a very few instances of steady current flow and power output with the tracker circuit. Al-Diab (2010) achieved an overall power efficiency of ~49.5% [37] while Iqbal et al. (2015) achieved the power efficiency of ~9% [10]. One reason for the comparatively lower power increase from the solar tracker was the frequent movement of the motor, failing to

steadily the position of the PV panel at peak current rating.

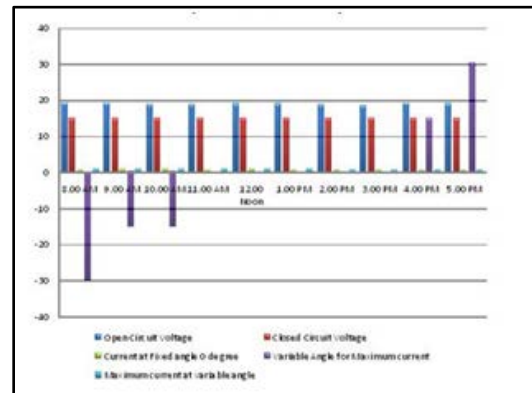


Figure 11: Current and Power Output Comparison for a fixed PV Panel versus a Sun-Tracking Panel using DC Geared Motor controlled by a microcontroller [10]

## DISCUSSION AND CONCLUSION

The fundamental premise of a solar tracker to improve the power output and efficiency of a fixed solar panel was confirmed in the present study, as all sun tracking systems, irrespective of their design and control logic, were able to increase the power output of the PV panel ranging from by 9% to 74%. Moving to the design description, graphical representations of the three design criteria of power output and efficiency, cost, and complexity are provided in figure 12 (a), (b), and (c).

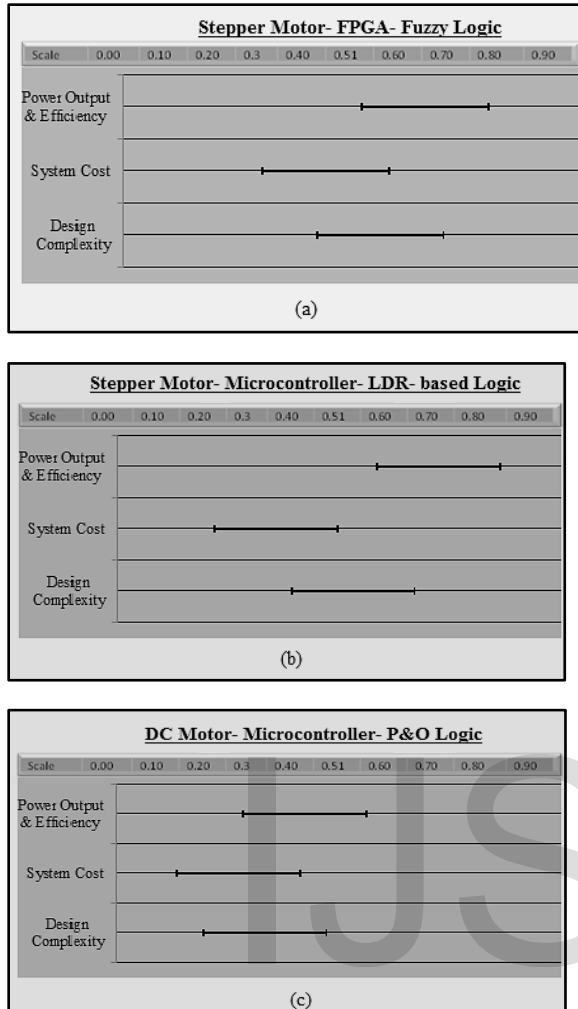


Figure 12: Design Evaluation based on the three-point criteria (a) Using Stepper motor, FPGA and fuzzy logic (b) Using Stepper motor and microcontroller-based (c) Using DC geared motor and P&O algorithm

The highest power output and efficiency were achieved with system configuration of figure 12(b), using a microcontroller and an LDR-based logic. The system configuration was also more economical than that with an FPGA, while the circuit complexity level was almost the same. Thus, for smaller projects with defined and fixed number of solar panels, system (b) can prove to be the most efficient.

However, as the number of panels increase, the number of LDR sensors will increase proportionally, adding to the complexity of the circuit design. In such a scenario, FPGA-based system (a) would prove to be more efficient and feasible. Lastly, for small-scale projects with a limited budget, stepper motors can be replaced with dc geared motors and microcontrollers can be used programmed with the P&O technique of the MPPT algorithm to achieve the highest economic efficiency of the sun-tracking system for solar panels.

## REFERENCES

- [1] V. Gekas, N. Frantzeskaki, and T. Tsoutsos, "Environmental impact assessment of solar energy systems. Results form a life cycle analysis.," *Protection and Restoration of the Environment VI*, Skiathos. 2002.
- [2] S. Kalogirou, "Environmental benefits of domestic solar energy systems. ," *Energy Conversion and Management*, vol. 45, p. 3075–3092, 2004.
- [3] N. Chen, X. Zhang, Y. Bai, and H. Zhang, "Environmental Friendly PV

- Power Plant.," *Energy Procedia*, vol. 16, p. 32 – 37, 2012.
- [4] J. Figueiredo and J. Costa, "Intelligent sun-tracking system for efficiency maximization of photovoltaic energy production.," *RE&PQJ*, vol. 1, no. 6, pp. 80-84, 2008.
- [5] F. Dincer and M. Meral, "Critical Factors that affecting efficiency of solar cells.," *Smart Grid and Renewable Energy*, vol. 1, pp. 47-50, 2010.
- [6] IRENA, "Solar photovoltaics: Renewable energy technologies: cost analysis series," IRENA Working Paper 2012.
- [7] A. Blakers, N. Zin, K. McIntosh, and K. Fong, "High Efficiency Silicon Solar Cells.," *Energy Procedia*, vol. 33, pp. 1-10, 2013.
- [8] N. Kyura and H. Oho, "Mechatronics: An industrial perspective," *IEEE/ ASME Transactions On Mechatronic*, vol. 1, no. 1, pp. 10-15, 1996.
- [9] Y. Huang et al., "The design and implementation of a solar tracking generating power system.," *Engineering Letters*, vol. 17, no. 4, pp. 1-5, 2009.
- [10] K. Iqbal, T. Islam, M. Chowdhury, and A. Imteaj, "Construction of single axis automatic solar tracking system," *International Journal of u- and e-Service, Science and Technology*, vol. 8, no. 1, pp. 389-400, 2015.
- [11] N. Afgan and M. Carvalho, "Multi-criteria assessment of new and renewable energy power plants," *Energy*, vol. 27, p. 739-755, 2002.
- [12] H. Mousazadeh et al., "A review of principle and sun-tracking methods for maximizing solar systems output.," *Renewable and Sustainable Energy Reviews*, vol. 13, p. 1800-1818, 2009.
- [13] J. Agee, A. Obok-Opok, and M. Lazzar, "Solar tracker technologies: market trends and field applications.," *Advanced Materials Research*, vol. 18-19, p. 339-44, 2007.

- [14] R. Chao, s Ko, S. Pai, and C. Chang, "Evaluation of a photovoltaic energy mechatronics system with a built-in quadratic maximum power point tracking algorithm.," *Sol. Energy*, vol. 2009, no. 83, p. 2177–2185, 2009.
- [15] M. Alata, A. Al-Nimr, and Y. Qaroush, "Developing a multipurpose sun tracking system using fuzzy control.," *Energy Conversion and Management*, vol. 46, no. 7-8, p. 1229–1245, 2005.
- [16] T. Tudorache and L. Kreindler, "Design of a solar tracker system for PV power plants.," *Acta Polytechnica Hungarica*, vol. 7, no. 1, pp. 23-39, 2010.
- [17] D. Myers, "Solar radiation and measurements for renewable energy applications; data and model uncertainty.," *Energy*, vol. 30, p. 1517–1531, 2005.
- [18] H. Ghosh, N. Bhowmik, and M. Hussain, "Determining seasonal optimum tilt angles, solar radiations on variously oriented, single and double axis tracking surfaces at Dhaka.," *Renewable Energy*, vol. 35, p. 1292–1297, 2010.
- [19] F. Salem, "Mechatronics design of solar tracking system.," *International Journal of Current Engineering and Technology*, vol. 3, no. 3, pp. 750-762, 2013.
- [20] Z. Xinhong, W. Zongxian, and Y. Zhengda, "Intelligent solar tracking control system implemented on an FPGA.," *Nios II Embedded Processor Design Contest—Outstanding Designs 2007*.
- [21] S. Das, Sadhu P., N. Pal, and S. Mukherjee, "Single axis automatic solar tracking system using microcontroller.," *TELKOMNIKA Indonesian Journal of Electrical Engineering*, vol. 12, no. 12, pp. 8028 - 8032, 2014.
- [22] C. Saravanan, M. Panneerselvam, and W. Christopher, "A novel low cost automatic solar tracking system.," *International Journal of Computer Applications*, vol. 31, no. 9, pp. 62-67, 2011.

- [23] K. Chong and C. Wong, "General formula for one-axis sun tracking system and its application in improving tracking accuracy of solar collector.," *Solar Energy*, vol. 83, pp. 298-305, 2009.
- [24] B. Hamed and M. El-Moghany, "Two axis tracker using fuzzy controller via PIC16F887a.," in *The 4th International Engineering Conference –Towards engineering of 21st century.*, 2012.
- [25] S. Arsalan, "Sun tracking system with microcontroller 8051," *International Journal of Scientific & Engineering Research*, vol. 4, no. 6, pp. 2998-3001, 2013.
- [26] B. Krishna and K. Sinha, "Tracking of Sun for solar panels and real time monitoring using LabVIEW. ," *Journal of Automation and Control Engineering*, vol. 1, no. 4, pp. 312-315, 2013.
- [27] TOKEN, "Light-dependent photoresistors for sensor applications," Data Sheet 2010.
- [28] Y. Chan, M. Moallem, and W. Wang, "Efficient Implementation of PID Control Algorithm using FPGA technology.," in *43rd IEEE Conference on Decision and Control*, 2004.
- [29] S. Hon and M. Kolte, "FPGA based standalone solar tracking system.," *International Journal of Scientific and Research Publications*, vol. 3, no. 10, 2013.
- [30] W. Zhao, B. Kim, A. Larson, and R. Voyles, "FPGA implementation of closed loop control system for small scale robot.," in *International conference on advanced robotics-ICAR*, 2005, p. 70–77.
- [31] M. Zolkifli, M. Robian, S. Saon, and A. Kadir, "FPGA based maximum power point tracking of photovoltaic system using anfis controller.," *ARPJ Journal of Engineering and Applied Sciences*, vol. 11, no. 8, pp. 5094-5097, 2016.
- [32] Rockwell Automation, "Solar tracking application," Hong Kong, Rockwell

- Automation White Paper 2011.
- [33] S. Yuvarajan and S. Xu, "Photo-voltaic power converter with a simple maximum-powerpoint-tracker.," in *Proc. International Symposium on Circuits and Systems*, 2003, pp. 399-402.
- [34] B. Bekker and H. Beukes, "Finding an optimal PV panel maximum power point tracking method," in *Proc. 7th AFRICON Conference in Africa*, 2004, pp. 1125-1129.
- [35] H. Bounechbaa, A. Bouzida, K. Nabtib, and H. Benalla, "Comparison of perturb & observe and fuzzy logic in maximum power point tracker for PV systems.," *Energy Procedia*, vol. 50, p. 677 – 684, 2014.
- [36] N. Mutoh, M. Ohno, and T. Inoue, "A method for MPPT control while searching for parameters corresponding to weather conditions for PV generation systems.," *IEEE Transaction on Industrial Electronics*, vol. 53, no. 4, 2006.
- [37] Ahmad Al-Diab, "Variable step size P&O MPPT algorithm for PV systems.," in *OPTIM 12th International Conference on Optimization of Electrical and Electronic Equipment*, 2010, pp. 1097-1102.
- [38] P. Esum and L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques.," *IEEE Transactions on Energy Conversion*, vol. 22, no. 2, pp. 439- 449, 2007.
- [39] X. Zheng, Y. Zhang, Y. Yu, J. Zhang, and J. Shi, "Recognition of marrow cell images based on fuzzy clustering.," *I.J. Information Technology and Computer Science*, vol. 1, pp. 40-49, 2012.
- [40] A. Chin and B. McBride, "Design, modeling and testing of a standalone single axis active solar tracker using MATLAB/Simulink.," *Renewable Energy*, vol. 36, pp. 3075-3090, 2013.
- [41] R. Chao, S. Ko, F. Pai, H. Lin, and C. Chang, "Evaluation of a photovoltaic energy mechatronics system with a built-

in quadratic maximum power point

83, p. 2177–2185, 2009.

tracking algorithm.," *Solar Energy*, vol.

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