International Journal of GEOMATE, Oct., 2021, Vol.21, Issue 86, pp.92-99
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2021.86.j2293
Geotechnique, Construction Materials and Environment

IMPROVEMENT OF A SOLAR PANEL TRACKING SYSTEM USING ADDITIONAL MASS POSITION ADJUSTMENT

Ali Basrah Pulungan[1,2], *Lovely Son[3], Syafii[3], Syamsul Huda[3] and *Ubaidillah Ubaidillah[4]

[1] Department of Mechanical Engineering, Engineering Faculty, Universitas Andalas, Indonesia;
[2] Engineering Faculty, Universitas Negeri Padang, Indonesia
[3] Engineering Faculty, Universitas Andalas Padang, Indonesia
[4] Engineering Faculty, Universitas Sebelas Maret Solo, Indonesia

*Corresponding Author, Received: 10 Aug. 2021, Revised: 08 Sept. 2021, Accepted: 23 Sept. 2021

ABSTRACT: This study aims to obtain an effective solar panel tracking mechanism using energy-efficient electric actuators. Furthermore, we designed and implemented a semi-active solar tracking system. A tracking system is proposed to control solar panel orientation using a moving mass, a spring system, and an actuator. The weight of the moving mass and the spring constant are optimized to reduce actuator size. A stepper motor was used for this case. This electric drive is not the prime mover of the solar tracker; hence, it works against mass elements lighter than solar panel weight as used in the active solar tracker. Experimental results suggest that the average power required by the stepper motor is 0.21% of the energy generated by the solar tracking system. The results indicate that the proposed solar panel tracker works satisfactorily to control solar panel orientation.

Keywords: Energy consumption, Additional mass position, Output power, Semi-active, Solar tracking

1. INTRODUCTION

Solar energy is a renewable energy source that is used for electricity generation. It is estimated that solar energy can provide about 27,000 times the energy produced from all other energy sources [1]. Besides, the Earth's surface receives average solar radiation of 600 W/m2/day [2].

Solar panels have disadvantages concerning low power output (less than 20% efficient); hence, conventional applications are restricted [3]. Solar panels have low efficiency, and it is a significant challenge hindering solar energy development and use. The power output of solar cells is determined by several factors, namely temperature, radiation levels, and the sunlight angle [4]. Using a solar tracking system is a viable alternative to maximize energy production. This system can adjust solar module orientation and align them to sunlight direction; hence, the modules always face the sun despite changes in position throughout the day [5].

Solar tracking designs generally use an actuator comprising an electric motor to form the main driver. This tracker system has good performance; however, it requires relatively more electrical power because it is a prime mover working directly against the gravitational force on the solar tracking system. This research proposes a new solar tracking system design comprising a moving mass-based orientation control. The electric drive in this system is designed to work against mass elements lighter than the solar panels in the active tracker system.

2. LITERATURE REVIEW

2.1 Solar Tracking System

A solar tracker is a device used to point solar panels towards the sun. The ideal tracker allows solar panel cells to face the sun. It can change solar module elevation angle (throughout the day), latitude (during changing seasons), and azimuth angle. Based on motion direction, solar trackers are classified into single-axis and multiple-axis trackers. Meanwhile, passive (mechanical) and active (electrical) tracking methods classify these systems based on tracker movement [6].

Both systems have advantages and disadvantages related to installation and operation. Cost, reliability, energy consumption, maintenance, and overall performance are different parameters to analyse such systems [7].

The dual-axis tracker is relatively complex but more efficient because it tracks the sun on both axes. It is the best choice for locations having seasonal variations in the sun's position throughout the year. Single-axis trackers are better suited for places around the equator with no significant changes in the sun's position throughout the year [8].

2.1.1 Passive (mechanical) Tracking

Passive tracking, also known as mechanical tracking, is a sunlight tracking method that has been in use for a long time; it works based on thermal expansion. The system works by combining two bimetallic strips and shape memory alloys. Solar heating causes imbalance, causing the tracker to move, as depicted in Figure 1.

The Shape Memory Alloy passive tracker design was developed using NiTi, CuZnAl, and CuAlNi alloys. The sun movement test can be performed beginning with an angle of 60^0 [9]. Another type of passive tracking system is called a Semi-Passive Solar Tracking Concentrator (SPSTC), which collects sunlight with minimal mechanical effort and movement. This system consists of a micro-heliostat and Fresnel lens [10].

Passive solar tracking works based on the thermal expansion of a combination of two bimetallic strips made of aluminium and steel. The two strips have different thermal expansion coefficients, causing imbalance and facilitating movement [6].

The thermal expansion induction concept has also been used for dual-axis passive tracking systems. It is based on material length expansion when exposed to sunlight.

The measurement process uses three thin flat vertical strips with different orientations, reinforced with a lever to allow sunlight tracking. Using such a measurement-based tracking system can increase solar panel power production by 28% [11].

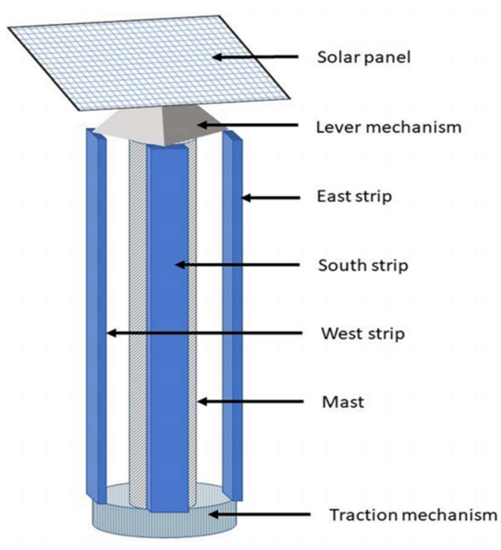


Fig. 1. Schematic of the passive solar tracking system based on the different thermal expansion coefficients [11].

Passive (mechanical) tracking is a straightforward and easily implementable tracking system. It generally requires a less complex structure, lesser cost, and relatively less installation equipment. In addition, passive trackers seldom require additional power as they operate using solar radiation only [6]. It is also possible to develop these trackers in tropical areas with high sun availability and slight variation in sunlight azimuth throughout the year [12]. However, the drawback is that it produces lower energy than an active tracker. Besides, passive trackers are also limited to areas with relatively high levels of solar heat.

2.1.2 Active (electrical) Tracking

Active solar tracker or electrical solar tracking system uses a motor and gear based electric actuator to change solar panel orientation, as shown in Figure 2. Value and direction tracking control signals serve as input for the motor. Motor drive control can be implemented using a microprocessor or Programmable Logic Controller (PLC) based on sensors or available data. These trackers are classified into two groups based on motion direction: single-axis and multiple-axis trackers.

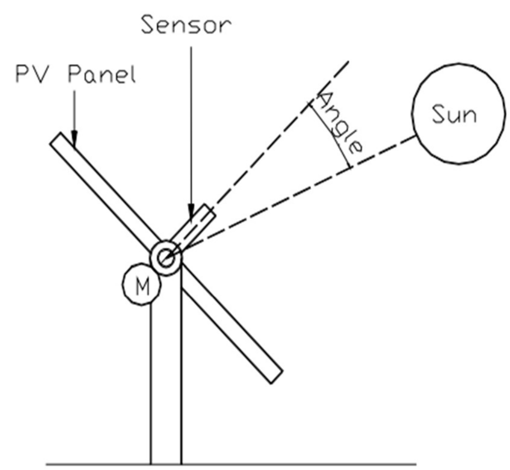


Fig. 2. An active solar tracker [6]

The single-axis active tracking system uses solar panels to track the sun from east to west using a single pivot point, as shown in figure 2. The single-axis tracking system generally consists of two LDR sensors positioned on both sides of the panel. Several studies on this single-axis tracking system actuators indicate that system controls can be implemented using a microcontroller that drives DC motors, stepper motors, or servo motors [12-20].

The dual-axis tracker is another active tracking system that tracks the sun from east to west and north to south using two pivot points. The dual-shaft tracking system uses four LDR sensors, two motors, and a controller. LDR sensors are facing four different directions; a motor is used to tilt the tracker towards the east-west direction of the sun. Another sensor and motor are installed on the bottom of the tracker to tilt the tracker towards the north-south direction of the sun. Using such a system, solar radiation levels on the panels can be maintained above 140 w/m^2 [21].

2.2 Challenges of Solar Tracking Systems

Single- and dual-axis techniques for passive and active solar trackers are commonly used to increase the solar panel output power [22]. Both types of trackers have advantages and disadvantages. Passive (mechanical) tracking comprises a simple system that is easy to implement and comprises fewer complex structures. It is cheaper and requires less installation equipment. Additionally, passive trackers seldom require an additional power supply as they operate on solar radiation [6]. It is also possible to develop these trackers, especially in tropical areas with high sunlight availability throughout the year and minimal variation in azimuth angle [15].

Several previous researchers worked on the passive (mechanical) solar tracker. Passive methods rely on the thermal expansion of compressed gas points, differential thermal expansion, or memory alloy materials. The efficiency of this system is 2% -28% higher than fixed systems [6],[9-11],[23]. The current passive solar tracker also has limitations. The thermal expansion based working mechanism is limited due to relatively little expansion, limiting length expansion. The tracking system also requires accurate distance control and lever adjustment [11]. Length expansion provides restricted solar panel movement, limiting the peak efficiency compared to a fixed system. Passive trackers are typically not the first choice for extremely cold regions since low temperatures affect tracker operation.

Meanwhile, active (electric) solar trackers comprise a single-axis (rotates around one axis) or dual-axis tracker (rotates around two axes) using an electric motor. A value and direction tracking control signal is input to the motors. Motor drive control can be implemented using a microcontroller or Programmable Logic Controller (PLC) based on sensors or available data [24].

Several previous researchers worked on single- or multiple-axis active (electrical) tracking using direct current (DC) motors [12-17],[21],[25],[26]. Researchers achieved an average efficiency gain of about 29.37% [24].

Though active tracking systems provide better efficiency, they have higher energy losses due to actuator operation. Active single-axis tracking actuators consume about 14%-28% of the average daily power generation [27].

Oscillations during tracker movement is a problem concerning tracker instability. Such movements might be caused by electric motors or an external disturbance like wind [6]. Such events cause tracking errors and control system failure [7].

2.3 The New Solar Tracker Strategy

Considering several problems of both passive and active sunlight tracking systems, developing a new tracking system can address challenges concerning energy consumption and oscillation disturbance. The proposed process comprises a tracking system with a semi-active control system whose dynamic properties can be changed without external energy. Semi-active control techniques can control damping, stiffness, and mass balance [28][29]. Semi-active systems are cost-efficient and consume less energy than active control systems [30].

A new solar tracking system is proposed in this study. The system can be regulated by changing the mass position at a specific distance from the axis point of the solar panel, as shown in Figure 3. A low-power stepper motor is used to move mass across a trajectory. The stepper motor has advantages like simple open-loop control and ease in changing movement direction.

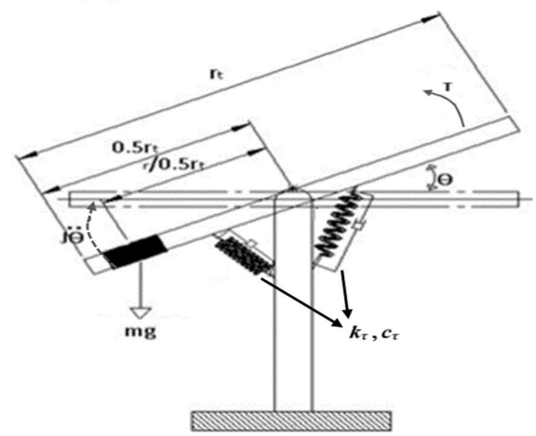


Fig. 3 Schematic of solar tracking system with additional mass

Using the expression for mass rotating with a small angle θ, the torque can be expressed as:

$$J\ddot{\theta} + c_\tau\dot{\theta} + k_\tau\theta = \tau \qquad (1)$$

Where τ is the torque (Nm), k_τ is the equivalent rotational stiffness (Nm/rad), c_τ is the torsional damping coefficient (Nm/rad/sec) obtained from inherent damping, J is the moment of inertia of the solar panel (kgm^2), $\dot{\theta}$ is the angular velocity and $\ddot{\theta}$ is the angular acceleration. An additional mass *m* (kg) placed a certain distance from the equilibrium point *r* (m) will cause the system to move by angle θ . The torque on the solar panel due to the added mass can be specified as:

$$\tau = mgrcos\theta \qquad (2)$$

Additional mass values (m) and equivalent rotational stiffness (k) were obtained using statics analysis [29]. Thus, the mass used for the system to traverse the required path should have its weight relative to the solar panel m/mp (%) and a distance from the symmetrical axis relative to half the trajectory r/0.5r_t (%).

3. MATERIAL AND METHODS

3.1 Specifications

This study proposes a technique for controlling solar panel orientation using imbalanced gravitational forces on the solar panel due to the movement of the added mass.

Centre of mass positioning works using energy-efficient, practical, and easy to operate stepper motor based electric drive. This electric drive is not the prime mover of the solar tracker. Therefore, it does not work against the solar trackers. However, it works against a mass that is lighter than the weight of the solar panel. It is expected that this working mechanism ensures higher solar panel energy efficiency. Figure 4 depicts the stepper motor-based ball screw mechanism used for this study. The NEMA17HS4401 stepper motor is used with the A4988 stepper driver. The Arduino Uno +CNC Shield controller uses the G-code programming language (computer numerical control (CNC) programming language), as shown in Figure 5. Tables 1 and 2 list the specifications of the stepper motor and solar panel used for this study.

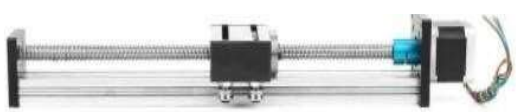


Fig. 4 Ball screw with stepper motor mechanism for solar tracker

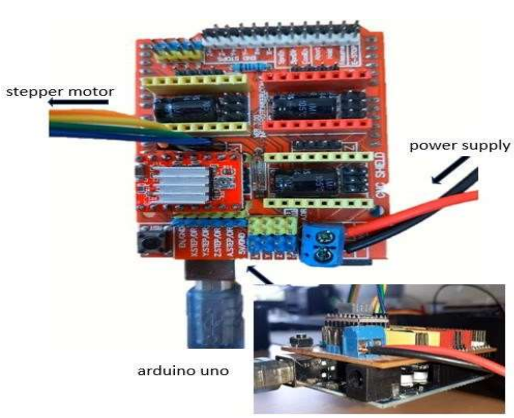


Fig. 5 Arduino Uno +CNC Shield controller

Table 1 Stepper motor specifications

Specifications	Indicator
Colour	Silver + Black
Materials	Aluminium Alloy
Size	650 x 64 x 50 mm
Slide Width	78 mm
Number of Sliders	1
Horizontal Load	56 kg
Vertical Load	15 kg
Current	1.2 A
Voltage	12 V
Resistance	3.2 Ohms
Step Angle	1.8°
Torque	45 N.cm
Accuracy	0.1 mm

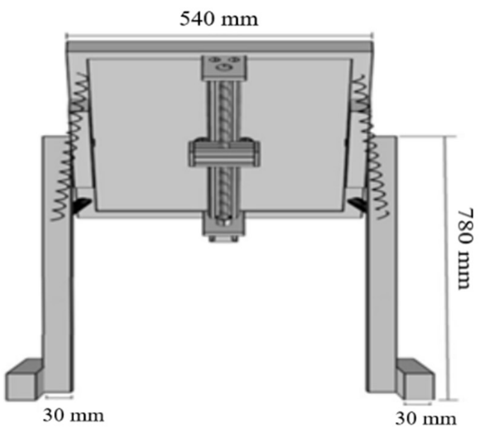
Table 2 Solar panel specifications

Performances	Indicator
Peak Power (Pmax)	50 W
Cell Efficiency	16.93%
Max. Power Voltage (Vmp)	17.8 V
Max. Power Current (Imp)	2.81 A
Open Circuit Voltage (Voc)	21.39 V
Short Circuit Current (Isc)	3.03 A
Power Tolerance	± 3%
Max. System Voltage	1000 V
Operating Temperature	-4°C to 85°C

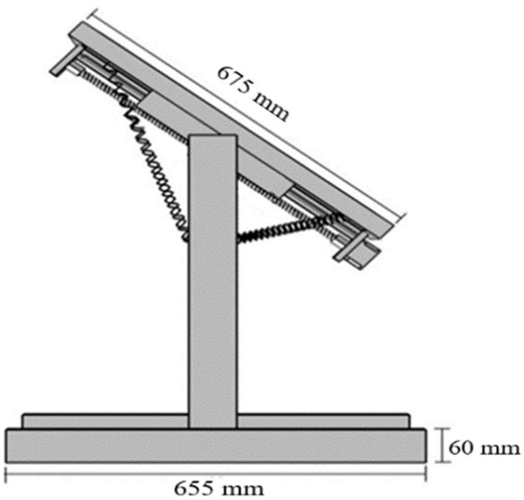
3.2 Design

The semi-active control for the solar panel orientation control platform will be implemented with mass and spring stiffness parameters. The mass added to the platform has a variable position, and the stiffness is set constant. The design of the solar tracker system in this study is shown in Figure 6. An additional mass is placed on the ball screw connected directly to the stepper motor. The added mass can be replaced by different weights, as needed. The mass position is changed by adjusting the stepper motor via the stepper driver with the Arduino Uno controller and the CNC Shield.

Mass position shift occurs in five positions, ranging from 1 to 5. Every position comprises two hours of stop time. The distance between any two positions is 10 cm, adjusted to the length of the track on the ball screw. Any change in mass position changes solar panel orientation, as shown in Table 3. Solar panel voltage and current are measured between 07:00 am and 04:30 pm. Solar tracker voltage and current measurements are needed to determine the effectiveness of additional mass in the tracking system.



a. Bottom view



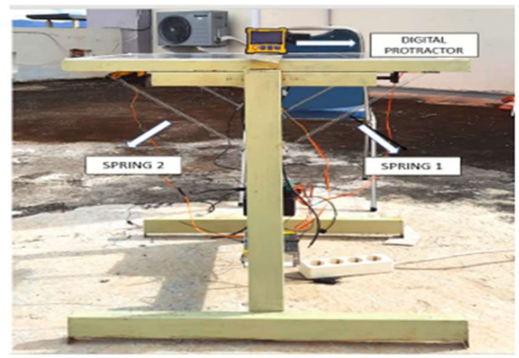
b. Side view

Fig. 6 Solar tracking system design with additional mass

3.3 Experimental Setup

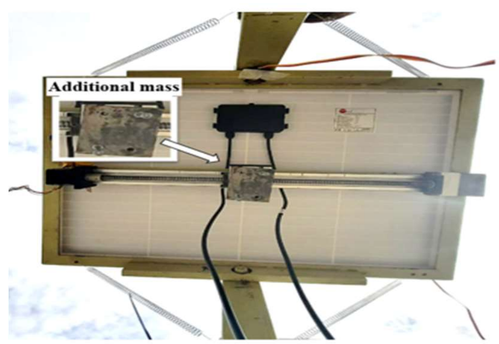
Two solar panels rated 50 Wp were used for this experiment. One panel was installed in a fixed position; no orientation change between 07:00 am and 04:30 pm. This panel was installed to measure output.

This experiment was started by adjusting the load position to the ratio between the additional mass and solar system weight (m/mp) = 30%. The five mass positions were separated by 10 cm each. Distance (r) is relative to half the trajectory length (r/0.5rt). This position change is implemented based on time settings. Mass displacement causes a change in solar panel orientation. Spring stiffness is k=200 N/m. It is determined based on the force in the solar panel system due to the angular acceleration caused by an additional 2 kg mass. This experiment uses a digital protractor for measuring the angle at every position. The complete schematic of the solar panel with the added mass position is shown in Figure 7.



a. Position view

b. Side view at 12.42^0



c. Bottom view

Fig. 7 Experimental setup of the solar system with an additional mass tracking system

This experiment aims to ensure the stepper motor-based ball screw used in the solar tracker mechanism has low energy consumption and is unaffected by additional mass and positional change. Therefore, the experimental setup was carried out by varying the additional mass by ½ kg, 1 kg, and 2 kg or m/m_p, equivalent to 7.5%, 15% and 30%.

4. RESULTS AND DISCUSSION

The ball screw based solar tracker was used to install a solar panel. An identical 50 Wp solar panel was installed and measured simultaneously. Experimental results like the voltage, current, and power consumption for stepper motor operation are specified in Table 3.

Table 3 Experimental results for the stepper motor

Position	Change Position Time (s)	Voltage (V)	Current (A)	Power (W)	Angle (^{0})
1-2	20.38	9.31	0.63	5.87	24.06
2-3	20.18	9.30	0.63	5.87	12.42
3-4	20.26	9.31	0.63	5.87	00.30
4-5	20.27	9.30	0.63	5.87	13.80
5-1	61.20	9.40	0.62	5.87	26.30

The operating time of the stepper motor at each additional mass position indicates the corresponding energy consumption. All position pairs are separated by the same distance, as described in the design section. The position shift from five to one shows a west-east change in solar panel position during noontime. Figure 8 depicts a schematic of the additional mass positioning.

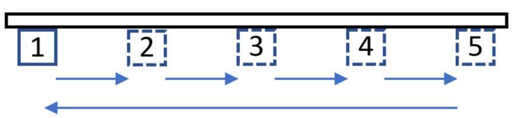


Fig. 8 Additional mass positioning scheme

Table 3 shows that the stepper motor consumed 5.87 W average power. This motor operates based on a predetermined time setting only during the additional mass transfer process. Experimental results indicate that the power required by the stepper motor is not affected by the increase in the mass and mass position in the trajectory. The results show that the stepper motor rotates the ball screw, not directly driving the solar panel platform. This strategy is better for reducing actuator energy consumption by adjusting solar panel orientation using minimal power. Solar panel output power is measured between 07.00 am and 04.30 pm. The results of these measurements are shown in Figures 9, 10, and 11.

Furthermore, Table 4 describes that the power required by the stepper motor is unaffected by the added mass and trajectory position. Experimental data shows that the stepper motor in the semi-active tracking mechanism application is effective. The average output power of the tracking system is 7.01 W (66.58 Wh) more than the fixed system power of 5.79 W (55.03 Wh). Efficiency improvement using a tracker system can be calculated by comparing output power differences. Thus, a tracker system provides 21% more efficiency than a fixed system. The energy consumption of the stepper motor is 0.14 Wh, or 0.21% of the energy generated by the tracker system, as shown in Table 3.

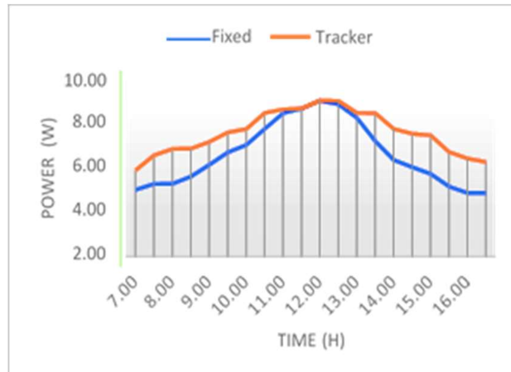


Fig. 9 Solar panel power output for fixed and tracking systems

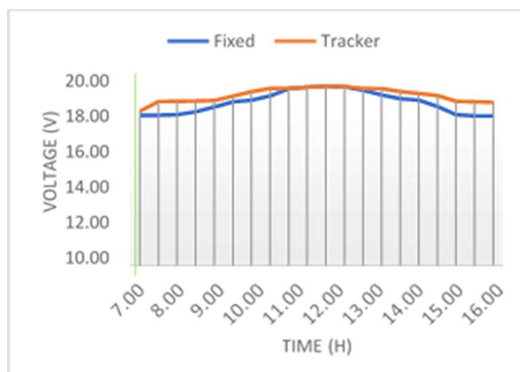


Fig. 10 Solar panel output voltage comparison for fixed and tracker systems

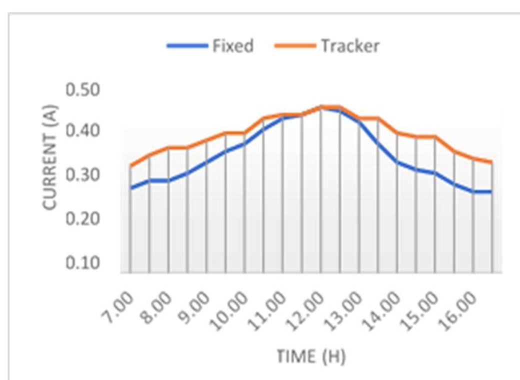


Fig. 11 Solar panel current comparison for fixed and tracker systems

Table 4 Stepper motor power consumption for different additional mass values

Position	m/mp=7,5%			m/mp=15%			m/mp= 30%		
	Current (A)	Voltage (V)	Power (W)	Current (A)	Voltage (V)	Power (W)	Current (A)	Voltage (V)	Power (W)
1-2	0.12	12.50	1.50	0.12	12.50	1.50	0.12	12.50	1.50
2-3	0.13	12.28	1.60	0.12	12.28	1.60	0.13	12.28	1.60
3-4	0.14	12.42	1.74	0.14	12.42	1.74	0.14	12.43	1.74
4-5	0.16	11.52	1.96	0.15	11.52	1.96	0.17	11.52	1.96
5-1	0.24	11.51	2.76	0.23	11.51	2.76	0.24	11.52	2.76

These results indicate that the power consumption of the tracker system is less than [27], which is then an alternative solution for developing a solar tracker system with low actuator power consumption.

5. CONCLUSION

This study contributes to the body of knowledge by comparing solar panel performance with and without a tracking system. An additional-mass based solar tracker provides 21% more power output than the fixed system during the measurement period. The results show that the power consumption of the stepper motor as an actuator is 0.14 Wh or 0.21% of the power generated using the tracker system.

These results indicate that implementing the stepper motor on the tracking mechanism is effective. This study lists solutions implemented for active and passive solar tracking. Additionally, the experimental results complement the simulation in [29] using the semi-active control method with mass, stiffness, and damping used as the dynamic parameters.

6. ACKNOWLEDGMENTS

The authors would like to thank Lembaga Penelitian dan Pengabdian Masyarakat Universitas Negeri Padang for funding this work with a contract number : 1577/UN35.13/LT/2020.

7. REFERENCES

[1] Alexandru C. and Tatu N.I., “Optimal design of the solar tracker used for a photovoltaic string,” *J. Renew. Sustain. ENERGY*, vol. 5, 2013.

[2] Juang J. and R. Radharamanan, “Design of a Solar Tracking System for Renewable Energy,” 2014.

[3] Ayvazyan G.Y., Kirakosyan G. H. and Vardanyan A. H., “Maximum Power Operation of PV system using fuzzy logic control,” *Armen. J. Phys.*, vol. 1, 2008.

[4] Singh G. K., “Solar power generation by PV (photovoltaic) technology : A review,” *Energy*, vol. 53, 2013, pp. 1–13.

[5] Eke R. and Senturk A., “Performance comparison of a double-axis sun tracking versus fixed PV system,” *Sol. Energy*, vol. 86, no. 9, 2012, pp. 2665–2672.

[6] Clifford M. J. and Eastwood D., “Design of a novel passive solar tracker,” *Sol. Energy*, vol. 77, no. 3, 2004, pp. 269–280.

[7] Nsengiyumva W., Chen S.G., Hu L. and Chen X., “Recent advancements and challenges in Solar Tracking Systems (STS): A review,” *Renew. Sustain. Energy Rev.*, vol. 81, no. April, 2018, pp. 250–279.

[8] Ya'u J. M., A Review on Solar Tracking Systems and Their Classifications,” *J. Energy, Environ. Chem. Eng.*, vol. 2, no. 3, 2017, pp. 46–50.

[9] Poulek V., “Testing the new solar tracker with shape memory alloy actuators,” *Conf. Rec. IEEE Photovolt. Spec. Conf.*, vol. 1, 1994, pp. 1131–1133.

[10] León N., García H. and Ramírez C., “Semi-passive solar tracking concentrator,” *Energy Procedia*, vol. 57, 2014, pp. 275–284.

[11] Brito M. C., Pó J. M., Pereira D., Simões F., Rodriguez R. and Amador J. C., “Passive solar tracker based in the differential thermal expansion of vertical strips,” *J. Renew. Sustain. Energy*, vol. 11, no. 4, 2019.

[12] Beltrán A. J., González J. L., Rubio S. and García-Beltrán C. D., “Design, manufacturing and performance test of a solar tracker made by a embedded control,” *Electron. Robot. Automot. Mech. Conf. CERMA 2007 - Proc.*, , 2007, pp. 129–134.

[13] Tudorache T. and Kreindler L., “Design of a Solar Tracker System for PV Power Plants,” *Acta Polytech. Hungarica*, vol. 7, no. 1, 2010, pp. 23–39.

[14] Chin C.S., Babu A. and Mcbride W., “Design, modeling and testing of a standalone single axis active solar tracker using MATLAB/ Simulink,” *Renew. Energy*, vol. 36, no. 11, 2011, pp. 3075–3090.

[15] Sharma P. and Malhotra N., “Solar Tracking System Using Microcontroller,” in *Proceedings of 2014 1st International Conference on Non Conventional Energy (ICONCE 2014)*, 2014, pp. 77–79.
[16] Abdulrahman A., Al-Nehari H.A., Almakhlafy A.N. and Baggash M., “Design and Implementation of Solar Tracking System,” *Int. J. Eng. Tech. Res.*, vol. 4, no. 1, 2016, pp. 71–75.
[17] Yandi W., Syafii S., and Pulungan A.B., “Tracker Tiga Posisi Panel Surya untuk Peningkatan Konversi Energi dengan Catu Daya Rendah,” *J. Nas. Tek. Elektro*, vol. 6, no. 3, 2017, pp. 159-167.
[18] Konar A. and Mandal A. K., “Microprocessor based automatic sun tracker,” *IEE Proc. A Phys. Sci. Meas. Instrumentation. Manag. Educ. Rev.*, vol. 138, no. 4, 1991, pp. 237–241.
[19] Syafii, Son L., Pulungan A.B. and Asni N. “Design of compact raspberry pi based tracker to improve conversion efficiency of solar energy,” *Int. J. Adv. Trends Comput. Sci. Eng.*, vol. 8, no. 6, 2019, pp. 3171–3175.
[20] Pulungan A. B., Risfendra R., Purwanto W., Maksum H. and Setiawan O., “Design and Development of Real Time Monitoring Single Axis Solar Tracker By Using Internet of Things,” *Int. J. GEOMATE*, vol. 18, no. 69, 2020, pp. 81–87.
[21] Roth P., Georgiev A. and Boudinov H., “Design and construction of a system for sun-tracking,” *Renew. Energy*, vol. 29, 2004, pp. 393–402.
[22] Sumathi V., Jayapragash R., Bakshi A. and Kumar P., “Solar tracking methods to maximize PV system output – A review of the methods adopted in recent decade,” *Renew. Sustain. Energy Rev.*, vol. 74, no. February 2016, 2017, pp. 130–138.
[23] Mwithiga G. and Kigo S. N., “Performance of a solar dryer with limited sun tracking capability,” vol. 74, 2006, pp. 247–252.
[24] Pulungan A. B., Son L. and Syafii, “A Riview of Solar Tracking Control Strategies,” in *EECSI*, 2018, pp. 631–635.
[25] Al-mohamad A., “Efficiency improvements of photo-voltaic panels using a Sun-tracking system,” *Appl. Energy*, vol. 79, 2004, pp. 345–354.
[26] Huang B.J., Ding W.L. and Huang Y.C., “Long-term field test of solar PV power generation using one-axis 3-position sun tracker,” *Sol. Energy*, vol. 85, no. 9, 2011, pp. 1935–1944.
[27] Cristian G., Longo M., Roscia M. and Pagano M., “Comparative analysis of fixed and sun tracking low power PV systems considering energy consumption,” *ENERGY Convers. Manag.*, vol. 92, 2015, pp. 143–148.
[28] Liu Y., Matsuhisa H. and Utsuno H. “Semi-active vibration isolation system with variable stiffness and damping control,” *J. Sound Vib.*, vol. 313, no. 1–2, 2008, pp. 16–28.
[29] Pulungan A.B., Son L., Huda S., Syafii, and Ubaidillah, “Semi active control of solar tracker using variable position of added mass control,” *2019 16th Int. Conf. Qual. Res. QIR 2019 - Int. Symp. Electr. Comput. Eng.*, 2019, pp. 1–5.
[30] Azadi M., Behzadipour S. and Faulkner G., “Performance analysis of a semi-active mount made by a new variable stiffness spring,” *J. Sound Vib.*, vol. 330, no. 12, 2011, pp. 2733–2746.