A Comparative Experimental Performance Analysis for Fixed Solar PV Systems and Solar Tracker PV Systems in a Tropical Region

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ABSTRACT

Solar photovoltaic (PV) systems promise a reliable future for renewable energy adoption, with the capability for mitigating greenhouse gas emissions and combating climate change while providing a sustainable energy solution to the planet. This study investigates the efficiency of solar tracking technology in tropical regions, focusing on Sri Lanka, which is an island located near the equator. In this study, a comparative performance analysis of a fixed-ground mounted solar PV system and a solar tracking PV system was conducted under identical system conditions and environmental conditions. The power output, operating temperature, short circuit current (I_{sc}), open circuit voltage (V_{oc}) data were collected continuously for 11 hours for both systems with 5-minute time intervals. The experimental results show a significant enhancement of the electrical power output of the solar tracking PV system compared to fixed-ground mounted solar PV systems. The average power output enhancement was 14.46% and the study also observed a 4.43% higher solar panel operating temperature in solar tracking PV systems. Results show that the single-axis solar tracking PV system consistently outperforms the fixed-ground mounted system, particularly in the morning and evening, due to its ability to maintain perpendicular sunlight incidence.

Key Words: solar photovoltaics, solar tracking technology, ground mounted solar PV systems, PV efficiency enhancement

INTRODUCTION

Solar PV systems are a promising renewable energy source that provides solutions to the global energy crisis while acting as a green energy source by reducing greenhouse gas emissions and the effects of climate change. Solar PV systems work by directly converting sunlight into electrical power using semiconductor materials and there are several parameters that affect the efficiency of solar PV panels such as solar irradiation, ambient temperature, wind speed, type of solar PV installation, etc [1][2]. PV solar panels can be installed in many ways such as fixed ground mounted, fixed rooftop mounted, ground mounted with solar tracking system, floating solar system, building integrated solar PV systems, etc [3]. The fixed solar photovoltaic systems are typically mounted with a fixed angle, aligned to north in the southern hemisphere and aligned to south in the northern hemisphere. But, tracking solar PV systems track the path of the sun to collect more sunlight and generate more electricity during the day. Solar tracking systems are becoming increasingly popular in tropical countries where the sun's path is comparatively vertical and there is year-round high solar irradiation. Solar tracking PV systems can be basically divided into two categories, single-axis solar tracking systems and dual-axis solar tracking systems. Single-axis solar tracking systems track the movement of the sun in one direction, usually east-west, and dual-axis solar tracking systems track the movement of the sun in both the east-west and north-south directions. According to experimental studies, solar tracking systems can significantly improve the energy output of solar PV systems in tropical countries. The main advantages of solar tracking systems are: in tropical nations, solar tracking systems have the potential to produce up to 30% more electricity than fixed solar photovoltaic systems, and solar tracking systems can operate more efficiently in low light on cloudy, morning, and evening days, also solar tracking systems can help to reduce the risk of solar PV panels overheating, hence increasing their lifespan and performance. The main disadvantages of solar tracking systems are: that the cost of solar tracking systems is higher than that of fixed PV solar systems compared to fixed solar PV systems, installing and maintaining solar tracking systems is more challenging compared to a fixed solar PV system. For tropical countries that receive a lot of solar radiation, solar tracking systems can be a worthwhile investment despite their high cost and complexity. The higher initial cost of solar tracking systems may be more than offset by higher power output and improved low-light performance. There are several researches conducted on solar tracking systems performance in recent years in many areas around the globe [4]-[8]. In this study, two identical solar PV pilot systems were developed and a comparative performance analysis was conducted providing identical environmental parameters. The results of this research will help to understand the performance of solar PV tracking systems in tropical countries located near the equator and also to improve the design and performance of solar tracking systems and reduce their initial installation cost. In this article, section 02 discusses the methodology, section 03 presents the results and discussion, and section 04 discusses the conclusions of this study.

METHODOLOGY

The first phase of the procedure was to conceptualize the design of the solar tracker system. The tracker system's structure and operation principle were modeled 3D using SolidWorks software. SolidWorks software generated a 3D computer model of the structural frame using GI box bar sections for supporting and rotationally moving the solar panel via tracking axes. This approach made it easier to visualize and optimize the initial design, and to validate the operation principle before hardware implementation.

Fig 1: Final design of the solar PV mounting structure

Fig 2. is an image of the implementation of the mounting structure and the solar panel. Fig 3. displays the mechanical method used for the solar tracker using a gearbox that was designed to rotate the shaft attached to the solar PV panel mounting structure, and a NEMA 23 stepper motor was used to rotate it. The control system was developed as a time based solar tracker system without irradiance detection sensors. A control unit was developed using an Arduino microcontroller to control the operation of the NEMA 23 stepper motor. The control program used was a customized program written in the Arduino IDE to control the rotation degree movements of each stepper motor in precise increments to keep the rotation of the solar panel accurate, tracking the path of the sun. The parameters such as rotation velocity, steps for a rotation, maximum rotation angle were considered in developing the time-based control algorithm. The final experimental setup was developed following the initial design developed through SolidWorks as shown in Fig 1.

Fig 2: Developed solar PV mounting structure

As shown in Fig 3., the NEMA 23 stepper motor was coupled to a matching high-precision profiler shaft supported by bearings, providing precision movement controlled by an Arduino UNO microcontroller.

Fig 3: NEMA 23 stepper motor coupled with the shaft

For parameterized tracking, specific turning parameters were included in the Arduino control code to specify the number of motor steps per tracking rotation, specific degree increments for each movement, rotation velocity, and timing between movements for smoothly responsive automatic solar tracking.

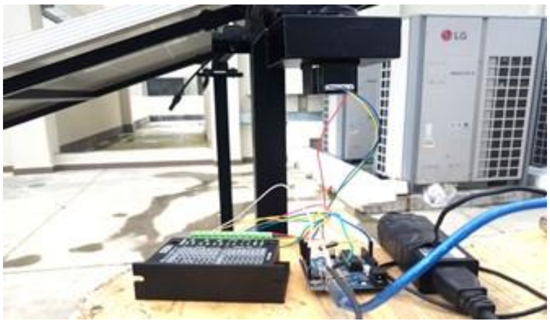


Fig 4: Solar tracker system with Arduino controller

Arduino control code was assembled and programmed to operate with full-scale functional design with all structural, mechanical, electrical and electronic components integrated mounting structure. Another similar experimental setup was developed with identical system parameters to conduct and comparative analysis between two technologies. Both the systems were located at Faculty of Technology, Sabaragamuwa University of Sri Lanka and measurements were obtained under identical environmental and system parameters. analysis of power output between fixed and tracking solar PV systems revealed compelling differences throughout the day.

RESULT AND DISCUSSION

The power output, operating temperature, open circuit voltage (V_{oc}) and short circuit current (I_{sc}) data were collected continuously for 11 hours (7:00 AM to 6:00 PM) for both systems with 5-minute time intervals.

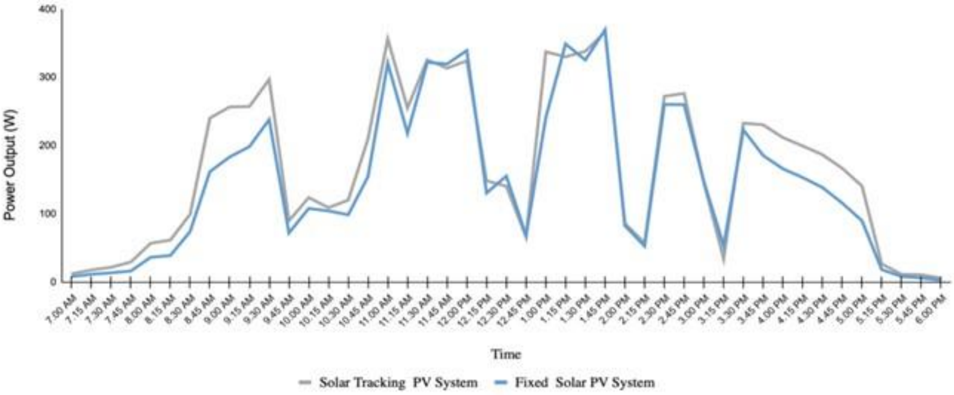


Fig 5: Power output data of solar tracking and fixed type solar PV systems

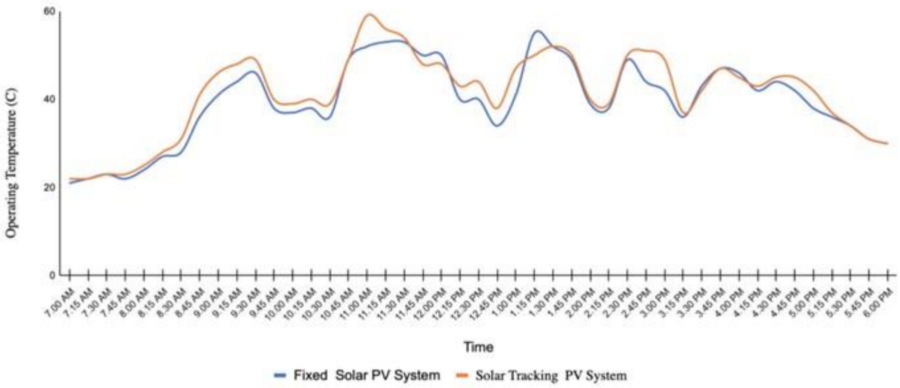
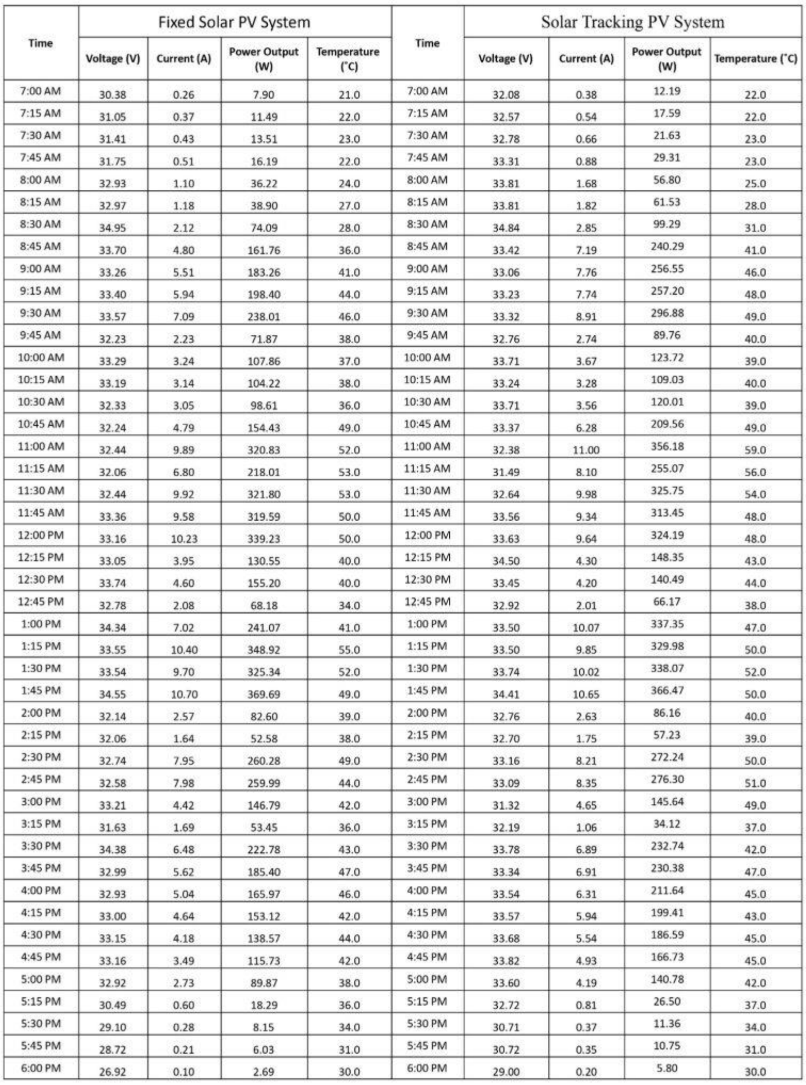


Fig 6: Solar panel operating temperature of solar tracking and fixed type solar PV systems

Fig 5. demonstrates the total power output of two solar PV systems under identical environmental conditions. During the morning period (7:00 AM to 10:00 AM) and late afternoon period (3:00 PM to 6:00 PM), the solar system with the tracking mechanism has generated a comparatively higher power . The reason for better performance of the tracking system during these two periods can be justified with its ability to optimize panel orientation towards the sun, maximizing sunlight capture and thus power generation. The observed trends in power output, current generation, voltage levels, and surface temperature highlight the advantages of solar tracker-based systems over fixed systems in tropical environments. All the obtained data for the system parameters are presented in table 01.

Table 01: The complete data set obtained through the experimental procedure



Time	Fixed Solar PV System				Time	Solar Tracking PV System			
	Voltage (V)	Current (A)	Power Output (W)	Temperature (˚C)		Voltage (V)	Current (A)	Power Output (W)	Temperature (˚C)
7:00 AM	30.38	0.26	7.90	21.0	7:00 AM	32.08	0.38	12.19	22.0
7:15 AM	31.05	0.37	11.49	22.0	7:15 AM	32.57	0.54	17.59	22.0
7:30 AM	31.41	0.43	13.51	23.0	7:30 AM	32.78	0.66	21.63	23.0
7:45 AM	31.75	0.51	16.19	22.0	7:45 AM	33.31	0.88	29.31	23.0
8:00 AM	32.93	1.10	36.22	24.0	8:00 AM	33.81	1.68	56.80	25.0
8:15 AM	32.97	1.18	38.90	27.0	8:15 AM	33.81	1.82	61.53	28.0
8:30 AM	34.95	2.12	74.09	28.0	8:30 AM	34.84	2.85	99.29	31.0
8:45 AM	33.70	4.80	161.76	36.0	8:45 AM	33.42	7.19	240.29	41.0
9:00 AM	33.26	5.51	183.26	41.0	9:00 AM	33.06	7.76	256.55	46.0
9:15 AM	33.40	5.94	198.40	44.0	9:15 AM	33.23	7.74	257.20	48.0
9:30 AM	33.57	7.09	238.01	46.0	9:30 AM	33.32	8.91	296.88	49.0
9:45 AM	32.23	2.23	71.87	38.0	9:45 AM	32.76	2.74	89.76	40.0
10:00 AM	33.29	3.24	107.86	37.0	10:00 AM	33.71	3.67	123.72	39.0
10:15 AM	33.19	3.14	104.22	38.0	10:15 AM	33.24	3.28	109.03	40.0
10:30 AM	32.33	3.05	98.61	36.0	10:30 AM	33.71	3.56	120.01	39.0
10:45 AM	32.24	4.79	154.43	49.0	10:45 AM	33.37	6.28	209.56	49.0
11:00 AM	32.44	9.89	320.83	52.0	11:00 AM	32.38	11.00	356.18	59.0
11:15 AM	32.06	6.80	218.01	53.0	11:15 AM	31.49	8.10	255.07	56.0
11:30 AM	32.44	9.92	321.80	53.0	11:30 AM	32.64	9.98	325.75	54.0
11:45 AM	33.36	9.58	319.59	50.0	11:45 AM	33.56	9.34	313.45	48.0
12:00 PM	33.16	10.23	339.23	50.0	12:00 PM	33.63	9.64	324.19	48.0
12:15 PM	33.05	3.95	130.55	40.0	12:15 PM	34.50	4.30	148.35	43.0
12:30 PM	33.74	4.60	155.20	40.0	12:30 PM	33.45	4.20	140.49	44.0
12:45 PM	32.78	2.08	68.18	34.0	12:45 PM	32.92	2.01	66.17	38.0
1:00 PM	34.34	7.02	241.07	41.0	1:00 PM	33.50	10.07	337.35	47.0
1:15 PM	33.55	10.40	348.92	55.0	1:15 PM	33.50	9.85	329.98	50.0
1:30 PM	33.54	9.70	325.34	52.0	1:30 PM	33.74	10.02	338.07	52.0
1:45 PM	34.55	10.70	369.69	49.0	1:45 PM	34.41	10.65	366.47	50.0
2:00 PM	32.14	2.57	82.60	39.0	2:00 PM	32.76	2.63	86.16	40.0
2:15 PM	32.06	1.64	52.58	38.0	2:15 PM	32.70	1.75	57.23	39.0
2:30 PM	32.74	7.95	260.28	49.0	2:30 PM	33.16	8.21	272.24	50.0
2:45 PM	32.58	7.98	259.99	44.0	2:45 PM	33.09	8.35	276.30	51.0
3:00 PM	33.21	4.42	146.79	42.0	3:00 PM	31.32	4.65	145.64	49.0
3:15 PM	31.63	1.69	53.45	36.0	3:15 PM	32.19	1.06	34.12	37.0
3:30 PM	34.38	6.48	222.78	43.0	3:30 PM	33.78	6.89	232.74	42.0
3:45 PM	32.99	5.62	185.40	47.0	3:45 PM	33.34	6.91	230.38	47.0
4:00 PM	32.93	5.04	165.97	46.0	4:00 PM	33.54	6.31	211.64	45.0
4:15 PM	33.00	4.64	153.12	42.0	4:15 PM	33.57	5.94	199.41	43.0
4:30 PM	33.15	4.18	138.57	44.0	4:30 PM	33.68	5.54	186.59	45.0
4:45 PM	33.16	3.49	115.73	42.0	4:45 PM	33.82	4.93	166.73	45.0
5:00 PM	32.92	2.73	89.87	38.0	5:00 PM	33.60	4.19	140.78	42.0
5:15 PM	30.49	0.60	18.29	36.0	5:15 PM	32.72	0.81	26.50	37.0
5:30 PM	29.10	0.28	8.15	34.0	5:30 PM	30.71	0.37	11.36	34.0
5:45 PM	28.72	0.21	6.03	31.0	5:45 PM	30.72	0.35	10.75	31.0
6:00 PM	26.92	0.10	2.69	30.0	6:00 PM	29.00	0.20	5.80	30.0

The surface temperature comparison between the fixed solar PV and tracking PV systems is as presented in Fig: 6, indicates potential differences in thermal characteristics. Understanding these differences could provide insights into thermal management strategies and overall system efficiency.

CONCLUSIONS

The solar tracking PV system and fixed solar PV systems were provided identical environmental and system conditions to conduct this comparative performance analysis. A significant observation is the performance improvement during the morning session (7.00 AM to 9.15 AM) and evening session (3.45 PM to 6.00 P.M) compared to the difference during the day time. The main reason for this is, the solar tracking system was able to capture the sunlight perpendicularly by using an optimized solar panel position angle during the morning and evening sessions. At that time, the increase in the angle of sunlight falling on the fixed solar PV system also led to more observation on the operation temperature difference between these two systems. The average power output enhancement was 14.16% and the study also observed a 4.43% higher solar panel operating temperature in solar tracking type PV systems. The results obtained through this experimental comparison demonstrate the significant performance benefits of solar tracker PV systems over fixed systems in a tropical region.

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