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Performance Enhancement of a Solar Photovoltaic System Using Photovoltaic Thermal Integration



Abstract - The performance of solar photovoltaic (PV) systems is significantly affected by variations in solar irradiance and operating temperature, particularly in hot climatic regions. The goal of this research is to develop a prototype of a solar tracking system with integration of thermal photovoltaic (PV/T) system, which is able to enhance the performance of the solar photovoltaic modules in a solar energy system. The operating principle of the device is to keep the photovoltaic modules constantly aligned with the sunbeams, which maximizes the exposure of solar panel to the Sun's radiation. As a result, more output power can be produced by the solar panel. After successful completion of a solar tracking system, we integrate the hardware model of solar thermal photovoltaic using heat exchanger on the dual axis solar tracker. The results demonstrate that the PV/T system consistently outperforms the conventional static PV system. An average temperature difference of 3.1 °C between inlet and outlet water confirms effective heat removal. The PV/T configuration achieves an average improvement of 3.7% in open-circuit voltage, 3.1% in short-circuit current, and an overall 6.23% increase in output power, with a maximum power enhancement of 8.04% compared to the static PV system.

Keywords: Solar photovoltaic, Photovoltaic thermal (PV/T) system, Dual-axis solar tracking, Solar energy efficiency, Thermal cooling, Experimental analysis

1. Introduction

The best energy compared to all the energies is the solar energy and even in the bad weather conditions it is possible to use the solar energy even in the seasons when there are clouds. "The amount of solar energy that gets to the earth in a single instance is approximately 10,000 times more than the rate of energy consumption that mankind is presently utilizing. The solar technologies can be used to provide heat, cooling, natural light, electricity and fuels to numerous applications. The solar technologies utilize the sun rays to convert them into electrical power by the use of the photovoltaic panels or the solar radiation which is focused by the mirrors. The prices of manufacture of solar panels have occasionally reduced over the past decade and they are no longer expensive but, in most cases, cheapest source of electricity [1]. Nonetheless, the solar PV energy has not been witnessed in the market to introduce the traditional sources despite the benefits. It is still a problem of maximization of power production of the PV systems in places that are not well exposed to the solar radiation. More advanced technologies to enhance the capabilities of the PV materials are yet to be held by the manufacturers, but, system design and the manufacturing of modules can be improved as well, which is a viable solution, and therefore solar PV power will be efficient, and this makes it a better option on the part of the customers. Maximization of the time of exposure of the Sun is one of the primary ways of efficiency because at any point the PV solar panels are at their optimum angle with respect to the sun rays with the aid of Sun tracking systems. The present study aims

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at developing a prototype of the light tracking system on the smaller scale but the designs can be applied to any solar energy system in the real world. The alternative of the techniques of realizing the efficiency to low cell surface temperature reduced at low rates to obtain greater efficiency and supply extra power, by cooling surface of the solar panel with water by means of copper tube [2].

The Photovoltaic Thermal (PV/T) is a combination of the photovoltaic and solar thermal. This technique has the advantage that it utilizes light and heat of the solar radiation in generation of electricity and hot fluids. The field of PV/T system is undergoing boom with new methodologies and techniques to empower the system to be more efficient and cheaper besides modelling and long period of operational use and viable application of the systems. The solar PV cells are also temperature sensitive as are all the other semiconductor devices. The band gap energy of the semiconductor material diminishes as the temperature increases thus the voltage decreases greatly and current is comparatively constant. In this relation, the effectiveness of ultrafine silicon solar cell in transforming energy reduces by approximately 0.3 percent as the product temperature is raised by 1 °C. The solar cell temperature may reach up to 50 °C above operating temperature and any effects of the high operating temperature is irreversible loss of cell efficiency and structural damage of the solar panel in case the thermal load is continued longer [4].

Literature of dual axis tracking and solar photovoltaic thermal system are utilized in order to unveil the efficiency. “The one of the designs was outlined by M.M Aji et.al which was a simulation of two axis solar tracker in which the solar module moved freely in two axis of rotation in order to achieve the maximum amount of solar energy possible by tracking the movement of the sun between east and West and north and south. The programming of the artificially modified tracking system is programmed into an adaptive tracking system with the help of closed-loop monitoring and Light Dependent Resistor (LDR) sensors as the inputs of the device, servo motors as the adjusters of the module, Arduino Uno as the brains of the device. The proposed tracking device creates power in which the average increment is about 26-27 percent better than the fixed system of PV [5].” F. Afrin et.al proposed that dual axis solar trackers be used in place of the solar panel, a format and an implementation of microcontroller controlled azimuthaltitude dual axis solar tracker was proposed, which tracks the sun on the solar panel according to the direction the sunlight would strike the panel [6]. A. H. Al-Waeli et.al gave a simulation and realisation of the solar panel with two axis solar tracker. It was a study that entailed experimenting a simulation of a functioning form of Dual-axis solar tracker and a simulation of a solar panel attached to a Maximum power point tracker (MPPT), boost converter to the load and Inverter [7]. A. “The performance of Dual Axis Solar Tracker (DAST) was compared with the Static Solar System (SSS) or a fixed-axis solar system by Masih et.al to identify the solar power that can be produced in the Ural region in the Russian Federation [8]. M. saeedi et.al had the goal of designing and mounting a two-axis solar tracker (DAST) in order to enhance the power generation of the PV panel. It is a powerful system that is readily and transfers the PV panel in two directions based on the solar radiation. Lastly, the PV panel output power using solar tracker was identified to be higher than the fixed panel [9].” R. Due to the deliberation of a new ball-joint driving device as the tracking system, Ramful et.al narrowed down the concepts to create inexpensive and small solar tracker in order to utilize the complete solar power per square meter of photovoltaic cells”. The performance of the solar-tracking system (cost-effective) with innovative tracking system has demonstrated that the full utilization of the solar energy that is present in the tropical countries through the utilization of the small to medium size solar panels are feasible [10]. P. “This article by Rani et.al suggested that single axis tracking system is implemented with the help of solar photovoltaic (SPV) cells and attached to Arduino Uno so that the maximum power could be obtained in a day. This paper will use an automatic single axis area tracking system as the key aspect. The positioning of the solar panel to the Sunlight and maximum solar radiation are experimented. In the meantime, the proposed solution can determine axis in a relatively short period and with respect to sun-rays to achieve MPP as the output when the motors are driven at any speed [11] J.F. Lee et.al in this research paper presented a low-cost prototype of two-axis solar track system. In the prototype of two-axis solar tracker, there was an assumption that low cost and light sensors microcontroller will be used to monitor the movement of the sun and trace throughout the year [12]. R. Hossain et al. have proposed a new kind of a heat exchanger of solar PV and thermal (PV/T) hybrid systems as well as examined the system behavior. “The PV/T has been compared with the comparison of the same solar PV panel in the same outdoor condition at Dhaka, Bangladesh. The results of the experiment indicate that the mean value of open circuit voltage (Voc) improvement is 0.97 V and Voc improvement maximum value is 1.3 V. Moreover, the total increase of the output

capacity of solar PV panel is 2.5 W [13]. M. The performance of hybrid PV/T solar panels was studied by one of the studies by Baicenau et.al that were founded on a researched study that was conducted not only through experimental research but also simulation research. The experimental part is supposed to measure and compare electrical and thermal performance of PV/T and PV at constant solar irradiance and ambient temperature as well as determine temperature distribution across the collectors by using IR images.” The second aspect of the paper, the simulation part, will provide a test of the technical feasibility of integrating the experimented type of PV/T panel combo into a highly efficient prototype of a solar house, in the terms of comparing a reference system with a group of PV and solar thermal collectors to the one with PV/T panels”. [14]. O. E. Manssouri et.al gave a mathematical modeling of a type of bi-fluid photovoltaic/thermal PV/T solar collector and modeled it according to the MATLAB software. In addition, the work of four bi-fluid PV/T collectors was compared at the condition of an operating mode of simultaneous working with the varying cooling fluid (eg.air, water). As per the received results, water- water cooled PV/T collector is preferable due to its efficacy and 11.16 and 54.22 electrical and thermal efficiency respectively [15]. “M. The new system suggested by Marimuthu et.al is a new PV/T water system which was installed on the non-transparent cell panels with transparent photovoltaic panel. This paper is meant to discuss the disadvantages of the PV/T water systems within the market. The action undertaken gives improved performances in terms of electrical and thermal performances.” The experiment synthesis has been modelled with respect to the AUTOCAD software and implemented and coded through MATLAB SIMULINK software [16].

On the basis of literature survey, the objectives of this research are as follows:

- To integrate the solar photovoltaic thermal with dual axis solar tracking system.
- To increase the efficiency of solar PV system with the help of implementation of solar thermal system.

2. Working principle of Solar thermal photovoltaic system

The operation of solar photovoltaic is highly dependent on weather conditions like temperature, precipitation, air condition, and most importantly solar irradiance. Like all other semiconductor devices, solar PV cells are sensitive to temperature. With the increase in temperature, the band gap energy of semiconductor material gets reduced, so the current increases slightly but the voltage decreases significantly. Therefore, the energy conversion efficiency of silicon solar cell reduces about 0.3% when its temperature increases by 1°C. The working temperature of solar cell could be as much as 50°C above the ambient temperature and consequences of high working temperature are, drop in cell efficiency and permanent structural damage of the solar panel if the thermal stress remains for a longer period.

$$I_{\text{cell}} = I_0 - I_{\text{ph}} (e^{qV/KT} - 1) \quad (1)$$

Equation (1) shows how temperature is related to current and voltage of a solar cell, where I_0 is the dark current, I_{ph} is the photo current, q is the charge of electron, V is the voltage, K is Boltzmann’s constant, and T is the temperature. The simulation result based on the current in equation (1) of silicon solar cell shows that the voltage of the cell reduces noticeably when its temperature increases which is shown in figure 1. However, the increment of cell current due to temperature raise is negligible. Therefore, the output power of solar cell decreases with the increase in temperature.

When thermal energy system is integrated with the solar photovoltaic system, it is called the photovoltaic and thermal (PV/T) hybrid system. Since, the hybrid system utilizes same area for the production of electricity and heat energy, it increases the overall efficiency of the system in terms of energy generation from per unit area.

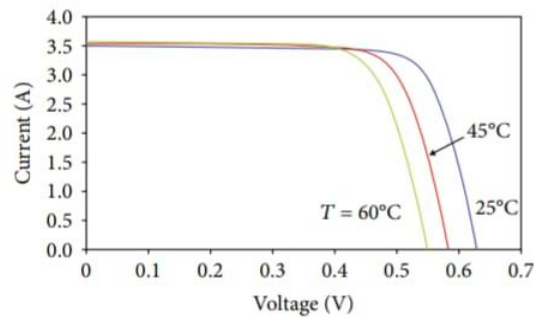


Fig 1: The impact of temperature on current and voltage of a solar cell [12].

3. Hardware implementation of Solar thermal photovoltaic system

In order to achieve the successful implementation of this research and design efficient system, we followed a structured methodology consisting of several steps. The first step was to conduct a software simulation to test the theoretical framework and identify potential issues or limitations. This allowed us to refine and optimize our design before proceeding to the next stage.

Once we had established a software simulation model, we proceeded to the hardware setup stage. This involved the selection of suitable hardware components and the integration of the PV/T into the existing system. We carefully tested and evaluated the performance of the hardware setup to ensure that it met the project requirements and performed optimally. Throughout the implementation and design process, we paid close attention to detail and conducted thorough testing and quality control measures. Hardware specifications of solar thermal PV/T system are shown in Table 1.

Table 1: Hardware specifications of solar thermal PV/T system

S.NO.	Component Name	Specification	Quantity
1.	Wooden Sheet	60*60 cm	1
2.	Battery	3.7 Volt	3
3.	ASMO motor	24 V, 5.3 RPM	2
4.	LDR	5-10 K Ω	4
5.	Arduino UNO	ATmega 328P	1
6.	Motor Driver (H-Bridge)	L298N	1
7.	LDR circuit	3.3V – 5V	4
8.	Solar panel	20 Watt	1
9.	Jumper Wire	Male to male	-
10.	Copper pipe	10mm	1

4. Results and discussion

Different parameters, water temperature at inlet and outlet of the PV/T system, voltage and current of the PV/T system and the normal solar PV system have been measured to evaluate performance of the systems shown in figure 2. The power output of the solar PV panels is calculated based the on the voltage and current readings. Temperature of water at inlet and outlet of the PV/T system, open circuit voltage, and short circuit current readings of the systems have been taken in every 30 min interval.



Fig.2: Measurement of voltage and current of solar thermal photovoltaic

The experimental measurements of inlet and outlet temperature of water, voltage, current & power are taken during the day of April 28, 2024 from 10:00 AM to 4:00 PM. It observed that at the beginning of measurements, radiation of the sun gradually increases to reach the maximum radiation at 12:00 noon. During the measurement we seen that the temperature of water is more at the outlet.

4.1 Performance analysis of the temperature of water at inlet and outlet of PV/T system

During the performance analysis of inlet and outlet temperature of water, it is seen that in most of the observations the temperature of water at outlet of the PV/T system is always higher than temperature of water at inlet of the system as shown in Figure 3. It indicates that the heat is effectively transferred from the PV/T system to the water when the water is circulating through the channels of the heat exchanger. The result shows that the heat exchanger works properly to transfer heat from the PV/T system to the circulation water and it should help to improve the electrical output of the PV/T system. The water flow rate is an important parameter to performance evaluation of the solar PV and thermal hybrid system. The water flow rate through the heat exchanger can be regulated by controlling the speed of the water pump. In our experiments, we have used normal water flow. The ambient temperature is lower compared to the water temperature at the outlet of the system.

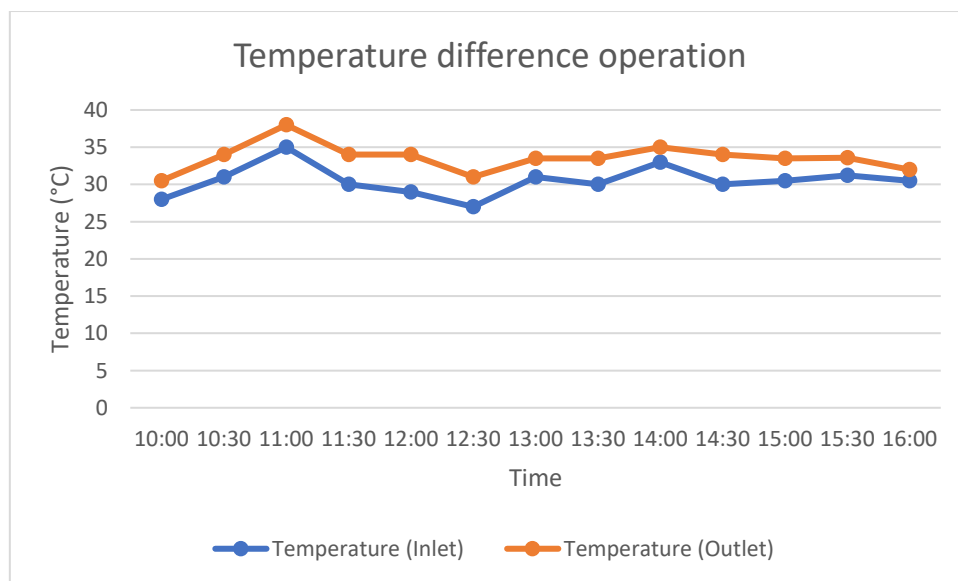


Fig 3: Performance analysis of water temperatures at inlet and outlet of thermal PV/T system

Table 2 shows that average temperature difference of water between outlet and inlet is 3.1°C, and maximum difference is more than 5°C. The performance of the PV/T system is better when the ambient temperature is lower compared to the water temperature at the outlet of the system.

Table 2: Performance analysis of the temperature of water at inlet and outlet of PV/T system

S.No.	Time	Temperature (Inlet)	Temperature (Outlet)	Temp. Difference
1	10:00	28°C	30.5°C	2.5°C
2	10:30	31°C	34°C	3°C
3	11:00	35°C	38°C	3°C
4	11:30	30°C	34°C	4°C
5	12:00	29°C	34°C	5°C
6	12:30	27°C	31°C	4°C
7	13:00	31°C	33.5°C	2.5°C
8	13:30	30°C	33.5°C	3.5°C
9	14:00	33°C	35°C	2°C
10	14:30	30°C	34°C	4°C
11	15:00	30.5°C	33.5°C	3°C
12	15:30	31.2°C	33.6°C	2.4°C
13	16:00	30.5°C	32°C	1.5°C

4.2 Performance comparison of static solar panel and photovoltaic thermal (PV/T) systems

This experimental work of design and efficiency improvement of a solar panel in the hot climate of Bundelkhand region enabled us to evaluate the enormous potential of solar energy (thermal and photovoltaic) for this region. The natural ventilation system has improved thermal efficiency. The performance comparison of static solar PV and photovoltaic thermal (PV/T) system on the basis of different electrical parameters like open circuit voltage, short circuit current and average power are shown in Table 3, Table 4, and Table 5 respectively, where it can be seen that average power in case of static solar PV and photovoltaic solar thermal PV/T system are 18.78W and 19.96W respectively. This installation of solar thermal PV/T have a higher total energy output. For the performance comparison of static solar panel and photovoltaic thermal (PV/T) systems, different parameters are measured which are as follows-

V_{OC} (PV) = Open circuit voltage of static PV

V_{OC} (PV/T) = Open circuit voltage of solar photovoltaic thermal (PV/T) system

I_{SC} (PV) = Short circuit current of static PV

I_{SC} (PV/T) = Short circuit current of solar photovoltaic thermal (PV/T) system

P (PV) = Power in static solar PV

P (PV/T) = Power in solar photovoltaic thermal (PV/T) system

Table 3: Voltage analysis of static solar PV and solar photovoltaic thermal (PV/T) system

S.No.	Time	VOC (PV) (Volt)	VOC (PV/T) (Volt)
1	10:00	20.2	20.8
2	10:30	20.1	21
3	11:00	20.1	20.9
4	11:30	20	20.9
5	12:00	20.1	21.1
6	12:30	20.1	21
7	13:00	19.8	21.2
8	13:30	19.3	20
9	14:00	19	19.8
10	14:30	19.7	20.2
11	15:00	20	20.5
12	15:30	20	20.2
13	16:00	20	20.1

Table 4: Current analysis of static solar PV and solar photovoltaic thermal (PV/T) system

S.No.	Time	Isc (PV) (Amp)	Isc (PV/T) (Amp)
1	10:00	0.88	0.92
2	10:30	0.92	0.96
3	11:00	0.97	1
4	11:30	1.01	1.03
5	12:00	1.02	1.05
6	12:30	1.03	1.04
7	13:00	0.99	1
8	13:30	1.04	1.04
9	14:00	1.03	1.03
10	14:30	1.01	1
11	15:00	0.85	0.88
12	15:30	0.8	0.85
13	16:00	0.77	0.8

Table 5: Power analysis of static solar PV and solar photovoltaic thermal (PV/T) system

S.No.	Time	P (PV) (Watt)	P (PV/T) (Watt)
1	10:00	17.77	19.13
2	10:30	18.49	20.16
3	11:00	19.49	20.9
4	11:30	20.2	21.52
5	12:00	20.5	22.15
6	12:30	20.7	21.84
7	13:00	19.1	21.2
8	13:30	20.07	20.8
9	14:00	19.57	20.39
10	14:30	19.89	20.2
11	15:00	17	18.04
12	15:30	16	17.17
13	16:00	15.4	16.08

Figure 4 shows that the average increment in open circuit voltage (V_{OC}) is 3.7% where the maximum increment in the open circuit voltage (V_{OC}) of solar photovoltaic thermal PV/T system is 7.07% as compared to static solar PV. Figure 5 shows that the average increment in short circuit current (I_{SC}) is 3.1% where the maximum increment in the short circuit current (I_{SC}) of solar photovoltaic thermal PV/T system is 2.95% as compared to static solar PV. The output power of both systems has been calculated from V_{OC} and I_{SC} readings. Figure 6 shows that there is an overall improvement in output power of the PV/T system in comparison to the existing PV system. The average increment in output power of the PV/T system is 6.23% more than exiting PV system, and maximum power increment is of the PV/T system is 8.04% more than exiting PV system.

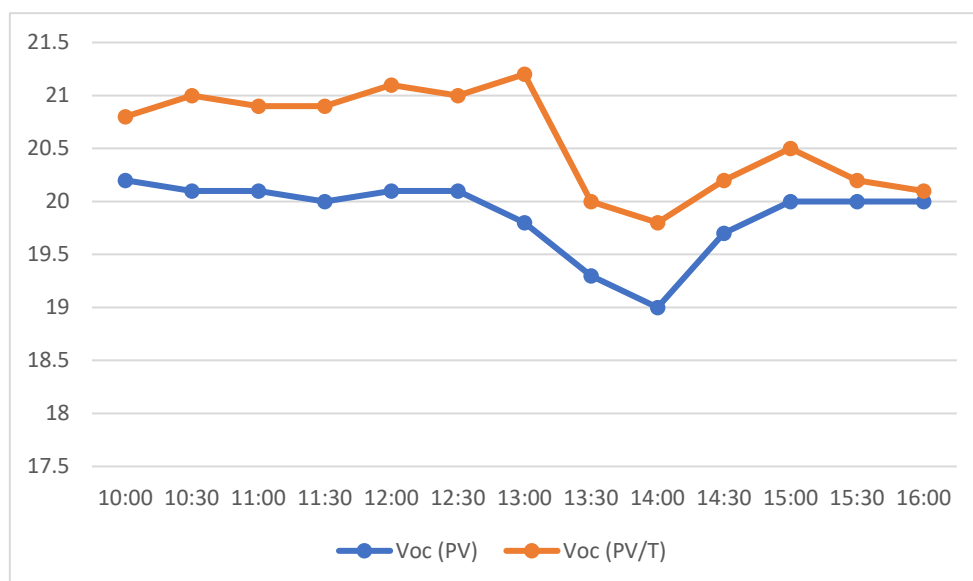


Fig 4: Comparison of open circuit voltages in static solar PV and solar photovoltaic thermal (PV/T) system

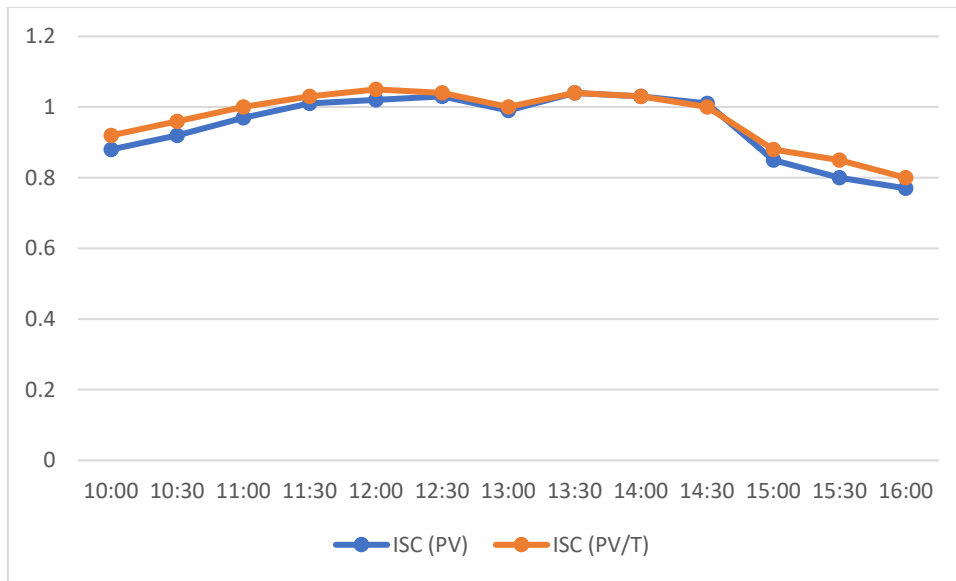


Fig 5: Comparison of short circuit currents in static solar PV and solar photovoltaic thermal (PV/T) system

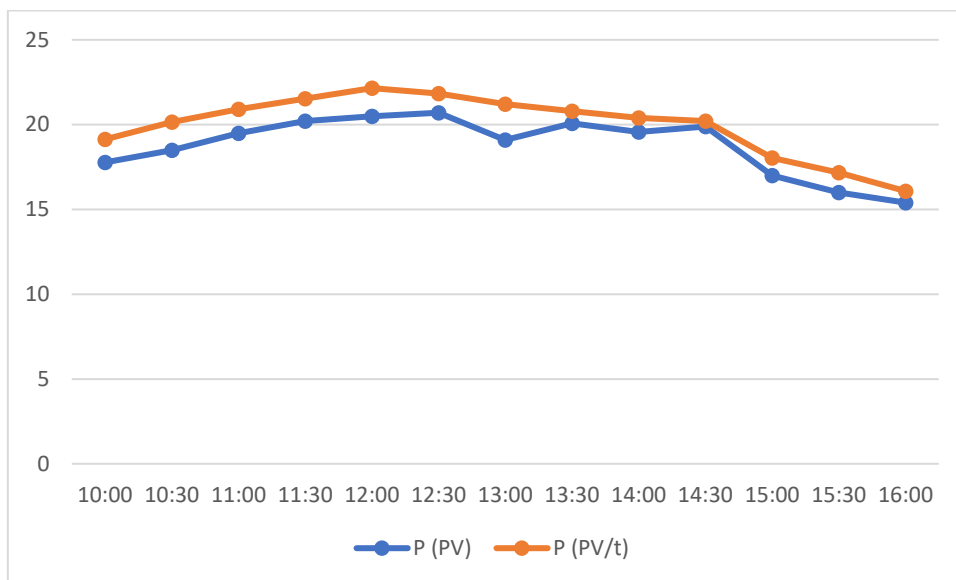


Fig 6: Comparison of output power in static solar PV and solar photovoltaic thermal (PV/T) system

5. Conclusion

The current project is based on static solar, dual axis tracking solar panels and photovoltaic thermal (PV/T) system. These panels change their orientation in relation to solar radiation to increase the efficiency and results in maximum production of energy and helps in getting full benefit of optimal angle between solar panels and solar radiations. The execution of solar tracking system was made clear because of our sufficient research and preplanning of our goals and objectives. The main agenda of this project is to achieve maximum power and efficiency of solar PV. Because the issue of global warming must be controlled by making use of alternatives that are environmental friendly. Photovoltaic Thermal (PV/T) system produces 6.23% more average power as compare to static solar PV.

6. Future Scope

Following future aspects related to this research are as follows-

- This project can be implemented as a completely automated system in future. By the use of dual axis tracking system solar PV can be flat in direction of flow of air. That can help to safeguard the solar plant Grid.
- In the newspaper “Hindustan Times” mentioned that due to high storm in state Madhya Pradesh, Khandwa district omkareshwar aisa largest floating solar panel were blown away in the storm. Solar plant Grid of 278 MW destroyed. That could be protected by dual axis solar tracking.
- The fluctuations in the output can be overcome using proper DC-DC converter. They can improve the steady-state accuracy by reducing the steady state error.
- Sometimes nonlinear type of controllers like fuzzy logic, fuzzy with PID controller and other types can also be studied and suitable one is included with the system.

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