DEVELOPMENT OF PHOTOVOLTAIC POWER SYSTEM FOR UNMANNED AERIAL VEHICLE (UAV)

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ABSTRACT

Over the past few years, interest in solar powered UAV has rapidly expanded across commercial, industrial, as well as governmental domains. This paper presents the development of photovoltaic power system for solar powered UAV. The purpose of this study is to develop a set of methodology for photovoltaic (PV) power system design on UAV. The study also perform parametric analysis and performance data collection on PV power system. The PV power system developed in this study is for fixed wing UAV with maximum takeoff weight (MTOW) of less than 1.2kg. First, solar simulator is built in order to provide a controlled test condition for the execution of experiment. The performance of solar simulator is evaluated in term of spatial non-uniformity and temporal instability, which is in class C (≤10%) and class B (≤5%) respectively, according to the ASTM standards. Next, the irradiance data at Skudai area (1.534⍰ N and 103.659⍰ E) is collected and plotted. The irradiance curve showed that maximum irradiance occur at 1pm under clear sky condition, with 960$W/$. After encapsulation and soldering of PV cells, experiment to study the current-voltage (I-V) characteristics of PV cells is carried out, where maximum power generated from PV power system can be predicted from the I-V curve. The power generated should be able to maintain a steady flight of UAV. However, the first version of PV power system has failed to meet the requirement, thus another improved design of PV power system is proposed. Performance of the improved design has been analysed and calculated, where the results proved that the improved design of PV power system able to provide enough power supply for steady cruise of solar-powered UAV.

KEYWORDS

photovoltaic power system, solar powered, UAV

INTRODUCTION

An unmanned aerial vehicle (UAV) is a flying robot, in other words can be defined as vehicles that operating on air autonomously or controlled telemetrically with no pilot on board [1]. Recently, there are concerns raising on the endurance capabilities of UAVs [2]. To address on this issue, increasing development and research of solar powered UAV has come to light. The photovoltaic (PV) cells are introduced into the system by mounting them on the fixed wing solar-powered UAV, collecting sun rays directly from the sun, then convert light energy into electrical energy. The solar power obtained from the PV cells can be used to propel the motor, power the electronics components, and recharge the batteries [3]. With proper design to ensure obtaining enough solar power from the sun, solar-powered UAV has conclusively been shown that able to redefine endurance capabilities.

Many end users choose UAV over conventional remote sensing technologies due to their benefits in terms of less power consumption, less risky, ease to data collection, and ultra-high spatial resolution [4]. They are widely used for several applications in both military and civil domains, such as minesweeping, monitoring, logistics and agriculture uses. Meanwhile, solar powered UAV can be employed in many missions such as topographical mapping, ozone monitoring, and collection of data for weather and global warming studies due to its cost effectiveness, environmental efficiency, and capable of long endurance flight and does not require much maintenance [5]. For instance, in 2002, the solar-powered UAV, Pathfinder-Plus used to collect high-spatial resolution, multispectral imagery of the Kauai Coffee Plantation, the largest coffee plantation in the USA. Imagery obtained is analyzed for the mapping of coffee field ripeness, and for the identification of drip irrigation problems and weed proliferation [6].

Until recently, the application of small scale solar powered UAV has seen sparse research activity and is only partially explored. A recent paper published by P. Oettershagen et. al. presents the detail design of AtlantikSolar, a small 6.9 kg hand-launchable low-altitude solar-powered UAV completed an 81-hours continuous flight [7]. Also, another paper by V. S. Dwivedi and J. Patrikar constitutes the detailed design, fabrication a low altitude long endurance solar powered UAV, MARAAL to be operated day-night in subtropical region [8]. There are other similar papers highlighted on the UAV design, electrical components, control system, payload. However, detailed studies on the propulsion system of UAV that solely based on solar energy are still insufficient and required more researches.

The development of PV power system for a 1.2kg solar-powered hand-launched, fixed wing UAV is the focus in this project. Optimization of the solar energy obtained is the prior study in this project, therefore the study on irradiance curve trend in Skudai area (1.534°N and 103.659°E), arrangement of PV cells and choosing the correct specifications of electronics components for the PV power system is critical. Next, parametric analysis and performance data collection is carried out on the solar-powered system. Solar simulator is built and experiments to study the I-V characteristics of PV cells are performed in the solar simulator. The power generated from the PV powered system is expected sufficient to maintain a steady flight of UAV. Performance analysis on the PV power system need to conduct to ensure the system has met the requirement. Table 1 shows the flight parameters of proposed UAV.

Table 1: Flight parameters of proposed UAV

Parameters	Values
MTOW	1.2kg
Type of wing	Plank flying wing
Type of airfoil	MH54
Surface area of airfoil (S)	0.299m^2
Airfoil chord (b)	0.26m
Aircraft Drag Coefficient	0.015

2.0 PERFORMANCE ANALYSIS

In a solar-powered UAV, PV cells are the primary source of energy to turn the motor. Theoretically, the power generated by PV cells is calculated using equation from Dwivedi *et al.*, 2018 [9] :

$$P_{PV} = \eta_{PV} \times \eta_{MPPT} \times S_{PV} \times G \quad (1)$$

where η_{PV} is the efficiency of PV cells used, η_{MPPT} is the efficiency of MPPT, S_{PV} is the total area of the PV cells installed, G is the available irradiance and P_{PV} is the power generated from PV cells. Also, the experimental value of power generated can be obtained from the power-voltage (P-V) curve, which is the power at maximum point, P_{MP}.

Next, Anderson, 2016 [10] is used as reference for the analysis of power required at steady climb. Figure 1 give general picture of steady cruise, which assist the power required calculation. Firstly, the lift coefficient can be predicted by using the lift equation, as shown below. In level flight, the aircraft lift is equal to the take-off weight. Given that L is lift, W is weight of UAV, ρ is surrounding air density, V is velocity, S is surface area of airfoil.

$$C_L = \frac{2L}{\rho V^2 S} = \frac{2W}{\rho V^2 S} \qquad (2)$$

Given the drag polar of the UAV wing is given by

$$C_D = C_{D,W} = C_{Do,W} + \frac{{C_L}^2}{\pi ARe} \qquad (3)$$

where $C_{D,W}$ is the coefficient drag of wing, $C_{Do,W}$ is the zero lift drag of wing, and e is the efficiency factor. The fuselage drag component for a lightweight UAV is not accounted since the value is very small [11].

The drag can be computed now using drag equation.

$$D = \frac{1}{2}\rho V^2 S C_D \qquad (4)$$

From Figure 1, thrust T is assumed to be aligned with flight path and UAV is flying at sea level. Summing up forces parallel to the flight path, thrust is equivalent to drag.

$$T = D \qquad (5)$$

In order to obtain the curve of power required, maniputed the cruising velocity of UAV up till a certain range, the multiply the velocity with the drag produced, the power required is then obtained.

$$P_{required} = TV = \mathrm{DV} \qquad (6)$$

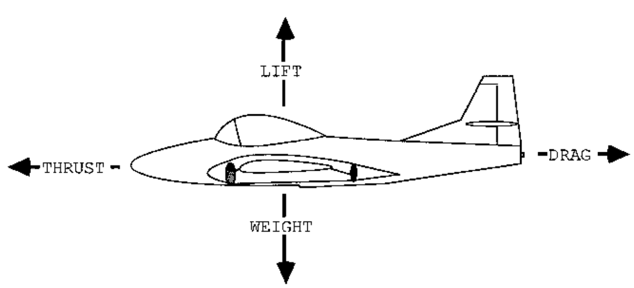

Figure 1: Steady cruise of UAV [10]

3.0 DEVELOPMENT OF SOLAR SIMULATOR

The evaluation on the performance of PV cell can be carried out either under sunlight in the outdoor environment or in a closed laboratory environment with the help of a solar simulator and weather conditions. In many cases, indoor solar simulator is preferable due to reasons such as simplicity, reproducibility and reliability[12]. Figure 4 shows the design of solar simulator. Two 150W full spectrum LED lights are selected as main light source due to cost, power efficient, compactness and steady performance. The distance between light source to test area is 0.14m, in which the irradiance that can be obtained at this distance is 28.42W/m^2.

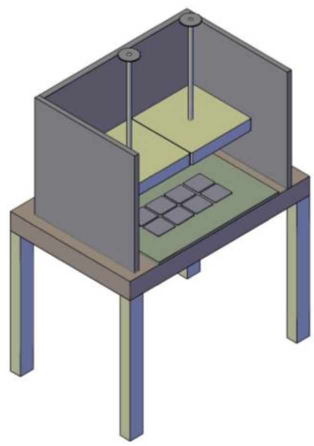

Figure 4: Solar simulator

Also, according to ASTM E927 (Standard Specifications for Solar Simulation for Terrestrial Photovoltaic Testing), the three main performance classification for solar simulator are spectral match, spatial non-uniformity and temporal instability. The graph of classification of simulator performance are as shown in Table 2. The spatial non-uniformity (SNU) and temporal instability is evaluated through equation (7) and (8), where I is the irradiance.

$$SNU = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \times 100\% \quad (7)$$

$$TI = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \times 100 \quad (8)$$

Upon evaluated, the solar simulator created has class C and class B performance across both categories, as shown in table 2. Thus experiments can be conducted on this solar simulator and the result data is reliable.

Performance Parameter	Class	ASTM Standards
Spatial non-uniformity	Class A	$\leq 3\%$
	Class B	$\leq 5\%$
	Class C	$\leq 10\%$
Temporal instability	Class A	$\leq 2\%$
	Class B	$\leq 5\%$
	Class C	$\leq 10\%$

Table 2: Classification of simulator performance

4.0 IRRADIANCE CURVE IN SKUDAI AREA

The measurement station is set up at the wide space right in front of Aeronautical Laboratory UTM, Skudai (1.534°N and 103.659°E). The data is collected from 27 August 2020 till 2 September 2020, during the daytime from 7:00am till 6:00pm. The irradiance is measured using RS PRO ISM 410 Solar Meter, while the measurement only occur at a condition with clear sky. The average ambient temperature throughout the day is 31℃.

The graph in Figure 5 demonstrate that the irradiance increase gradually from 7:00am and reach its maximum irradiance on 1:00pm, which is 960 W/m^2. After reaching the peak, the curve then show a downward trend as it approach 6:00pm in the afternoon before the sun sets.

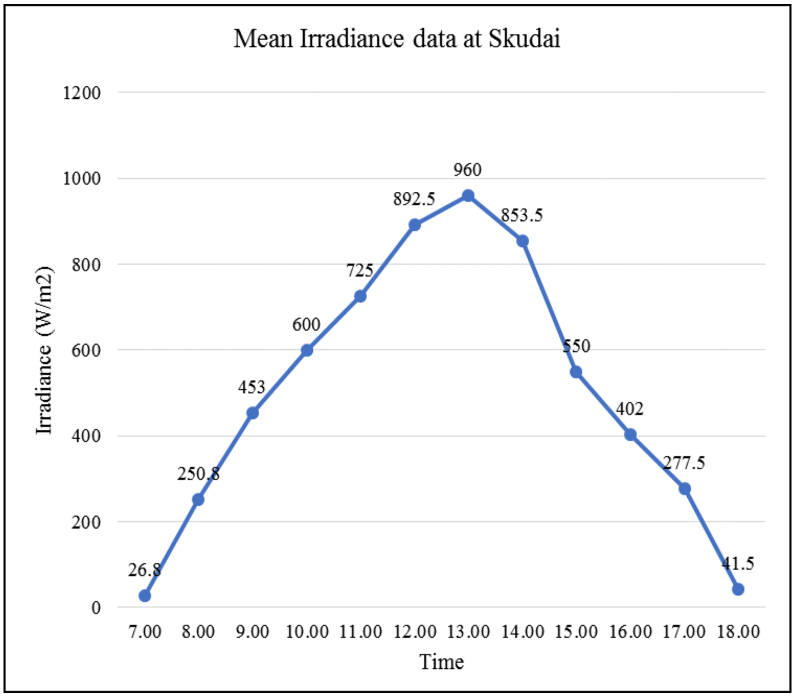

Figure 5: Mean irradiance data in Skudai

5.0 CHECKING, ENCAPSULATION AND SOLDERING OF PV CELLS

Before performing encapsulation and soldering, the open circuit voltage, V_{oc} and short circuit current, I_{sc} of each PV cells are measured. The output is as displayed in Figure 6. All PV cells are tested in the solar simulator. Through checking, the data proved that there is no defective PV cells as the performance of all cells are relatively uniform and stable.

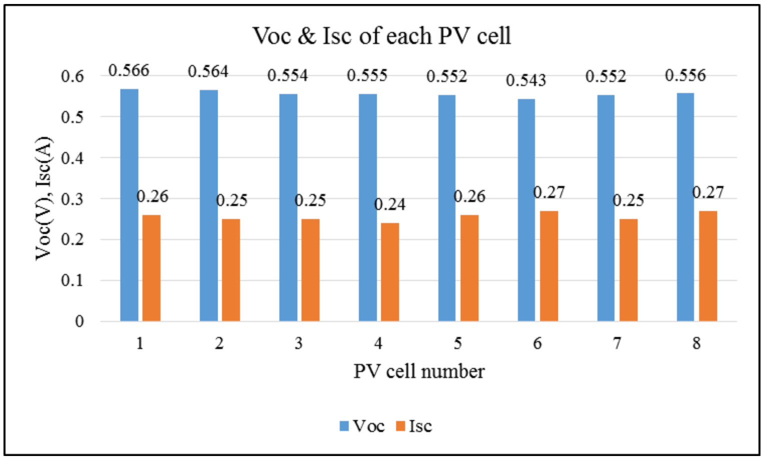

Figure 6: Open circuit voltage and short circuit current of all PV cells

Next, the two criteria for a good encapsulation of PV cells are to be able to provide protection against outdoor condition and maintain the performance of the cells at the same time. The lay-up should be capable to provide optical and electrical transmissivity. The common material of encapsulate the PV cells includes Ethylene vinyl acetate (EVA), laminating sheets, Oralight film and transparent covering film. In this project, A4 220gsm transparent covering sticker is selected to protect the PV cells, as it fulfil all the criteria and easily available. The light transmissivity of the transparent is tested, which up to 99.41%. We also found out that there is no performace drop occur due to the encapsulation process.

In order to generate enough power for the PV power system, all PV cells are required to be connected in series. To begin with the soldering of PV cells, there's few safety instructions to take note. Clean the surfaces thoroughly before start soldering. A zero-halogen, non-rosin organic flux is recommended to use in both the soldering tabs to cell contacts. The low solids content could leave no residue on the cell after soldering. Meanwhile, a soldering paste which composed of metal powder activated flux and blending agents is not recommended. Next, take note on the terminal and connect the negative (-) plug of first cell to the positive (+) plug of the second cell. A soldering temperature of 400℃ is recommended. Do not inhale the dust and fumes produced from soldering lead during soldering process as it is hazardous. Also, PV cells are made into thin sheets which are fragile and susceptible to corrosion by fingerprints, therefore it is recommended to wear protective equipment such as rubber gloves when handling with PV cells.

Upon complete the soldering process, checking is required, which we obtained open circuit voltage, V_{oc} of 4.01V and short circuit current, I_{sc} of 0.26A. The output can proved that all joint is soldered well will miminal performance drop due to soldering.

6.0 I-V CHARACTERISTICS OF PV CELLS

Two experiments are executed to study the I-V characteristics of the PV cells. The first experiment is carried out to investigate the relationship between irradiance, open circuit voltage, V_{oc} and short circuit current, I_{sc} of the PV cells is conducted. The PV cells are placed under condition of different irradiance, and the value of $V_{oc}$and I_{sc} is recorded and computed into Figure 7 and Figure 8. From both figure, we noticed that at irradiance of 1004W/m^2 , the maximum voltage and current is 6.08V and 4.84A respectively.

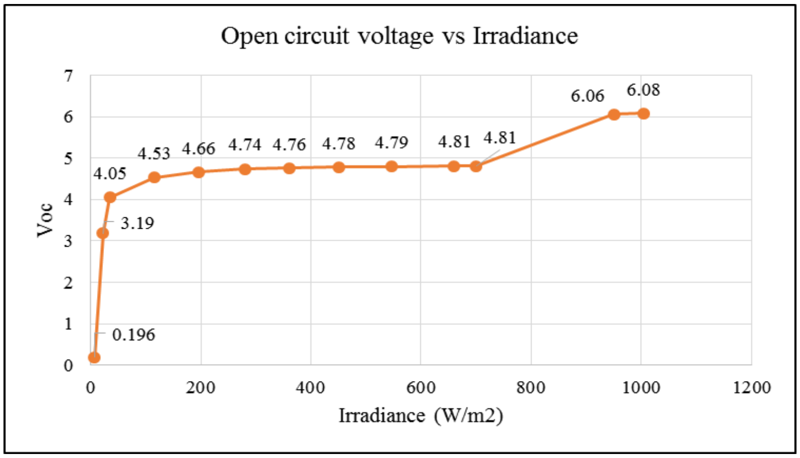

Figure 7: Graph of open circuit voltage against irradiance

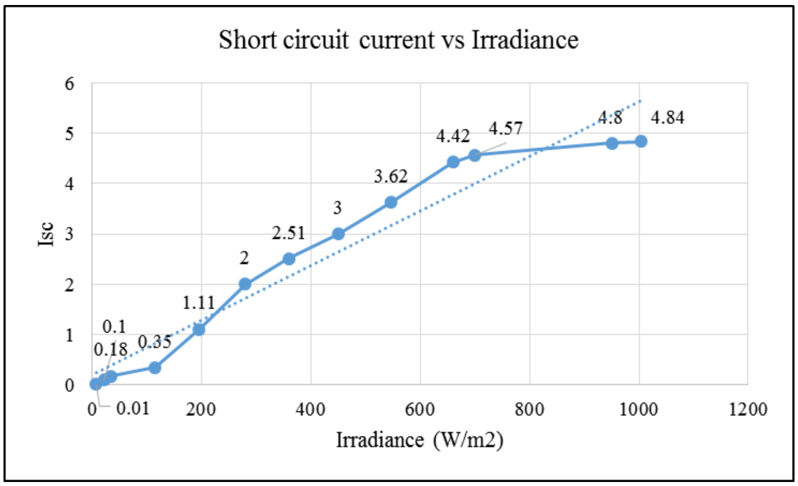

Figure 8: Graph of short circuit current against irradiance

On the second experiment, detailed studies on the I-V characteristics are performed in solar simulator. The setup of the experiment is as shown as Figure 9. The results of this experiment is as shown in Figure 10.

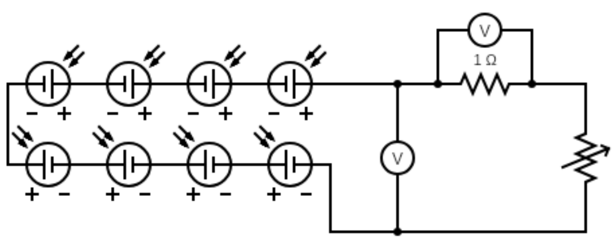

Figure 9: Experimental Setup to study the I-V characteristics of PV cells

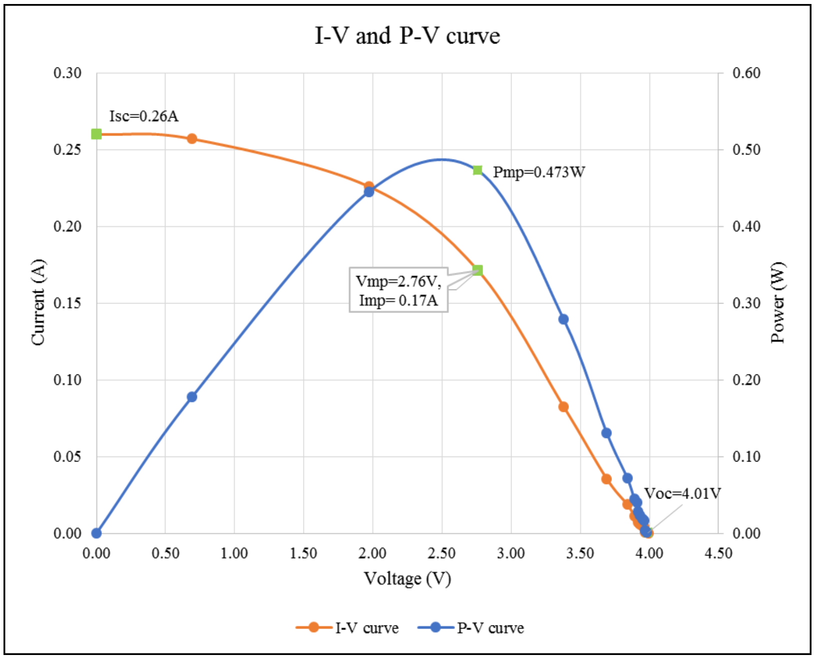

Figure 10: I-V and P-V curve of the PV cells

The information we obtained from Figure 10 is listed in Table 3. We noticed that the maximum power generated in solar simulator is relatively low, which is only 0.473W. When the PV cells are connected with other components in the PV power system, the power generated might insufficient to support the system.

I-V characteristics	Value
Maximum power point, P_{MP}	0.473W
Voltage at maximum power point, V_{MP}	2.76V
Current at maximum power point, I_{MP}	0.17A
Fill factor, FF	0.45
Irrdiance at solar simulator, I	28.42W/m^2
Conversion efficiency	13.32%

Table 3: Findings from P-V and I-V curve

7.0 DEVELOPMENT OF PV POWER SYSTEM

The setup and testing of the PV power integrated circuit performed at the outdoor space under full Sun condition, where the circuit is as shown in Figure 11. However, the test run is unsuccessful as the PV cell could not provide sufficient and stable power to operate the ESC signal generator and micro brushless. To solve this issue, the ESC signal generator has connected to an extended battery supply in order to get a constant 5V DC supply. The test run is performed again, but still increasing the ESC signal through ESC signal generator do not help in starting the motor. Thus, to improve the performance, we can increase the number of PV cells as well as install a maximum power point tracker (MPPT) on the circuit to maximize the power obtain from PV cells.

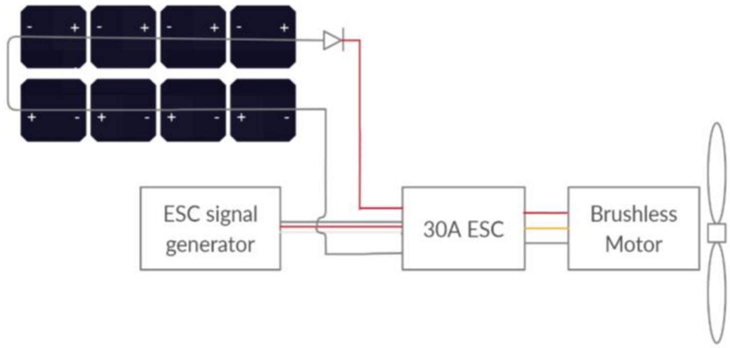

Figure 11: PV Power circuit

Next, an improved design of integrated PV power system is as displayed in Figure 12. The number of PV cells are double up till 16 cells, with 8 cells on each side of wing. All cells are connected in series. Also, MPPT is installed into the system.

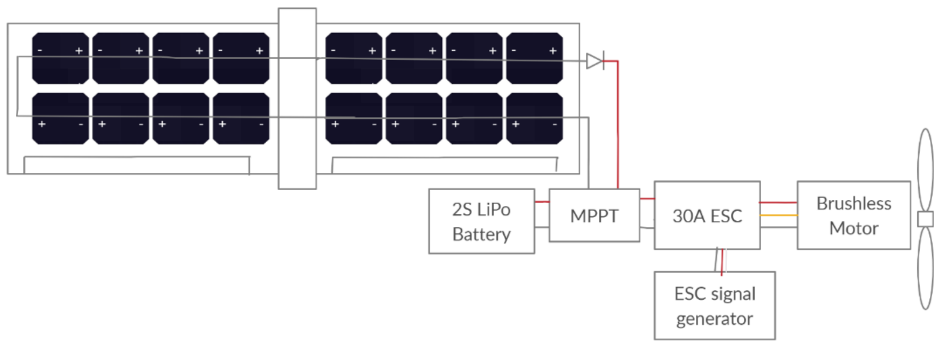

Figure 12: Improved design of PV power circuit

Prior to carry out performance analysis on this circuit, it is important to know the specifications of every electronic components in the system. The selection of components include 16 pieces of C60 Sunpower PV cell, Genasun 10A MPPT, 2S 7.2V 1300mAh 20C LiPo battery, C10 Micro brushless outrunner 2900kv, 5×3 propeller, ESC signal generator and 30A Skywalker ESC.

To initial the performance analysis, assume the system is tested in clear sky condition with irradiance of at least 500 W/m^2 and above, an approximate of open circuit voltage and short circuit current that can be produced is 9.6V and 4A, by referring to Figure 7 and Figure 8. To further study on the performance of the system, the I-V and P-V curve trend in Figure 10 is referred and a predicted I-V and P-V curve is plotted as shown in Figure 13.

As observed in figure 13, the maximum power point is at 17.94W. However, the value tends to change due to factors such as the irradiance, load and temperature. To utilize the PV cells efficiently, the system should operate about this maximum power point and thus MPPT is needed, which the typical efficiency of MPPT is about can be up to 98%. Thus, power generated from the improved PV power system at irradiance of 500 W/$m^2$is about 17.58W. Thus, when referred back to the irradiance curve to find the period where irradiance is more than 500W/m^2, thus we can suggest that the suitable flying time if from 9:30am till 3:30pm, on clear sky condition.

Next, the curve of power required for steady cruise of UAV is computed, and analysed together with the power available (generated) by PV power system at irradiance of 500 W/m^2. The graph is as displayed in Figure 14. From the graph, we observed that the maximum velocity is 17m/s, while the stall speed is 4m/s. Also, the most recommended flying speed for cruising is 10m/s, with the minimum power required of 10.527W.

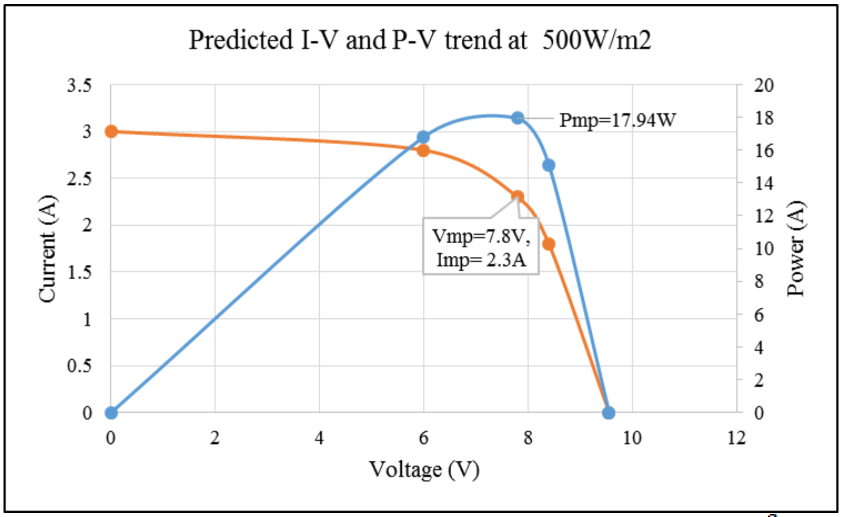

Figure 13: Predicted I-V and P-V curve at irradiance 500 W/m^2

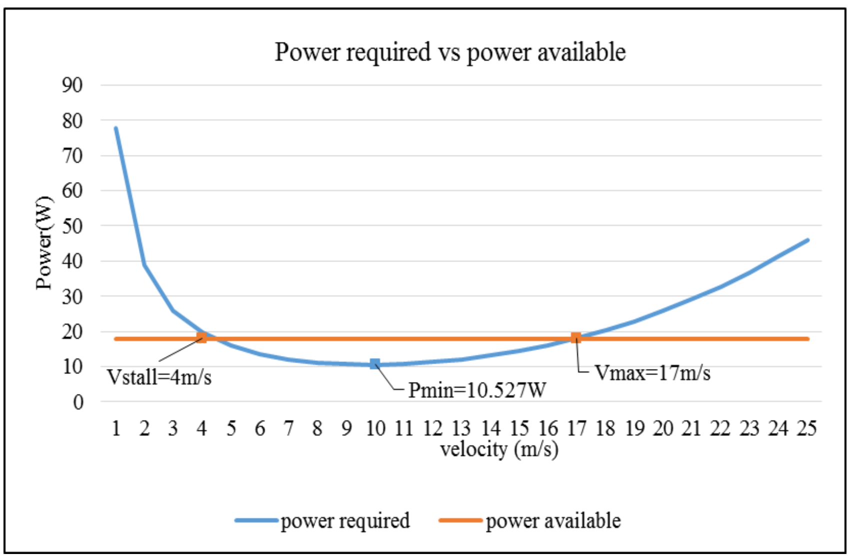

Figure 14: Power required against power available

8.0 CONCLUSION

In conclusion, the objectives of this project have achieved. The design methodology of PV power system has developed and executed, which include literature review on past projects, solar simulator development, selection of electronic components, development and test run of PV power circuit. Next, parametric analysis and performance data collection on PV power system is performed, where the I-V and P-V characteristics of PV cells, irradiance curve in Skudai are collected. These data are then contribute to the performance analysis of the improved design of PV power system.

Also, some recommendations on future work includes investigation on the contribution of temperature and Sun's angle of incidence to the power generated from PV power system, as well as development of PV power system based on the improved design.

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