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Laboratory-Scale Single Axis Solar Tracking System: Design and Implementation

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ABSTRACT

This paper presents the design and development of a laboratory-scale single axis solar tracking system. The chronological method was implemented into the system because it has high accuracy and can save more energy as compared to other types of solar tracking system. The laboratory-scale single axis solar tracking system can be used to identify the suitable and safe workspace for the installation of the actual solar tracking system plant. Besides, the validity of the laboratory-scale single axis solar tracking system was examined experimentally. The angle of rotation, 15° per hour is preferable to be implemented into the designed laboratory-scale single axis sun tracking system due to the high performance ratio which is 0.83 and can save the energy up to 25% during sunny days.

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1. INTRODUCTION

The world population isincreasing throughout the year and the electricity demand is also growing rapidly [1]-[2]. Most of the countries like Bangladesh and Pakistan which mostly use fossil fuels such as crude oil and coal to generate the electricity[3]. Using fossil fuels to generate electricity will emit a lot of greenhouse gases such as carbon dioxide, CO_2. The greenhouse gases will cause global warming, which may lead to the climate change in the world. The temperature on our earth is increasing throughout the year. The scientists estimate that the world temperature will raise up six degree celcius if the greenhouse gases emissions are let uncontrollable [4]. Therefore, due to the concern on the environment and depletion of fossil fuels reserves, many countries have started the research and development of renewable energy to fulfill the energy demand in their countries [5]-[6].

There are several types of renewable energy such as solar, wind, hydropower and geothermal source [7]-[8]. However, solar energy has more benefits as compared to other renewable energy. Advantages of solar energy are always available, inexhaustible and environment friendly. The solar energy can be converted into electricity by using the photovoltaic (PV) panels [9]. Malaysia government is supportive in the development of renewable energy such as solar energy by developing the Sustainable Energy Development Authority (SEDA Malaysia). SEDA is a statutory body under the Ministry of Energy, Green Technology and Water. Malaysia Feed in Tariff (FiT) scheme is managed by SEDA Malaysia. The house owners who install the home solar system can sell the generated electricity to Tenaga Nasinal Berhad (TNB) by using the on-grid system which connected with the national grid network [10].

Malaysia has a potential to widely apply solar PV system due to its coordinate on the earth. Malaysia is at the equator of the earth which lies between 1°N and 7°N, and 100°E and 119°E. Malaysia receives more than 10 hours sunlight every day and 6 hours direct sunlight. The solar irradiation level in

Malaysia is around 800W/m^2 to 1000W/m^2. Due to the long period of receiving sunlight, Malaysia has a great potential to develop the solar energy [10]-[11].

In Malaysia, the sunlight is always directly located on the land and its solar radiance does not vary by seasons. Malaysia is at equator and do not experience four seasons; therefore, it is suitable to use the single axis tacking system instead of dual axis tracking system. In Malaysia, the altitude of the sun's position does not change much [11]. According to [12]-[13], if the altitude is slightly misaligned, it only causes less power loss. According to [14], the greatest sun elevation difference in UTeM, Melaka is only 13,27° which leads to less than 3.4% of power loss. Table 1 shows the direct power loss due to solar panel misalignment is shown where $loss = 1 - \cos(I)$ [12].

Table 1. Direct power loss (%) due to misalignment (angle)[12]

Misalignment (I°)	Direct power loss (%)
0	0
1	0.015
3	0.14
8	1.0
15	3.4
23.4	8.3
30	13.4
45	30
60	>50
75	>75

In this project, single axis solar tracking system is chosen rather than the dual axis solar tracking system. Single axis solar tracking system has more beneficial as compared to the dual axis solar tracking system such as simpler mechanism, low installation cost and less maintenance is required.

There are three types of solar tracking system which are active solar tracking system, passive solar tracking system and chronological tracker [15]-[16]. However, chronological solar tracking system is chosen in this research due to more energy efficient as compared to active solar tracking system. The active type solar tracking system consists of controller, light sensor and actuator to search and direct the solar panel towards the sun position. On the other hand, the chronological tracker tracks the sun by the solar time (hour angle) which does not require excessive search mode.

Based on Rubio in [17], the energy saving is the most important factor which must be considered in designing the solar tracking system. The time and date based solar system was designed to prevent the excessive search mode of the sun position during the prolonged cloudy weather condition which may consume high power in driving the actuator. In [18], Huang had designed a one axis and three position solar tracking system in order to minimize the energy consumption of the actuator. By minimizing the energy consumption, more energy can be saved for other applications usage. Besides, the main drawback of dual axis sun tracking system met by Bakos in [19] was the sensor mode fail to track and follow the sun orbit accurately during the low solar irradiance level condition. This condition may cause a significant decrease in the overall system efficiency. There are several researches which had implemented the time-based system in the designed of the solar tracking system due to that lower cost and lower power consumption which can save more energy [20]-[21]. Furthermore, according to S. Ahmad in [22], Malaysia is more suitable to install time and date based solar tracking system because Malaysia has the perpetual cloud formation. The time and date based solar tracking system is preferred in this project to maximize the total energy yield and at the meantime can minimize the power consumption by the actuator.

The flexible and laboratory scale PV system and solar tracking system can be used as teaching and learning facilities. Furthermore, the laboratory scaled solar system can also be used as a basic set of tools or start up for the local researcher [23]. This facility can provide an opportunity for the researchers to perform the research based on the solar energy. They can perform the installation and maintenance on the solar system independently without requiring any oversea expertise. The researchers can also enhance and improve the existing solar system by using the knowledge gained such as including the tracker and maximum power point tracking (MPPT) controller into the system. The energy harvest efficiency of the solar system can be increased by adding the tracker and MPPT controller. Furthermore, the laboratory scale solar system is very important to the developing countries such as Africa. In Africa, there is less than 25% of the population who has access to electricity [24]. By introducing the small-scaled stand-alone PV system to the African, they can generate their own electricity by using the solar source which is always available and free [24]. Besides, according to the survey done by Yaungket in [25], the residents in the rural area lack of knowledge regarding the PV system. The laboratory-scale solar system can be introduced to them to have a better understanding regarding the PV system. Therefore, the residents can perform the maintenance individually when the system malfunctioning.Besides, the laboratory-scale solar tracking system can also be used as teaching and learning facilities for understanding the behavior and operation of the solar tracking system.

In this project, a laboratory-scale single axis solar tracking system is designed and developed. By constructing the laboratory-scale single axis solar tracking system, the working mechanism and the electromechanical system of the solar tracking system are studied. Besides, the laboratory-scale solar tracking system is user friendly.

Moreover, the laboratory-scale solar tracking system is convenient to be moved for performing the experiments to identify a suitable workspace for installation of the actual solar tracking system plant. This research is important for Faculty of Electrical Engineering of Universiti Teknikal Malaysia Melaka (UTeM) to identify a safety workspace for the solar tracking system plant. The actual solar tracking system plant is still cannot be operated due to the limited workspace.

The rest of this paper is outlined as follows: Section 2 presents the experimental setup of the designed laboratory-scale single axis solar tracking system. Besides, the transfer function of the DC geared motor mechanism and the block diagram of the designed laboratory-scale single axis solar tracking system are presented. The method to collect and analysis the data output from the solar panel are also be presented. In section 3, the results obtained from the experiment are analyzed and evaluated. Finally, the conclusion is presented in section 4.

2. DESIGN OF THE LABORATORY-SCALE SINGLE AXIS SOLAR TRACKING SYSTEM

Figure 1 shows the actual solar tracking system plant in FKE, UTeM with the dimension of 11800(*l*)x6000(*w*) mm and the total surface area is around 70m^2. In this project, the laboratory-scale solar tracking system is scaled down to ratio 462: 1 in comparison to the actual plant. The dimension of the laboratory-scale solar panel is 340(*l*)x450(*w*) mm as shown in Figure 2. The solar tracking mechanism is driven by DC geared motor. The free body diagram of the DC motor geared mechanism is illustrated in Figure 3. Table 2 shows the parameter of the DC geared motor mechanism used in the designed system.

Figure 1. Solar tracking system plant in FKE, UTeM

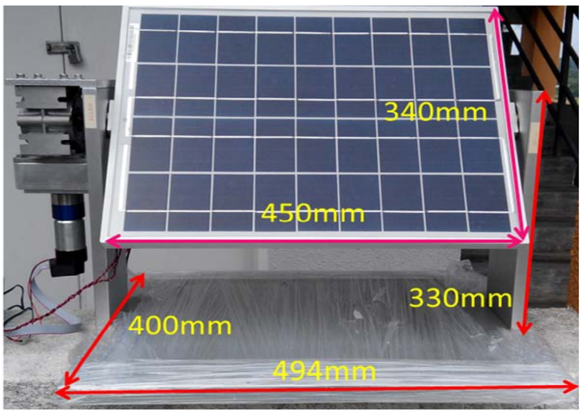

Figure 2. Laboratory-scale solar tracking system

The relationship between the armature current, $i_a(t)$, the applied armature voltage, $e_a(t)$ and the back emf $v_b(t)$ is :

$$R_a I_a(s) + L_a s I_a(s) + v_b(s) = E_a(s) \tag{1}$$

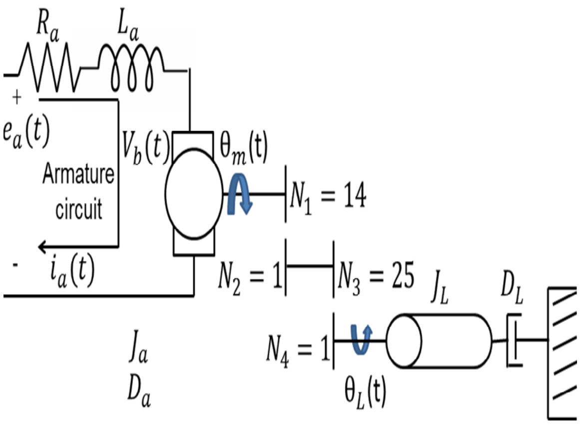

Figure 3. DC geared motor mechanism

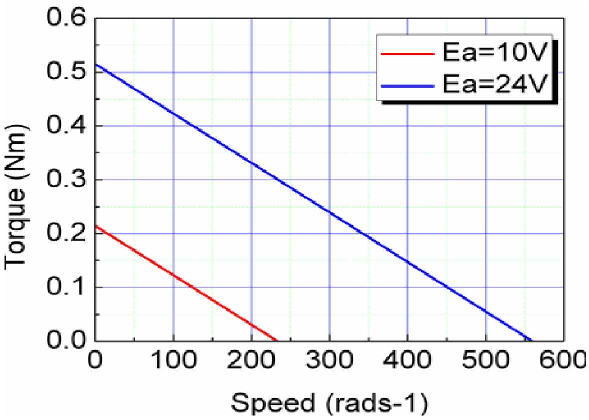

Figure 4. Torque-speed curves with an armature voltage, e_a as a parameter

The mechanism is described in the transfer function:

$$\frac{\theta_m(s)}{E_a(s)} = \frac{K_t/(R_a J_m)}{s\left[s + \frac{1}{J_m}\left(D_m + \frac{K_t K_b}{R_a}\right)\right]} \tag{2}$$

Table 2. Parameter of the DC geared motor mechanism

Parameters	Values	S.I. Unit
Equivalent inertia , J_m	2731.75	kgm^2
Equivalent damping , D_m	641×10^3	Nms/rad
Terminal resistance , R_a	2	Ω
Back-emf constant , K_b	42.88	$mV/rads^{-1}$
Torque constant , K_t	42.90	mNm/A

After the values are substitued into the Equation 2, the overall DC geared motor transfer function is:

$$\frac{\theta_m(s)}{E_a(s)} = \frac{7.85\times10^{-6}}{s(s+234.68)} \tag{3}$$

Based on Figure 4, when the armature voltage, e_a is reduced to 10V, the motor torque and speed are reduced. However, the geared motor still has sufficient torque to rotate and hold the load in the static position. The functional diagram of the overall system is shown in the Figure 5. The LDR sensor is used to detect the day time and night time at the surroundings. Furthermore, the microcontroller is used as an integrated control unit for the solar tracking system. The DC geared motor is used as an actuator in the solar tracking system which driven by the motor driver and feedback by an encoder to identify the angle of rotation of the solar tracking system.

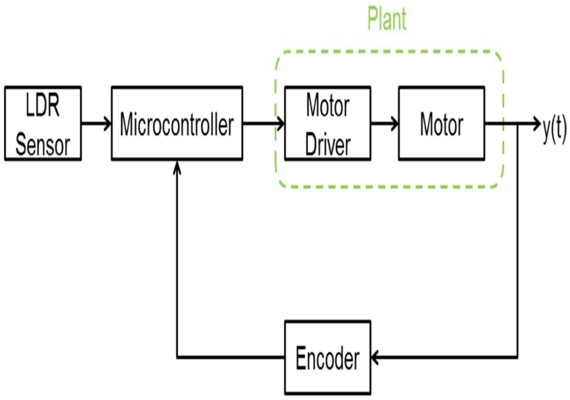

Figure 5. Functional diagram of designed laboratory-scale solar tracking system

3. DATA COLLECTION

The power monitoring system is set up which functions to monitor the solar panel voltage output and current output. All the output parameters are measured by using the DC power meter and stored in the data logger in every minute. Firstly, the default angle of rotation for the solar tracker is set to 15° per hour. Secondly, the angles of rotation are set to 10° per hour and 20°per hour, which is ±5° differences from the default angle. These experiments are conducted to determine the power output and performance ratio differences between them. The experiment is continued by changing the angle of rotation to 7.5° per 30 minutes. This experiment is conducted to determine significant changes in the power output and performance ratio of the solar panel by changing the angle of rotation more frequently as compared to 15°per hour. Each of the experiments will be conducted for 5 days from 8:00a.m to 3:00p.m. The angle of rotation of the solar tracker is shown in Figure 6.

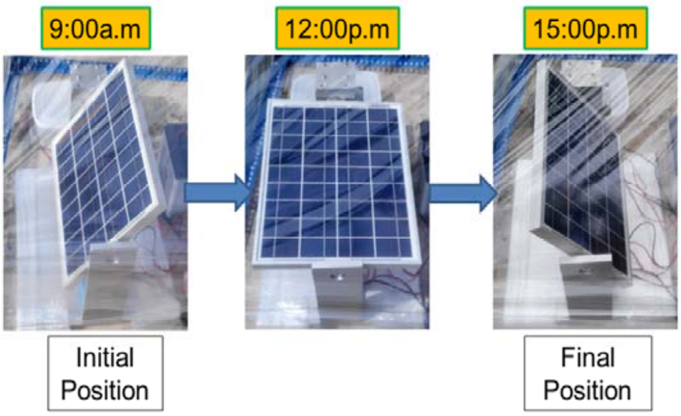

Figure 6. The position of the solar panel from 9:00a.m to 15:00p.m

The performance ratio [26] is calculated by using:

$$Performance\ Ratio,\ PR = \frac{E_{Real}[Wh]}{E_{Theoretic}[Wh]} \tag{4}$$

$$E_{Theoretic} = \frac{I_{solar} \times P_{STC}}{I_{STC} \times Loss_{reflection} \times Loss_{spectrum}} \tag{5}$$

where,

E_{Real} = Total energy output from the solar panel, Wh
$E_{Theoretic}$ = Total energy harvested from the sun, Wh
I_{solar} = Accumulated solar radiation on each day, Wh/m^2
P_{STC} = Rated power of solar panel, W
I_{STC} = Standard irradiance condition, Wh/m^2
$Loss_{reflection}$ = Irradiance incidence reflection loss ($Loss_{reflection}$ = 0.9 when the solar tracking system is covered)
$Loss_{spectrum}$ = Irradiance spectrum loss ($Loss_{spectrum}$ =0.9 when the solar tracking system is covered)
Nominal Operating Condition (NOCT)
($P_{STC} = 20W$ and $I_{STC} = 1000\ Wh/m^2$)

4. RESULTS AND ANALYSIS

The laboratory-scale single axis solar tracking system was designed and developed. The solar tracking system is convenient as it can be moved to any workplace to perform the experiments. The required workspace of the actual solar tracking system plant can be identified based on the scale between the actual solar tracking system plant and the designed solar tracking system. This experiment is important to ensure the actual solar tracking system plant is installed at a suitable and safe workspace which will not affect its performance and operation.

The performance of the laboratory-scale solar tracking system is validated by conducting a series of experiment at the selected workplace at FKE, UTeM. The results obtained are discussed in two parts. First, the power output and performance ratio of ±5°angle differences from 15°per hour are compared. Next, the power output and performance ratio of angle of rotation 7.5° per 30 minutes is compared with the angle of rotation 15° per hour.

4.1. Performances of the Solar Tracking System between ±5°Angle Differences from Default Angle, 15° per Hour

From Figure 7 to Figure 12, the power output of the solar panel showslinear relationship of the solar irradiation level with time. The power output of the solar panel varied with the variation of solar irradiance level throughout the experiment from 8:00a.m until 3p.m. Figure 10 shows the power output of angle of rotation 10° from 12:00p.m to 3:00p.m were independent with the variation of the solar irradiance levels. The power outputs did not vary linearly with the solar irradiance level during noon time because the solar panel was not facing perpendicular to the sun. At 12p.m, the solar tracker was rotated to 70° from the initial position (30°) which was not in the horizontal position (90°) facing perpendicular to the sun. Therefore, there were some power losses occurred in the afternoon.

Figure 12 shows the power output of the angle of rotation 20° in the morning from 9:00a.m to 11:30a.m. The power output of the solar panel was not varying linearly with the changes of the solar irradiance level. At 11:00 a.m, the solar tracker was rotated to 90° which was around 15° more than the calculation from solar time (75°). At that current time, the solar tracker was not facing perpendicular to the sun. Therefore, there were some power losses occurred due to the position mismatched between solar tracker and the sun.

The performance ratios of each angle of rotation were calculated. Table 3 shows that the performance ratio of 15° per hour is 0.83 and it is 9.64% higher than other angles of rotation. Although there are slight differences in the average of total solar irrdiance level, but the angle of rotation 15°per hour has shown the highest energy harvested as compared to other angles of rotation.

The energy harvested of 20° per hour is 21% lower as compared to the angle of rotation 15° and 10°. There were some irradiance losses (Irradiance incidence reflection losses and Irradiance spectrum loss) occurred which caused by the transparent cover as shown in Figure 13. The energy losses difference was calculated by using Equation 6 and the data comparisons are obtained from Table 4 (Total solar irradiation on 9/4/2015 and 22/4/2015 were 4612 Wh/m^2 and 4647Wh/m^2 and the total energy outputs were 64.6Wh and 50.2Wh). From 17/4/2015 to 24/4/2015, the transparent cage was added to prevent damage to the actuator due to rain. The irradiance losses were considered in the performance ratio calculation to have a comparative analysis with the angle of rotation 15°and 10°.

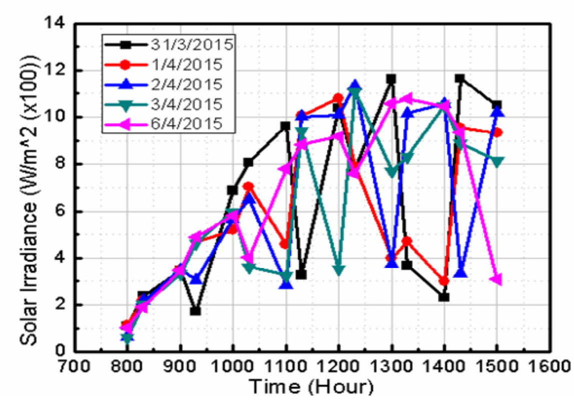

Figure 7. Solar irradiance level from 31/3/2015 to 6/4/2015

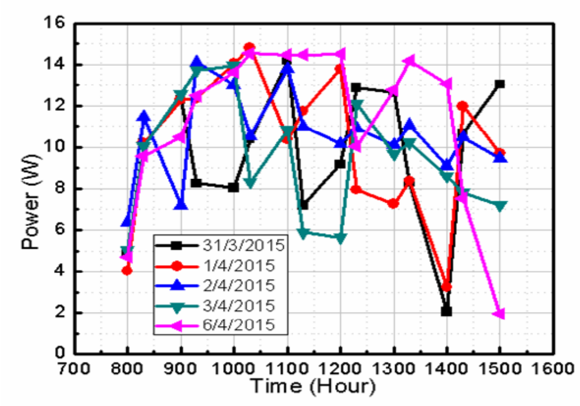

Figure 8. Power output from 31/3/2015 to 6/4/2015 of 15° per hour

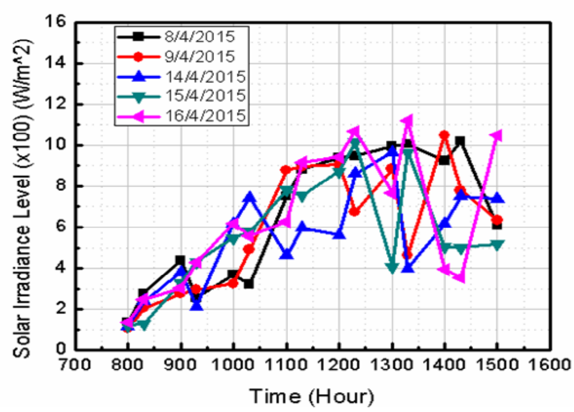

Figure 9. Solar irradiance level from 8/4/2015 to 16/4/2015

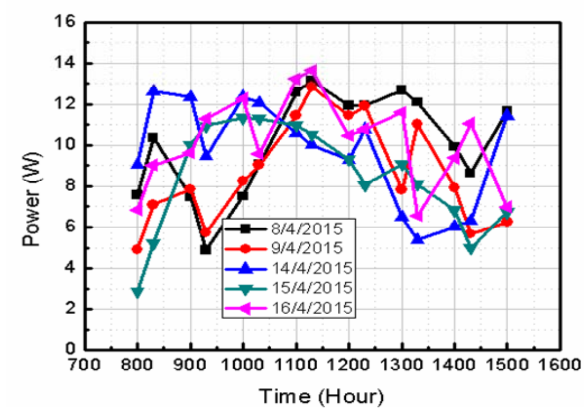

Figure 10. Power output from 8/4/2015 to 16/4/2015 of 10° per hour

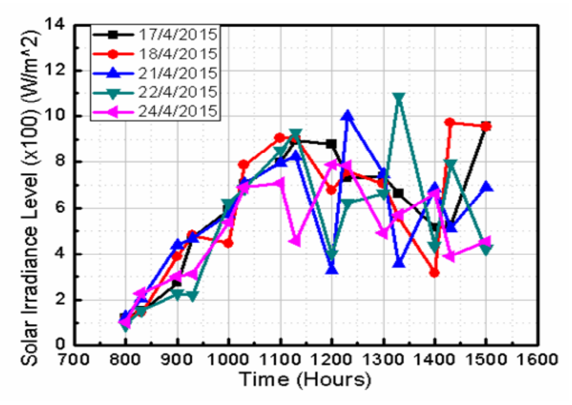

Figure 11. Solar irradiance level from 17/4/2015 to 24/4/2015

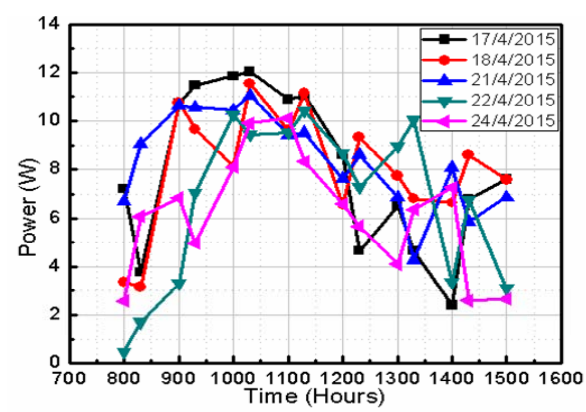

Figure 12. Power output from 17/4/2015 to 24/4/2015 of 20° per hour

Figure 13. Transparent cage was added to the solar tracking system

Table 3.Total solar irradiance and total energy harvested on each day from 31/3/2015 to 24/4/2015

Date	Angle of 15° Total Solar Irradiance (Wh/m^2)	Total Energy (Wh)	Date	Angle of 10° Total Solar Irradiance (Wh/m^2)	Total Energy (Wh)	Date	Angle of 20° Total Solar Irradiance (Wh/m^2)	Total Energy (Wh)
31/3	4707	74.3	8/4	5235	75.8	17/4	4824	60.1
1/4	4706	77.4	9/4	4612	64.6	18/4	5160	60.3
2/4	4939	80.2	14/4	4581	72.1	21/4	4917	62.8
3/4	4476	70.7	15/4	4402	63.2	22/4	4647	50.2
6/4	5061	84.2	16/4	5091	76.2	24/4	4276	46.1
AVG.	4778	77.4	AVG.	4784	70.4	AVG.	4765	55.9
P.R	0.83		P.R	0.75		P.R	0.74	

$$Energy\ Difference = \frac{64.6 - 50.2}{64.6} \times 100\% = 21\% \quad (6)$$

4.2. Performance Evaluation of Frequent Turning the Solar Panel towards the Sun

The power output from the solar panel has the linear relationship with the solar irradiance level as shown in Figure 14 and Figure 15. The energy harvested from the solar panel can be increased by turning the solar panel more frequently. Based on Table 4, the performance ratio of 7.5° per 30 minutes is 0.87 which is 4.6% higher than 15° per hour. The performance ratio of the system was increased because the solar tracker was turned more frequently (every 30 minutes) to align the solar panel for facing perpendicular to the sun.

The total energy harvested from 25/4/2015 to 30/4/2015 were increased by 20% to have a comparative analysis with the angle of rotation 15°. From 25/4/2015 to 30/4/2015, the solar tracker was covered with a transparent cage to prevent from directly get caught in the rain. Although the performance ratio of angle of rotation 7.5° per 30 minutes was higher than the angle of rotation 15° per hour, the power consumption was high due to frequent actuating the DC geared motor as shown in Table 5. The energy consumption of the actuator was two times more as compared to 15°per hour. Therefore, the angle of rotation 7.5° per 30 minutes is not preferable to be implemented in the designed laboratory-scaled single axis solar tracking system. The energy harvested of angle of rotation 7.5° per 30 minutes is insufficient to operate the solar tracking system due to the total power consumption is 42% more than the energy harvested.

Therefore, angle of rotation 15° per hour is preferable to be used in the designed solar tracking system due to high energy saving which can save up to 25% during the sunny condition. Table 6 shows that Malaysia is a suitable location to develop the solar PV system because the weather in Malaysia is mostly sunny condition with the average daily solar irradiance level higher than 600W/m^2 [27].

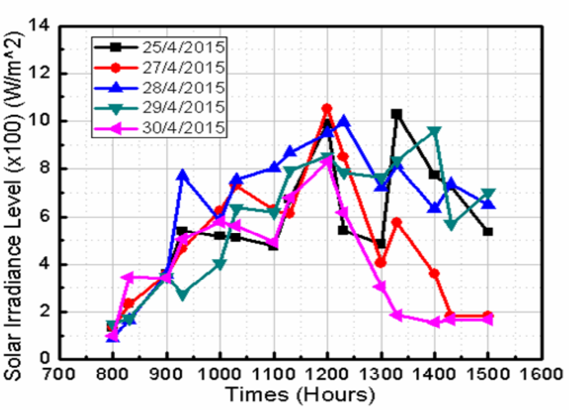

Figure 14. Solar irradiance level from 25/4/2015 to 30/4/2015

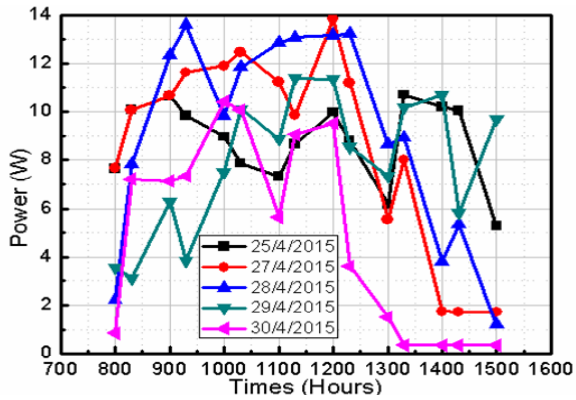

Figure 15. Power output from 24/4/2015 to 30/4/2015 of 7.5° per 30 minutes

Table 4. Performance comparison between angle of rotation 15° per hour and 7.5° per 30 minutes

Angle of 15°			Angle of 7.5°			
Date	Total Solar Irradiance (Wh/m^2)	Total Energy (*Wh*)	Date	Total Solar Irradiance (Wh/m^2)	Total Energy (*Wh*) (Covered by Cage)	Total Energy (*Wh*) (Increase 20%)
31/3	4707	74.3	25/4	4619	66.1	79.3
1/4	4706	77.4	27/4	4110	64.6	77.5
2/4	4939	80.2	28/4	5179	69.0	82.8
3/4	4476	70.7	29/4	4717	59.2	71.0
6/4	5061	84.2	30/4	2913	36.9	44.3
AVG.	4778	77.4	AVG.	4308	59.2	71.0
P.R	0.83		P.R		0.87	

Table 5. Total energy consumption of the solar tracking system in angle of rotation 15° and 7.5°

Angle of 15°		Angle of 7.5°	
Types	Total Energy Consumption (*Wh*)	Types	Total Energy Consumption (*Wh*)
Electrical Components	16.5	Electrical Components	16.5
Arduino Board	0.94	Arduino Board	0.94
DC Geared Motor	45.5	DC Geared Motor	91.0
Total	62.94	Total	108.44

Table 6. Average solar irradiance level from 31/3/2015 to 30/4/2015

Date	Average of Solar Irradiance Level (W/m^2)	Date	Average of Solar Irradiance Level (W/m^2)	Date	Average of Solar Irradiance Level (W/m^2)	Date	Average of Solar Irradiance Level (W/m^2)
31/3	627.6	8/4	697.9	17/4	643.2	25/4	615.9
1/4	627.4	9/4	615.0	18/4	688.0	27/4	548.0
2/4	658.6	14/4	610.7	21/4	655.6	28/4	690.5
3/4	596.8	15/4	587.0	22/4	619.6	29/4	629.0
6/4	674.7	16/4	678.9	24/4	570.2	30/4	388.4
Average of overall solar irradiance level = 621.2							

5. CONCLUSION

The laboratory-scale single axis solar tracking system was successfully designed and constructed. The workspace limitation of the solar tracking system can be identified and determined by using the laboratory-scale solar tracking system. The laboratory-scale solar tracking system can be used in the teaching and learning process. By performing a series of experiments on the designed solar tracking system, the angle of rotation 15° per hour is the most preferable as compared to other angles of rotation. The angle of rotation 15° per hour is preferable because it has high performance ratio that is 0.83 and low power consumption which can save energy up to 25%. Malaysia is suitable to develop the solar PV system because the average daily solar irradiance level in Malaysia is around 621.2 W/m^2 which is mostly sunny condition.

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