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Performance Monitoring and Evaluation of Solar Photovoltaic System under Adverse Environmental Condition

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Abstract – **Environmental condition affects the output performance of solar photovoltaic (PV) system. In this study, IoT optimization methods were used to improve and monitor the performance of a small-scale solar PV system. The potential of solar tracking, condition monitoring and output prediction modelling were combined and harnessed to determine the output performance of the solar PV system under adverse environmental condition. An Arduino Uno microcontroller system using Light Dependent Resistor (LDR) and DHT11 sensors was developed for solar tracking and condition monitoring of a 20 W solar PV panel with rated open-circuit voltage of 21.6 V. ThingSpeak IoT platform was used for the real-time condition monitoring of the solar PV system in which output voltage, temperature and humidity were recorded. A Multiple linear regression (MLR) model equation was developed using the collected data from the IoT. The result obtained showed that solar PV panel exposed to an ambient temperature of 26 to 35 ^{0}C is sufficient to yield a stable maximum output voltage of 20 V bounded within the margin of ± 0.5 at humidity level below 50%. The predicted output voltage based on the MLR model equation showed high accuracy when compared with the measured output voltage data with percentage reduction of 0.79 to 9.42 % from the maximum measured output voltage recorded at any time period. However, when compared with the open-circuit output voltage of the solar panel, it ranges from 7.91 to 20.18 %. This will help in proper load management during cloudy weather condition.**

Keywords-solar tracking; condition monitoring; ThingSpeak platform; IoT; Multiple Linear Regression

I. INTRODUCTION

Solar photovoltaic (PV) system has grown to become massively deployed power supply system due to the non-localized nature of the solar resource [1], [2]. This is as a result of the gradually decreasing cost and the increasing energy conversion efficiency [3]. These have contributed to the increase in the installation of small-scale solar PV system in developing countries especially for lighting and small appliance use. However, solar PV panels are affected by environmental factors such as solar irradiance, ambient temperature, humidity which impacts on the panel temperature, voltage and current output [4], [5].

Furthermore, solar irradiation level is dependent on the time of the day, location and climatic condition of the environment in which the solar PV panel is installed [3]. Hence, these environmental factors and the resulting output voltage affects the amount of power generation of solar PV cell [6]. Consequently, there arises the need to explore the possibilities of achieving optimal performance of installed solar PV system.

II. LITERATURE REVIEW

Solar PV system are typically mounted at tilted angle to harvest the energy from the sun. But the incorporation of solar trackers has contributed to the design optimization and improve efficiency. According to [7], the evolution of solar tracking system started from purely mechanical system, to automated electronic controlled system, and then to micro-controller-based system which had been implemented in its various forms.

Solar tracking system are classified into single axis and dual axis based on the degree of rotation of the solar panel to the direction of the sun. The study proposed a single axis solar tracking system using Arduino Nano microcontroller, dc motor, LDR sensor. In a similar study, [8] developed an IOT solar tracking system using LDR, servomotor, NodeMCU, and ThingSpeak cloud platform. The study concluded that solar panel delivers more power when equipped with tracking system than when it is installed in a stationary position. A dual-axis solar tracker system in manual and automatic mode of operation was developed by [9]. The system was designed such that the manual mode was controlled through an IOT interface while the automatic mode rotates with the sun position using LDR sensors.

Solar PV systems have benefitted immensely from Internet of Things (IoT) technology which have been applied for monitoring and control in diver fields of study [10], [11]. According to [12], solar PV monitoring is essential to ensure the system is operating optimally due to early detection of potential problem in the installation. In the study by [13] and [14], ESP 32 module and Blynk IoT was used for real time monitoring of solar PV system. Additionally, measured value of the PV panel and the reported value on the IoT paltform have been shown to have no significant deviation [15]. However, [16] proposed the use of heat generation activities for solar panel energy conversion instead of the use of solar light. The study concluded that significant electricity can be generated through the burning of waste using solar panel. The study does not account for the effect of thermal heat on the solar panel.

Ref. [4] suggested that the prediction of solar PV output power can improve the efficiency of solar panel output. The prediction accuracy is said to be dependent on the accuracy of the input data while too much data can make the prediction complicated. Solar output prediction using machine learning approach was carried out by [17]. The study compared the prediction output of multiple linear regression (MLR), support vector machine (SVM) and gaussian regression (GR) models. They concluded that MLR model outperformed the other models while SVM performed poorly among the three models. However, in a comparative assessment of different machine learning algorithm for predicting solar output, [12] concluded that Random Forest outperformed other models such as linear regression, support vector machine, K-nearest neighbor and decision tree. Meanwhile in their study, [4] proposed several optimization algorithms to improve the prediction accuracy of SVM model. The study concluded that hybrid improved multi-verse optimizer algorithm (HIMVO) outperform particle swarm optimizer (PSO), dragonfly algorithm (DA), and multi-universe algorithm (MVA).

From the literature reviewed, researchers have combined several approaches to optimize the performance of solar PV panel. Some of the approaches implemented in these studies include solar tracking, real-time condition monitoring and output prediction. The focus of this study is to harness the potential of solar tracking, condition and output monitoring, and output prediction modelling for performance optimization of solar PV panel. The main contribution of this study is to determine the performance of these solar PV system under adverse and unstable environmental condition.

III. Methodology

A. Experimental Setup

The setup of the solar PV system used in this study is shown in Figure 1.

Figure 1. The developed solar PV system with solar tracking and monitoring system

A 20W solar PV panel was used in this study as a result of the increasing penetration of small sized PV panels for lighting and low-power applications. The environmental factor in which a PV panel is mounted is significant to the performance of the PV system. Therefore, the temperature and humidity of the installation environment was chosen as the parameter of interest in this study. The open-circuit voltage was used as the reference for the performance evaluation of the solar PV system.

The circuit connection of the components in the control box for the IoT-based solar tracking and condition monitoring system for the solar PV panel is shown in Figure 2.

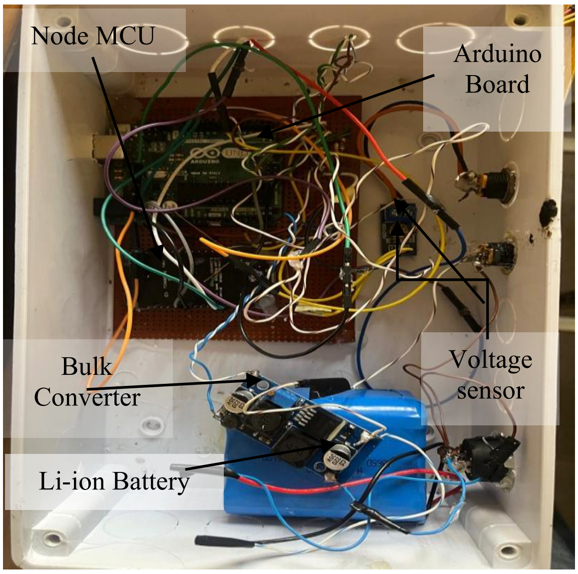

Figure 2. Circuit connection of hardware components for the tracking and condition monitoring system

The specification of the PV panel is as shown in TABLE I.

TABLE I. PARAMETERS OF THE SOLAR PANEL

S/N	Solar Module (GLD-1820)	
	Parameter	***Rating***
1	Maximum Power	20 W
2	Voltage at maximum power	18 V
3	Current at maximum power	1.11 A
4	Open circuit voltage	21.6 V
5	Short circuit current	0.92 V

B. Operation of the solar PV System Setup

The flowchart of Figure 3 describes the step-by-step approach to the implementation of the research based on the approach employed to monitor, collect and analyze the data of solar PV system experimental setup.

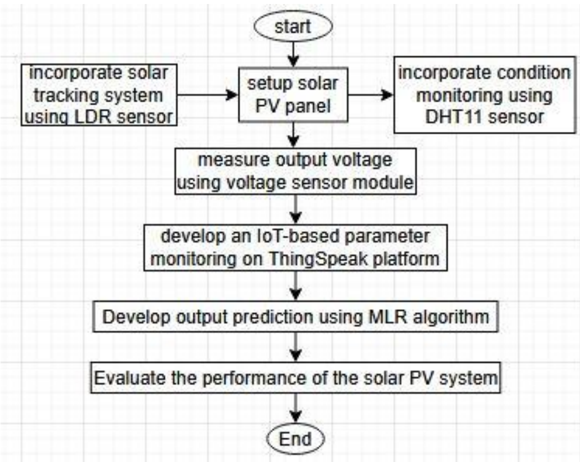

Figure 3. Procedure for the research implementation

C. Solar Tracking System

Two (2) units of light dependent resistors (LDR) and a servomotor was used to achieve the rotation of the solar panel. The design consists of a frame to hold the PV panel to enable the rotation of the panel with the use of the DC servomotor. The flowchart for the tracking system is shown in Figure 4.

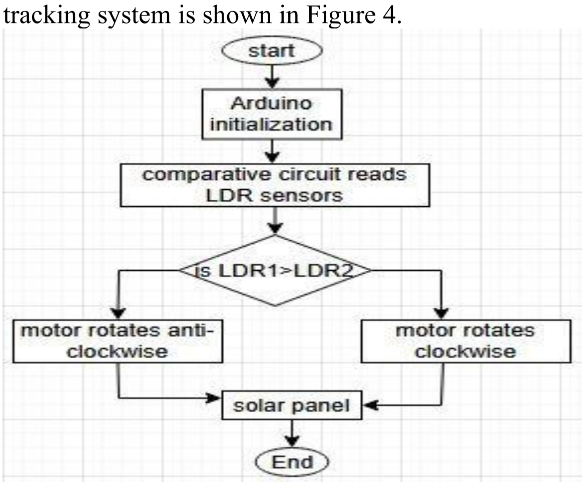

Figure 4. Flowchart of solar-tracking

The two (2) LDR sensors were mounted on the opposite ends of the panel. An Arduino microcontroller was used to read the data from these sensors through a comparator circuit to signal the motor in the direction to rotate.

D. IoT-Based Condition Monitoring System

The DHT11 sensor was mounted on the surface of the solar panel to measure the ambient temperature and humidity of the environment in which the solar panel was mounted. A voltage sensor module was connected to the output of the solar PV panel to measure the open-circuit output voltage of the panel which can then be compared with the specification on the PV panel nameplate for evaluation. These sensors were connected to the Arduino Uno microcontroller and then to the ESP8266 NodeMCU for data transmission through WiFi for real-time monitoring.

An IOT interface using ThingSpeak platform was used for real-time condition monitoring of the PV system remotely. This platform was chosen because of the graphical visualization of data stream from the sensors in real-time and other features that include statistical analysis and data processing. The data used for the analysis were collected in the days when there were light rain, cloudy weather and intermittent sunshine throughout the day. The choice of the season is to determine if solar installation will meet the desired need of the users at the period of the year with no high sunny days.

E. Prediction Modelling

MLR algorithm was used to predict the output voltage. MLR models the relationship between solar panel output (dependent variable, Y) and multiple independent variables (X_1, X_2, X_3, ..., X_n). This is expressed in "1".

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \epsilon. \quad (1)$$

where y is the predicted solar panel output, X_1, X_2, $X_3 \ldots Xn$ is the independent variables, β_0 is the intercept, β_1, β_2, ..., β_n is the regression coefficients and ϵ is the error term.

IV. RESULTS AND DISCUSSION

A. Simulation Modelling

The simulation of a solar tracking system in Proteus software is shown in Figure 5. The use of LDR establish the need for solar tracking for optimal solar energy harvesting by solar panel. This study observed that significant motor rotation was not achieved for the solar PV panel during the period of light rain, high cloudy weather and intermittent sunshine. Although other studies have reported panel rotation under good, sunny and clear weather condition.

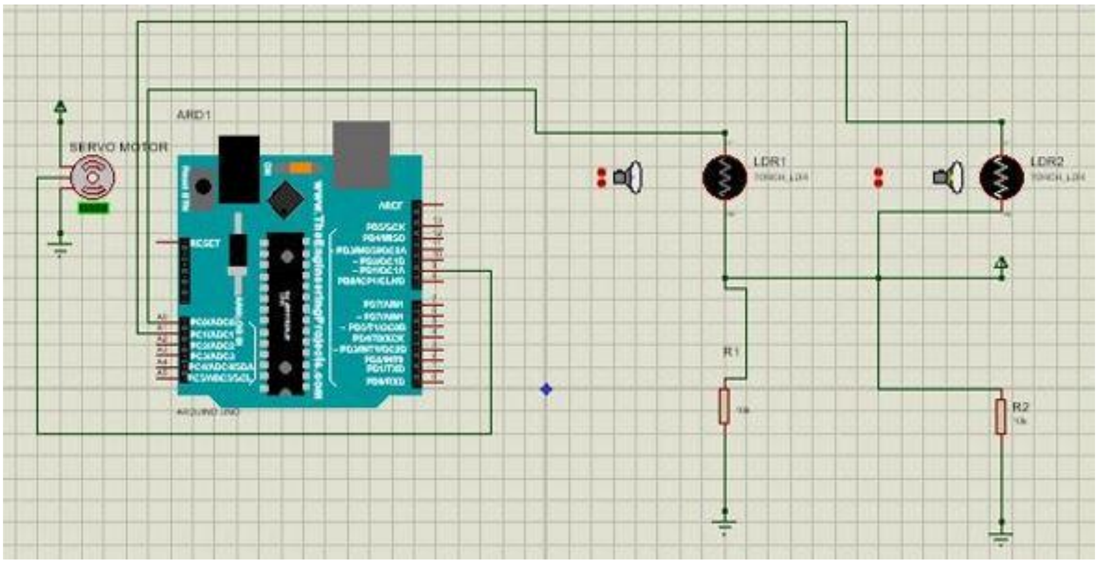

Figure 5. Simulation model of solar tracking system in Proteus software

B. Data collection on IoT Platform and Analysis

The GUI interface on IOT-based ThingSpeak platform for real-time monitoring of the solar PV system is shown in Figure 6. Temperature, humidity and output voltage are visualized in real-time.

A total of 1667 datapoints were collected and stored in the cloud at 2-minute interval. The data was collected between 8 am and 5 pm daily for 7 days. The output voltage tends to be higher and stabilizes at temperature between 26 to 35 ^{0}C as shown in Figure 7, but the voltage tends to decrease slightly as the temperature increases beyond 40 ^{0}C. Hence, it is not the direct sunlight on the panel but the irradiance level that is of utmost importance for solar PV power generation.

Figure 6. Real-time visualization of solar PV system parameters on ThingSpeak interface

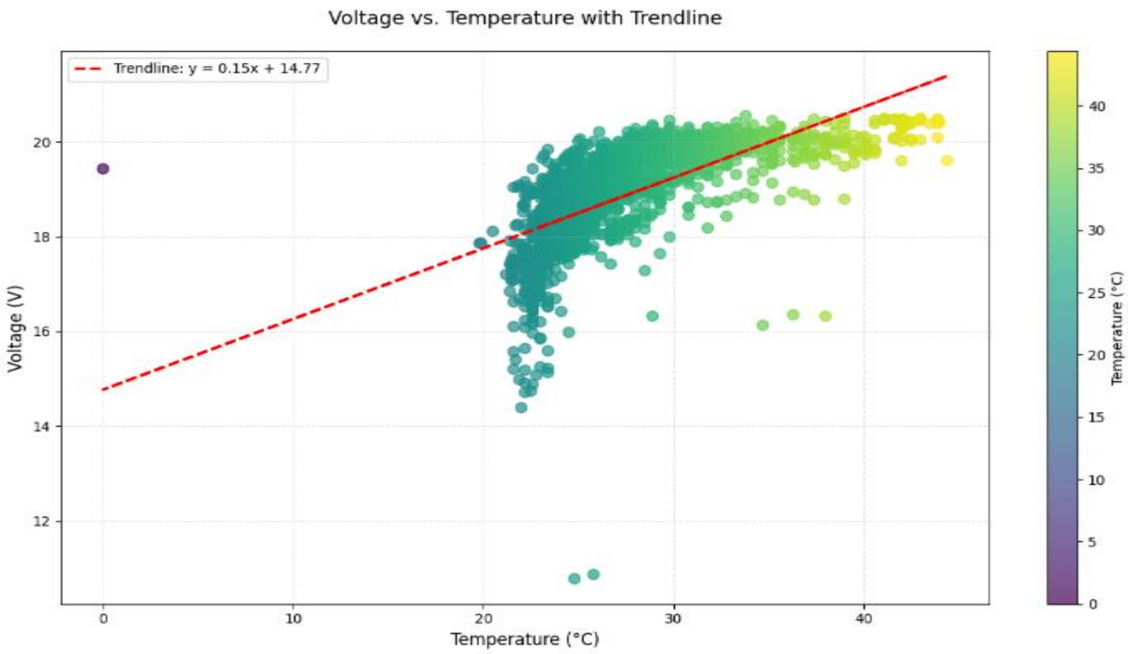

Figure 7. Plot of output voltage against ambient temperature

Furthermore, as observed in Figure 8, the output voltage frequently exceeds 19.5 V at low humidity below 50 %, which eventually peaks at 20.55 V but the output voltage stabilizes around 16 – 18 V at humidity level above 85 %.

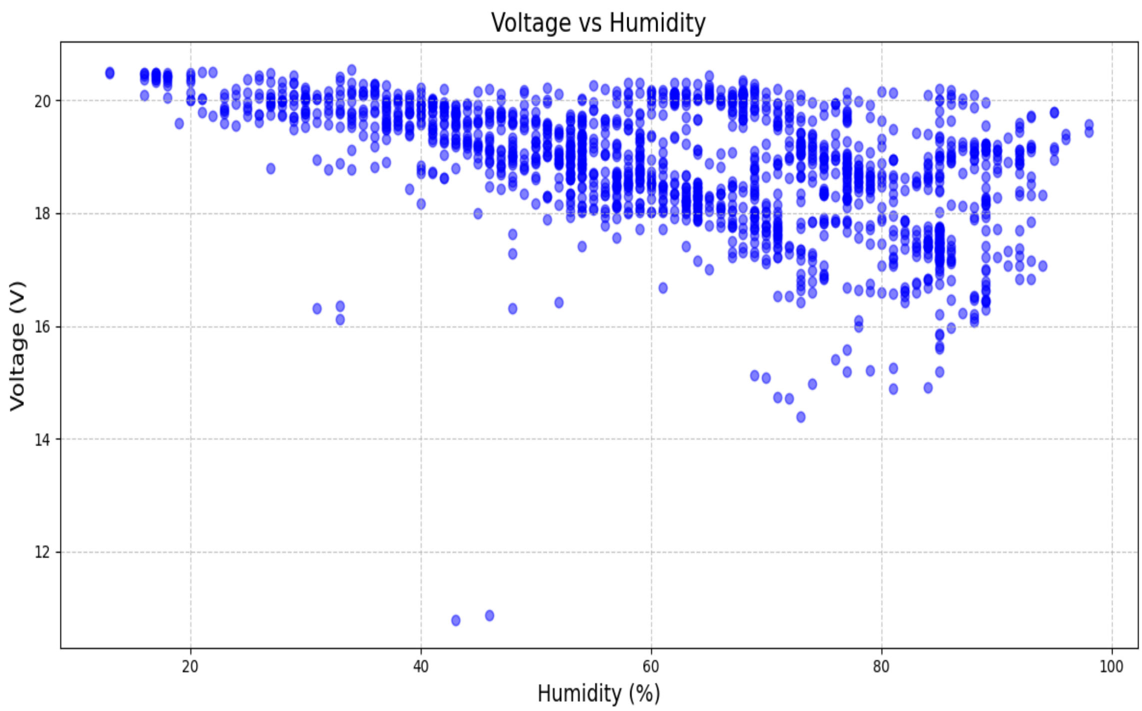

Figure 8. Plot of output voltage against humidity

From Figure 9, it can be deduced that high humidity level significantly affects the output voltage and hence power supply during the period may not be guaranteed for a long time. These results showed that higher temperature and humidity level negatively affects the output voltage. Hence, it is not the direct sunlight on the panel but the irradiance level that is of utmost importance for solar PV power generation.

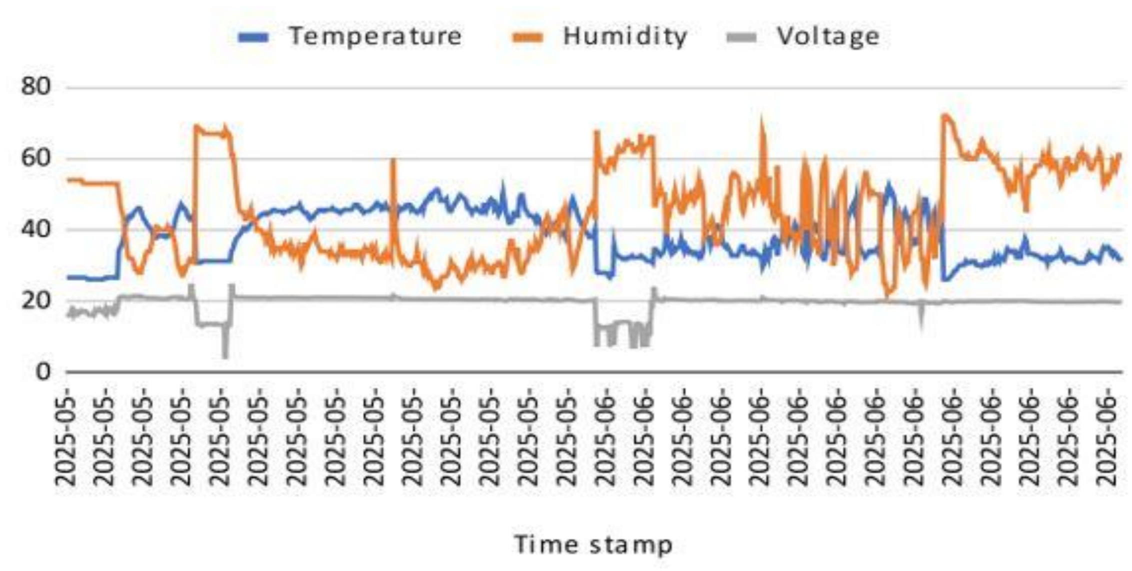

Figure 9. Plot of temperature, humidity and output voltage against data timestamp

The developed MLR model equation for the data collected is shown in “2”.

$$V = \beta_0 + \beta_1 t + \beta_2 T + \beta_3 t^2 + \beta_4 T^2 + \beta_5 (tT) + \beta_6 (tH) + \beta_7 (TH) \quad (2)$$

where t is time (s), T is the temperature and H is the humidity.

The estimated coefficient of the developed model is shown in TABLE II.

From the model description above, the generated predicted voltage is shown in Fig. 10.

TABLE II. ESTIMATED COEFFICIENTS OF THE MODELED EQUATION

Term	Coefficient	Interpretation
β_0 (intercept)	9.48619817	Baseline voltage at zero input values
$\beta_1 t$	-0.01816410	Slight voltage declines with increasing ime (before interaction effect)
$\beta_2 T$	0.77368503	Voltage increases with temperature, but conditional on quadratic and interaction effects
$\beta_3 t^2$	-0.00001265	Small negative curvature over time
$\beta_4 T^2$	-0.01523271	Voltage peaks at a temperature and then bends downwards
$\beta_5 (tT)$	0.00076134	Synergistic positive interaction between time and humidity
$\beta_6 (tH)$	0.00010289	Minor positive interaction between time and humidity
$\beta_7 (TH)$	-0.00095924	Humidity reduces the positive effect of temperature

The measured output voltage for each of the days the experiment was setup with the predicted output voltage of the solar PV panel obtained from the MLR model equation is shown in Fig. 10. The output voltage from the solar panel was correlated with the environmental condition for the days in which the experiment was setup. The days in which the weather condition with heavy rainfall that disrupted data collection were removed to ensure data consistency. There were two extreme days (Day1 and Day 4) with the measured voltage at the upper and lower end of the plot.

The output voltage showed a gradual increase from early morning which peaks later in the day and then starts to decline as seen in Figure 10. This is a common trend for all of the days in which the experiment was set up regardless of the different weather condition recorded for each of the days. The predicted output voltage obtained from the model equation showed high correlation with the measured output voltage for most of the days except for the two extremes days. Higher temperature and lower humidity accounts for the highest measured output voltage data in Day 1 while lower temperature and higher humidity account for the lowest measured output voltage for Day 4. Hence, the MLR model equation replicates accurately the correlation between the output voltage and the environmental condition based on the obtained data for the days in which the experiment was conducted as seen in Figure 11. Furthermore, the predicted voltage is within ± 10% of the measured experimental voltage as seen in Figure 11.

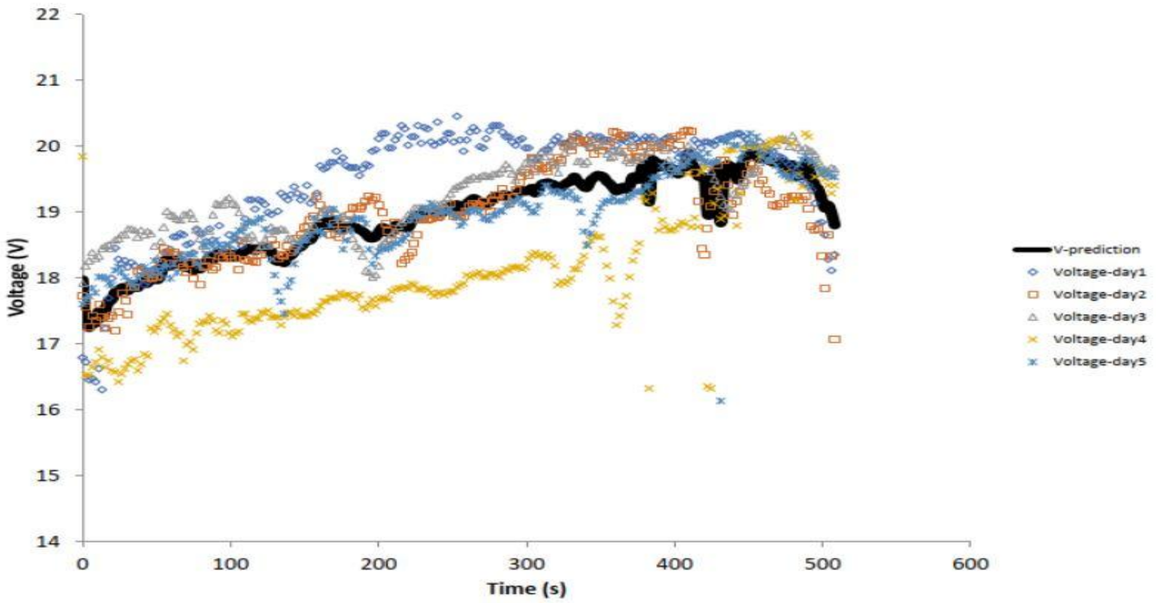

Figure 10. Solar panel output voltage prediction using MLR model equation

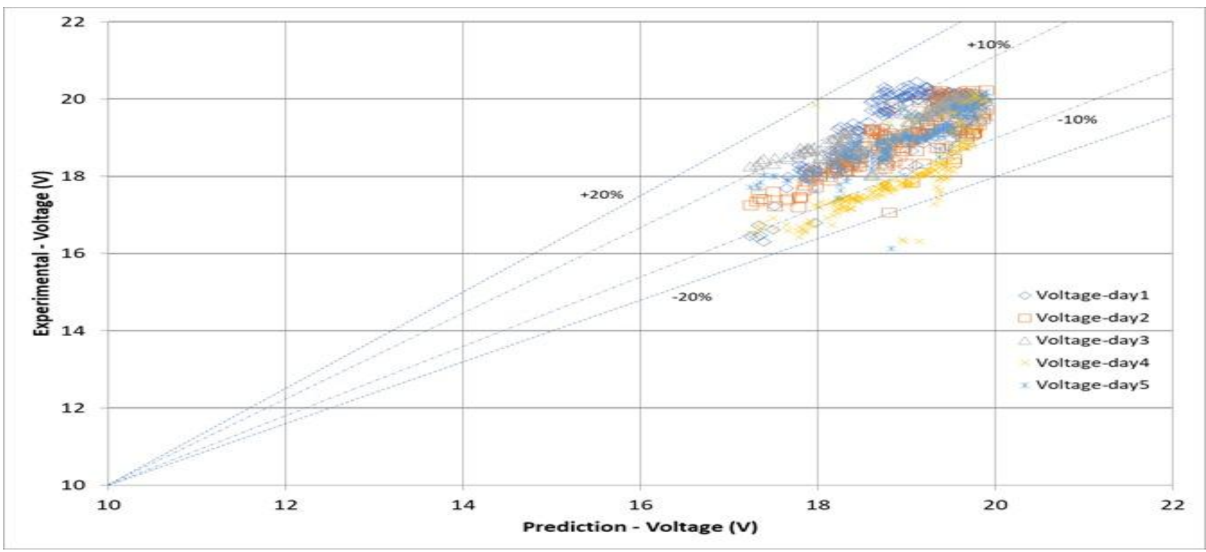

Figure 11 Correlation of prediction voltage with the measured experimental voltage

CONCLUSION

Solar tracking is optimized at a temperature range of 26 to 35 ^{0}C to yield maximum stable output voltage at humidity level below 50%. The output voltage of solar PV panel reduces as temperature increases beyond 40 ^{0}C. The output voltage becomes more unstable and reduces further at humidity level above 60% which then stabilizes at a lower voltage range of 16 – 18 V at humidity level above 85%. Hence, Solar panel will not be able to supply its designed maximum load under adverse environmental condition.

Furthermore, the developed MLR model equation captures the interaction between the output voltage and the environmental condition resulted in the high accuracy obtained for the predicted output voltage. The predicted output voltage has a percentage reduction of output voltage of 0.79 to 9.42 % from the maximum possible experimental voltage recorded. The predicted output voltage can be used as the expected output of the solar PV panel for maintaining proper load management during cloudy weather condition in tropical region in which the study was conducted.

Further statistical analysis of the collected data showed that the predicted output voltage deviated from the measured maximum experimental output voltage at any time period range from as low as 0.79 to as high as 9.42 %. Whereas, when the expected output voltage was compared with the open-circuit output voltage of the solar panel, the deviation ranges from 7.91 to 20.18 %. Since weather condition is the determining factor for the output voltage, the percentage reduction in the output voltage based on the time period of the experimental recorded output voltage is a more reliable expected output voltage for planning load management during cloudy weather condition.

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