Solar Radiation Estimation Using Discriminate Analysis Algorithm for The Output Voltage of Photovoltaic Module

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Abstract. A study of solar radiation in one area is very important to decide the area is suitable or not to be constructed the generation of photovoltaic (PV) system. The solar radiation can be recorded using the equipment of solar power meter or weather station. But it is due to the limitation of equipment, maybe a technical error occurs on the equipment, thus the equipment has a problem to record the data of solar radiation or one area has no equipment of solar radiation recording. An estimation method of solar radiation is needed to solve the problem. This paper presents an estimation of solar radiation using discriminate analysis algorithm (DAA) that it is applied to the output voltage of PV module. The data of daily measured solar radiation, maximum and minimum temperature are obtained from Chuping Weather Station through the web of world weather online for the year of 2019. The maximum and minimum temperature are as predictor variables in the DAA to obtain the daily estimated solar radiation. The result of daily estimated solar radiation is applied to the output voltage of PV module and compared to the output voltage of PV module applied by the daily measured solar radiation using the statistical analysis, they are root mean square error (RMSE) and error percentage. The results show that the estimated and measured solar radiation have RMSE of 0.257 and error percentage of 1.649%. They indicate that the DAA is acceptable to estimate the solar radiation.

1. Introduction
The technical limitation of weather recording causes the data of solar radiation is not available in one area, although it is understood that the solar radiation is important part of the photovoltaic (PV) construction system, but it becomes difficulty to decide a suitability of PV system [1]. The researchers have studied the estimation of solar radiation to make sure one area is suitable or not to be generated a PV power generation system. Some methods have been applied to obtain the estimation of solar radiation in one area.

Benjamin’s method, Jordan and Liu’s empirical method are applied to estimate the hourly solar radiation in Depok, West Java, Indonesia by [2], [3]. The result of daily estimated solar radiation is compared to the hourly measured solar radiation in order to know the effect of the coefficient of turbidity factor and climate condition in the solar radiation parameters. Two dimensionless A and B are contented in Jordan and Liu’s empirical method. They are given by 0.88 and 0.26, respectively in a normal
condition based on the data of cloud cover from measurement result. The results show that the methods can be applied in the Depok city, Indonesia based on the results of root mean square error (RMSE) and means bias error (MBE).

Four methods of solar radiation estimation (spectral, Bird and Hulstrom, Davies and Hay, Lacis and Hansen methods) are applied by [4] in a few Algeria sites. The methods based on the determination of transmission coefficients in atmospheric obtained from meteorological data (ambient temperature, air pressure and humidity). The results show that the four methods are applicable to estimate the solar radiation in a few Algeria sites.

The performance of PV module is very influenced by solar radiation, thus an estimation of hourly solar radiation using genetic algorithm based on Fuzzy (GABF) has been conducted by [5] in Surabaya, Indonesia. The hourly estimation of solar radiation based on the wind direction, wind speed, humidity and temperature. These four parameters are as estimator variables to estimate the hourly solar radiation. The result shows that the GABF with four estimator variables (wind direction, wind speed, humidity and temperature) can be applied to estimate the hourly solar radiation in Surabaya, Indonesia. If it is compared to the hourly measured solar radiation that it has RMSE of 1.44. A small RMSE value that can be obtained as indicator of acceptable estimation.

The discriminate analysis (DA) is one part of machine learning that can classify the target data based on the estimator data. The DA has been applied in some engineering areas, a pre-processed data by applying the DA to improve the performance of input data of processed image by [6]. An identification of colour texture retrieval using the DA based on the tint, structure and pattern is conducted by [7]. The DA is applied to diagnose the mechanical fault by [8] based on the discriminative features extracted and selected from measurement vibration. The machine learning has also applied in a fabrication model to optimize the costs of production and equipment [9].

This paper presents the DAA application to estimate the solar radiation based on the minimum and maximum temperature as the estimator variables. The measured data of solar radiation, minimum and maximum temperature are recorded from Chuping Weather Station through the web of world weather online for the year of 2019. MATLAB software is used to implement the DAA application with the measured solar radiation is written in the matrix name of label, the measured maximum and minimum temperature are written in matrix name of feat. The all data is saved in biner format with extension of dot mat (.mat). The result of estimated solar radiation is applied in the output voltage of PV module and they are validated using root mean square error (RMSE) and error percentage.

2. Methodology

The data collection of measured solar radiation, minimum and maximum temperature are presented in this section. The process of discriminate analysis algorithm (DAA) to estimate the solar radiation based on the minimum and maximum temperature is also explained in this section. The result of estimated solar radiation is applied to the formulation of PV module output voltage. The estimated solar radiation is compared to the measured solar radiation, also the output voltage of PV module for the input data of estimated solar radiation is compared to the input data of measured solar radiation using root mean square error (RMSE) and error percentage.

2.1 Data of solar radiation and temperature

The data of solar radiation and temperature are obtained from Chuping Weather Station through the web of world weather online for the year of 2019. The data of solar radiation is as the daily measured solar radiation that it is written in column matrix with the element number of 365 and it is given by matrix name of label. The minimum and maximum temperature are arranged in a matrix with the array of 365 x 4. Two of four columns in the matrix are for the daily minimum and maximum temperature, the other columns have element of 0 and it is given by matrix name of feat. Both matrix (label and feat) are as data in the biner format of MATLAB and they are saved in extension of dot mat (.mat).
2.2 Discriminate analysis algorithm to estimate solar radiation

Discriminate analysis is a statistical method to classify an observation set into the predefined groups. The observation set is the daily measured solar radiation, minimum and maximum temperature. While the predefined groups are the total groups of daily measured solar radiation, minimum and maximum temperature in one year that includes the observation set number of 365 sets.

A proposed discriminate function which is solar radiation function as function of the minimum and maximum temperature is given by equation (1).

\[ S = 3 + aT_{\text{min}} + bT_{\text{max}} \]  

where:

- \( S \) = Solar radiation (MJ/m\(^2\))
- \( T_{\text{min}} \) = Minimum temperature (°C)
- \( T_{\text{max}} \) = Maximum temperature (°C)
- \( a, b \) = Coefficient of minimum and maximum temperature

The minimum temperature, \( T_{\text{min}} \) and the maximum temperature, \( T_{\text{max}} \) are as the estimator variables. The coefficient of minimum temperature, \( a \) and the coefficient of maximum temperature, \( b \) are values decided by DAA as the results of training data (solar radiation, minimum and maximum temperature).

2.3 Parameters and formulation of PV module

The measured and estimated solar radiation are applied to measure and estimate the output voltage of PV module with the electrical parameter data and the formulation of PV module output voltage are shown in Table 1 and equation (2) and (3), respectively.

| Table 1. Electrical parameter of PV module |
|-------------------------------------------|
| Parameters | Value |
| Open circuit voltage, \( V_{\text{oc}} \) | 30 V |
| Maximum voltage at maximum solar radition, \( V_{\text{max}} \) | 30 V |
| Minimum voltage at minimum solar radition, \( V_{\text{min}} \) | 27 V |
| Coefficient temperature at open circuit voltage, \( T_{C_i} \) | -0.104 V/°C |

\[ V_{\text{oc}} (S, T) = \left[ 1 + \frac{V_{\text{max}} - V_{\text{min}}}{V_{\text{max}}} \cdot \frac{S - S_{\text{max}}}{S_{\text{max}} - S_{\text{min}}} \right] \left[ V_{\text{max}} + \tau_s (T) \right] \]  

\[ \tau_s (T) = 1 + \frac{T_{C_i}}{100\%} (T - T_N) \]  

where:

- \( S \) = Solar radiation (W/m\(^2\))
- \( S_{\text{max}} \) = Maximum solar radiation (1000 W/m\(^2\))
- \( S_{\text{min}} \) = Minimum solar radiation (800 W/m\(^2\))
- \( T \) = Temperature (°C)
- \( T_N \) = Nominal temperature (25 °C)
3. Result and Discussion

The maximum and minimum temperature and solar radiation for the year of 2019 are the training data. The measured solar radiation data is as the real data and it is as comparison to the estimated data based on the maximum and minimum temperature. The temperature data is displayed in a graph and analysed in term of the lowest and highest values.

The result of daily estimated solar radiation is displayed in a graph through the year of 2019. It is analysed in term of minimum, maximum and average values and compare to the measured solar radiation to obtain the values of RMSE and error percentage. The monthly of measured and estimated solar radiation are also explained in this section. They are displayed in the same bar graph to be easy to compare the both solar radiations.

The measured and estimated solar radiations become the basic of input data of PV module output voltage with the same maximum and minimum temperature. It is due to the PV module output voltage is affected by the both solar radiation and temperature. The PV module output voltages based on the measured and estimated solar radiations are analysed in term of average values and found the value of RMSE to make sure that the estimated solar radiation is valid for the output voltage of PV module.

3.1 Maximum and minimum temperature

The data of maximum and minimum temperature throughout the year of 2019 are shown in Figure 1. They are the daily maximum and minimum temperature. They have different data pattern on the day by day throughout the year of 2019. The both temperatures decide the estimated solar radiation by following the pattern of measured solar radiation or the both temperatures are trained to obtain the estimated solar radiation.

The daily maximum temperature has the lowest and highest values are 26.1 °C and 36.7 °C, respectively as shown in Figure 1 and Table 2. It means that the daily maximum temperature has temperature range 26.1 °C to 36.7 °C throughout the year of 2019. The lowest and highest maximum temperature occur on 7th June 2019 and 11th March 2019, respectively as shown in Figure 1. Whereas, the daily minimum temperature has the lowest and highest values are 20.8 °C and 26.2 °C, respectively as shown in Figure 1 and Table 2. It means that the daily minimum temperature has temperature range 20.8 °C to 26.2 °C throughout the year of 2019. The lowest and highest minimum temperature occur on 22nd January 2019 and 24th April 2019, respectively as shown in Figure 1. The daily maximum and minimum temperature have the different value pattern every day, but they should be able to identify the daily solar radiation and decide to obtain the estimated solar radiation.

| Table 2. Maximum and minimum temperature |
|-----------------------------------------|
| Maximum temperature (°C) | Minimum temperature (°C) |
| Lowest | Highest | Lowest | Highest |
| 26.1 | 36.7 | 20.8 | 26.2 |
3.2 Measurement and estimation of solar radiation

The daily estimated solar radiation as an estimation result using DAA based on the maximum and minimum temperature is shown in Figure 2. It is included the daily measured solar radiation to be easy to observe them. It can be observed that the results of estimated solar radiation are higher or lower than the measured solar radiation for some days, but the results of estimated solar radiation have also almost or same to the measured solar radiation for some days. They show that the capability of DAA in the estimation of solar radiation. They are needed to be validated using RMSE or error percentage to show that the DAA can be applied in the estimation of solar radiation.

The lowest and highest measured solar radiation are 5.07 MJ/m² and 27.06 MJ/m² that occur on 19th May 2019 and 7th March 2019, respectively as shown in Figure 2 and Table 3. The measured solar radiation has the average value of 18.31 MJ/m². Whereas, the lowest and highest estimated solar radiation are 8.07 MJ/m² and 26.98 MJ/m² that occur on 7th January 2019 and 9th March 2019, respectively as shown in Figure 2 and Table 3. The estimated solar radiation has the average value of 18.01 MJ/m².

The daily measured and estimated solar radiation give the RMSE value of 0.257 as shown in Table 4 and error percentage, $e$ of 1.649% that it is based on their average values of measured and simulated solar radiation. The statistical analysis shows that DAA is acceptable and it can be applied to estimate the solar radiation.
Figure 2. Daily measured and estimated solar radiation throughout the year of 2019

Table 3. Maximum, minimum and average solar radiation

| Measured solar radiation (MJ/m²) | Estimated solar radiation (MJ/m²) |
|----------------------------------|-----------------------------------|
| Lowest | Highest | Average | Lowest | Highest | Average |
| 5.07   | 27.06 | 18.09 | 8.07   | 26.98 | 18.01 |

Table 4. Maximum and minimum temperature

| Statistical analysis | RMSE | Error percentage, e (%) |
|----------------------|------|-------------------------|
|                      | 0.257| 1.527                   |

The monthly measured and estimated solar radiation as shown in Figure 3 can be obtained from the daily measured and estimated solar radiation. The values of monthly solar radiation show that the monthly estimated solar radiations are higher or lower than the measured solar radiation for some months throughout the year of 2019, but the estimated solar radiation is same to the measured solar radiation in month of December 2019.
3.3 Output voltage of PV module

The output voltage of PV module depends on the solar radiation and temperature. When the solar radiation increase causes the output voltage of PV module also increase, inversely when the solar radiation decrease causes the output voltage of PV module also decrease. But the increasing and decreasing of PV module output voltage are affected by the temperature and usually the increasing and decreasing of PV module output voltage are not too significant.

The daily measured and estimated solar radiation are as input data of PV module output voltage formulation as stated in equation (2) and (3) followed by the maximum and minimum temperature. The minimum, maximum and average output voltage of PV module based on the measured solar radiation at maximum temperature are 26.10 V, 27.82 V and 27.11 V, respectively as shown in Figure 4 and Table 5. While the minimum, maximum and average output voltage of PV module based on the estimated solar radiation at maximum temperature are 26.17 V, 27.79 V and 27.08 V, respectively as shown in Figure 4 and Table 5. If the daily estimated output voltage of PV module is compared to the daily measured output voltage of PV module for both same daily maximum temperature, thus they have RMSE of 0.0147. One value of RMSE closed to zero, it means that the DAA has a good performance in the estimation of solar radiation.

The minimum, maximum and average output voltage of PV module based on the measured solar radiation at minimum temperature are 26.85 V, 28.76 V and 27.93 V, respectively as shown in Figure 5 and Table 6. While the minimum, maximum and average output voltage of PV module based on the estimated solar radiation at minimum temperature are 27.04 V, 28.84 V and 27.90 V, respectively as shown in Figure 5 and Table 6. If the daily estimated output voltage of PV module is compared to the daily measured output voltage of PV module for both same daily minimum temperature, thus they have RMSE of 0.0147. One value of RMSE closed to zero, it also means that the DAA has a good performance in the estimation of solar radiation.
Figure 4. Output voltage of PV module at maximum temperature

| Measurement (volt) | Estimation (volt) |
|-------------------|------------------|
| Lowest | Highest | Average | Lowest | Highest | Average |
| 26.10  | 27.82  | 27.14   | 26.17  | 27.79  | 27.08   |
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**Figure 5.** Output voltage of PV module at minimum temperature

**Table 6.** Output voltage of PV module at minimum temperature

|               | Measurement (volt) | Estimation (volt) |
|---------------|--------------------|-------------------|
| Lowest        | 26.85              | 26.90             |
| Highest       | 28.76              | 28.90             |
| Average       | 27.93              | 27.92             |

4. Conclusion

Estimation of solar radiation has been conducted using DAA based on the maximum and minimum temperature recorded by Chuping Weather Station through the web of world weather online for the year of 2019, some conclusions can be deduced:

The lowest and highest minimum temperature throughout the year of 2019 are 20.8°C and 26.2 °C. While the lowest and highest maximum temperature throughout the year of 2019 are 26.1 °C and 36.7 °C. The daily minimum and maximum temperature are different every day in the temperature range of 20.8 °C to 26.2 °C and 26.1 °C to 36.7 °C, respectively. The different minimum and maximum temperature decide the result of estimated solar radiation using DAA.

The solar radiation estimated by DAA has RMSE of 0.257 and error percentage, $e$ of 1.649%. It indicates that the DAA is acceptable to estimate the solar radiation. The measured solar radiation and the result of estimated solar radiation are applied to the formulation of PV module output voltage for the same minimum and maximum temperature. They show that the RMSE values are 0.0147 for the minimum temperature and also 0.0147 for the maximum temperature. The RMSEs are close to zero, they indicate that the DAA has good performance to estimate the solar radiation.
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