Modelling of electric characteristics of 150-watt peak solar panel using Boltzmann sigmoid function under various temperature and irradiance

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Abstract. Solar energy utilized with solar panel is a renewable energy that needs to be studied further. The site nearest to the equator, it is not surprising, receives the highest solar energy. In this paper, a modelling of electrical characteristics of 150-Watt peak solar panels using Boltzmann sigmoid function under various temperature and irradiance is reported. Current, voltage, temperature and irradiance data in Denpasar, a city located at just south of equator, was collected. Solar power meter is used to measure irradiance level, meanwhile digital thermometer is used to measure temperature of front and back panels. Short circuit current and open circuit voltage data was also collected at different temperature and irradiance level. Statistically, the electrical characteristics of 150-Watt peak solar panel can be modelled using Boltzmann sigmoid function with good fit. Therefore, it can be concluded that Boltzmann sigmoid function might be used to determine current and voltage characteristics of 150-Watt peak solar panel under various temperature and irradiance.

1. Introduction
Research on current and voltage modelling on solar cells was carried out by Eckstein in 1990 at The University of Wisconsin - Madison. Eckstein wrote about the Effect of temperature and irradiance on I-V characteristics in the Solarex MSX-30 module [1]. Soto W D, Klen S A and Beckman W A studied about ideality factor parameters, reverse saturation current, light current, shunt resistance, and series resistance of diode at irradiance level of 1000 W/m² and the cell temperature is 25°C [2]. Chenni R, Makhlouf M, Kerbache T and Bouzid A examined series resistance modelling of solar cells and the effect of mounting photovoltaic cells in series and parallel [3]. Dzimano wrote about neural network modelling using single diode as a model of solar cell structure [4]. Villalva M G, Gazoli J R and Filho E R investigated current modelling that consists of solar cell current, saturation current and incorporating thermal voltage parameter [5]. Priambodo P S, Poespawati N R and Hartanto D wrote about open circuit voltage of solar cell output. This voltage is determined by photogenerated current, diode saturation current at reverse bias condition and temperature. The diode saturation current depends on the structure design and the choice of materials for solar cell diode, while photogenerated
current depends on the illumination intensity as well [6]. Our group research at Universitas Indonesia also examined the utilization of heat pipe on cold surface of thermoelectric with low-temperature heatsink from a solar cell simulated with combination of a bulb and a collector plate [7]. Bellia H, Youcef R and Fatima M studied about a detail modelling of the effect of irradiance and temperature on the parameters of Photovoltaic module. The chosen model was a single diode model with both series and parallel resistors for greater accuracy [8]. Humada A M, Hojabri M, Mekhilef S and Hamada H M examined techniques based on single diode and double diode models. The main parameters of interest was photocurrent, reverse diode saturation current, ideality factor of diode, series resistance, and shunt resistance [9].

In this paper, the current and voltage characteristics are modelled using Boltzmann sigmoid function with good fit. According to our knowledge, the use of Boltzmann sigmoid function to model the electric characteristics of solar panel has not been studied yet. This paper is written preliminary research of thermal management on solar cell to improve its efficiency. As stated by other researchers, the efficiency of solar panels decreases as the panels’ temperature increases [10-19]. Therefore, it is important to study about thermal management on solar panel.

2. Methodology
This research was conducted in Denpasar City located at 8°35'31" to 8°44'49" south latitude and 115°00'23" to 115°16'27" east longitude in June 2017. Current and voltage data was collected using 150-Watt peak solar panel at various temperatures and irradiance levels. Temperature data was taken at front and back panel. Temperature data collection was done using TMP36 temperature sensor which has ±2 °C accuracy with 0.5 °C linearity. The average temperature (T_M) was processed based on the front panel temperature (FPT) and back panel temperature (BPT) of solar panel. Irradiance (Irr) data collection was done using Lutron Solar Power Meter SPM-1116SD with 10 W/m² accuracy and 0.1 W/m² resolutions for irradiance<1000 W/m² and resolution of 1 W/m² for irradiance≥1000 W/m². Further data was processed with Origin software for fitting process. The results obtained from the fitting process indicate that parameters in Boltzmann Sigmoid Function (BSF) in Equation (1) have adjusted R² values close to 1 with current-voltage curve of 150-Watt peak solar panel.

\[
y = A_2 + \frac{A_1 - A_2}{1 + e^{\left(\frac{x-x_0}{a}\right)}}
\]  

These parameters are then used to determine the current-voltage characteristics of 150-Watt peak solar panel at different irradiance and temperature levels.

3. Result and Discussion
3.1. Data Observation
The observation was conducted using 150-Watt peak polycrystalline solar panel. It yields irradiance (Irr), front panel temperature (FPT), back panel temperature (BPT), current and voltage data as shown in Table 1. During the observation, short circuit current (I_{SC}) and open circuit voltage (V_{OC}) and 5 (five) current and voltage pairs (I_1-V_1 to I_5-V_5) data was collected.

| Irradiance (W/m²) | FPT (°C) | BPT (°C) | I_{SC} (A) | V_{OC} (V) | V_1 (V) | I_1 (A) | V_2 (V) | I_2 (A) | V_3 (V) | I_3 (A) | V_4 (V) | I_4 (A) | V_5 (V) | I_5 (A) |
|------------------|---------|---------|-----------|----------|--------|-------|--------|-------|--------|-------|--------|-------|--------|-------|
| 103-105          | 30.44   | 30.69   | 0.83      | 18.5     | 6.1    | 0.82  | 10.6   | 0.81  | 14.8   | 0.78  | 16.2   | 0.7   | 17.9   | 0.32  |
| 241-258          | 38.19   | 39.88   | 2.08      | 18.4     | 6.9    | 2.03  | 10     | 2     | 14.4   | 1.91  | 15.9   | 1.65  | --     | --    |
| 304-308          | 35      | 34      | 2.39      | 19.4     | 5.9    | 2.39  | 10.6   | 2.37  | 14.9   | 2.33  | 16.7   | 2.04  | 18.1   | 1.33  |
| 382-390          | 38.38   | 37.44   | 3.08      | 19.5     | 6.3    | 3.05  | 10.9   | 3.01  | 15     | 2.94  | 16.5   | 2.61  | 18     | 1.76  |
| 448-454          | 41.25   | 38.44   | 3.55      | 19.5     | 6      | 3.4   | 10.2   | 3.4   | 14.2   | 3.3   | 16.7   | 2.8   | 18.3   | 1.5   |
| 546-556          | 41.63   | 39.13   | 4.35      | 19.7     | 6.5    | 4.2   | 10     | 4.1   | 14.4   | 4.1   | 16.6   | 3.5   | 18.3   | 2.03  |
Table 2. Irradiance, temperature, current and voltage data of 150 Watt-peak solar panel (cont’d)

| Irradiance (W/m²) | FPT (°C) | BPT (°C) | ISC (A) | V_OC (V) | I₁ (A) | V₁ (V) | I₂ (A) | V₂ (V) | I₃ (A) | V₃ (V) | I₄ (A) | V₄ (V) | I₅ (A) | V₅ (V) | I₆ (A) |
|-------------------|----------|----------|---------|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 650               | 46.19    | 42.75    | 5.21    | 5.09   | 4.93 | 19.6 | 5.21  | 6.4   | 5.09  | 14.9  | 5.21  | 19.6  | 5.21  | 4.93  | 19.6  |
| 820-830           | 49.5     | 46.81    | 6.56    | 9.7    | 7.62 | 19.5 | 6.56  | 6.7   | 9.7   | 14.4  | 6.56  | 19.5  | 6.56  | 7.62  | 19.5  |
| 900               | 55.69    | 52.81    | 7.2     | 10.6   | 8.8  | 19.1 | 7.2   | 6.9   | 10.6  | 14.3  | 6.9   | 19.1  | 7.2   | 8.8   | 19.1  |
| 995-998           | 54.81    | 50.63    | 7.95    | 10.1   | 7.6  | 19.5 | 7.95  | 6.1   | 10.1  | 14.3  | 6.1   | 19.5  | 7.95  | 7.6   | 19.5  |
| 998-1006          | 52.5     | 48.09    | 7.98    | 10.5   | 7.7  | 19.1 | 7.98  | 6.3   | 10.5  | 14.4  | 6.3   | 19.1  | 7.98  | 7.7   | 19.1  |
| 983-1000          | 57.31    | 55.19    | 7.88    | 10.6   | 7.6  | 19.5 | 7.88  | 6.2   | 10.6  | 14.5  | 6.2   | 19.5  | 7.88  | 7.6   | 19.5  |
| 1020-1040         | 57.19    | 54.48    | 8.2     | 10.3   | 7.8  | 14.6 | 8.2   | 6.1   | 10.3  | 14.6  | 6.1   | 19.5  | 7.8   | 6.1   | 19.5  |
| 1020-1060         | 51.56    | 40.25    | 8.09    | 10.2   | 7.8  | 14.9 | 8.09  | 6.6   | 10.2  | 14.9  | 6.6   | 16.9  | 7.8   | 6.6   | 19.5  |
| 1150-1170         | 49.31    | 49.13    | 9.15    | 10.8   | 8.97 | 14.5 | 9.15  | 6.1   | 10.8  | 14.5  | 6.1   | 16.9  | 8.97  | 6.1   | 19.5  |

3.2. Data Exploration
The obtained data is then processed using Origin software. The results of data exploration are shown in Figure 1 for current-voltage relation at different irradiance levels, whereas in Figures 2 and 3 for current-voltage relations with different temperature means (T_M) at particular irradiance.

Figure 1. Current-voltage characteristics on 150-watt peak solar panels.

remark
L1 : Irradiance = 103-105 W/m², T_M = 30.56 °C.
L2 : Irradiance = 241-258 W/m², T_M = 39.03 °C.
L3 : Irradiance = 304-308 W/m², T_M = 34.5 °C.
L4 : Irradiance = 382-390 W/m², T_M = 37.91 °C.
L5 : Irradiance = 448-454 W/m², T_M = 39.84 °C.
L6 : Irradiance = 546-556 W/m², T_M = 40.38 °C.
L7 : Irradiance = 650 W/m², T_M = 44.47 °C.
L8 : Irradiance = 820-830 W/m², T_M = 48.15 °C.
L9 : Irradiance = 900 W/m², T_M = 54.25 °C.
L10 : Irradiance = 995-998 W/m², T_M = 52.72 °C.
L11 : Irradiance = 1150-1170 W/m², T_M = 49.22 °C.
Figure 2. Current-voltage characteristics with temperature difference at Irr ≈ 1030 W/m².

Figure 3. Current-voltage characteristics with temperature difference at Irr ≈ 1000 W/m².

3.3. Data Fitting

Based on the data obtained in Table 1 and the curves shown in Figures 1-3, fitting process is used to obtain current-voltage characteristic equations for 150 Watt-peak polycrystalline type solar panel. The fitting process shows that BSF gives results with a reduced chi-square statistic value near 0 and adjusted R² approaching 1. The result of data fitting using BSF is shown in Table 2.
Table 3. Irradiance, temperature, BSF parameters and statistics of 150-Watt peak solar panel.

| Irradiance (W/m²) | Tₑ (°C) | Boltzmann Sigmoid Function Parameters | Statistics |
|-------------------|---------|--------------------------------------|-------------|
|                   |         | A₁  | A₂  | x₀   | dx   | Reduced Chi-square | Adj R-square |
| 103-105           | 30.565  | 0.82016 | -71.77800 | 23.86800 | 1.20043 | 6.19279×10⁻⁵ | 0.99941      |
| 241-258           | 39.035  | 2.04103 | -23.51702 | 21.93816 | 1.44755 | 0.00144 | 0.99778      |
| 304-308           | 34.50   | 2.38612 | -2.77884  | 19.56473 | 1.07986 | 1.42928×10⁻⁴ | 0.99982      |
| 382-390           | 37.91   | 3.05141 | -3.69267  | 19.72963 | 1.20282 | 8.81763×10⁻⁴ | 0.99932      |
| 448-454           | 39.84   | 3.44124 | -3.04574  | 19.34902 | 1.22187 | 0.00595 | 0.99666      |
| 546-556           | 40.38   | 4.22192 | -3.50454  | 19.46560 | 1.25871 | 0.01031 | 0.99604      |
| 650               | 44.47   | 5.08239 | -3.56772  | 19.13747 | 1.31445 | 0.0106   | 0.99737      |
| 820-830           | 48.15   | 6.40337 | -2.51055  | 18.41101 | 1.16759 | 0.01733 | 0.99756      |
| 900               | 54.25   | 6.94410 | -2.11574  | 18.08592 | 1.18958 | 0.03418 | 0.9961       |
| 995-998           | 52.72   | 7.79526 | -5.21083  | 18.69723 | 1.56387 | 0.03334 | 0.99686      |
| 998-1006          | 50.25   | 7.80523 | -5.85533  | 18.96515 | 1.4874  | 0.01594 | 0.99861      |
| 983-1000          | 56.25   | 7.76106 | -3.21984  | 18.09081 | 1.54328 | 0.04181 | 0.99589      |
| 1020-1040         | 55.83   | 7.99027 | 0.17302   | 15.92966 | 0.83264 | 0.10617 | 0.99127      |
| 1020-1060         | 45.90   | 7.94694 | -5.49052  | 18.86610 | 1.66215 | 0.01217 | 0.99882      |
| 1150-1170         | 49.22   | 9.08778 | -2.68868  | 18.27200 | 1.42616 | 0.01519 | 0.99875      |

Figure 4. Relation between irradiance and $A₁$.

Table 4. Linear statistics for relation between irradiance and $A₁$.

| Intercept | Slope | Statistics |
|-----------|-------|------------|
| Value     | Std err | Value     | Std err | Adj R-square |
| 0.01156   | 0.03702 | 0.00777   | 5.44987×10⁻⁵ | 0.99951      |

From Figure 4 and Table 4, it can be stated that the relation between irradiance and $A₁$ follows Equation (2).

$$A₁ = 0.00777 \times Irr + 0.01156$$ (2)
Meanwhile the relation between irradiance and $A_2$ is shown in Fig. 5 and Table 4. This relationship indicates an exponential relationship.

![Figure 5. Relation between irradiance and $A_2$.](image)

**Table 5.** Exponential statistics for relation between and irradiance and $A_2$.

| y₀      | A        | $R_0$   | Statistics |
|---------|----------|---------|------------|
| Value   | Std err  | Value   | Std err    | Value   | Std err | Reduced Chi-square | Adj R-square |
| -2.42692 | 1.50446  | -215.36358 | 38.53096  | -0.01084 | 0.00164 | 14.32301          | 0.96744      |

From Figure 5 and Table 5, it can be stated that the relation between irradiance and $A_2$ follows Equation (3).

$$A_2 = -2.42692 + -215.36358 e^{-0.01084 \times irr}$$

The relation between irradiance and $x_0$ is shown in Figures 6 and Table 5. This relation indicates an exponential decay relationship.

**Table 6.** Exponential decay statistics for relation between irradiance and $x_0$.

| y₀      | A        | $t_1$   | Statistics |
|---------|----------|---------|------------|
| Value   | Std err  | Value   | Std err    | Value   | Std err | Reduced Chi-square | Adj R-square |
| 18.34933 | 0.29824  | 9.07315 | 1.28965    | 213.09862 | 44.25401 | 0.26048          | 0.91376      |
From Figure 6 and Table 6, it can be stated that the exponential decay relationship between irradiance and parameter $x_0$ follows Equation (4).

$$x_0 = 18.34933 + 9.07315 e^{-\frac{I_{rr}}{13.9655}}$$

(4)

Meanwhile the relation between irradiance level and $dx$ parameter is shown in Fig. 7 and Table 6. This relation indicates an irregular relationship.

**Table 7.** Descriptive statistics of $dx$.

| Mean  | Std dev | Min  | Median | Max  |
|-------|---------|------|--------|------|
| 1.27935 | 0.14429 | 1.07986 | 1.22187 | 1.56387 |
From Figure 7 and Table 7, it can be stated that the relation between irradiance and $dx$ is represented by Equation (5).

$$dx \approx 1.27935$$  \hspace{1cm} (5)

Modelling results using BSF with parameter values determined by Equation (1-5) for 150-Watt peak polycrystalline solar panel for irradiance level of 650 W/m$^2$, 820-830 W/m$^2$ and 995-998 W/m$^2$ are shown in Figure 8.

![Figure 8. Modelling of electric characteristics using BSF of various irradiance.](image)

**Table 8. Paired sample t test result of BSF and various irradiance level.**

| Irradiance ($W/m^2$) | t statistic | Prob>|t| |
|----------------------|-------------|----------------|
| 650                  | -2.0038     | 0.09194        |
| 820-830              | -2.3785     | 0.05488        |
| 995-998              | -2.3916     | 0.05391        |

**Remark**

All rows at the 0.05 level, the difference of the population means is NOT significantly different from the test difference (0).
The result of modelling using BSF using Equation (1-5) for 150-Watt peak type polycrystalline solar panel for specific level irradiance with temperature difference are shown in Figures 9 and 10.

**Figure 9.** Modelling of electric characteristics using BSF of Irr ≈ 1000 W/m².

- **remark**
  - L1 : Irradiance ≈ 1000 W/m², T_M = 56.25 °C.
  - BSF L1 : Result of L1 using BSF
  - L2 : Irradiance ≈ 1030 W/m², T_M = 50.25 °C.
  - BSF L2 : Result of L2 using BSF

**Figure 10.** Modelling of electric characteristics using BSF of Irr ≈ 1030 W/m².

- **remark**
  - L1 : Irradiance ≈ 1030 W/m², T_M = 55.83 °C.
  - BSF L1 : Result of L1 using BSF
  - L2 : Irradiance ≈ 1030 W/m², T_M = 45.90 °C.
  - BSF L2 : Result of L2 using BSF
The difference test between measurement data on a particular irradiance (with temperature difference) with BSF result is done by paired sample t-test method. Test results in Table 9 show that at 0.03 level, there is no significant difference between measurement data and BSF result.

Table 9. Paired sample t test result of BSF and various temperature.

| Irradiance ($W/m^2$) | $T_M$ (°C) | t statistic | Prob>|t| |
|----------------------|-----------|-------------|-------|
| ≈ 1000               | 56.25     | -2.61653    | 0.03977 |
| ≈ 1000               | 50.25     | -2.45506    | 0.04945 |
| ≈ 1030               | 55.83     | -1.86680    | 0.11117 |
| ≈ 1030               | 45.90     | -2.05055    | 0.08618 |

Remark
All rows at the 0.03 level, the difference of the population means is NOT significantly different from the test difference (0).

4. Conclusion
BSF can be used to determine the electric characteristics of 150-Watt peak polycrystalline-type solar panels at various irradiance and temperature levels. The BSF parameter values for solar panels are determined in Equation (1-5). Statistics show that at the 0.05 level, there is no significant difference between the measurement data of various irradiance levels with BSF results and at the 0.03 level, there is no significant difference between the measurement data of various level temperatures at a certain level irradiance with BSF results.

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