Modeling and simulation of temperature effect in polycrystalline silicon PV cells

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Abstract. Due to the human needs of energy, there is a need to apply new technologies in energy conversion to supply the demand of clean and cheap energy in the context of environmental issues. Renewable energy sources like solar energy has one of the highest potentials. In this paper, solar panel is the key part of a photovoltaic system which converts solar energy to electrical energy. The purpose of this paper is to give a MATLAB/ Simulink simulation for photovoltaic module based on the one-diode model of a photovoltaic cell made of polycrystalline silicon. This model reveals the effect of the ambient temperature and the heating of the panel due to the solar infrared radiation. Also the measurements on the solar cell exposed to solar radiation can confirm the simulation.

1. Introduction

The most important device which converts solar radiation to electric energy is photovoltaic cell.

The International Energy Agency said that "the development of affordable, inexhaustible and clean solar energy technologies will have huge longer-term benefits. It will increase countries energy security through reliance on an indigenous, inexhaustible, enhance sustainability, reduce pollution, lower the costs of mitigating climate change, and keep fossil fuel prices lower than otherwise.

Solar cells are made of semiconductors, and every type of semiconductor has a property called a band gap that is different from that of other semiconductors. The band gap defines the longest wavelength of light a semiconductor can absorb (it is transparent to longer wavelengths). It also fixes the maximum amount of energy that can be captured from photons of shorter wavelength. The result is that long-wavelength photons are lost and short-wave ones incompletely utilized.

Light shining on the solar cell produces both a current and a voltage to generate electric power. This process requires firstly, a material in which the absorption of light raises an electron to a higher energy state, and secondly, the movement of this higher energy electron from the solar cell into an external circuit. The electron then dissipates its energy in the external circuit and returns to the solar cell.

A variety of materials and processes can potentially satisfy the requirements for photovoltaic energy conversion, but in practice nearly all photovoltaic energy conversion uses semiconductor materials in the form of a p-n junction.
2. Analysis of circuit

The equivalent circuit of a solar cell consists of a diode and a current source connected in parallel. The current source produces the photocurrent $I_{ph}$, which is directly proportional to solar irradiance $G$.

The main parameters used to characterize a PV (photovoltaic) cell are its short-circuit current and its open-circuit voltage [1],[2].

![Simplified equivalent circuit of solar cell.](image)

The equation of the current voltage $I_{pv}$–$V_{pv}$ simplified equivalent circuit is derived from Kirchhoff’s law:

$$I_{pv} = I_{ph} - I_d$$  \hspace{1cm} (1)

Where

$$I_d = I_0 \left[ e^{\frac{q(V_{pv})}{NKT_j}} - 1 \right]$$  \hspace{1cm} (2)

So it becomes:

$$I_{pv} = I_{ph} - I_0 \left[ e^{\frac{q(V_{pv})}{NKT_j}} - 1 \right]$$  \hspace{1cm} (3)

Where:

$I_{ph}$ - is the photocurrent that is equal to short-circuit current, $I_0$ - is the reverse saturation current of the diode, $q$ - is the electron charge, $k$ - Boltzman constant, $N$ - is diode ideality factor, $T_j$ - is junction temperature of the panels, $I_d$ - is the current shunted through the intrinsic diode, $V_{pv}$ - is the voltage across the photovoltaic cell.

$$I_{pv} = I_{sc} - I_0 \left[ e^{\frac{q(V_{pv})}{NKT_j}} - 1 \right]$$  \hspace{1cm} (4)

We can determine the reverse saturation current $I_0$ by setting $I_{pv}$ =0. [2]

$$I_{pv} = 0$$  \hspace{1cm} (5)
\[ V_{\text{pv}} = V_{\text{oc}} \]  
\[ 0 = I_{\text{ph}} - I_0 \left[ \frac{q(V_{\text{oc}})}{NKT} - 1 \right] \]  

Thus we obtain, taking into account the fact that, with this model, the photocurrent is equal to the short-circuit current: \[2\]  
\[ I_0 = \frac{I_{\text{sc}}}{e^{\frac{q(V_{\text{oc}})}{NKT}} - 1} \]  

### 2.1. Ohmic losses model
To obtain a better representation of the electrical behaviour of the cell of the ideal model, the second model takes account of material resistivity and the ohmic losses due to levels of contact. These losses are represented by a series resistance \( R_s \) in the equivalent circuit.[3],[4],[5]

![Simplified equivalent circuit of solar cell with \( R_s \).](image)

The corresponding equations are:
\[ I = I_{\text{ph}} - I_S \left( \exp \left( \frac{q(V + R_s I)}{NKT} \right) - 1 \right) - \left( \frac{V + R_s I}{R_{\text{sh}}} \right) \]  

Where:
- \( I_{\text{ph}} \) - is the photocurrent that is equal to short-circuit current, \( I_s \) - is the reverse saturation current of the diode, \( q \) - is the electron charge, \( k \) - Boltzmann constant, \( N \) - is diode ideality factor, \( T \) - is junction temperature of the panels, \( V \) - is the voltage across the photovoltaic cell, \( R_s \) and \( R_{\text{sh}} \) are the series resistor respectively shunt resistor [6].

### 2.2. Effects of Solar Radiation Variation
The above model includes two subsystems: one that calculates the PV cell photocurrent which depends on the radiation and the temperature according to next equation: [3],[7],[8]

\[ I_{ph} = [I_{sc} + K_i(T - 298)] \frac{\beta}{1000} \]  \hspace{1cm} (10)

2.3. Effect of Varying Cell Temperature

The diode reverse saturation current varies as a cubic function of the temperature and it can be expressed as: [54]

\[ I_s(T) = I_s \left(\frac{T}{T_{nom}}\right)^3 \cdot \exp\left(\frac{T}{T_{nom}} - 1\right) \frac{E_g}{N V_t} \]  \hspace{1cm} (11)

Where:

- \( I_s \) is the diode reverse saturation current,
- \( T_{nom} \) is the nominal temperature,
- \( E_g \) is the band gap energy of the semiconductor and \( V_t \) is the thermal voltage. [9],[10],[5]

As a result, the complete physical behaviour of the polycrystalline photovoltaic cell is dependent on \( I_{ph}, I_s, R_s \) and \( R_{sh} \) on one hand, and on the other hand dependent on 2 external parameters: temperature and solar radiation. [11],[12]

Based on the following equation the SIMULINK model was developed in the figure 3.

\[ I = I_{ph} - I_s \left(\exp\frac{q(V + R_s I)}{N_i K T} - 1\right) \cdot \frac{(V + R_s I)}{R_{sh}} \]  \hspace{1cm} (12)

Where:

Table 1. The values used in the block diagram of the solar cell.

| Parameter | Value |
|-----------|-------|
| \( I_s \) | 0.1nA |
| \( q \) | 1.6029 \times 10^{-19} \text{C} |
| \( K \) | 1.3819 \times 10^{-23} \text{J/K} |
| \( N \) | 1.5 |
| \( T_{nom} \) | 25\(^\circ\)C |
| \( I_{sc} \) | 5.1A |
| \( K_i \) | 0.0017 A/\(^\circ\)C |
| \( V_T \) | 2.57 mV |
| \( E_g \) | 1.12 |
Figure 3. Block diagram of the solar cell model used in Matlab/Simulink software.

For a given value of the solar radiation, of temperature, $R_s$ and $R_{sh}$, the following characteristics were generated based on the model.

Figure 4. P-V and I-V characteristics of the solar cell.

In the figure 4 we can observe the dependency of the generated current respectively the power depending on the voltage of the polycrystalline solar cell.

In the following figure the curves of the current depending on temperature values of 25°C, 50°C, 75°C si 100°C.

For the figure 5 the value of the solar radiation was maintained constant at 1000W/m² and the temperature of the polycrystalline cell was varied by 25 degrees Celsius. Therefore the curves of the
current depending on voltage and the power depending on voltage were generated by the Simulink software.

![Graph of I-V characteristics for temperature variation between 25 and 100 °C.]

**Figure 5.** I-V characteristics for the temperature variation between 25 and 100 °C.

It is obvious that the generated voltage by constant solar radiation depends inversely proportional with the temperature growth, thus effecting the generated power of photovoltaic cell. To facilitate the observation of the descending current I introduced an exponential regression trendline.

The decrease of the generated current is because of the solar movement on the sky and implicitly the changing angle of the Sun to the normal line of the solar pannel.

![Graph of measured current.]

**Figure 6.** A selection of the measured current.

To analyse the effect of the temperature upon the generated current we will zoom in on a representative section of the measurements made in partly cloudy weather.

On the selected portion a linear regression curve was added, from which we can see that there is an decrease in the generated current of the solar cell. The decrease is about 150mA, and is according to the simulation. If the temperature increases by roughly 10 degrees celsius the current is inversly proportional and decreases by 150mA. As the temperature increases the current drops.
This decrease of the generated current is due to the exposure of the polycrystalline silicon to the mainly infrared radiation in the solar spectrum.

3. Conclusions
Using the Matlab/Simulink software it has been demonstrated the influence of temperature cell’s junction and solar radiation upon the performances and therefore the efficiency of solar cell.

The studied effects are: temperature dependence, solar radiation change and series resistance influence. The solar cell with series resistance model offers a more realistic behavior for the photovoltaic systems, and the simulation give us a good perception of the influence of external factors like solar radiation and temperature.

The measurements we made in partly cloudy weather indicates that after a period of time while the Sun is covered by clouds the silicon cell starts to cool down so the effect of temperature upon the polycrystalline cell is easily visible when the Sun begins to shine.

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