



Mathematical Modeling and Simulation of PV System using MATLAB/Simulink.

KEYWORDS

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ABSTRACT This paper presents a step by step procedure for the simulation of photovoltaic modules with MATLAB/Simulink. One diode equivalent circuit is employed in order to investigate I-V (current voltage) and P-V (Power voltage) Characteristics of a typical solar module. The proposed model is designed with the use of Simulink block libraries.

Introduction

Solar cells also called photovoltaic cells, convert sunlight directly into electricity. PV cell gets its name from the process of converting light (photons) to electricity (voltage), which is called the PV effect.

Sunlight can be converted to electricity due to the Photo-voltaic effect discovered in 1839 by Edmund Becquerel, a French scientist. Historically, it has been about 50 years since the first operational silicon solar cell was demonstrated. However, the last 20 years have seen large improvements in the technology, with the best confirmed cell efficiency being over 24%.

Today, thousands of people power their homes and businesses with individual solar PV systems. Utility companies are also using PV technology for large power stations. The panels are mounted at a fixed angle facing south, or they can be mounted on a tracking device that follows the sun, allowing them to capture the most sunlight.

Photovoltaic energy is the conversion of sunlight into electricity. A photovoltaic cell, commonly called a solar cell or PV, is the technology used to convert solar energy directly into electrical power. A photovoltaic cell is a non-mechanical device usually made from silicon alloys. Sunlight is composed of photons, or particles of solar energy. These photons contain various amounts of energy corresponding to the different wavelengths of the solar spectrum. When photons strike a photovoltaic cell, they may be reflected, pass right through, or be absorbed. Only the absorbed photons provide energy to generate electricity. When enough sunlight (energy) is absorbed by the material (a semiconductor), electrons are dislodged from the material's atoms. Special treatment of the material surface during manufacturing makes the front surface of the cell more receptive to free electrons, so the electrons naturally migrate to the surface. When the electrons leave their position, holes are formed (step 3). When many electrons, each carrying a negative charge, travel toward the front surface of the cell, the resulting imbalance of charge between the cell's front and back surfaces creates a voltage potential like the negative and positive terminals of a battery. When the two surfaces are connected through an external load, electricity flows (step 4).

A PV cell is semiconductor with n-type silicon at the top and p-type silicon on the bottom of the cell to form a pn junction that could generate 0.5 to 0.6 V (V_{cell}) at the junc-

tion. A current of the PV cell (I_{cell}) is defined by the area of the cell in combination with the amount of irradiation (G) and temperature (T). A PV module converts light into electricity and the amount of power generated, for a specific cell, depends on both G and T.

A PV cell is conventionally represented by a current source (I_L), one or two parallel diodes (D), a shunt resistance (R_{sh}), and a series resistance (R_s). Usually the value of R_{sh} is very large and that of R_s is very small, hence they may be neglected to simplify the analysis. Fig. 4.1 shows equivalent circuit of photovoltaic cell [1].

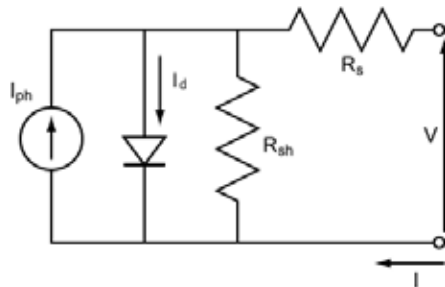


Fig.2 The one-diode circuit equivalent of a PV cell

PV cells are grouped in larger units called PV modules which are further inter connected in a parallel-series configuration to form PV arrays. Now, a PV module consists of a number of PV cells connected in series to allow for a usable high voltage level.

For modelling of photovoltaic array, we must be calculating photo current, reverse saturation current, saturation diode current etc. so first we complete mathematical modelling of PV array. In next sections we are going to do mathematical modelling of the PV system and to implement that using MATLAB/Simulink software.

Mathematical Modeling and Simulink Model of PV Array Photo Current

Fig.3 shows the Simulink model of the photo current. The module photo current I_{ph} of the photovoltaic module depends linearly on the solar irradiation and is also influenced by the temperature according to the following equation:

$$I_{ph} = I_{rr} [I_{sc} + \{KI (T_{op} - T_{ref})\}] \quad (1)$$

Where,

- I_{ph} = Photo Current
- I_{rr} = Solar insolation (kW/m²)
- I_{sc} = Short circuit current
- KI = Short circuit current temperature co efficient
- T_{op} = Operating temperature °C
- T_{ref} = Reference temperature °C

From equation (4.1) we can also see that the photo current also depends upon the solar insolation I_{rr} and short circuit current I_{sh} . As photo current I_{ph} depends upon the solar irradiance it will vary with the variation of solar irradiation.

Reverse Saturation Current

Fig. 4 shows Simulink model of reverse saturation current I_{rs} . From this model we can obtain the value of reverse saturation current. Physically, reverse saturation current is a measure of the "leakage" of carriers across the p-n junction in reverse bias. This leakage is a result of carrier recombination in the neutral regions on either side of the junction.

Mathematically it can be represented by the equation:

$$I_{rs} = I_{sc} \left[\frac{1}{\exp\left(\frac{V_{oc} - q}{k T_{op} N}\right)} - 1 \right] \tag{2}$$

Where,

- I_{rs} = Reverse saturation current
- V_{oc} = Open circuit voltage
- q = Electron charge (1.6×10^{-19})
- k = Boltzmann's constant (1.38×10^{-23} J/K)
- C = No.of cells in module (36)
- N = Ideal factor (1.36)

2.3 Shunt Current

Fig. 5 shows Simulink model of shunt current I_{sh} . Using this Simulink model we are able to obtain shunt current.

The shunt current is mathematically represented by the equation:

$$I_{sh} = \frac{V + I R_s}{R_p} \tag{3}$$

Where,

- I_{sh} = Shunt Current
- V = Voltage
- I = Load Current
- R_s = Series resistance
- R_p = Parallel resistance

2.4 Diode Current

Fig.6 shows Simulink model of the diode current I_d . Mathematically diode current can be represented by the following equation:

$$I_d = I_{rs} N_s \left[\exp\left(\frac{V + I R_s}{n V_t C N_d}\right) - 1 \right] \tag{4}$$

Where,

- I_d = Diode current
- N_p = No. of parallel modules
- N_s = No. of series Modules
- V_t = Thermal voltage

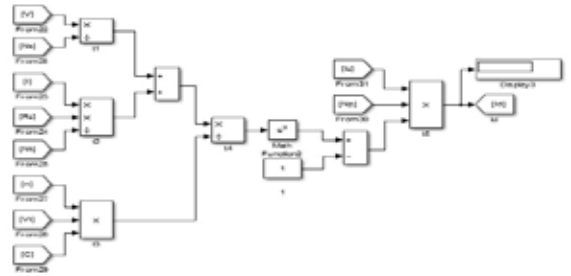


Fig.6 Simulink model of diode current Id.

From equation (4), we can see that with variation in number of series and parallel connected PV modules, diode current I_d will vary. It is also linearly proportional to the reverse saturation current I_{rs} .

2.5 Load Current

Fig. 7 shows Simulink model of load current I . from this Simulink model we can obtain output current of the designed PV system.

Mathematically, it can be represented by the following equation:

$$I = I_{ph} N_p - I_d - I_{sh} \tag{5}$$

Where,

I = Load current

From the equation (5), we can see that I depends upon the values of photo current I_{ph} , diode current I_d , and shunt current I_{sh} . So, value of load current will vary with variations in photo current, diode current and shunt current. Load current also depends upon N_p . So, with increase in number of parallel connected strings of modules, load current will also increase.

2.6 Saturation Current

Fig. 8 shows Simulink model of saturation current I_s . So, using this Simulink model we are able to obtain saturation current of the designed PV array.

Mathematically saturation current can be represented by the equation:

$$I_s = J_{01} \left[\frac{T_{op}}{T_{ref}} \right]^3 \exp\left[\frac{q E_g}{k n} \left(\frac{1}{T_{op}} - \frac{1}{T_{ref}} \right) \right] \tag{6}$$

Where,

I_s = Saturation current

E_g = Band gap energy of the semiconductor (1.12 eV)

Thermal Voltage

Fig.9 shows Simulink model of the thermal voltage V_t . Using this Simulink model we can obtain output of thermal voltage. Mathematically thermal voltage V_t can be represented by following equation:

$$V_t = \frac{k T_{op}}{q} \tag{7}$$

From the equation (7), we can see that thermal voltage V_t is directly proportional to the operational temperature T_{op} . As thermal voltage is directly proportional to the opera-

tional temperature, value of thermal voltage varies with the change in operational temperature.

PV Module and Array

As we know that to obtain required voltage and current we have to connect number of solar cells in series and parallel combination which forms a module of PV system. By arranging these modules in series and parallel combination we can obtain required power.

Fig. 10 shows no. of PV cells per module in PV array and no. of series and parallel modules in designed PV system.

PV array is created by putting 36 model based modules together in series and parallel. Array consists of 12 modules in series string and 3 strings in parallel, totaling 11.694kWDC power.

Simulink Model of PV System

Now, we want to obtain graphs of power, voltage and current of the designed PV array. IV characteristic and PV characteristic are also required. All these results can be obtained by the Simulink model shown in to fig. 11.

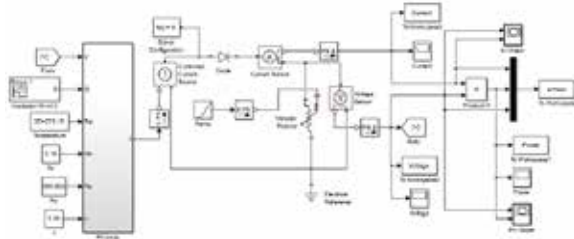


Fig.11 Simulink model of designed PV System

The workspace is added to measure current, voltage and power in this model. As shown in fig.11, XY Graph block is used to obtain PV and IV characteristics and scope blocks are used to obtain wave forms of the current, voltage and power. Final Simulink model of the designed PV system is as shown into fig. 11.

The final model takes the irradiation, temperature, series resistance, parallel resistance, ideality factor and module voltage and gives the output current. The output current is sensed by the current sensor. Output voltage is obtained across variable resistor, which can be sensed by the voltage sensor.

All the specifications used for the various parameters used in the design of the PV system are listed in table 1[1].

Table 1 Specifications for one module

Parameter	Value
Nominal Maximum Power(Pmax)	300W
Optimum Operating Voltage(V_{mp})	36.1V
Optimum Operating Current(I_{mp})	8.30A
Open Circuit Voltage(V_{oc})	44.6V
Short Circuit Current(I_{sc})	8.87A
Ideality factor	1.36
Module Efficiency	15.63%

RESULTS

From the simulation of the designed PV system, we have obtained various results. Figure 4.11 shows the wave form of the output power.

Figure 4.12 shows the waveform of the output voltage. Figure 4.13 shows the waveform of the load current. Figure 4.14 shows obtained IV characteristics. Figure 4.15 shows obtained PV characteristic.

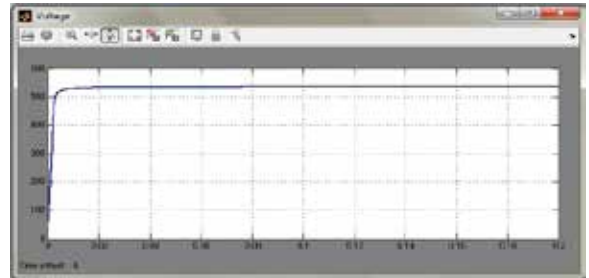


Fig.13 Output Voltage of designed PV System

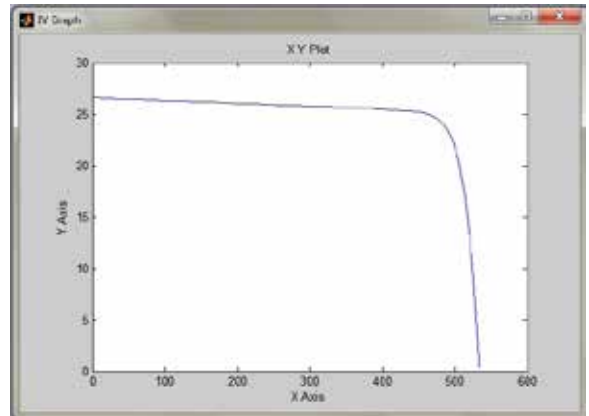


Fig.15 IV Characteristic

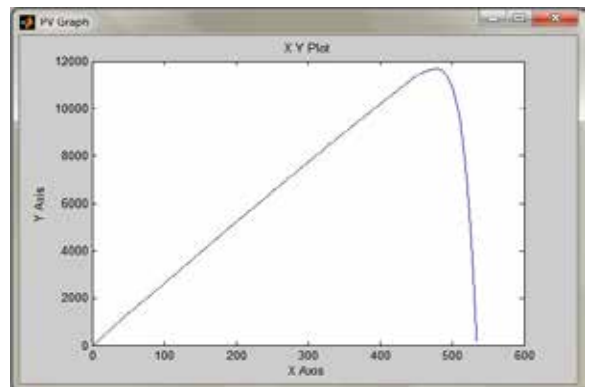


Fig.16 PV Characteristic

Results obtained from the simulation of the designed PV System are listed in Table 2.

Table 2 Obtained Results of designed PV System

Parameter	Value
Power	11694 W
System Voltage	534.0635 V
Load Current	26.5967 A

CONCLUSION

Mathematical modeling of PV system has been done. Based on the literature review and theories, PV system is designed. Designed PV system is developed in MATLAB/Simulink software. Simulink-based Model of a photovoltaic (PV) system using the single-diode model of a PV solar cell was developed. The proposed model takes the datasheet values (I_{sc} , V_{oc} , I_m and V_m) along with the cell temperature, sunlight/irradiance and ideality factor as input and outputs the I-V and P-V characteristics. This model is implemented with Simulink blocks.

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