

# Simulation of a Solar Photovoltaic Panel

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## 1 Abstract

This tutorial will describe how to simulate the V-I characteristics of a photovoltaic (PV) module. The tremendous growth in integration of renewable energy sources such as PV and wind turbine generators has been welcomed as cutting carbon emissions is becoming a priority. From an engineering perspective, it becomes important to be able to fully model and analyze these sources before their deployment to ensure that their integration benefits the grid. Most importantly, the integration of renewable sources should not disrupt the operation of the grid. For this purpose, the first step is to understand their behavior and develop simulation models.

The simulation of the PV module in detail requires an in-depth understanding of the physics of the solar cell. This tutorial will address the major factors that affect production of energy from a solar cell but will not model every physical detail. The tutorial will describe how the detailed model of the solar cell has been simplified so that it can be modeled in a simulation.

The outline of the tutorial is as follows:

1. Basics of the operation of a PV cell/module
2. Factors affecting energy produced
3. Equation of PV voltage and current
4. Simulating the PV panel
5. Simulation results

This tutorial is accompanied by simulation files. It is recommended to try out the simulation files while reading the tutorial.

About the software: Python Power Electronics is a free and open source circuit simulator for power electronics and power systems professionals. It is available under the BSD 3.0 license agreement which is available with this tutorial and in every case as a LICENSE.txt file. Users of this tutorial are advised to read the license file. It should be noted that this tutorial is for learning and educational purposes. Implementation of the examples cited in this tutorial directly in a prototype cannot be guaranteed to work and the readers are responsible for taking precautions to prevent damage to their equipments and injury to themselves. For any queries, feel free to contact me at [pythonpowerelectronics@gmail.com](mailto:pythonpowerelectronics@gmail.com) or visit the project website <http://www.pythonpowerelectronics.com/>.

## 2 Literature

It is recommended that anyone genuinely interested in PV should read a bit on the physics involved in a solar cell. I had read on PV physics a long while back when I started my PhD and spent several days re-reading before writing this tutorial. The literature on this topic is vast and many of them are fairly complicated and difficult to understand for someone with a power electronics background. The simplest paper I could find is cited in the reference [1]. This paper also cites many of the other significant works in this field.

Besides this paper, a simple internet search provides several useful links that describe PV operation in fairly simple terms. Many of the manufacturers of PV modules also provide white papers and technical documents that are a good source of information. The technical specifications of the PV modules provided by manufacturers is a fairly important document and will be used in this tutorial as it is used in the reference.

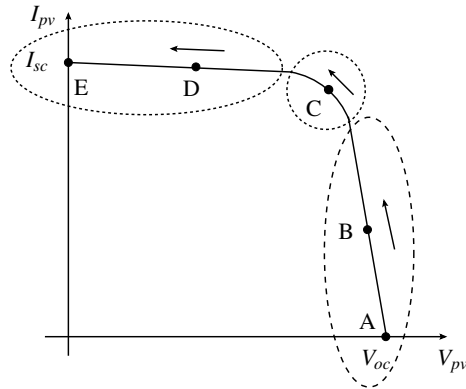


Figure 1: V-I curve of a PV cell

### 3 Characteristics of a PV cell

The figure above shows the V-I characteristics of a PV cell. As can be seen, a PV cell is not like a battery which supplies an almost constant voltage as long as it retains sufficient charge. The terminal voltage of the PV cell is a function of the current supplied by it. The V-I characteristic is divided into three regions and in that five points have been marked so as to describe how the PV cell functions. Consider the PV cell in state A which means it is open circuited and supplies zero current. The terminal voltage in this state is called  $V_{oc}$  or the open circuit voltage. As the load on the PV cell increases and it begins to supply current, the operating point is represented by B and it moves along the curve in the direction shown. The voltage decreases gradually as the current supplied increases. The operating point moves into the second region. This region is the most important because it is in this region (specifically point C) that the PV cell supplies maximum power. It is usually the objective of any power converter control scheme to adjust the terminal voltage and current to be as close to point C as possible. As the current increases, the operating point moves into the third region represented by point D. In this region, the voltage drops drastically as the current increases until it is short-circuited at point E. The current at point E is the short circuit current  $I_{sc}$ .

This tutorial will describe how a PV cell is modeled to achieve the above V-I characteristic. Moreover, the above characteristic is a function of incident solar radiation and temperature besides being influenced by the manufacturing process such as doping, type of silicon etc.

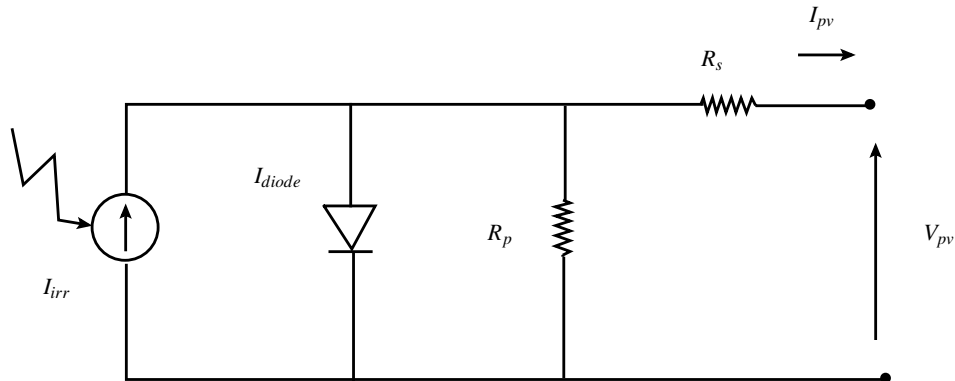


Figure 2: Equivalent circuit of a PV cell

#### 4 Basics of a PV cell

The figure above shows the equivalent circuit of a PV cell. From the V-I characteristics shown in the previous page, it is obvious that if we wish to model a PV cell, we cannot just model it as a voltage source behind an impedance. The current source on the far-left is the current generated by the PV cell and is called  $I_{irr}$  or iridescent current or the photo current. The resistances  $R_p$  and  $R_s$  model the losses in the solar panel. The diode shown in the middle is the tricky part to model. The conduction current of this diode varies according to the terminal voltage. For example, when the cell is at no-load, the output PV current  $I_{pv}$  is zero. So, the current generated  $I_{irr}$  must go somewhere because the only other path is the resistance  $R_p$  which being a parasitic resistance to model cell loss is very large. The current  $I_{irr}$  flows into the diode and the current drawn  $I_{diode}$  is equal to  $I_{irr}$ . As the load increases, the terminal voltage will decrease due to the resistive drop in  $R_s$ . As terminal voltage decreases, the current drawn by the diode (controlled current source) also decreases. At short-circuit, the entire cell current  $I_{irr}$  flows into the short as the diode is completely bypassed. This is the concept behind representing the PV cell in the above manner.

## 5 Reference conditions

The next part of the tutorial will describe how the operation of the PV cell can be modeled. The only way to describe the operation is through equations. It is highly recommended that a reader go through the reference [1] as that is the accurate manner of generating the equations. This tutorial will describe a simplified method as for power electronic applications, detailed modeling from a solid state physics point of view is unnecessary. To begin with, we will start with the operating conditions that are often specified in any manufacturer documents. These are Standard Test Condition (STC) and Nominal Operation Cell Temperature (NOCT).

STC is when the incident solar radiation is  $G_{ref} = 1000 \text{ W/m}^2$  and the cell temperature is  $T_{ref} = 25^\circ\text{C}$ . NOCT is the temperature of the PV cell and is usually equal to  $45^\circ\text{C}$ . This NOCT occurs also when the incident solar radiation is  $G = 800 \text{ W/m}^2$ , ambient temperature is  $T_{amb} = 20^\circ\text{C}$ . Here, it is important to make the distinction between ambient temperature and cell temperature. Ambient temperature is the atmospheric temperature while cell temperature is the temperature of the cell when it functioning and producing power.

There are other specifications such as AM 1.5 which implies Air Mass 1.5. This is an atmospheric condition and will not be used in this tutorial. Sometimes the wind speed is mentioned and this will also not be used in this report.

Next we will describe a sample manufacturer specification document.

## 6 Manufacturer specifications

In this tutorial, I will use the Canadian Solar panel CS6K-275M parameters and simulate it. To get the specifications, go to the Canadian Solar website and under solar panels, this can be found under the Standard 60 cells category. There are many specifications, but the table below lists the most important and which are needed for modeling the solar panel.

Table 1: Manufacturer specifications

Parameter	Value	Condition
$V_{oc}$	38.3 V	STC
$I_{sc}$	9.31 A	STC
$V_{mp}$	31.3 V	STC
$I_{mp}$	8.80 A	STC
Temp co-efficient for $I_{sc}$ ( $\alpha_T$ )	0.053 %/°C	
Temp co-efficient for $V_{oc}$ ( $\beta_T$ )	-0.31 %/°C	
No. of cells $N_{cells}$	60	

The parameters  $V_{mp}$  and  $I_{mp}$  are the voltage and current at the maximum power point at STC ( $G_{ref} = 1000 \text{ W/m}^2$  and  $T_{ref} = 25^\circ\text{C}$ ). The other important parameters are  $\alpha_T$  and  $\beta_T$ . The open circuit voltage  $V_{oc}$  varies with cell temperature and  $\beta_T$  is the co-efficient of change. In the above table,  $\beta_T$  is specified at a percentage which means it is relative to the  $V_{oc}$  value specified above at STC. The short circuit current  $I_{sc}$  varies with the co-efficient  $\alpha_T$  which is also specified as a percentage which means it is relative to the  $I_{sc}$  at STC. The equations in the coming pages will make this more clear.

## 7 Iridescent Current

Let us start with the most important component - the iridescent current. This current also called photo current is primarily affected by the incident solar radiation  $G$  but is also affected by the cell temperature  $T_{cell}$ . The equation for the iridescent current  $I_{irr}$  is:

$$I_{irr} = I_{irr}^{ref} \left( \frac{G}{G_{ref}} \right) \left[ 1 + \frac{\alpha_T}{100} (T_{cell} - T_{ref}) \right]$$

An explanation of the above equation.  $I_{irr}^{ref}$  is the iridescent current at STC. This is usually not specified by manufacturers but soon I will tell you how to calculate this. The fraction  $G/G_{ref}$  indicates how the iridescent current changes proportionally with the incident solar radiation. If incident solar radiation decreases to half, so will  $I_{irr}$ . Now the part in the bracket. As stated in the previous page, the short-circuit current, or for that matter any current generated by the PV cell is dependent on temperature. This dependence is through the co-efficient  $\alpha_T$ . In the panel chosen,  $\alpha_T$  is positive which means iridescent current increases with temperature. Different manufacturers specify  $\alpha_T$  differently. Some give the absolute value while some specify a percentage. In the previous page,  $\alpha_T$  is specified as a percentage. This is the reason why it is divided by 100 and multiplied by  $I_{irr}^{ref} (G/G_{ref})$ . If it is specified as an absolute value, the equation would be:

$$I_{irr} = I_{irr}^{ref} \left( \frac{G}{G_{ref}} \right) + \alpha_T (T_{cell} - T_{ref})$$

Always check if there is a % in the value of  $\alpha_T$ .

This equation is more or less independent except for  $I_{irr}^{ref}$ . Later, it will be described how  $I_{irr}^{ref}$  can be either calculated or approximated.



## 8 Diode current

After describing the iridescent current, the next will be describe the current through the diode that is anti-parallel to the iridescent current. This part is a bit complicated and even after simplification, needs quite a bit of calculation. The current through the diode is expressed as:

$$I_{diode} = I_o \exp \left[ \frac{q(V_{pv} + I_{pv}R_s)}{nkT_{cell}N_{cells}} - 1 \right] \quad (1)$$

The above equation is quite complicated. In the equation,  $q$  is the charge of an electron which is  $1.602 \times 10^{-19}$  C.  $k$  is Boltzmann's constant which is  $1.3806503 \times 10^{-23}$  J/K.  $n$  is the ideality factor of the diode and is determined by the manufacturing process. This can be calculated or assumed as will be described soon.  $N_{cells}$  is the number of cells in the PV panel and is usually specified by the manufacturer - in this case it is 60.

$V_{pv} + I_{pv}R_s$  is the voltage that appears across the diode. Therefore, the diode current is exponentially related to the voltage that appears across it. The non-linear nature of the equation due to the exponential is further made worse by the fact that  $I_o$  is not a constant but is a variable determined by another non-linear equation.

$$I_o = I_o^{ref} \left( \frac{T_{cell}}{T_{ref}} \right)^3 \exp \left[ \frac{qE_g^{ref}}{kT_{ref}} - \frac{qE_g}{kT_{cell}} \right] \quad (2)$$

In the above equation  $E_g$  is the bandgap energy which is another non-linear equation!  $q$  is the charge of an electron and  $k$  is the Boltzmann's constant as before. Even worse is that fact that  $I_o^{ref}$  is not a constant. However, as will be shown,  $I_o^{ref}$  can be calculated with a fairly simple assumption. But, the bandgap energy still needs to be calculated and is as follows:

$$E_g = 1.16 - 7.02 \times 10^{-4} \frac{T_{cell}^2}{T_{cell} - 1108} \quad (3)$$

As stated before, PV cell temperature  $T_{cell}$  is different from the air temperature. In this tutorial, I will simulate the PV panel to check if it matches the reported V-I characteristics. The V-I characteristics have been published for cell temperature. However, in real situations, only the air temperature is known. So the cell temperature can be calculated from the following equation:

$$T_{cell} = 273 + T_{amb} + \frac{NOCT - 20}{0.8 \times G} \quad (4)$$

## 9 Solving the equation

The PV output current is given by the equation:

$$I_{pv} = I_{irr} - I_{diode} - \frac{V_{pv} + I_{pv}R_s}{R_p} \quad (5)$$

Except for the last term which is the resistive drop, the first two terms are highly non-linear. The manufacturer provides the constants specified in the table before. But the above equation has several constants that need to be determined such as  $I_{irr}^{ref}$  the irradiance current at STC,  $I_o^{ref}$  which is the diode current at STC. The diode ideality factor  $n$  is also a variable and needs to be calculated. You are encouraged to read the reference [1] in which besides these three constants,  $R_s$  and  $R_p$  are also considered variables. All these are calculated from non-linear equations generated from boundary conditions. Furthermore, solving non-linear equations requires numerical techniques or the use of in-built functions in commercial software.

Unless you need an extremely accurate model to study the PV cell alone, all the variables listed above need not be calculated. For power electronic applications, only two variables need to be determined and these are  $I_{irr}^{ref}$  and  $I_o^{ref}$ . And these two can be determined by a fairly simple approximation. This tutorial will show you how to do so.

To begin with, we will assume the diode ideality factor  $n$ . Read the reference [1], particularly Section 3.1, where this is dealt with. The ideality factor ( $n$ ) accounts for the different mechanisms responsible for moving carriers across the junction. The parameter  $n$  is 1 if the transport process is purely diffusion and  $n \approx 2$  if it is primarily recombination in the depletion region. Some research papers suggest an  $n$  of 1.3 for silicon. We will assume  $n$  to be 1.3. This gets one variable out of the way.

## 10 Calculating $R_s$ and $R_p$

In the reference,  $R_s$  and  $R_p$  are calculated by solving the non-linear set of equations. However, this tutorial will describe how they can be computed by a fairly simple approximation and using the parameters from the datasheet. It is reasonable to assume that the ohmic losses in  $R_s$  and  $R_p$  are around 3-5% of the power produced by the panel. The manufacturer specifies the maximum power point. In this case, it is  $P_{pv}^{mpp} = 275\text{W}$ ,  $I_{pv}^{mpp} = 8.80\text{A}$  and  $V_{pv}^{mpp} = 31.3\text{V}$ .

Let us assume that 1.5% of  $P_{pv}^{mpp}$  occurs in  $R_s$  and another 1.5% occurs in  $R_p$ . Since the current through  $R_s$  is the PV panel current  $I_{pv}^{mpp}$ , the value of  $R_s$  is:

$$R_s = 0.015 \times \frac{P_{pv}^{mpp}}{(I_{pv}^{mpp})^2} = 0.015 \times \frac{275}{8.80^2} = 0.05326\Omega \quad (6)$$

The voltage across resistance  $R_p$  is  $V_{pv} + I_{pv}R_s$ . Using the value of  $R_s$  calculated above, the value of  $R_p$  is calculated by:

$$R_p = \frac{(V_{pv} + I_{pv}R_s)^2}{0.015 \times P_{pv}^{mpp}} = \frac{(31.3 + 8.80 \times R_s)^2}{0.015 \times 275} = 244.6675\Omega \quad (7)$$

It should be noted that  $R_s$  and  $R_p$  calculated above are for the panel which implies a series combination of 60 cells. To get the values for a single solar cell, you would need to divide them by 60. That is not necessary, but in case you wish to do any processing at the cell level, keep this in mind.

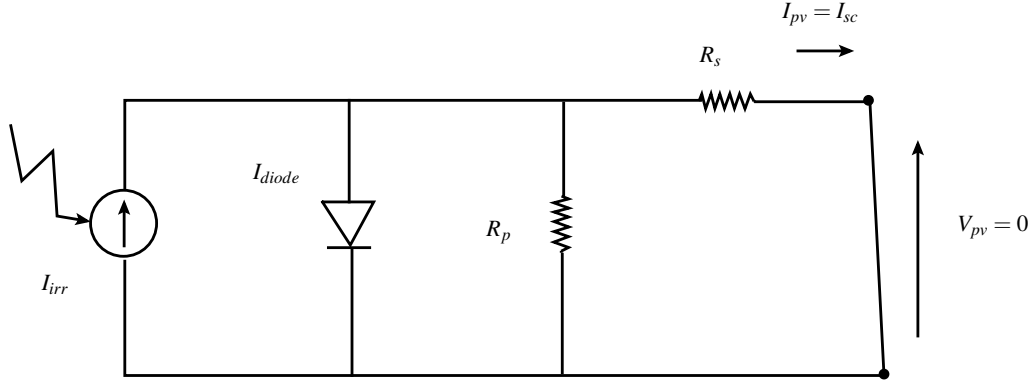


Figure 3: Calculating  $I_{irr}^{ref}$

## 11 Calculating $I_{irr}^{ref}$

The irradiance current is calculated by:

$$I_{irr} = I_{irr}^{ref} \left( \frac{G}{G_{ref}} \right) \left[ 1 + \frac{\alpha_T}{100} (T_{cell} - T_{ref}) \right]$$

To be able to determine the irradiance current at any operating condition with radiation  $G$  and cell/panel temperature  $T_{cell}$ , we need to first calculate the irradiance current at STC  $I_{irr}^{ref}$ . In the reference, this is again calculated by solving non-linear equations. However, it will be described below, how this can be approximated.

The figure above shows the PV panel short-circuited at STC with PV panel output current  $I_{pv}$  being  $I_{sc}$ . This current  $I_{sc}$  is usually specified at STC by the manufacturer in the product specifications. Since, it is at STC, the irradiance current  $I_{irr}$  is  $I_{irr}^{ref}$ . When the PV panel is short-circuited, the irradiance current  $I_{irr}^{ref}$  almost entirely flows into the short-circuit as it is the path of least resistance. So, therefore, the following approximation is possible -  $I_{irr}^{ref}$  is equal to  $I_{sc}$  specified at STC which in this PV panel case will be 9.31 A.

## 12 Calculating $I_o^{ref}$

The current through the diode is given by:

$$I_{diode} = I_o \exp \left[ \frac{q(V_{pv} + I_{pv}R_s)}{nkT_{cell}N_{cells}} - 1 \right] \quad (8)$$

At STC,  $I_o$  in the above equation will be  $I_o^{ref}$ . To calculate  $I_o^{ref}$ , let's look at what happens during open circuit. When the PV panel is open-circuited, PV output current  $I_{pv} = 0$ . The iridescent current  $I_{irr}^{ref}$  (assuming STC) will flow through the diode and the parallel resistance  $R_p$ . Therefore, the equation will be:

$$I_{irr}^{ref} = I_o^{ref} \exp \left( \frac{qV_{oc}^{ref}}{nkN_{cells}T_{ref}} - 1 \right) + \frac{V_{oc}}{R_p} \quad (9)$$

From which  $I_o^{ref}$  can be calculated as:

$$I_o^{ref} = \left( I_{irr}^{ref} - \frac{V_{oc}}{R_p} \right) \exp \left[ - \left( \frac{qV_{oc}^{ref}}{nkN_{cells}T_{ref}} - 1 \right) \right] \quad (10)$$

In the above equation, all values are known -  $I_{irr}^{ref}$  from previous calculation,  $V_{oc}$  from datasheet,  $R_p$  calculated before,  $q$  and  $k$  are constants,  $T_{ref}$  is STC temperature and  $N_{cells}$  from datasheet (60 cells).  $I_o^{ref}$  comes out to be  $1.23758 \times 10^{-7}$  A.

Now all the constants have been calculated -  $I_{irr}^{ref}$ ,  $I_o^{ref}$ ,  $R_s$ ,  $R_p$  and  $n$ . We are now ready to start calculating the PV current as will be shown next.

### 13 Calculating $I_{pv}$ and $V_{pv}$ in general

The constants in the previous section were calculated at STC using datasheet parameters. But STC is a test condition. For any incident radiation  $G$  and cell/panel temperature  $T_{cell}$ , we need to determine the PV panel voltage  $V_{pv}$  and current  $I_{pv}$ . So, let us first start with the cell/panel temperature. In this tutorial, I am going to test how accurate the PV panel model is and so I will compare it with values provided in the datasheet. In particular, I will compare the V-I characteristics generated with those provided in the datasheet. So therefore, I will be taking known values of cell/panel temperature. In general, it is the atmospheric temperature  $T_{amb}$  that is known. The cell/panel temperature is calculated as:

$$T_{cell} = 273 + T_{amb} + \frac{NOCT - 20}{0.8 \times G} \quad (11)$$

Where NOCT is provided in the datasheet and is typically 45°C.  $G$  is the actual solar incident radiation.

The next step is to calculate the irradiance current  $I_{irr}$  as follows:

$$I_{irr} = I_{irr}^{ref} \left( \frac{G}{G_{ref}} \right) \left[ 1 + \frac{\alpha_T}{100} (T_{cell} - T_{ref}) \right]$$

$\alpha_T$  is in the datasheet,  $G_{ref}$ ,  $T_{ref}$  are STC conditions,  $I_{irr}^{ref}$  has been calculated before and  $T_{cell}$  above.

The next step is to calculate the band gap energy  $E_g$  as follows:

$$E_g = 1.16 - 7.02 \times 10^{-4} \frac{T_{cell}^2}{T_{cell} - 1108} \quad (12)$$

It is dependent only on the cell/panel temperature which is above.  $E_g$  will help us calculating the diode current.

The next step is to calculate the value  $I_o$  as follows:

$$I_o = I_o^{ref} \left( \frac{T_{cell}}{T_{ref}} \right)^3 \exp \left[ \frac{qE_g^{ref}}{kT_{ref}} - \frac{qE_g}{kT_{cell}} \right] \quad (13)$$

$I_o$  is dependent on cell/panel temperature  $T_{cell}$  and the bandgap energy  $E_g$ . It needs the Boltzmann's constant  $k$  and the charge of an electron  $q$ .

With the calculation of  $I_o$ , the diode current can be calculated as follows:

$$I_{diode} = I_o \exp \left[ \frac{q(V_{pv} + I_{pv}R_s)}{nkT_{cell}N_{cells}} - 1 \right] \quad (14)$$

$I_{diode}$  needs besides the values calculated before, the value of  $V_{pv}$  and  $I_{pv}$ . It seems like we are caught in a chicken and egg situation, as  $V_{pv}$  and  $I_{pv}$  are what we are trying to calculate. All this means,

however, is that the calculations are being done iteratively. In this case,  $V_{pv}$  and  $I_{pv}$  are the measured values of PV panel voltage and current. More on this later.

The PV panel current is therefore:

$$I_{pv} = I_{irr} - I_{diode} - \frac{V_{pv} + I_{pv}R_s}{R_p} \quad (15)$$

In the above equation too,  $V_{pv}$  and  $I_{pv}$  are the measured values of PV panel voltage and current. Now that we have calculated  $I_{pv}$ , we need to realize the PV panel as a current source. The simplest way to realize a current source is as a voltage behind a resistance. This is shown in the figure below.

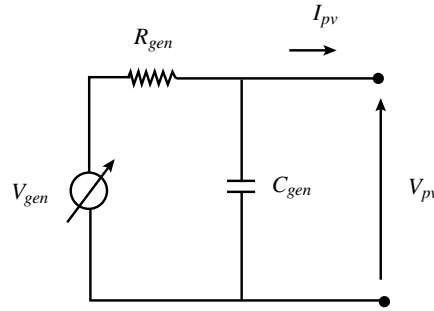


Figure 4: PV cell as a controllable voltage source

The voltage  $V_{gen}$  is calculated as:

$$V_{gen} = V_{pv} + R_{gen}I_{pv} \quad (16)$$

$R_{gen}$  can be chosen to any value. I choose it to be  $1 \Omega$ .  $V_{pv}$  and  $I_{pv}$  are the measured values at the terminal. The capacitor  $C_{gen}$  is to make the PV voltage smooth and without jitter.

So how does this work? Initially, the system is at rest and so measured values of  $V_{pv}$  and  $I_{pv}$  are zero. We choose  $G$  and  $T_{cell}$ . Calculate all the values as described above.  $I_{diode}$  calculation will use the zero measured values of  $V_{pv}$  and  $I_{pv}$ . The new value of  $I_{pv}$  will be calculated.  $V_{gen}$  will then be calculated to ensure  $I_{pv}$  flows through  $R_{gen}$ . This current charges the capacitor  $C_{gen}$  and voltage  $V_{pv}$  builds up. If a load is connected across the terminals,  $I_{pv}$  will be drawn. The new values of  $V_{pv}$  and  $I_{pv}$  are measured and fed back to the calculation process to update the value of  $I_{pv}$ . The system will reach steady state within a few iterations. The simulation results will show that.

## 14 Simulation of the PV panel

The simulation files provided in the package are as follows:

1. `pv1_volt.csv` contains the PV panel modeled as a controllable voltage source as shown in the previous page. The parameters for the components are provided in `pv1_volt_params.csv`.
2. `load1.csv` contains the load fed by the PV panel. This load is also a variable resistor to be able to generate the V-I characteristics. The parameters are in `load1_params.csv`.
3. `pv1_ivcurve.py` is the control file that calculates the PV current  $I_{pv}$  and subsequently generates the voltage  $V_{gen}$  that will produce this PV current. The variables used by the control file are in `pv1_ivcurve_desc.csv`.
4. `load_var.py` is the control file that changes the load resistor to generate the V-I characteristic of the PV panel. The variables used by the control file are in `load_var_desc.csv`.

`pv1_ivcurve.py` is the main file in this package. The user needs to check 4 lines in this program. Lines 31 and 32 specify the solar incident radiation  $G$  and the ambient temperature  $T_{amb}$ . Typically, the V-I curves will be generated for different values of  $G$  and cell temperature. The user can change these values and check out the resultant curve. Line 35 and 37 calculate the cell temperature. As stated before, the ambient temperature is different from the cell temperature. If the user wishes to know how the PV panel will behave for a certain air temperature, comment out line 37. Line 35 calculates the cell temperature from the ambient temperature and you do not need line 37. Line 37 is a special case. If you want to verify the code for a particular PV panel, the technical specifications provided by the manufacturer in the datasheet is usually for cell temperature and not the ambient temperature. In that case, specify  $T_{amb}$  in line 32 as if it were the cell temperature and leave line 37 uncommented. In this way,  $T_{amb}$  will be converted to Kelvin and used as the cell temperature.



## 15 Generating the V-I characteristic

The control file `pv1_ivcurve.py` will generate the PV current  $I_{pv}$  indirectly from the voltage source  $V_{gen}$ . However, if only this control file is used, a steady PV voltage and current will be generated. In several cases, that is all that is needed - generating the PV voltage and current for a particular temperature and incident radiation. However, in this tutorial, the objective is also to be able to generate the V-I characteristic of a solar panel and compare it with the technical specifications. For this purpose, the load has to be variable.

`load_var.py` is the control file that varies the resistance so as to generate PV currents ranging from the short-circuit current  $I_{sc}$  down to a negligible value of 0.01A (open-circuit). The PV voltage is measured and the load resistance value is adjusted so that  $I_{pv}$  is of the desired value. In this manner, by ensuring that  $I_{pv}$  varies over the entire range for a particular  $G$  and  $T_{cell}$ , the V-I characteristics are generated. Similarly, different values of  $G$  and  $T_{cell}$  can be chosen to generate a family of V-I characteristics to show how the PV panel behaves with changing incident radiation and temperature.

The next few pages will show the simulation results for a number of different conditions. The reader should compare these with the V-I characteristics specified in the technical documents.

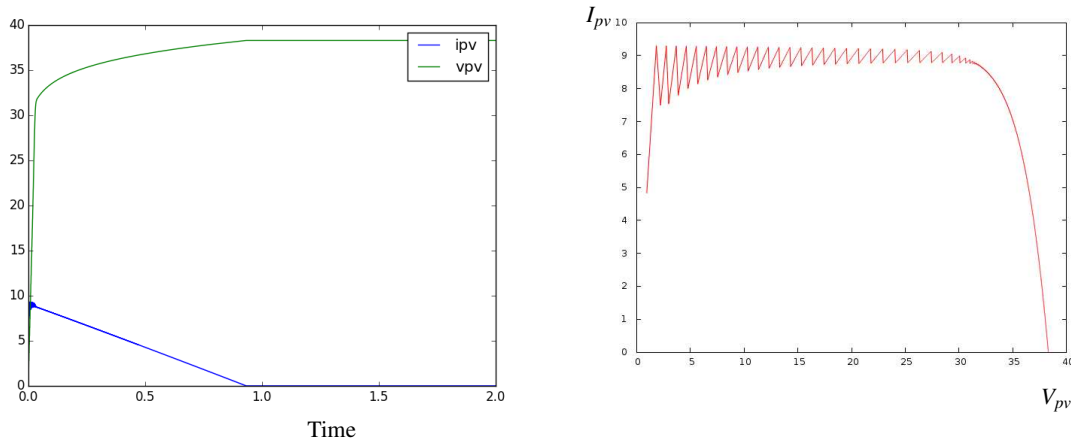


Figure 5: Simulation for STC

## 16 Simulation Results

The figure above shows the simulation result for the STC condition -  $G = G_{ref} = 1000 \text{ W/m}^2$  and  $T_{cell} = 25^\circ\text{C}$ . On the left are the waveforms of the PV voltage and current with time while on the right is the V-I curve that results from these values. As stated before, the load resistance is changed such that the PV current changes from short-circuit current  $I_{sc}$  down to  $0.01\text{A}$ . As a result, the waveforms of the PV voltage and current also change. At short-circuit, the PV voltage is close to zero. The PV voltage gradually increases as the load resistance is increased and the PV current decreased. Eventually, the PV current is close to zero and the PV voltage is at the open-circuit value.

On the right, the V-I characteristics can be seen to be similar to the V-I characteristics found in any PV panel technical specification. There are fluctuations in the upper left part of the curve. This is due to the fact that at short circuit, the PV current is very sensitive to the load resistance which has a very small value. Small changes in load resistance can cause large fluctuations in the PV current. However, this does not affect the PV characteristic but is merely a question of how finely you wish to tune the load resistance.

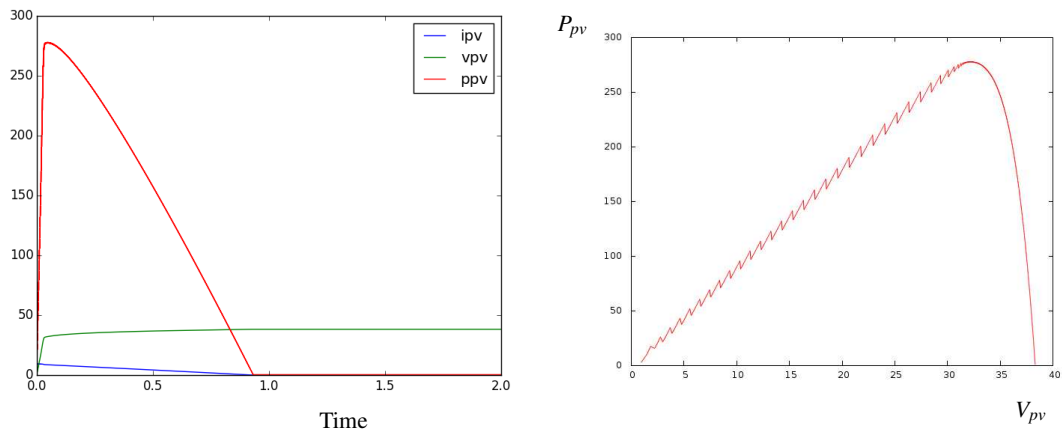


Figure 6: Maximum power point

The figure above shows the plots of the output power of the PV panel. The left figure shows how the power output changes with time as the load resistance is varied. It can be seen that the maximum power output of the PV panel is around 275 W which is the rated maximum output of the PV panel. To know where this maximum power point occurs, the figure on the right plots the power output with respect to the PV voltage. The maximum power point occurs in the region shown in the first section. This gives an idea of the challenge in extracting the maximum power from a PV panel. The output power falls fairly drastically away from the maximum power point. Therefore, an operating point that is significantly away from the maximum power point could result in a fairly large drop in power output and subsequently a fall in the revenue expected from a PV panel.

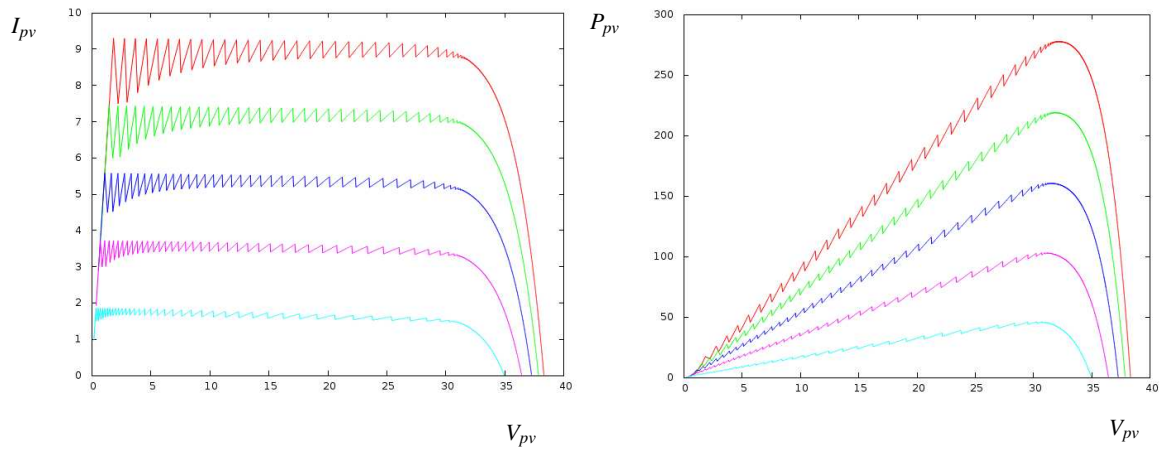


Figure 7: Changing  $G$

## 17 Changing incident solar radiation

The figure above shows how the V-I characteristic curves change when the incident solar radiation  $G$  decreases from the value at STC to  $800 \text{ W/m}^2$ ,  $600 \text{ W/m}^2$ ,  $400 \text{ W/m}^2$  and finally to  $200 \text{ W/m}^2$  - which may be the case on a cloudy day. The V-I characteristics can be seen to fairly similar to those found in the technical specification. As  $G$  decreases, the short-circuit current decreases since the irradiance current is proportional to  $G$ . The plot on the right shows how the maximum power output of the PV panel decreases with decreasing incident radiation.

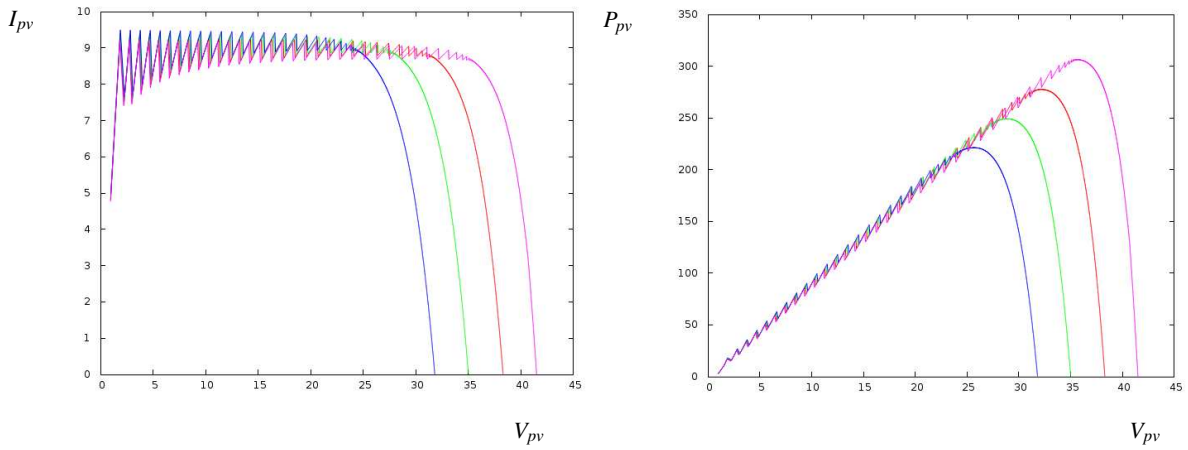


Figure 8: Changing  $T_{cell}$

## 18 Changing temperature

The figure above shows how the V-I characteristic changes with changing cell temperature  $T_{cell}$ . Besides the STC temperature of 25°C, temperatures of 45°C, 65°C and 5°C have been chosen. As the temperature increases from STC, the open circuit voltage decreases due to the negative temperature co-efficient  $\beta_T$ . With increasing temperature, the maximum output power from a PV panel decreases. Conversely, as temperature decreases from STC, the maximum power output of the PV panel increases. As with the previous case of changing  $G$ , the simulated curves with changing  $T_{cell}$  are quite similar to those found in the manufacturer specifications.

## 19 Conclusion

The objective of this tutorial has been to present the simulation of a PV panel in as simple terms as possible for someone who does not have a background in device physics (I don't either). The description provided shows all the different factors that influence PV voltage and current and the equations necessary to perform all the calculations. If the reader wishes to generate a rigorous PV panel model, the constants that have been either assumed or calculated by simple means, can be calculated by solving non-linear equations [1].

It is strongly recommended that the reader try to simulate a few different panels, particularly those that are popularly available in the geographical location. It would be absolutely ideal if the reader can also use the programs and description to model an actual PV panel that the reader may have access to either in a laboratory or a test environment.

The PV panel model described in this tutorial will be used in subsequent tutorials to simulate more complex systems with power converters. Eventually, the objective is to perform system studies to assess the impact of a solar farm on the system.

## References

- [1] H. Tian, F. Mancilla-David, K. Ellis, E. Muljadi, and P. Jenkins, "A cell-to-module-to-array detailed model for photovoltaic panels," *Solar Energy*, vol. 86, no. 9, pp. 2695 – 2706, 2012. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0038092X12002150>