ET3034TUx - 7.2.2 - PV Modules 2 - Temperature dependency of PV output

Welcome back.

So far, we have seen the important aspects to be taken into account while dealing with modules at the PV system level.

We also know that irradiance has an effect on the output of the PV module.

In general, all other parameters being unchanged, higher the irradiance, greater the output power generated.

In this block I would like to discuss with you the effect of a parameter of great importance: the temperature.

First, I'd like to answer the simple question, is a greater temperature better for the PV output?

Or is PV output independent of the temperature changes?

In this graph you see the I-V curve of a PV module at a given irradiance and temperature.

Now, if the temperature increases while the irradiance is constant we see an I-V curve that looks like this.

So we see that while the current has very minutely increased, there is a significant drop in voltage.

This means that the overall power output has decreased.

On the other hand, if the temperature were to decrease with respect to the original conditions while the irradiance were constant, the PV output would show an increase.

The minute increase in current with temperature can be explained with the fact that carrier concentration and mobility increase in the semiconductor with temperature.

This is consistent with our basic understanding that a semiconductor, unlike a regular conductor, exhibits better conductivity with increasing temperature and is a perfect insulator at absolute temperature of 0 K.

The decreasing effect on voltage can be explained from this form of the basic diode equation seen in the earlier weeks.

While the temperature affects the various terms in the equation, the net effect of temperature is that it decreases the Voc linearly.

The drop in open-circuit voltage with temperature is mainly related to the increase in the leakage current of the photodiode I_0 in the dark with temperature.

The I_0 strongly depends on the temperature.

We have dedicated one of the exercises this week to this effect.

The magnitude of reduction varies inversely with Voc.

This means that cells with higher Voc are less affected by the temperature than cells with lower Voc.

This means that a solar cell based on c-Si with a Voc of 0.65 V will be more affected than the a-Si with a Voc of 0.85 V.

So now you have an idea of the effect of temperature on the PV output.

But how do we quantify this effect?

If the temperature of the PV module were to increase by 10°C, how would the output be affected?

Well, the PV module manufacturers include what are known as the temperature coefficients in the datasheets of the commercial modules.

Temperature coefficient is nothing but the rate of change of a parameter with a temperature.

For instance, the temperature coefficient of voltage is the rate of change of the voltage with temperature.

Similarly, temperature coefficient of power is the rate of change of the output power with temperature.

A typical datasheet of a commercial PV module specifies temperature coefficients for the power, Voc and Isc under STC conditions.

Given these coefficients, how do we calculate the PV output with respect to the temperature change?

We can use this simple equation.

The term dX/dT denotes the temperature coefficient of the particular parameter.

The reference temperature taken for this calculation is the STC temperature, i.e.

25°C.

Let's take a look at an example.

If the maximum power output of a PV module under STC is 250 W, and the temperature coefficient of power is -2 W/°C, then the module's power output at a temperature of 30°C can be calculated as follows: P = 250 W + (-2 W/°C) *(30-25) °C = 240 W.

As you can see, the sign of the temperature coefficient determines if the parameter is increasing or decreasing with temperature.

In the exercises for this block you will be able to use this equation to estimate the effect of temperature on the various PV parameters.

Now, we must be careful while making these calculations.

In the previous example, when we said that the temperature was 30°C, did we mean the PV module's temperature?

Or the ambient temperature?

Should the two be the same?

As it turns out, the module temperature or the cell temperature, the popular term in literature, can be quite different from the ambient temperature.

Let's see why there should be a difference between the module temperature and the ambient temperature.

There could be several factors impacting the heat flow in and out of the modules.

Encapsulation of the solar cells is a major factor in increasing the operating temperature of the PV module.

The eventual operating temperature of a module will be a result of the thermal equilibrium between the heat generated by the PV module, the heat lost to the surrounding environment.

The heat exchange with the environment in turn could depend on several factors like: ambient temperature, wind, heat transfer coefficients between the module and the environment, and the thermal conductivity of the module's body.

Then how do we estimate the module temperature based on the ambient temperature if we have to account for so many factors?

Fortunately there is a model provided in literature that gives a reasonable estimate of the module temperature as a function of the ambient temperature.

This model is sometimes called the NOCT model, due to the use of the Nominal Operating Cell Temperature, or NOCT of the PV cell or module.

The NOCT is a parameter defined for a particular PV module.

NOCT is the temperature attained by the PV cell under an irradiance of 800 W/m², with a nominal wind speed of 1 m/s and an ambient temperature of 20°C.

Here, G is the irradiance at the instant when the ambient temperature is T_ambient.

The model gives the corresponding cell temperature as T_cell.

As can be seen from this equation, the cell temperature is not only a function of the ambient temperature but also of the irradiance.

This makes things interesting, because if we consider the irradiance and temperature changes over a calendar year, we would see an effect of both irradiance and temperature across the seasons.

This can be seen in the graph shown, which has been made using the actual ambient temperature and irradiance data as seen in the Netherlands in the year 2012.

The corresponding cell temperatures have been calculated using the NOCT model.

This graph outlines the main inferences from the NOCT model.

The line indicates the T_cell = T_ambient line.

There are no data values below this line, as there are no negative irradiance values.

This means that the cell temperature can never go below the ambient temperature.

The least cell temperature values will be equal to the corresponding ambient temperature, and these will occur when there is zero irradiance, or in other words, at night.

The uneven spread of the cell temperature above the ambient temperature can also be explained.

When the cell temperature is closer to the ambient temperature, this is because the impact of irradiance is lesser, meaning these sets of points correspond to the irradiance and ambient temperatures during winter.

Similarly, when the T_cell values go much higher than the T_ambient values, it's because the irradiance effect in the summer is quite high.

This gives us some fascinating insights.

This means that in summer, although the sun is shining more, the module is performing worse due to the temperature effects that bring down the PV output at a high cell temperature.

In winter, the detrimental temperature effects are far less, although the irradiance levels also fall severely in winter.

This means that the best ambient conditions for your PV module would be a cold day with plenty of sun.

So, how serious can this temperature effect be for a PV module's output over the calendar year?

At the PVMD group of the Delft University of Technology, we have done an extensive study on the temperature effects on the PV module's output.

In this graph you can see the efficiency of a PV module over a calendar year as modeled using actual temperature and irradiance data for the Netherlands in 2012.

It can be clearly seen how the efficiency is not constant but changing with the ambient conditions over the year.

To give you an idea of the deviation from the expected efficiency, the rated efficiency is shown for this model.

So you see, temperature effect cannot be underestimated, as it can turn out to be the biggest reason for a low PV yield.

The PV module considered here was a commercial polycrystalline module and the module's parameters were taken from the manufacturer's datasheet.

The difference between the expected PV yield with rated efficiency and the actual yield due to the temperature effect gives rise to a module ideality factor.

This is nothing but the ratio of the expected PV yield actually available taking into account the temperature effects.

If the module ideality factor is 80%, that means that the module has lost 20% of its annual energy yield due to temperature effects.

If the module ideality factor is 100%, that means the module is immune to temperature changes.

Now, the extent to which the temperature impacts the module output is a function of the PV technology and the manufacturing process, which collectively decides the temperature coefficients of the PV module; the temperature effect is also a function of the ambient conditions.

For the same technology, there could be a deviation in the temperature coefficients due to the manufacturing processes and other design modifications.

The following graph shows the spread of few of the common silicon based modules, based on their module ideality factors and the temperature coefficient.

These numbers have been calculated after modeling the temperature effects on these PV modules for the ambient conditions in the Netherlands in the year 2012.

The Sanyo HIT module shows the highest module ideality factor, owing to its low temperature coefficient of power.

More PV technologies are being analyzed at the Delft University to understand the extent of the temperature effects.

As said before, the a-Si technology show very low temperature coefficients due to their high open-circuit voltage.

This means they would show a better response under high temperatures.

However, their efficiencies are far lower compared to some of the best c-Si technologies.

But conventional c-Si modules are also very bulky.

Polycrystalline silicon modules cover a lot of area.

Monocrystalline modules are more area-efficient, but are more expensive.

a-Si modules are cheaper, lighter, and sometimes even flexible, but give poorer yields.

So there's plenty of optimization to be done just for the choice of your ideal PV module for your system.

The optimum choice will of course depend on the location, ambient conditions, the budget you have, among other factors.

Fascinating, right?

So this was a brief overview of the module level considerations.

In the coming blocks we shall look at more PV system components and concepts.

See you in the next block!