



Experiments with Alternative Energy

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Part 2 – External Conditions that Affect Solar Panels

This is the second in our series of Experiments with Alternative Energy. In Part 1 you were introduced to how a Parallax BS2 and PICAXE 28X2 can be configured in hardware and firmware to measure certain electrical aspects of solar panels; namely what their voltage, current and power outputs look like in both sun and incandescent light and the concept of the Maximum Power Point or MPP. This time we'll use these same microcontroller circuits and code to illustrate three primary conditions that affect solar panel operation in the real world – heat, shading and tilt angle.

If you ever considered installing solar panels on your home or business this article will have some meaning for you. That said, this is not an article on solar panel installation. Rather, it delves into the reasons why solar panels behave as they do by way of some interesting experiments; and how the concept of Maximum Power Point, which is affected by all these conditions, is so important when solar panels are used on moving vehicles. For what follows you will need the background from Part 1, so refer back to your July NV issue or visit their website for archives. Also, please visit www.learnonline.com and click on **Experimenter Kits** for details on the experiments mentioned here.

Solar Cell Equivalent Circuit

As a preliminary step in illustrating how heat, shading and tilt angle affect the performance of a solar panel it will be useful to examine the inner-workings of a typical silicon solar cell in terms of an equivalent circuit as shown in **Figure 1**. This way you can relate these issues to the same devices that you are accustomed to using in your other circuits. The equivalent circuit is embodied in the symbol for the

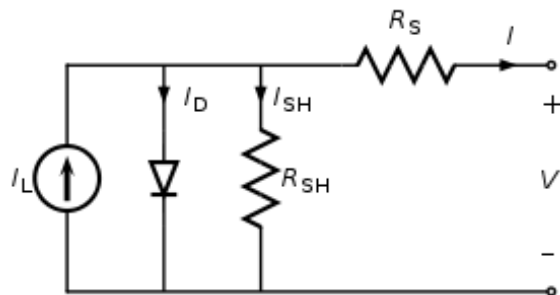


Figure 1 – Solar Cell Equivalent Circuit

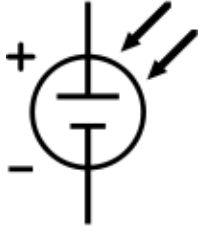


Figure 2 – Solar Cell Symbol

solar cell in **Figure 2**.

An ideal solar cell may be modeled by a current source in parallel with a diode; however, in practice no solar cell is this perfect so a shunt resistance and a series resistance component are added to the model to simulate voltage and current losses. Photons excite the solar cell's material and produce voltage and current flow through the p-n junction by electron and hole movement. This process can be expressed as follows:

$$V_j = V + IR_S$$

where

- V_j = voltage across both diode and shunt resistor R_{SH}
- V = voltage across the output terminals (volts)
- I = output current (amperes)
- R_S = series resistance

I'm purposely leaving out a lot of math and physics here to keep the focus of the explanation in the realm of basic electrical concepts that we all understand. For example, when a typical carbon resistor gets hot its resistance increases and visa versa. Well, the same thing happens to the shunt and series resistors in the equivalent circuit. As they heat up the output voltage decreases; however, the current stays mostly the same; you will see this as part of the experiment on heat. This cursory explanation should suffice to get acquainted with the basics of a typical silicon solar cell. You are, of course, encouraged to find out more to satisfy your level of curiosity and technical background. The web is the place to go.

How Solar Panels Are Rated - Voc and Isc

If you look up the specs on any solar panel sold today, you will see that it is rated by open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}). While the output power for either of these two extreme conditions is zero, the rating is an important issue in the choice of a solar panel, because by using these two ratings you can determine its overall power producing capacity. It brings the discussion back to what you were introduced to in Part 1 – the

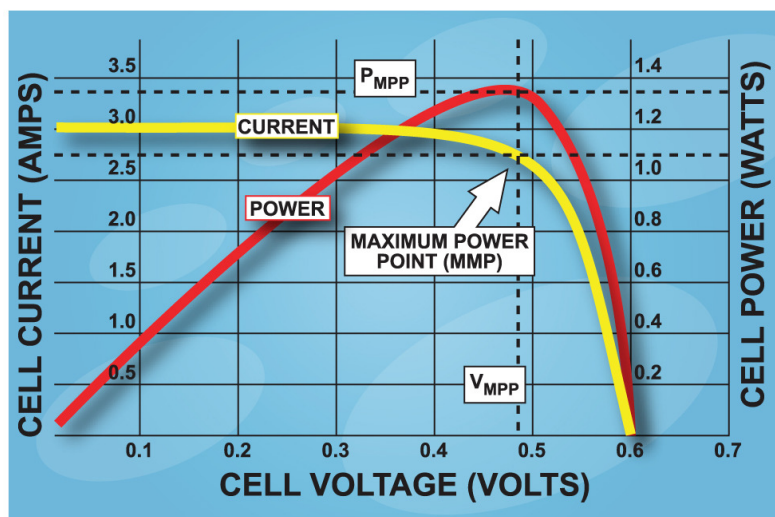


Figure 3 – IV Curve Plot Showing MPP

Maximum Power Point (MPP); that is, the load for which the cell can deliver maximum electrical power at a given level of sunlight. To illustrate the MPP, **Figure 3** is a plot of current versus voltage or what has commonly become known as an “IV curve”. Voltage is plotted on the horizontal axis with current and power plotted on the vertical axis. The maximum power, then, is dependent on the size of the Voc at the very top-left of the plot and the Isc at the bottom-right. The Maximum Power Point will exist somewhere in between depending on the amount of sunlight, heat and tilt angle.

The Effect of Heat

Let’s start with one unavoidable condition – heat. Regardless of where you live in either a hot or cold climate, radiant heat will deteriorate a solar panel’s performance and even life to some degree. Heat does two basic things. It affects the internal nature of the individual solar cells such that the cell cannot produce the same voltage and current when it was cooler. Heat also causes the resistance to increase in the wires that connect the solar cells together. And the metal superstructures that hold the solar cells in place transfer their heat to the cells. The combination of these two factors reduces the overall current and voltage produced by the panel. **Figure 4** is a good illustration of where the power goes when a solar panel is exposed to sunlight. Some of it gets reflected off the surface and doesn’t produce any power. The majority of the sunlight enters the panel and part of it (the photons at particular wavelengths – see “band gap” from Part 1) generates the actual voltage and current depending on the type of material used for the solar cells. The rest of it gets converted into radiant heat that reduces the power output.

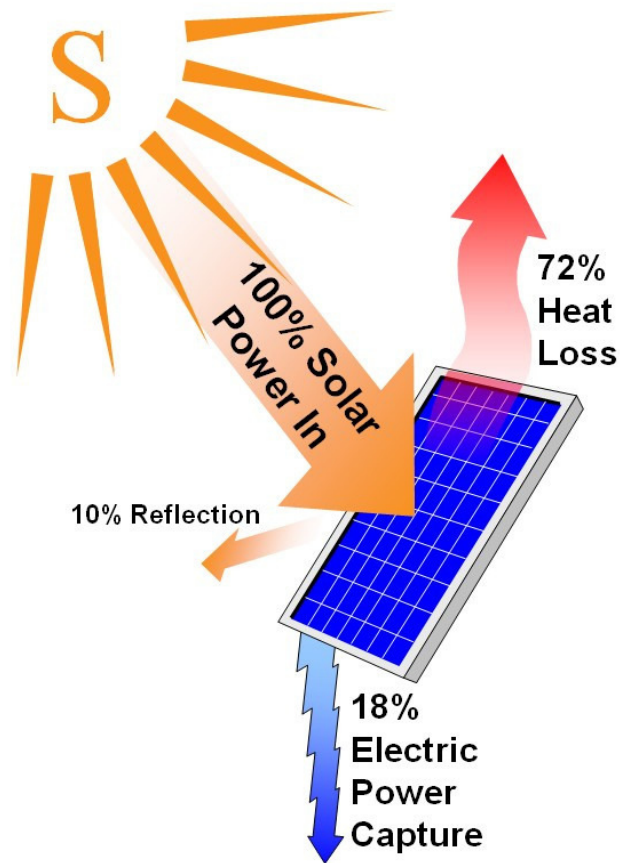


Figure 4 – Where the Power Goes

The cure for this condition is relatively simple – wind and/or cool temperatures. Just as a cool breeze can reduce your internal temperature, it can do the same for solar panels.

And not so surprisingly the power output improves when this happens. **Figures 5 and 6** are taken from the experiment entitled “The Effects of Heat on a Solar Panel”. They show what happens to the voltage, current, power and resistance (your BS2 and 28X2 circuits and code measure resistance, too) as the solar panel gets hot and then cools off. As the heat increases the voltage decreases but the current remains reasonably constant; the same is true during the cooling cycle except the voltage increases proportionally with the panel temperature. The heating and cooling also shifts the Maximum Power Point somewhere else on the IV curve. I’ll address this shortly.

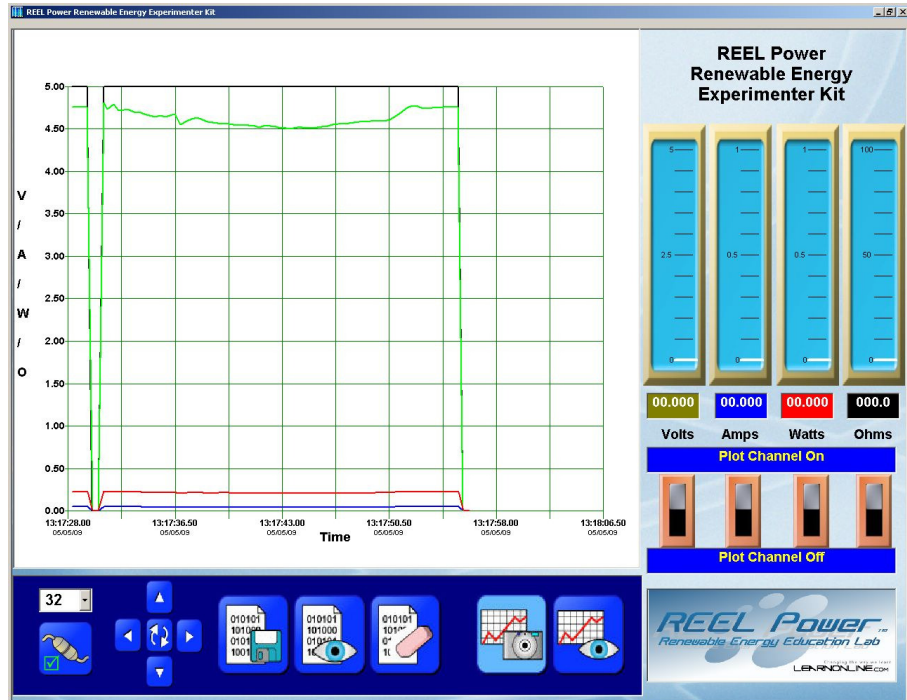


Figure 5 – Plot of Solar Panel Output Based on Heating and Cooling

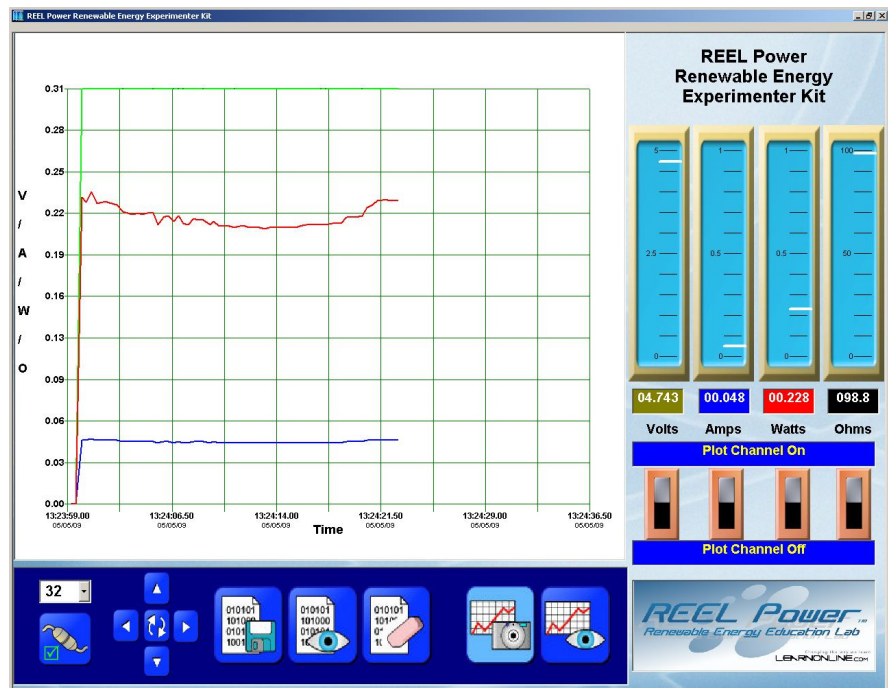


Figure 6 - Expanded View of Power (red) and Current (blue)

The Effect of Shading

Unlike heat shading is something that can, and should be, avoided because it is potentially more damaging to the solar panel than external heat itself. Since a solar panel is constructed of individual solar cells wired in series-parallel arrangements, if an individual solar cell or small cluster of them is shaded, the shaded cells essentially shut off current flow through the rest of the circuit. This is kind of like a string of holiday lights where if one burns out the rest quit operating; that one burned out light bulb broke the circuit to the rest of the string. If solar panels operated like this it might not be such a big issue; however unlike a string of light bulbs, the individual solar cells are all mini current and voltage generators that are looking for a place to deliver their power. A shaded cells blocks the current flow and causes the other illuminated cells to get hot trying to dissipate their power into a high resistance path created by the shaded cells.

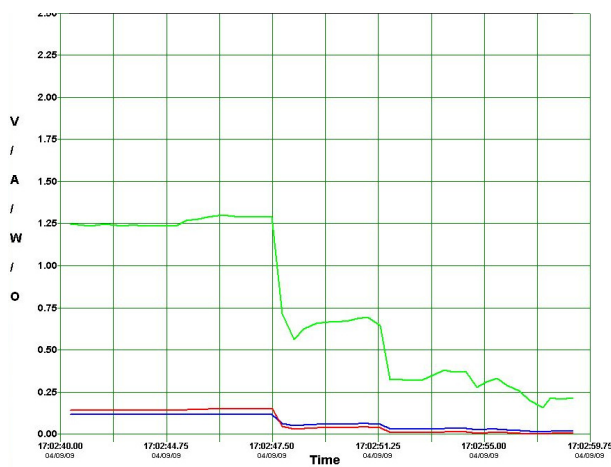


Figure 7 – Shade on Solar Panels in Series

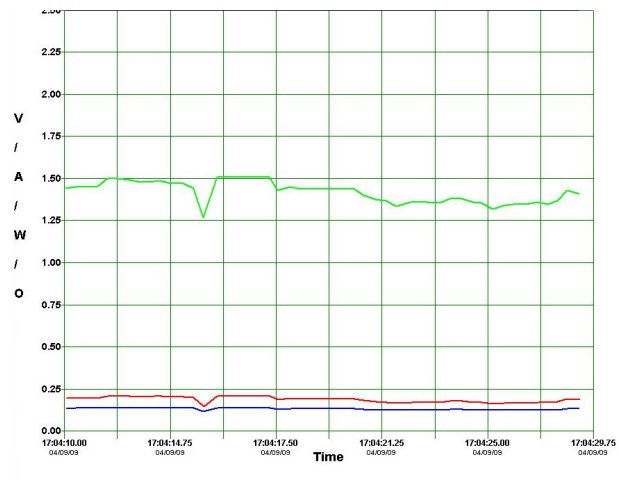


Figure 8 – Shade on Solar Panels in Parallel

Shading is caused by both natural and manmade obstructions. Clouds don't normally cause harm because they shade the entire panel; however, snow, trees and buildings can partially shade small areas of a panel long enough for permanent damage to occur. Some solar panels have blocking diodes to prevent this, but the cost for this is lower voltage output due to the diode drop itself.

One way around this condition is to configure solar panels in parallel rather than in series. This does not completely eliminate damage to the solar panel by the shaded cells but it does mitigate the overall performance of the entire system. For example, **Figure 7** illustrates what happens with two identical solar panels in series. Partially shading just a portion of one panel dramatically reduces the voltage and power output of the pair. On the other hand **Figure 8** shows the same panels in parallel. Shading the same amount of panel area does not affect the power output nearly as drastically, since some of the illuminated solar cells have somewhere to deliver their voltage and current. You can perform this experiment yourself by going to “The Effects of Shade on Solar Panels” on the LearnOnLine website at www.learnonline.com. Just click on the **Experiment Kit** menu link.

The Effect of Tilt Angle

It is fundamentally obvious that the best angle for a solar panel is one that points it directly in line with the light source. While this is indeed the case, most solar panels cannot be oriented directly toward the light source at all times. Since the sun [appears] to move across the sky during the day a solar panel can only gather a portion of its light depending on its fixed tilt angle. So there is a compromise to consider here; what angle is best for the given solar panel's application?

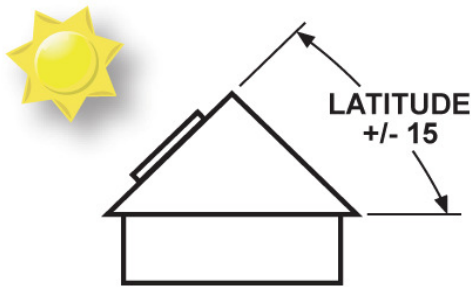


Figure 10 – Computing the Best Tilt Angle

What happens to the solar panel's voltage, current and power outputs under load at various tilt angles can be determined by examining **Figure 11**. As expected a fixed solar panel's electrical parameters react generally like this illustration. You can see for yourself by performing the “Effects of Tilt Angles on Solar Panels” experiment.

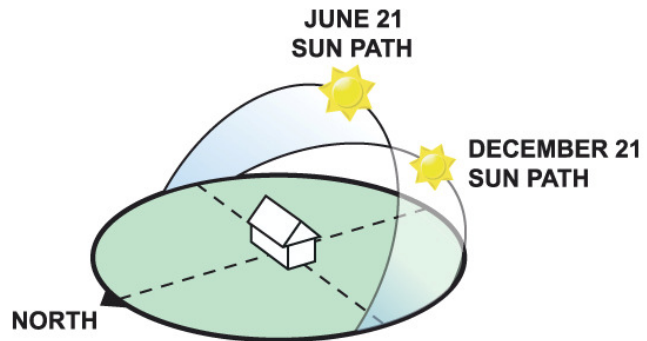


Figure 9 – Sun's Position Winter and Summer

Most applications for solar panels are on roof tops where the solar panel is mounted in a fixed position. **Figure 9** illustrates the sun's angle at its lowest and highest points during the year at the Winter and Summer Solstice, respectively, so the panel should be mounted somewhere between these two angles. One more consideration comes into play and that's your geographical location or, in particular, your latitude. Based on the latitude your panel should be mounted plus or minus 15 degrees from it as illustrated in **Figure 10**.

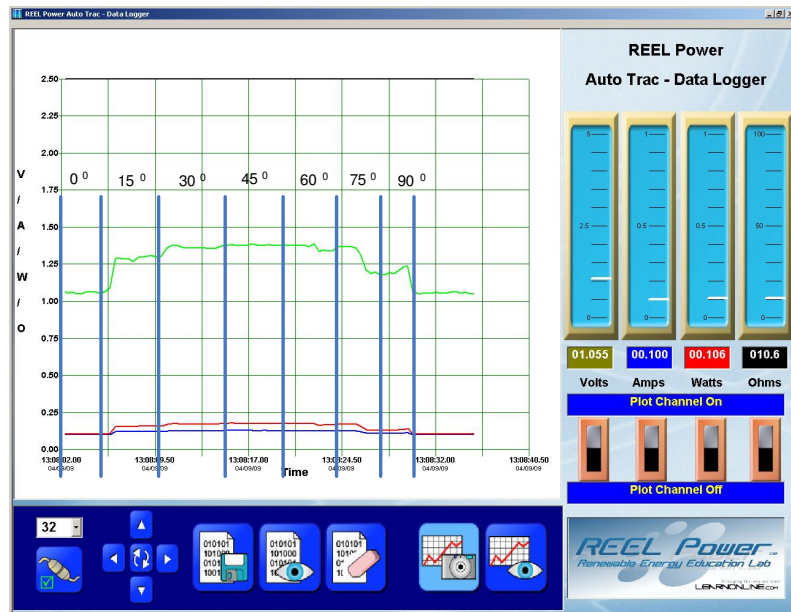


Figure 11 – Effect of Tilt Angle

Tracking the Shift in MPP

Now we come to the culmination of the effects of heat, shading and tilt angle – how these conditions shift the Maximum Power Point (MPP) – especially in mobile applications. To obtain the optimum performance from a solar panel it is important to understand how it behaves in a mobile application where it moves quickly among relatively fixed light, heat and shadow-producing sources. For a fixed solar panel **Figures 12 and 13** shows how just a solar panel's tilt shifts the MPP. Imagine what happens when we mount the same solar panels on a solar race car and put them in motion.

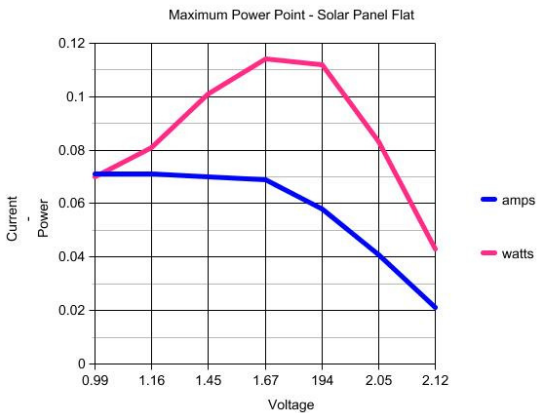


Figure 12 – MPP for Solar Panel Lying Flat

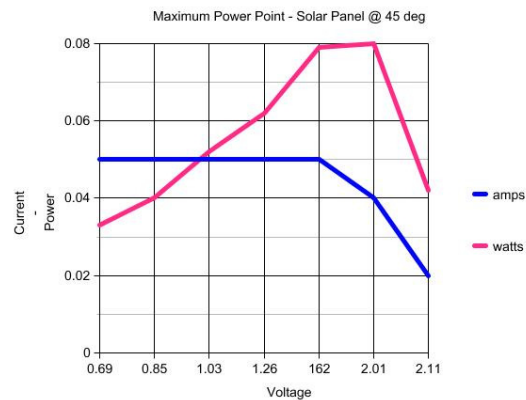


Figure 13 – MPP for Solar Panel at 45 degree Angle

A modern solar race car is made up of more than just an electric motor connected to solar panels with an ON-OFF switch in between. How would you ever get anywhere with the varying angles of light striking the fixed solar panels on the car's body? There are some very sophisticated electronics that go along to regulate its speed as well as its ability to acquire the maximum sun energy as it travels. One such device is called a Maximum Power Point Tracker or MPPT (one more acronym to deal with). An MPPT is really a DC-to-DC converter with some bells and whistles thrown in. What it doesn't do is mechanically track the sun as the car moves. What it DOES do is track the shift in MPP – thus the name. How it does this is quite interesting.

The MPPT controller sits between the solar panel and the car's battery as illustrated in

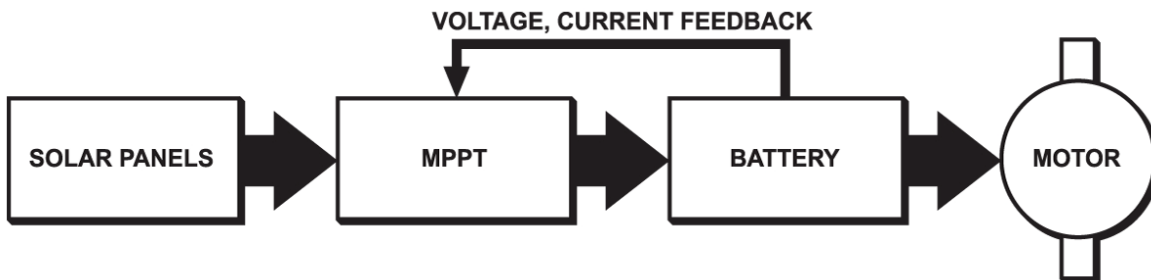


Figure 14 – MPPT Controller Block Diagram

Figure 14. As a high frequency DC-DC converter it takes the DC input from the solar panels at whatever voltage they are at and digitally converts it to a high frequency AC signal - then converts it back down to a DC voltage and current to exactly match the battery's needs right at that particular moment– all under microprocessor control (which could be done with a BS2 or 28X2 programmed in BASIC with no major issues). With a micro doing the work the connection between the panels and battery is actually “broken” for a few milliseconds during the normal operational cycle to "look" at the solar panel and battery independently to make needed adjustments. Refer to **Figure 15** for timing (image credit – Wikipedia).

Modern MPPT's are around 92 to 97% efficient in their conversion; however, expect a 20% to 45% power gain in winter and a 10% to 15% number in summer, consistent with what you've learned about heat. There is a lot more to say about MPPT technology and Boost and Buck converters which are what they are based on, so maybe we'll get into this in another article. It will certainly be worth your time spent since knowing how these devices work and, especially, how to design them will make you stand out in your technical career; it's a skill that many companies want in their technical employees.

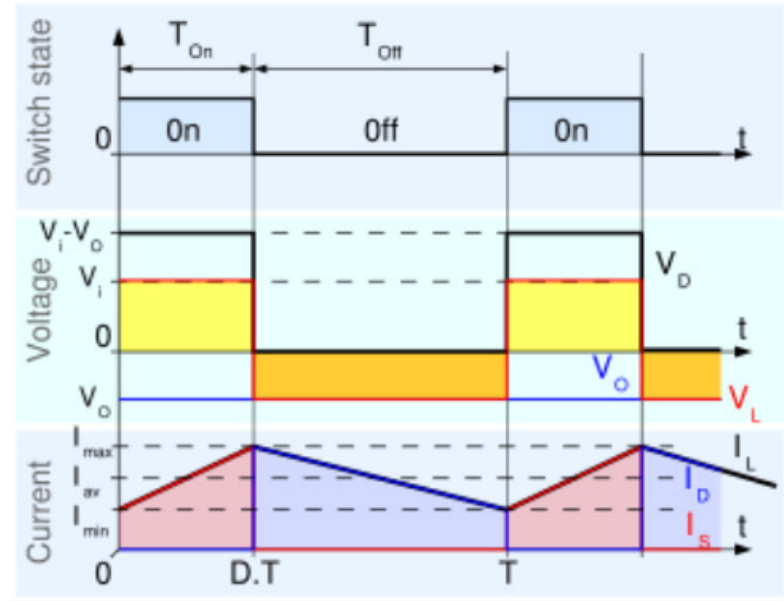


Figure 15 – MPPT Timing in Continuous Mode

Conclusions

Part 1 indicated that a main goal of these articles is to relate how model renewable energy devices compare to real world systems. I hope this article continues to satisfy that goal and that the experiments on the LearnOnline website inspire you to want to learn more about these renewable energy technologies including extensions to it like the MPPT.

Next time in Part 3 we'll put the BS2 and 28X2 through their paces by building a solar-powered battery charger with automatic charge and shutoff capabilities. This will be a fun and informative exercise because it will bring together a lot of the materials you have been exposed to in Parts 1 and 2 and pave the way as in integral component of Part 4 – another neat solar project that shall go without further mention at this point. In meantime, conserve energy and “stay green”.