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Rochester Institute of Technology (R.I.T.) engineering students have tackled the task of developing a maximum power point tracking (MPPT) system for use on the AMSAT Fox-2 satellite (see March/April 2013 *AMSAT Journal*). Their task was to prototype a system that optimizes the power delivered by the satellite's solar panels. I have previously published an article on a project to make the Fox-1 Attitude Determination Experiment accessible through a classroom simulator. Likewise, in this article, I continue my quest to make these Fox satellite experiments accessible beyond the handful of college engineering students who are directly involved in the developing the experiment to those schools, teachers, students, and the ham satellite enthusiast (you, the life-long-learner) who want to learn about the experiments and the fundamental concepts involved. Here you will find a project (simulator) that will allow you to explore the concept of MPPT, see an MPPT system in action, and observe how it behaves.

The need to optimize solar panel performance is not unique to space borne systems. Today's green energy initiatives highlight the need to gain every watt of power available from solar and other alternative energy sources. So the study and understanding of the MPPT concept has broad appeal, therefore the project described here is not limited to the Fox satellites. Also it must be recognized that there are many different approaches to solving the MPPT challenge, and the approach described here is just one approach. In fact, the approach you will read about is for academic, learning purposes only, and is not a system that is anywhere close to "flight ready." The system is developed to present the fundamentals "bluntly and obviously."

Solar Panel Basics

To begin, a review of some solar panel basics are in order, and I stress basics. A solar panel contains layers of stratified material that is sensitive to light and a solar panel will therefore produce a current when exposed to light. The amount of current produced depends on a number of factors but we'll look at just two; the intensity of the illumination hitting the surface of the solar panel (the number of photons) and the operating temperature of the solar panel (efficiency of the photon/panel interaction). The intensity of illumination is fairly intuitive, but what is interesting is that the efficiency of the solar panel goes up as the

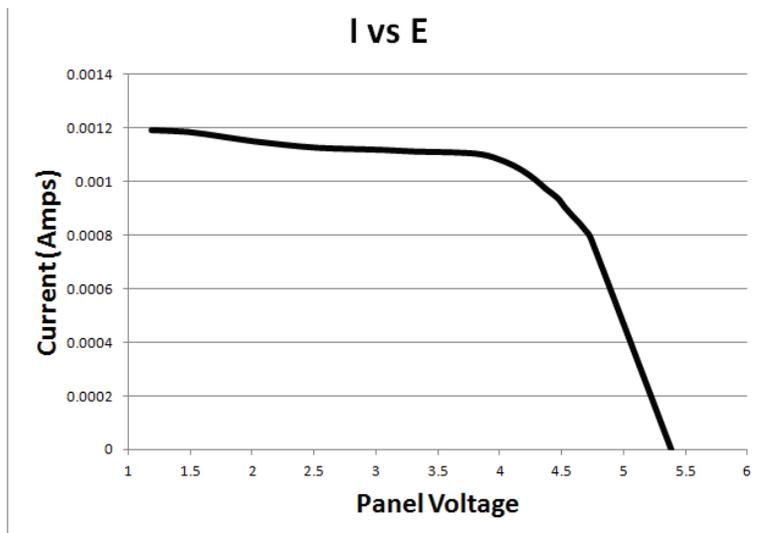


Figure 1

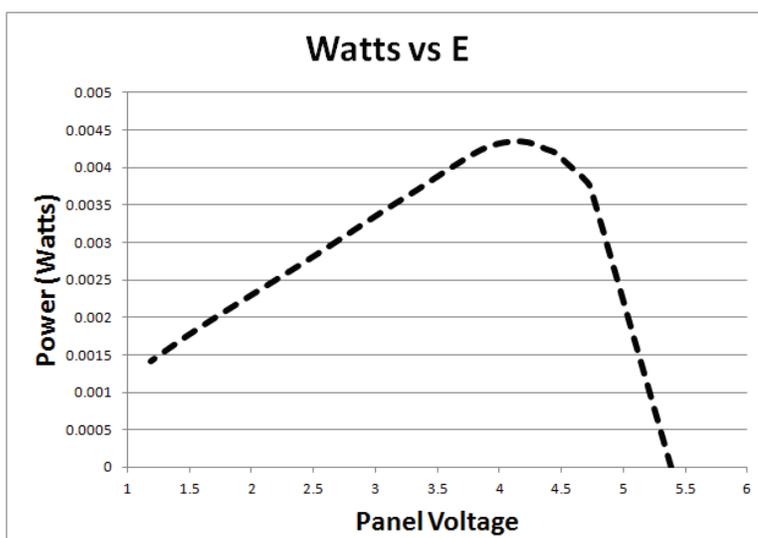


Figure 2

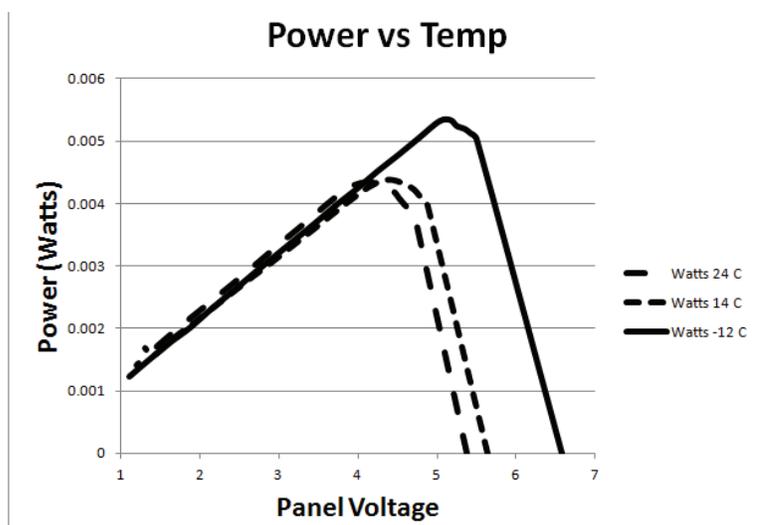


Figure 3



Solar Panel Profiler and MPPT Determination Experiment Block Diagram

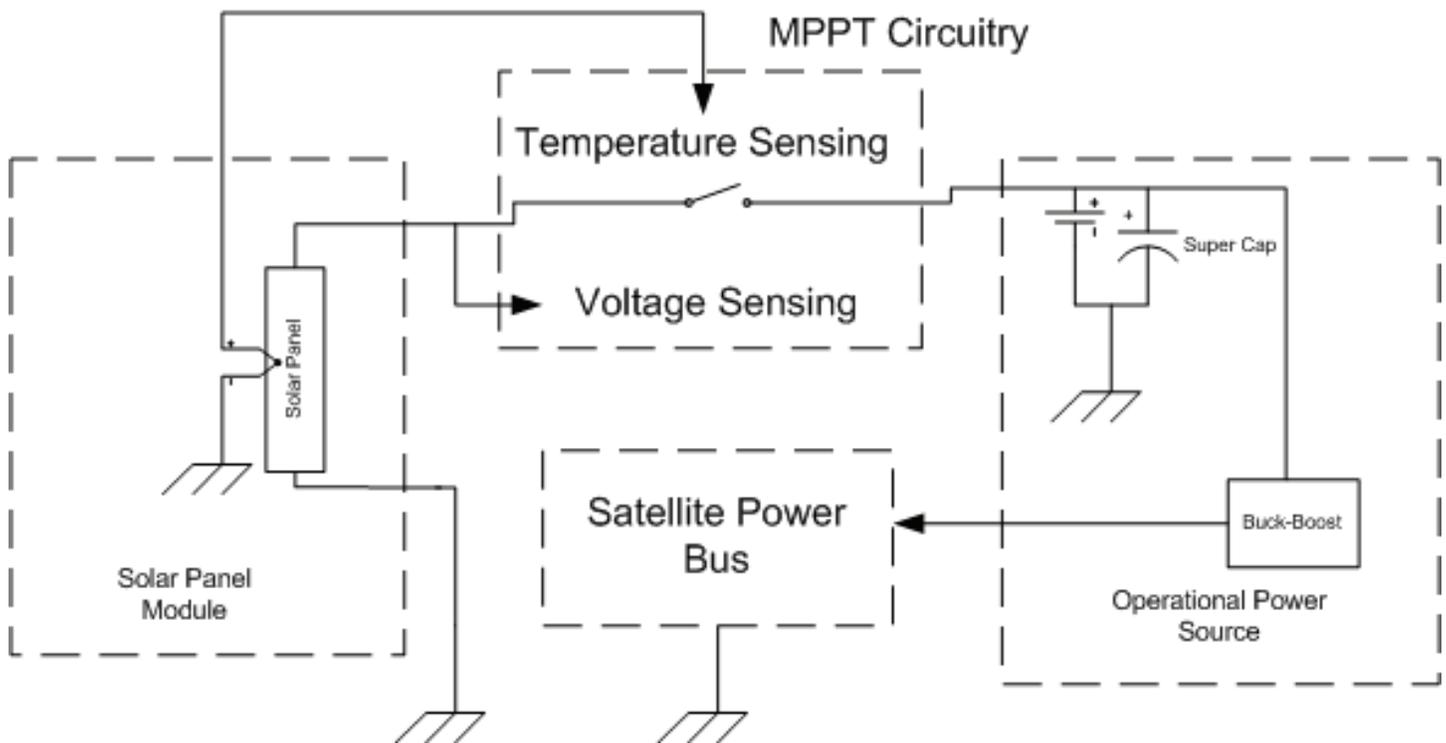


Figure 4

operating temperature goes down...the purpose of the MPPT circuitry is to adjust the solar panel operating point in response to changes in temperature to maximize operating efficiency.

Let's assume that we keep the two variables, light intensity and operating temperature, constant. When a solar panel is illuminated, with no load attached, the panel will produce a voltage (the open circuit voltage) however no power is produced because there is no current flow. If you attach a variable load (a variable resistor) across the solar panel, and measure the resistance as you adjust the resistor through its range and measure the corresponding voltage across the load, a graphic curve as depicted in figure 1 is produced. You need to use a little Ohm's law to calculate the current from the measured voltage and resistance. If you trace the plot of current vs. voltage, you notice that at zero current (open circuit) the voltage is around 5.5 volts, as the current flow increases (the load resistance decreases) the panel cannot produce enough current to hold the open circuit voltage level and the voltage drops down to virtually zero as the current demand increases. This voltage drop is because there are not enough photons of light striking the solar panel but also the drop can be

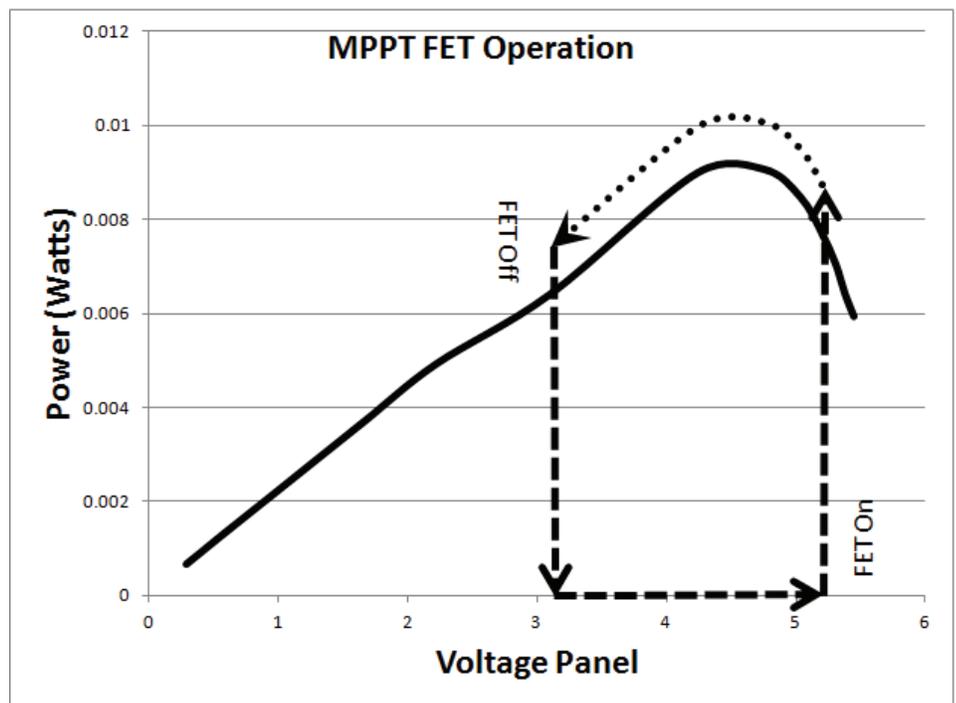


Figure 5

Solar Panel Profiler and MPPT Determination Experiment Jumper Set-up	Profile	J1	J2	J3
	MPPT	---	XX	XX
	---	XX	---	---
	---	= shorted XX = open		

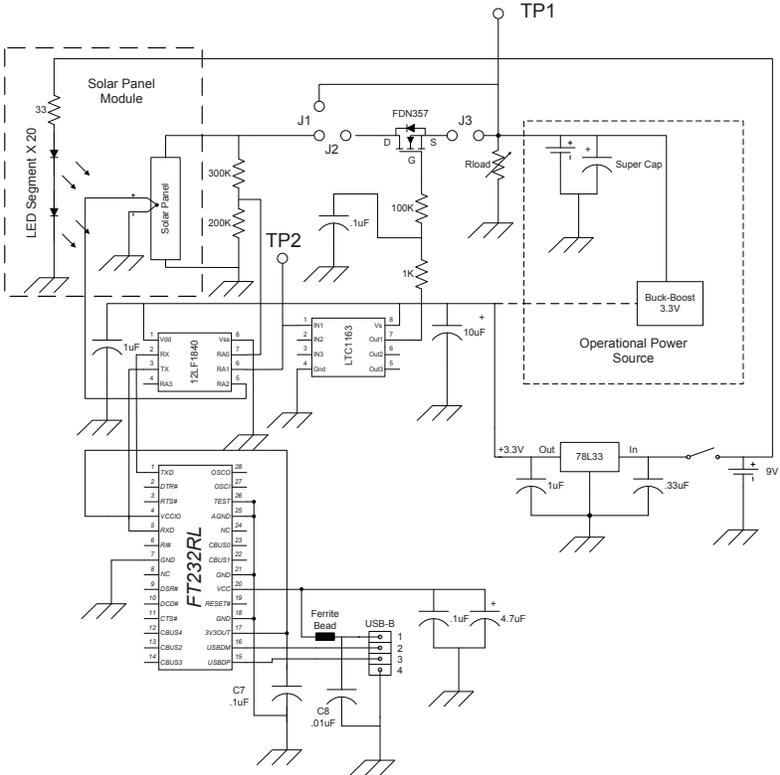


Figure 6



Figure 7

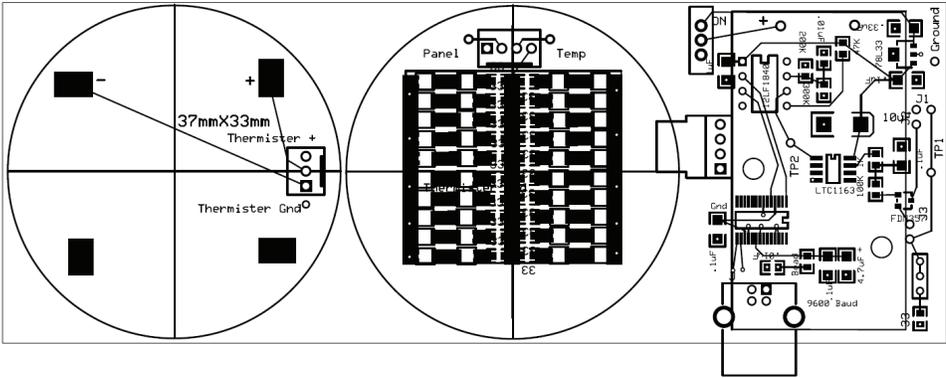


Figure 8, above

attributed to the internal resistance of the solar panel. This is an interesting look at the solar panel performance and useful for understanding solar panel behavior under load at constant illumination and constant operating temperature.

Now, let's apply some more Ohm's law and calculate the power produced by the solar panel as a function of the panel voltage. Figure 2 is a plot of power vs. voltage.

Notice that the power output of the panel peaks at around 4.25 volts. So under the fixed illumination level and operating temperature, the maximum power point (MPP) is 4.25 volts. If we were able to keep the load conditions (or the panel operating voltage) at or around the MPP, then the panel would be operating at peak efficiency...and this is the whole point of the MPPT.

If we were to vary the temperature of the panel, another characteristic of a solar panel will come to light (pun intended), the panel efficiency improves as the temperature goes down. Figure 3 is a plot of three data sets collected at room temperature (24°C), in a refrigerator compartment (12°C), and

in a freezer compartment (-12°C) of my household refrigerator. Notice the dramatic improvement of the solar panel output power when in the colder environment of a freezer.

MPPT Basics

To reiterate, in the most basic terms, the purpose of the MPPT circuitry is to adjust the solar panel operating conditions in response to changing panel temperatures to keep the panels operating at or near peak efficiency.

Figure 4 illustrates a simplified block diagram of the power components of a satellite. The left block represents the solar panels mounted on the satellite exterior surfaces that provide power for the satellite and replenish the battery/super capacitor power storage components when the panels are illuminated. The right block represents the batteries and/or super capacitors that provide power to the satellite during the eclipse portion of the orbit. Within this block is some sort of buck-boost power circuit that regulates the voltage from the battery to a level consistent with the operation of the satellite even if the voltage of the battery drops below the required voltage level.

The power from the buck-boost circuit is connected to the satellite's central power bus for distribution. The upper center block represents the MPPT circuitry.

Within the MPPT circuitry are connections to temperature sensors and voltage sensors that are monitoring the operating conditions of the solar panels. The MPPT logic in turn toggles the solar panels on and off of the storage batteries in step with the sensor readings to keep the voltage output on the solar panels at or near the maximum power point (the sweet spot). Figure 5 graphically represents this MPPT process. When the solar panel voltage drops below a specific value, a FET switch opens to isolate the panel from the load. As the panel voltage rises under no load, the MPPT circuitry monitors the voltage rise. At the point when the voltage reaches a specific high voltage value, the FET switch is closed connecting the panel to the load. Continuing this cycle, as the panel voltage drops under the load, the MPPT control circuitry will open the FET switch when the voltage reaches the specified low value and the cycle repeats.

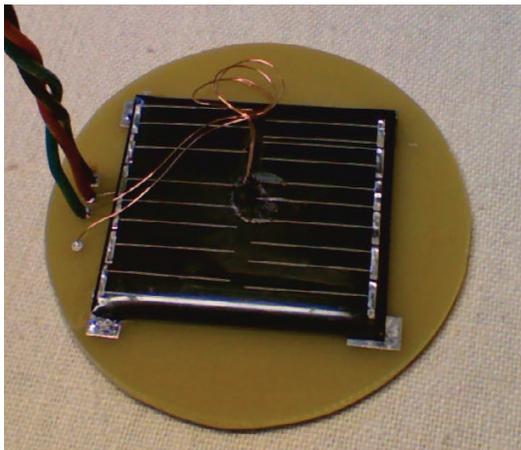


Figure 9

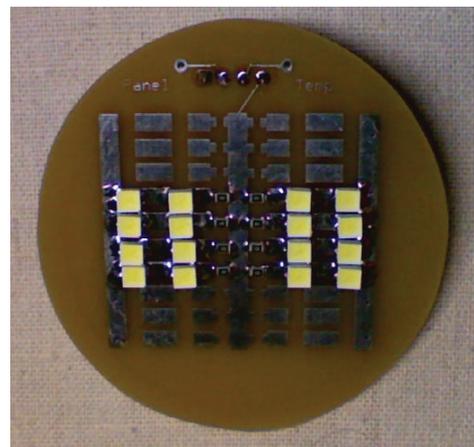
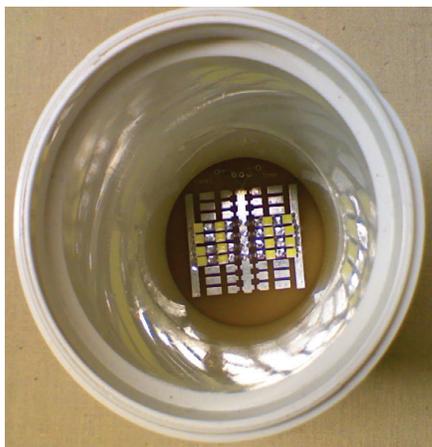


Figure 9

Simulating MPPT in the Classroom

The MPPT classroom simulator circuit diagram is depicted in figure 6. You will notice the similarity to the block diagram of figure 4. There are two parts to the simulator; the solar panel (this is a hobbyist solar panel and not the panels actually used on the satellite) and illumination source, and the MPPT circuitry with an interface to a personal computer (figure 7). The circuit board layout for this project is illustrated in figure 8, the solar panel and light source LED sections are cut and separated from the main board for mounting in the ends of a 1 ½ inch PVC compression coupler fitting. This arrangement allows the illumination source to be controlled by limiting the exposure of the solar panel to ambient light. Figure 9 depicts the solar panel mounted on the PCB and installed in one end of the compression coupler. Notice the thermistor glued to the center of the panel. Figure 10 depicts the LEDs installed on the illumination PCB and mounted in the other end of the compression fitting. The connecting umbilical wiring provides 9-volts to the illumination PCB and returns voltage from the solar panel and signals from the thermistor to the MPPT main board.

Using the MPPT system

There are two separate exercises that can be performed using the MPPT classroom system; solar panel profiling, and MPPT exploration.

Solar panel profiling

To develop a profile of the solar panel, the MPPT circuitry is isolated from the solar panel and the load (a 10-turn pot) by removing jumpers (figure 11). A VOM is connected to appropriate test points, and a USB cable is connected between the board and a PC running a GUI written for this project (and used here to measure the temperature of the solar panel figure 12). The compression coupler assembly is brought to the desired temperature by placing the compression coupler assembly in convenient temperature environments, for instance room temperature (around 20°C) and in your home refrigerator food (around 12°C) and freezer (around -14°C) compartments. The load resistance is set at specific resistance intervals (I recommend 250 ohm steps), power is applied to the illumination board, and panel voltage is measured with the VOM and recorded in a data table. This process is repeated through the load resistance range (6K to 1K ohms). The data is entered

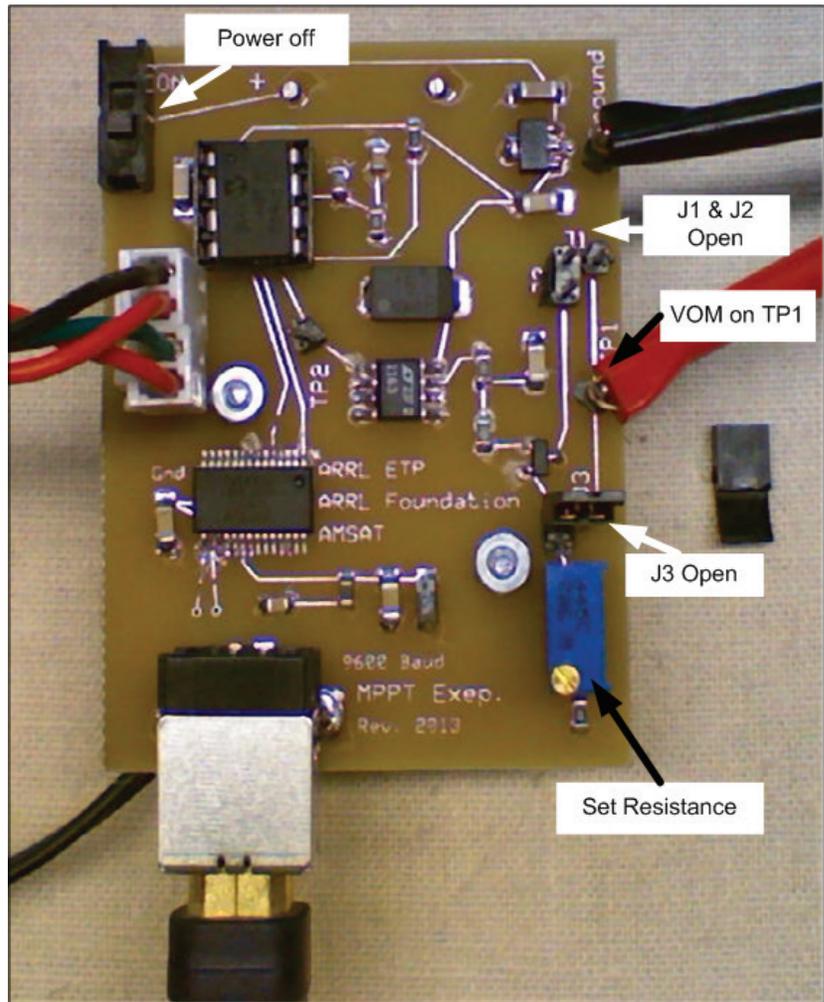


Figure 11

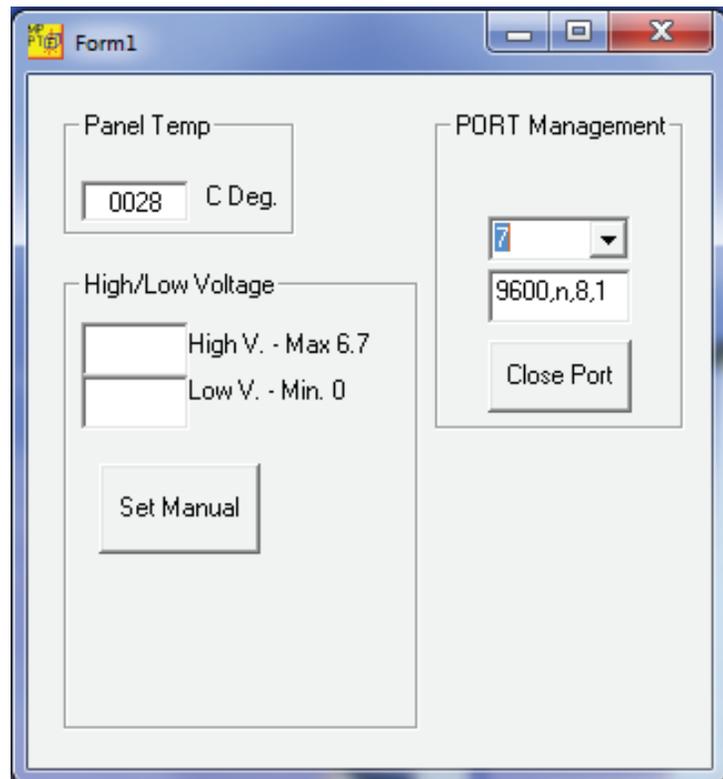


Figure 12



into Excel and the graphing capabilities of Excel are used to graph the data. Likewise the profile is accomplished for the other temperatures of interest. The end result of this activity would look something like figure 13.

By looking at the peak power output points and inserting this information into a graphing calculator, the algorithm for the relationship between solar panel temperature and maximum power point is determined. The MPPT formula for the prototype system is shown in figure 13. This algorithm is entered in the PIC program that is used in the MPPT logic for controlling the system in the automatic tracking mode.

MPPT Auto Tracking Mode

The central component of this MPPT circuit is a PIC® microcontroller. The analog to digital converter (ADC) resources of the PIC are used to monitor the temperature of the solar panel and the voltage produced by the panel. The temperature dependent, calculated optimum power point (from the algorithm developed during the profiling of the solar panel previously) is used to determine if a FET switch is turned on or off

to either isolate or connect the solar panel to the load. The hysteresis of the FET switch activation above or below the MPP is pre-set in software when the PIC is programmed. The MPPT circuitry is connected into the circuit by jumping J2 and J3. An oscilloscope is connected to the FET controlling signal at TP2 and to the panel output voltage at TP3 (figure 14). On power-up the system operates in the auto mode. The MPPT system behavior is illustrated in the oscilloscope screen shot in figure 15. The bottom square wave trace is the FET switching signal, the upper saw tooth wave is the solar panel voltage. If you compare the actual waveforms produced by the MPPT circuitry in operation to figure 5 and the discussion earlier, you should be able to make the connection from the academic to the practical presentation of the MPPT concept.

The user can also observe the MPPT circuit behavior while responding to temperature changes by placing the compression coupler assembly in different temperature environments. The PIC is programmed to read the temperature at approximately 15 second intervals and make corresponding adjustments in the voltage hysteresis.

Manually Exploring MPPT

The GUI also allows the user to experiment with various high and low voltage settings to bracket the MPP and see the circuit's behavior (figure 16 and 17). The user can also monitor the MPPT circuitry as it responds to variations in load by adjusting the load resistor and observing the pulse width changes in response to the load changes and the corresponding change in the voltage slope when the panel is connected to the load.

Finally, the class can really get into depth of the MPPT operation and behavior by writing their own software to control the system.

Summary

There is a lot that can be learned from the study of the behind the scenes systems that make satellite communications possible, such as MPPT and Attitude Determination Experiment (Wobble). Additionally, there are lots of learning opportunities made possible by receiving and analyzing the telemetry data being transmitted by the satellites. From the academic and life-long-learner points of view, the Fox borne

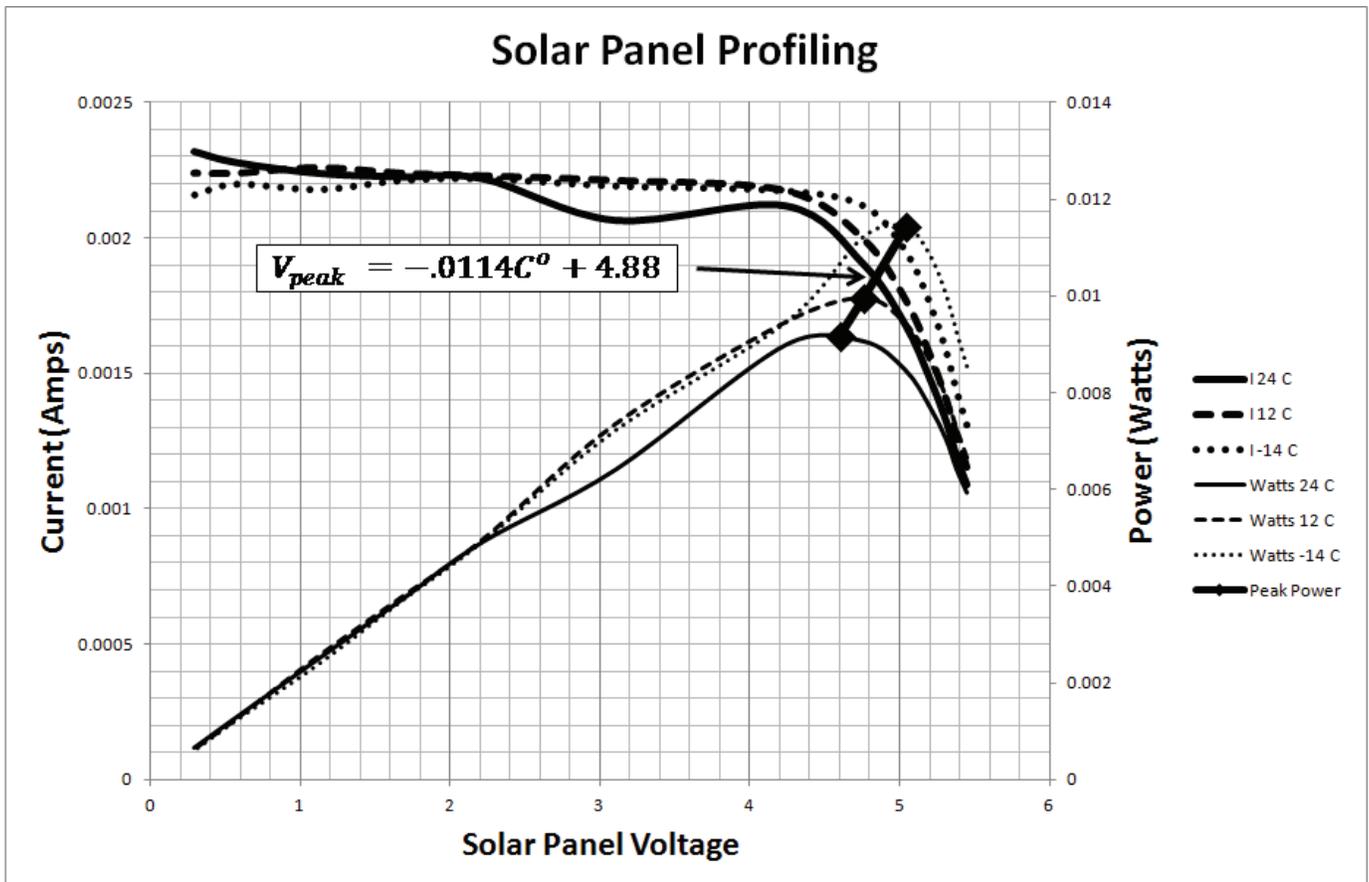


Figure 13

experiments are as important, if not more important, than the voice transponders they support. So I hope you will take some pass time to participate in the experiments, and become more proficient and capable satellite operators in the process.

As with the Wobble simulator project that was the subject of the companion article, this MPPT system project was made possible because of the generous support of the ARRL Foundation. I appreciate that they supported my own learning that resulted from the

development of this project.

Questions? Let me know. Detailed operating procedures for using the MPPT classroom system are available, along with other detailed information that you will need to duplicate the project, is available from the author by a simple e-mail request to m Spencer@arrl.org. Availability of kits/boards and that kind of thing are being considered. Watch the AMSAT web resources for news.

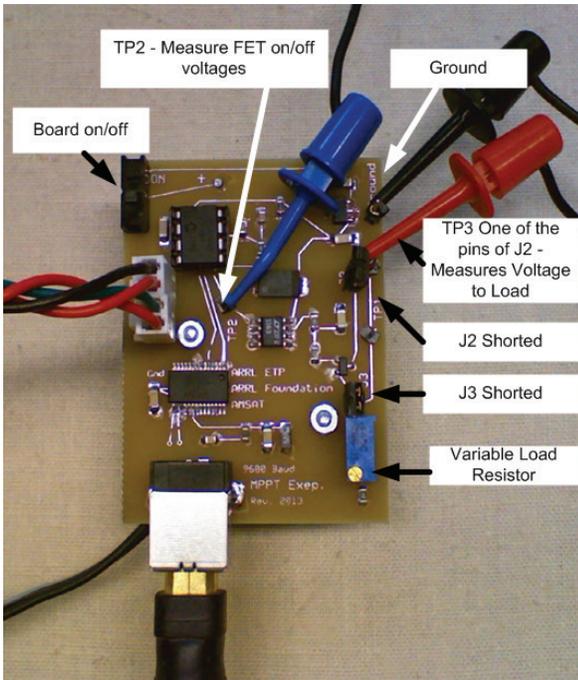


Figure 14

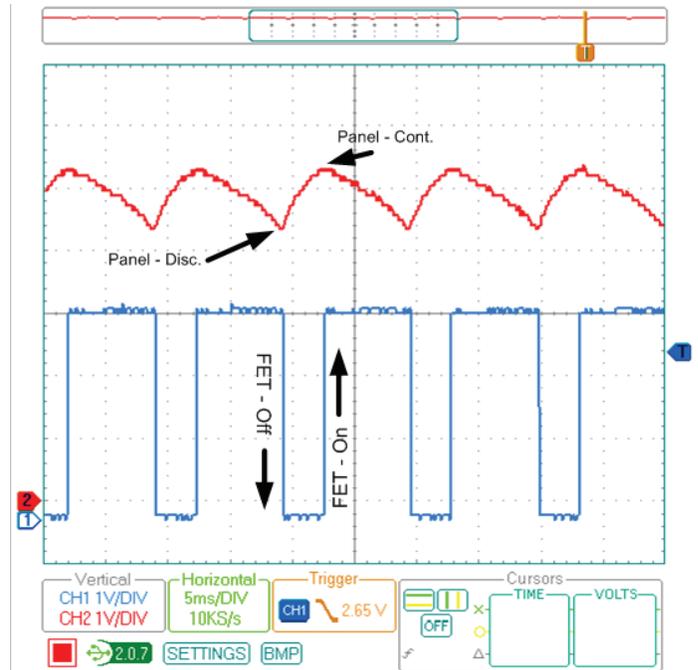


Figure 15

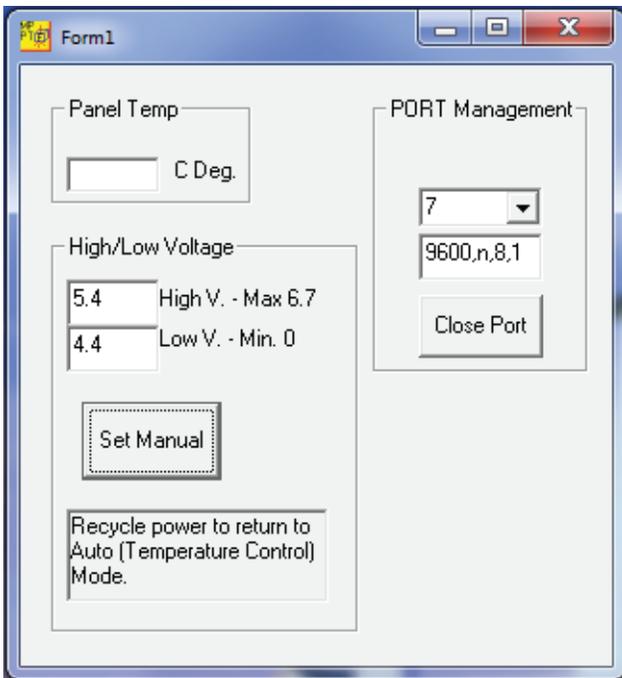


Figure 16

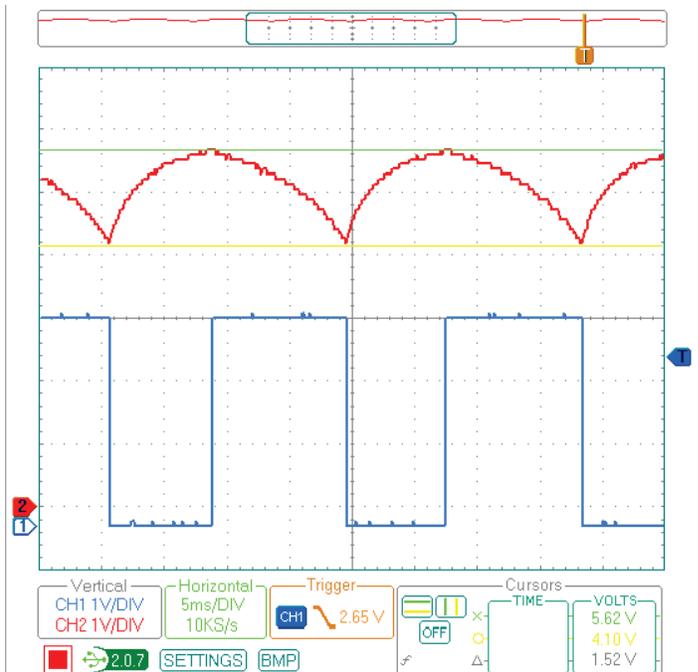


Figure 17

