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This is the first of a four part series of articles which aims to introduce the Fox-2 Maximum Power Point Tracker, (MPPT), to AMSAT members. Fox-2 is a 3U Cubesat which will be the successor to the Fox-1 family of satellites. This upgraded satellite will incorporate seven solar cells on each of its four sides producing up to 9.12 Watts of power per panel. The MPPT that has been designed for Fox-1 is not rated to handle this much power with the hardware used, forcing a completely new design to be implemented. AMSAT sponsored four students at the Rochester Institute of Technology (RIT) in Rochester, NY during a two-quarter senior design project lasting twenty weeks as part of the Kate Gleason College of Engineering (KGCOE) multidisciplinary senior design program to design the Fox-2 MPPT. These four electrical engineering students were Brenton Salmi, KB1LQD, Bryce Salmi, KB1LQC, Ian MacKenzie, KB3OCF, and Daniel Corriero who are shown in Figure 1. Our group considers itself privileged to have worked with AMSAT through Tony Monteiro, AA2TX, on this large undertaking. It was a rewarding and educational experience none of us will forget and from which all of us have gained crucial hands-on experience.

Figure 1: Fox-2 MPPT Design Team (left to right) Ian MacKenzie, KB3OCF; Brenton Salmi, KB1LQD; Bryce Salmi, KB1LQC; and Daniel Corriero

This series will cover the following topics:

- Part 1: Maximum Power Point Tracking Basics, Customer Needs, and Requirements
- Part 2: Analog Maximum Power Point Tracking and Circuit Protection
- Part 3: Health and Status Telemetry System
- Part 4: Test Results and conclusion

Maximum Power Point Tracking

Solar panels are both simple in operation but complex to connect to. Those of you who have used a solar panel have likely attached a battery or device to it and obtained power from the sun. However, it's unlikely that the maximum power from the panel was being produced by this setup, even in direct sunlight. This is because solar cells produce their maximum power at a specific operating voltage called the maximum power point voltage or the MPPV as shown in Figure 2. The upper line of the graph is the I-V curve of the example solar cell in which the x-axis is the voltage of the solar cell and the y-axis is the current. As can be seen, when the solar cell is operating in a short circuit, the current is maximum but the voltage is zero. This means no power is delivered to the payload. Similarly, when the solar cell is operated in an open circuit, the maximum voltage is generated but no current is delivered to the payload. Again, this results in no power being delivered to the payload. The lower line of the graph shows the power curve of the solar cell in which the x-axis is the voltage and the y-axis is the power delivered to the payload. Forcing the solar panel to operate at the maximum power point (MPP) will extract the maximum amount of power from the panel. On Figure 2, this point is located just to the left of the knee of the I-V curve at the point where it crosses the dashed vertical line.

Maximum Power Point Voltage Variance

The MPPV varies with solar irradiance (i.e. solar radiation intensity, given in W/m^2) as well as with the temperature of the solar cells. As shown in Figure 3, the intensity of the light hitting a solar cell generates a current which varies with respect to the cell's voltage. However, the MPPV of the I-V curve, which is generally located close to the knee, does not move left or right much which means that the MPPV stays in roughly the same spot. Now, in Figure 4, the intensity of the light hitting the example solar cell was held constant while the temperature was varied. The "knee" moves drastically left and right indicating that the MPPV has shifted with temperature. If the small percentage of power that is lost by not tracking the MPP with the changing light intensity can be deemed acceptable, then tracking the MPPT due to the temperature change simplifies the solution. This still maximizes a large majority of the power that would otherwise be lost.

Implementing Solar Panels

There are four common methods to implement solar panels on small spacecraft such as Cubesats. These methods include direct energy transfer and three MPPT algorithms (constant voltage, maximum current, and perturb and observe). Any MPPT method that is implemented should be designed efficiently so as to provide more power than by directly connecting the solar panel to the battery through direct energy transfer. If a method of MPPT is inefficiently designed, it can harm the satellite's operational capabilities and should not be implemented. MPPTs are usually designed with a DC/DC converter to provide an impedance match between the high impedance of the solar panel to the low impedance of the payload. Treating an MPPT as a method of impedance matching can help visualize what it is doing in order to maximize power.

Direct Energy Transfer

Direct energy transfer (DET) is an extremely simple method of implementing solar panels and can be found on many simple satellites. DET is accomplished by directly connecting the spacecraft battery to the solar panels and thus the voltage of the battery determines the operating voltage of the solar panel. If the nominal battery voltage is designed to be close to the maximum power point voltage of the solar panel, the system will generally be efficient. It will not track the maximum power point voltage as it shifts with irradiance and temperature however. Additionally, if the battery short-circuits, the panels will produce almost no power. This renders the satellite inoperable unless the battery is designed to disconnect from the solar panels in the event of a failure.

Constant Voltage

An extremely simple method of MPPT is implemented by assuming that the maximum power point voltage of the panel corresponds to 76% of the open circuit voltage of the solar panel. The calculated operating voltage shifts with irradiance and temperature change. A DC/DC switching converter is used to force the solar panel to operate at this voltage. It does this by varying the pulse width modulation in order to conduct the correct amount of current into the payload. The panel voltage then changes accordingly. While 76% of open circuit voltage is an estimated value, this method

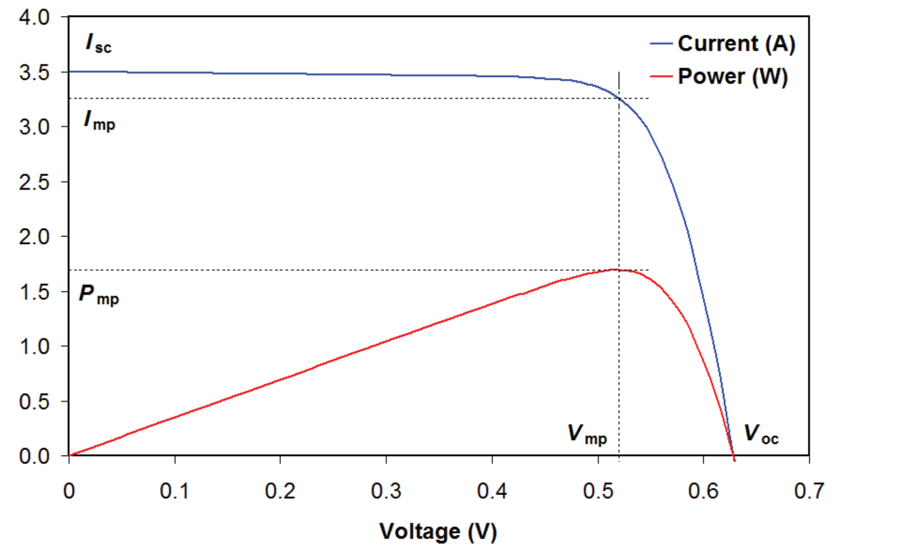

Figure 2: An example solar panel current - voltage (I-V) curve and associated power curve. The top line is the I-V curve and the lower line is the power extracted from the solar panel. Notice that at the Vmp the maximum power is produced. [1]

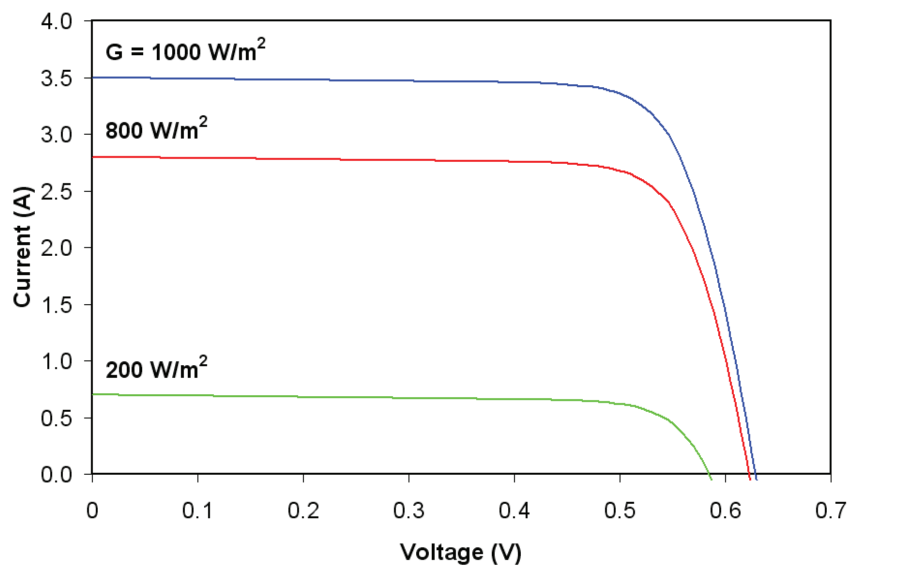

Figure 3: The I-V curve of an example solar panel with constant temperature as solar intensity is varied. Notice that the "knee" of the curve is relatively static over varying solar intensity. [1]

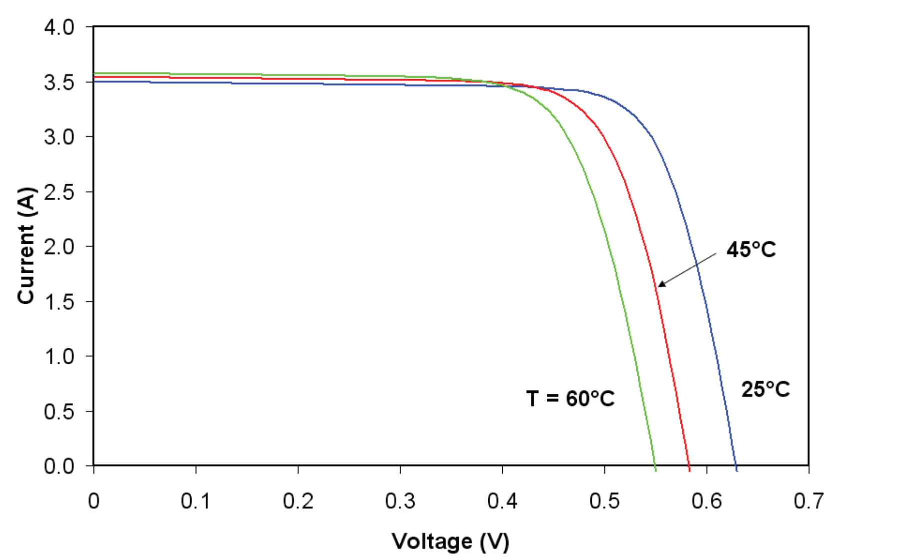

Figure 4: The I-V curve of an example solar panel with constant solar intensity as the temperature is varied. Notice that the "knee" of the curve varies widely over temperature. [1]

also requires the payload to periodically be disconnected from the solar panels to measure the open circuit voltage, limiting the possible efficiency of this method.

Maximum Current

One method that is ideal for short duration Cubesat missions (about six months duration) is the maximum current method. A DC/DC converter is placed between the solar panel and the battery such that the battery determines the DC/DC converters output voltage since it's on the same voltage node. Since the battery voltage changes slowly with respect to the switching frequency of the converter, the converter's output voltage can be assumed to be nearly constant. Pulse width modulation can be used to change the panel voltage. This maximizes the current into the battery and will provide maximum power. This eliminates the need for a microprocessor to compute power by measuring the current and voltage. Since voltage is constant, maximum power correlates to maximum current. However, since the battery is required for this method of MPPT, it is not suitable for Fox-2 due to the need for the MPPT to operate without the presence of a battery.

Perturb & Observe

The perturb and observe method of MPPT is commonly used and often implemented with a microcontroller in commercial systems. The microcontroller controls a DC/DC converter and also monitors the power produced by the solar panel. A small change in panel voltage, or perturbation, is applied by means of an increase or decrease in panel voltage. The DC/DC switching converter is driven again with pulse-width modulation to vary the current from the solar panel. This, in turn, varies the solar panel voltage over the I-V curve. The computed power that is then obtained determines the direction of the next perturbation. If the power increases, a perturbation in the same direction is applied, if the power decreases, a perturbation of the opposite direction is applied to the solar panel. The perturb and observe method never operates directly at the MPP since it will, at best, oscillate around the MPPV under normal operation. However, the algorithm must be prevented from tracking on a local maximum on the power curve. As well, it must be prevented from accidentally tracking in the wrong direction in fast-changing illumination conditions, such as when the spacecraft is spinning.

Also, the implementation of a microcontroller means that this solution is likely more susceptible to radiation effects than others methods which are not implemented with discrete digital states.

Fox-2 Maximum Power Point Tracking Algorithm

The Fox-2 maximum power point algorithm is based on the assumption that the MPPV changes more significantly due to temperature effects than due to variations in illumination. The algorithm is completely analog and implemented with operational amplifiers and a pulse-width modulator (PWM) integrated circuit. An analog MPPT is generally more tolerant to radiation events such as single event effects (SEE), and total ionizing dose (TID). This robustness will allow the spacecraft to operate for its projected five-year lifetime.

Figure 5 shows the block diagram of the circuit delivered to AMSAT. All blocks inside the dashed box were within the Fox-2 MPPT project scope. The DC/DC converter is a buck converter that is controlled by the PWM MPPT feedback control circuitry. This control circuitry obtained solar panel

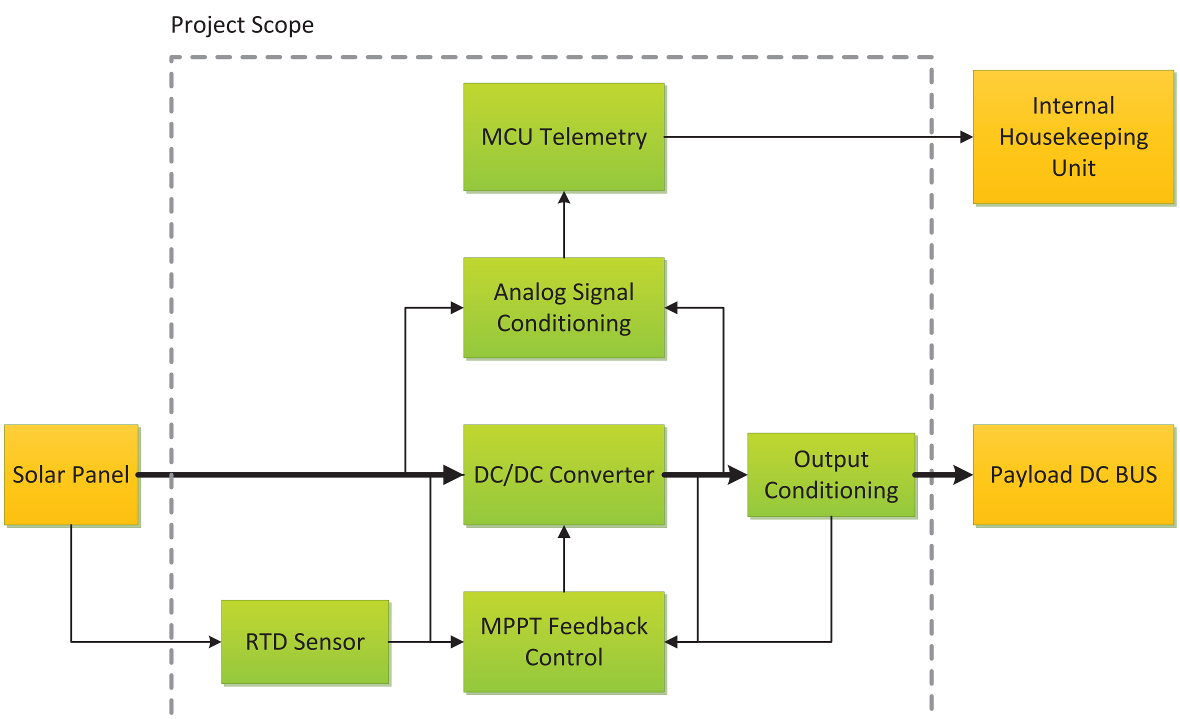

Figure 5: The AMSAT Fox-2 Maximum Power Point Tracker high-level block diagram. All blocks within the dashed box were within the scope of our project.

High-Level MPPT Diagram

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voltage and temperature measurements used to maximize power. Additionally, safety circuitry allowed the output voltage to be monitored and conditioned. Analog measurements were conditioned and sampled with an analog-to-digital converter (ADC) using a Texas Instruments MSP430 microcontroller. This microcontroller produced telemetry data for the Fox-2 Internal Housekeeping Unit (IHU).

Maximum power is produced by predicting the MPPV using an accurate temperature measurement of the solar panel from a resistive temperature detector (RTD). Using a solar panel comprised of known solar cells, such as the Spectrolab UTJ cells, analog circuitry can accurately predict the correct operating voltage for maximum power transfer. By keeping losses in the DC/DC converter as low as possible, a net gain in power over direct energy transfer is obtained since tracking of the maximum power point voltage over temperature occurs. The Fox-2 MPPT algorithm and physical implementation will be more thoroughly explored in the second installment of this series of articles.

Fox-2 MPPT Customer Needs

Customer needs cover general project objectives that had to be achieved by the circuit delivered to AMSAT. Figure 6 details the needs specified by AMSAT which our team strived to meet. These needs were organized in order of importance ranging from "must have" to "preference". The top three needs for the Fox-2 design include maximizing the energy transfer between the solar panel and the payload, meeting all environmental requirements, and providing a limited output voltage so as to not damage the payload.

If the energy transfer through the MPPT DC/DC converter is inefficient, the benefits of an MPPT are quickly erased and DET becomes a better alternative. Additionally, the satellite will experience harsh temperatures in the vacuum of space where only conduction and radiation are the methods of heat transfer. Temperature variations occur multiple times per day due to the orbit. This results in both electrical and mechanical stresses on the components which have to be accounted for. The electrical stresses can result in changes in the component operating characteristics while the mechanical stresses could lead to cracking.

Fox-2 MPPT Engineering Specifications

The design of the Fox-2 MPPT, and the hardware which was built and delivered to AMSAT, had to meet a specific set of requirements. Every specification required a test to prove that it was satisfied. The specifications shown in Figure 7 were carefully determined through several meetings with Tony Monteiro over the phone and email. Specifications which were hard to test by the senior design group, such as the radiation specification, were achieved by providing analysis and documentation. This presented a level of assurance that the specification was indeed met with a certain amount of confidence regarding the radiation susceptibility of the design. Overall, the specifications have been listed in order of importance with a different scaling from the customer needs document due to RIT documentation requirements.

Some of the specifications should be mentioned in detail as they are not clearly presented in Figure 7. The power produced by each panel is in fact 9.12 W when the solar panel is cold and operating in full sunlight. This occurs immediately following an eclipse when the satellite is extremely cold but also fully illuminated and before any substantial heating from the sun has been received. The specification of 7.24 W was an error which was eventually corrected and the required 9.12 W was tested on the physical MPPT. The output voltage of the MPPT will be covered in more detail in the second installment of this series. Overall, the output voltage is not regulated but is, rather, limited. At no point should the output voltage of the MPPT nominally operate above 4.1 V. Any voltage below this is generally acceptable down to about 3.3 V. During operation, the output voltage will only ever deviate from 4.1 V when more power is requested from the solar panel than it can provide at the MPP. When this occurs, the MPPT circuitry will track the predicted MPPV to continue providing maximum power to the payload in varying load conditions. As the current demand from the payload increases, the output voltage must drop due to conservation of energy in order to maintain the maximum power available from the solar panel. The circuit was also tested to -40° C and +85° C operating temperatures since the circuit boards inside the satellite are protected from direct exposure to the sun and black of space. The solar panels, however, are exposed and will experience -60° C to +60° C temperatures which the MPPT must account for in its operating voltage calculation. Lastly, an important specification that drove the design was the requirement to design a circuit in which at least four MPPT devices could fit into the area of one Cubesat circuit board.

Final Thoughts

We hope you enjoyed the technical dive into the world of satellite design. This has been an extremely educational and rewarding project. Having the opportunity to share the design and some of our knowledge is quite a privilege. The next AMSAT Journal will present into the schematics and theory of operation for the Fox-2 MPPT. We're sure many of you are eager to learn about the design of the circuit. If you want to skip ahead and read more about this project we invite you to visit the RIT EDGE website where our project has been documented on by visiting:

http://edge.rit.edu/edge/P13271/public/Home

Thank you for reading about our senior design project.

References and Attributions

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Project: **P13271 AMSAT Maximum Power Point Tracker**
Revision #: 2 Date: 4/29/2013

Customer Need #	Importance	Description	Comments/Status
CN1	1	Maximize energy transfer between solar panel and load	Efficiency
CN2	1	Meet environmental requirements	Temperature, Radiation
CN3	1	Provide limited output voltage	Customer supplied upper limit
CN4	2	Meet mechanical constraints	Component size and form factor
CN5	2	Communicate status information with satellite IHU	Health and status information
CN6	2	Recover from soft errors in software	Watchdog

IHU Internal Housekeeping Unit

Importance Rating Scale

Must have	1
Nice to have	2
Preference	3

Figure 6. Customer needs specified by AMSAT Engineering, organized by importance ranging from "must have" to "preference".

Project: **P13271 AMSAT Maximum Power Point Tracker**
Revision #: 2 Date: 5/5/2013

Spec. #	Importance	Source	Function	Specification (metric)	Unit of Measure	Marginal Value	Ideal Value	Comments/Status
S1	9	AMSAT	CN1,CN3	Maximum Power Input	Watts	7.24	>7.24	27 cm^2 cells, Qty=7
S2	9	AMSAT	CN1	Input Voltage Max	Voltage	22	>22	NASA Derating
S3	9	AMSAT	CN3	Limited Output Voltage	Voltage	<4.1	4.1	Operating voltage limit
S4	9	AMSAT	CN1	MPPT Efficiency	Percentage	90.00%	>90%	Conversion efficiency
S5	9	AMSAT	CN1	MPPT Response Time	Milliseconds	100	<100	
S6	9	AMSAT	CN2	Maximum Operational Temperature	Celsius	85	>85	Industrial Specifications
S7	9	AMSAT	CN2	Minimum Operational Temperature	Celsius	-40	<-40	Industrial Specifications
S8	9	AMSAT	CN2	TID Radiation Expectation	kiloRad	30	>30	Published data
S9	6	AMSAT	CN2,CN4	Component Height Restriction	Millimeter	<8.1	5	Topside clearance
S10	6	AMSAT	CN2	Layout Area Constraint	Cm^2	144.5	<144.5	Tall items on topside
S11	6	AMSAT	CN5,CN6	IHU Communications	Pass/Fail	N/A	N/A	Fox-1 Specifications (I2C)

IHU Internal Housekeeping Unit

Importance Rating Scale

Must have	9
Nice to have	6
Preference	3

Figure 7: Fox-2 MPPT engineering specifications as agreed upon with AMSAT Engineering.

KySat-2 Announces Telemetry Dashboard Software and Tracking Aids

The KySat-2 CubeSat launch is scheduled as part of the ORS-3/ELaNa-4 mission on November 19 from Wallops Island, VA. The Kentucky Space Team requests that Amateur Radio stations track and help in the collection of telemetry data.

To help track KySat-2, a web page has been setup to assist radio amateurs. To help decode packets from KySat-2, software for radio amateurs to download and install is available at: **http://ssl.engineering.uky.edu/amateur-radio-operators/**

Initially, the software will support receive-only operation, but after spacecraft checkout, it is intended that the software will also support limited commanding.

An Advanced Satellite Orbit Tracking Tool to visualize KySat-2's orbit in real-time can be viewed at: **http://k2asot.engr.uky.edu/**

For more information on general information on KySat-2, visit: **http://kysat2.engr.uky.edu/** and **http://kentuckyspace.com/**