Evaluation of Solar Array Peak Power Tracking Technologies for CubeSats

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ABSTRACT

The increasing complexity and capability of small satellite missions is placing more stringent requirements on spacecraft power systems. Higher power demands are usually met with deployable solar panels and platforms that require attitude determination and control systems which add mass, complexity, and risk to the mission. Finally, to make more efficient use of the solar panels under varying conditions, peak power tracking technologies are employed which electrically match the load and solar arrays. This paper evaluates the effectiveness of popular peak power tracking methods and compares them to fixed operating point and direct energy transfer designs and shows that for many missions peak power tracking offers little or no advantage over direct energy transfer approaches.

INTRODUCTION

On-orbit power generation is necessary for all but the simplest satellite missions. While missions with lifetimes on the order of weeks could be designed to survive on primary batteries, any mission that must last longer or consume more power must be able to generate energy to replenish stored energy reserves. While there are options for power generation (fuel cells and nuclear-thermoelectric), the relative size, mass, and expense of the more exotic solutions make photovoltaics the popular choice for the vast majority of missions.[1] There are several properties of photovoltaics that must be considered during the design of a power system. These include the effect of total radiation dose, power generation at varying solar incidence angles, response to temperature, and a non-linear current-voltage relationship.

A Solar Array Interface is used to connect the solar arrays to the rest of the spacecraft system. Currently, there are two major commercial providers of CubeSat power supplies both of which use a Maximum Power Point Tracking (MPPT) Solar Array Interface; a MPPT Solar Array Interface changes its behavior to extract the most power out of a solar array.[2,3] A 2010 survey of pico- and nano-satellite missions show that 46% of missions use a Direct Energy Transfer (DET) Solar Array Interface; in a DET Solar Array Interface the solar arrays are connected directly to the battery usually through a diode to prevent reverse current while in eclipse. The rest used some sort of active Solar Array Interface, including MPPT, which connects the solar arrays to the batteries through a switching converter.[4] Finally, university satellite programs have successfully flown missions using DET however some programs are currently using and developing MPPT Solar Array Interfaces.[5,6,7]

This paper studies several designs of Solar Array Interfaces each of which accounts for these characteristics in different ways. Each design is evaluated for small satellite missions and compared to the maximum power that could be generated in a typical Low Earth Orbit. It is argued that, for the majority of small satellite missions, more sophisticated MPPT systems are not necessary and can be detrimental to the overall mission and that a design based on DET proves to be a better choice.

BACKGROUND

A solar cell must be operated carefully to ensure efficient generation of power. To reach that end, various control schemes have been designed, called MPPT, which manipulate either operating voltage or current of the solar array. MPPT's manipulate the operating point of the solar array by controlling the operation of a switching converter between the solar arrays and load. The switching converter acts as a load transformer resulting in the solar array driving an ideal load regardless of the actual load. The switching converter then drives a battery or other energy storage devices to deal with load transients. An MPPT can also account for changes in solar cell performance due to environmental factors such as incidence angle, temperature, and radiation damage. Furthermore, the use of a switching converter between the solar arrays and the rest of system decouples the two designs allowing the solar arrays, the battery, and the load to be designed with little regard to one another.
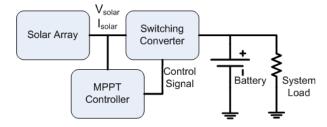
Figure 1: MPPT Block Diagram

These benefits do not come without a cost however. MPPT's are complicated active control systems that must be carefully designed to ensure stable operation. Each solar cell string must be operated independently to ensure maximum efficiency so there must be a MPPT and switching converter system for each string. Finally, the necessary switching converter has an efficiency less than 100% which lowers the overall system efficiency.

While there are many MPPT controller options, in this study we compare three popular approaches that are representative for the majority of controller options.[8] The MPPT controllers studies include: Fractional Voltage, Perturb and Observe (P&O), and dP/dV. These are compared with a Fixed Point controller, a Temperature Compensated (TC) Fixed Point controller and a Direct Energy Transfer (DET) system.

EXPERIMENT

The solar array interfaces, as well as other orbital parameters, were implemented in Simulink® to model their behavior in an orbital environment and compare their performance. Simulink® is MATLAB-based tool for graphical modeling and simulation of time-varying dynamic systems. As Simulink® is, in essence, a differential equation solver; it gives the option of using different solvers that can trade accuracy for speed. To ensure stability, all the designs were tested with multiple solvers and the ode45 Dormand-Prince Method was used for all comparisons between designs.[9]

Orbit

The orbit used for the simulations is a 650 km orbit at 97 degree inclination. This gives an orbital period of 97.73 minutes with a maximum eclipse of 35.38 minutes. This assumption sets the orbital period and eclipse durations for the simulations, which directly affect the thermal model and solar power production.

Attitude

Rotation rates directly affect the performance of an MPPT system. Performance degradation occurs when the solar energy appears and disappears too quickly beyond the response time of the MPPT circuitry. A rotation rate of 1 degree per second is assumed for the

simulations in this paper. This rate is typical for passively stabilized nanosatellites.[10] A later section shows the effect of an increased rotation rate on the performance of the various EPS designs described in this paper.

The attitude assumed for this paper consists of a flat plate with solar cells mounted on both sides rotating on an axis normal to the sun. The solar cells on both sides of the plate are being controlled by the same solar array interface, though only the sun facing solar cells are considered as those would dominate the performance. This is consistent with body mounted solar cells on a CubeSat with opposite sides being controlled by the same Solar Array Interface. The rotation, while not typical in practice, does expose the solar arrays to all possible incidence angles and thus, is a good method to determine the efficiency of the Solar Array Interfaces.

Temperature

Temperature has a direct effect on solar cell performance, most notably on the voltage response but also on the available current. A temperature model was implemented which varies from -30 to +40 degrees celcius and follows a radiative heating curve. More information on the thermal model and the effect on solar cells can be found in reference 11.

Analysis

The fundamental solar cell equation governing the solar cell behavior is given as:

$$I = I_{ph} - I_o(e^{(V+IR_S)/(nV_T)} - 1) - \frac{V + IR_S}{R_{SH}} \quad (1)$$

where I is the solar cell current, I_{ph} is the short circuit current, I_o is the reverse saturation current, V is the solar cell voltage, R_s is the cell series resistance, n is the quality factor, V_T is the thermal voltage and R_{sh} is the cell shunt resistance.[11] The solar cell parameters for this simulation are based on a Spectrolab improved triple junction solar cell and were set to match the manufacturer's specifications.[12]

The simulations consist of each of the Solar Array Controllers going through a full sun cycle of an orbit while rotating at 1 degree per second and undergoing the associated temperature changes. The total integrated power over the sun cycle is then calculated in units of Watt·Seconds (1Ws = 1 Joule) and compared to the maximum possible integrated power given the environmental parameters and the specific solar cell modeled.

Simulation Setup

Figure 2 shows the generic Simulink setup with the Solar Array Controller, Temperature Model, Rotation Model, and Solar Cell Model. This setup is used for all the modeling except for the DET which is described in the following sections.

Also, each Solar Array Controller, except DET, incorporates a Battery Charge Regulator (BCR) model. The BCR is the switching converter that the Solar Array Controller manipulates to set the operating point of the solar arrays. The BCR modeled is a current mode switcher which, in practice, throttles its input current which in turn controls the solar cell behavior. For simulation it is modeled as a single gain, "Vfb -> Ireq" (seen in later figures), which translates the control signal from each Solar Array Controller into the requested current from the solar cell.
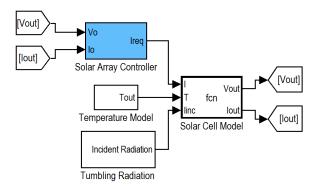
Figure 2: Generic Simulink Model

Ideal Response

Figure 3 shows the ideal operating behavior of the modeled solar cell over the sun portion of one orbit. This represents the ideal energy production and an upper bound on the performance of any design. The blue line represents the solar cell voltage corresponding to the maximum power generation and the red line represents the maximum power available. The total integrated power available is determined by the area under the power curve, seen in red in Figure 3, and for the solar cell model, the orbit and the environment parameters used in the simulation was 197.32 Ws.
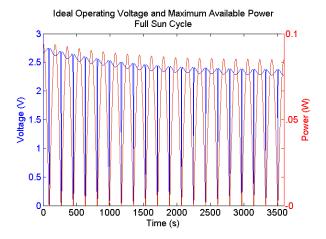
Figure 3: Ideal Operating Voltage and Power Generation

Two trends can be seen in Figure 3. The first is the result of spacecraft rotation leading to a sinusoidal shape of the available power and the steep decline in ideal operating voltage every time the "satellite" rotates. The other is the decrease over the entire simulation period of one sun cycle of the maximum available power and ideal operating voltage corresponding to the temperature response of the solar cell.

Each of the Solar Array Controllers is now described in turn. First, the theory of operation for each controller and how they compensate for the changing environment is discussed. Next, the implementation of each Solar Array Controller in Simulink is shown and discussed. Finally, their performance in the simulation is discussed and compared to the ideal For the Fractional, P&O, dP/dV, and TC fixed controllers only the performance over one rotation is shown in graphs as each tracks the temperature response. A full sun cycle is shown from the Fixed and DET controller as these are affected by temperature.

FRACTIONAL VOLTAGE PEAK POWER TRACKING

The theory of operation for the Fractional Voltage MPPT controller relies on the fact that there is a near linear relationship between the open circuit voltage (V_{OC}) and the maximum power voltage (V_{MP}) of a solar array. Thus the only information the controller must determine is V_{OC} and then, with a single gain, the operating point of the solar array can be set. V_{OC} can be determined by either briefly disconnecting the solar array from the load and using a Sample-and-Hold system or by dedicating a "pilot cell", an independent cell which is of the same type as that of the array and subject to the same environmental parameters, left open

and used as the reference.[13] While this ratio between V_{OC} and V_{MP} does vary slightly over different environmental parameters, the change is very slight.[11]

The fact that the optimal ratio is solar cell dependent is a primary weakness of the fractional voltage method; the optimal ratio is solar cell dependent. Therefore, each array must be independently characterized to set the optimal ratio to ensure optimal performance. Also, as this is not a true MPPT controller, errors in characterization have a direct impact on power generation.

Fractional Voltage EPS Model

Figure 4 shows the Simulink Implementation of the Fractional Voltage Solar Array controller using the Open Cicuit-Sample-Hold method.
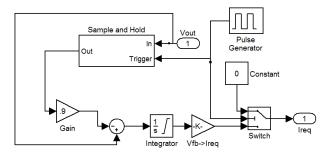

Figure 4: Simulink Model of Fractional Voltage Controller

The heart of this controller is a timer which outputs a 10 millisecond pulse once every second. This pulse triggers a switch which forces the requested current to zero simulating an open circuit condition. The pulse simultaneously triggers a sample and hold subsystem which sets the output to what the value of the input was when the trigger was last high. As the pulse triggers both the open circuit condition and sample and hold system, the sample and hold system is set to the open circuit value. The open circuit value is then passed through a gain equal to an optimal, empirically determined ratio which relates the open circuit voltage to the maximum power voltage. Finally, an integration of the difference between the operating voltage and the target operating voltage is used to adjust the Battery Charge Regulator.

Fractional Voltage Performance

Figure 5 shows the response of the fractional voltage controller over a single tumble acquiring the sun then losing it at a rotation rate of 1 degree/second. The thermal response followed the same trend as the ideal response and is not shown. During the single rotation the blue curve has two distinct sections; the upper portion corresponding to the open circuit voltage of the

solar cell and the lower portion is the system matching the operating voltage to the level determined by the controller. The total integrated power for the fractional voltage controller system is 195.66 Ws over one orbit (compared with 197.32 Ws for the ideal resulting in an efficiency of 99.1%).
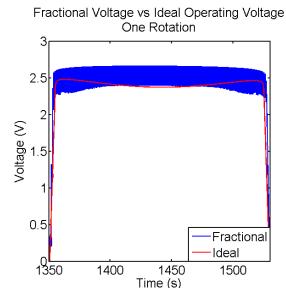

Figure 5: Fractional Voltage vs Ideal Operating Voltage

P&O PEAK POWER TRACKING

A P&O controller works by coupling a perturbating signal onto the solar cell voltage which induces a change in the solar array current. The phase of the perturbed power signal is compared to that of the perturbing signal and this phase difference determines the position of the operating voltage with respect to V_{MP}.[1] If they are in phase, the operating voltage is too low, as an increase in operating voltage leads to an increase in power, and, similarly, if they are out of phase the operating voltage is too high, as an increase in operating voltage leads to a decrease in power. A similar method, known as Climb the Hill, puts the perturbing signal on a control signal as opposed to directly on the solar cell voltage which, in practice, accomplishes the same result. P&O and Climb the Hill controllers are "true" MPPT controller and, thus, can be used as generic controller without regard to solar cell type and characterization.

P&O Model

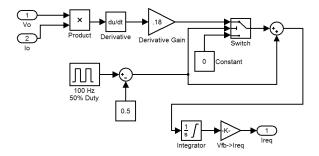Figure 6 shows the Simulink Implementation of the P&O Solar Array Controller.

Figure 6: Perturb and Observe Simulink Model

The implementation used was based on the "Climb the Hill" method which perturbs the control signal as opposed to the actual operating voltage. The power out of the solar array is calculated and differentiated. The derivative is then processed by a synchronous demodulator controlled by a +/- 0.5 volt amplitude square wave. It is this synchronous demodulator that allows the controller to track the peak power point. For the positive portion of the square wave the derivative is added to the value of the square wave. The positive 0.5 amplitude bias on the integrator initially causes a rise in the control voltage out of the integrator. If this rise leads to an increase in power the derivative signal is positive and the net input to the integrator is >0.5. Likewise, if the initial rise leads to a decrease in power the derivative signal is negative leading to a net input to the integrator of <0.5. The negative portion of the square wave is a fixed input to the integrator of -0.5. The square wave alone leads to a zero net change in the control signal but with the derivative added during the positive portion the controller settles around the optimal power point.

P&O Performance

Figure 7 shows the response of the P&O controller and the modeled system. As before, the blue line represents the actual solar array voltage and the red shows the ideal. Also, as described earlier, the blue line has two distinct portions. This is due to the oscillating nature of the P&O controller as discussed above. Besides the oscillations, the P&O controller, as seen, does a very good job of tracking the ideal operating voltage. The total integrated power of the P&O controller is 194.64 Ws over one orbit (compared with 197.32 for the ideal resulting in an efficiency of 98.6%).
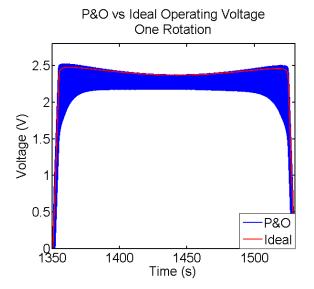

Figure 7: P&O vs Ideal Operating Voltage

dP/dV PEAK POWER TRACKING

In a dP/dV controller, power is locally maximized at whatever operating voltage causes dP/dV to equal zero and, as there is only one maximum on the power vs voltage curve, the maximum power point occurs when dP/dV equals zero. A dP/dV controller is also a "true" MPPT controller and can be used as generic controller without regard to solar cell type and quality of characterization.

dP/dV Model

Figure 8 shows the Simulink implementation of the dP/dV Solar Array Interface Controller.
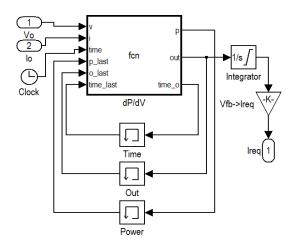

Figure 8: Implementation of dP/dV Controller

The output of the controller block is a fixed value but the sign is changed based on comparison of the two power values. At every time step, the power generated is computed and compared to the power calculated at the previous time step, with a fixed amount of time between calculations (simulating the conversion time of an Analog to Digital Converter) at each time step. If the power at that instant is greater than the previous power the sign of the output remains the same. If the power is less than the previous power the sign of the output is swapped. The output is fed into an integrator to produce the control signal to the Battery Charge Regulator. The operation of the dP/dV controller is similar to the operation of the P&O controller in that it causes the control signal to oscillate around the optimal point.

dP/dV Performance

Figure 9 shows the simulation results using the dP/dV controller. As seen, the controller works very well, though it does suffer from noise around the extremes of incidence angle values as it undergoes a 1 degrees per second rotation. This response is due to the fact that low irradiance means low power and, as such, small control voltage changes have exaggerated effects. The total integrated power for the dP/dV controller is 195.10 Ws over one orbit (compared with 197.32 for the ideal resulting in an efficiency of 98.9%).
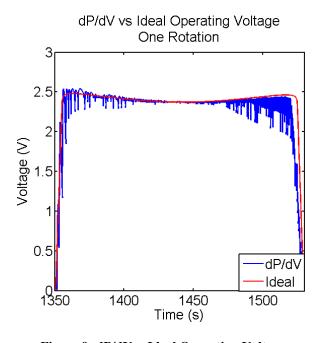

Figure 9: dP/dVvs Ideal Operating Voltage

FIXED VOLTAGE OPERATION

A Fixed Point controller sets the operating point based on a static voltage reference. This operating point must be empirically determined and, as such, any errors in characterization has a direct impact on solar array operation.

Modeling Fixed Voltage Operation

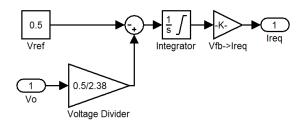Figure 10 shows the Simulink Implementation of the Fixed Voltage Solar Array Controller.

Figure 10: Fixed Voltage Model

This controller consists of an empirically determined reference setpoint and an error integrator to force the solar array voltage to equal the setpoint.

Fixed Voltage Operation Performance

Figure 11 shows the simulated response of the Fixed Voltage Controller. The behavior of the controller is fairly good, staying within 4% with a mean value less than 0.08% away from the setpoint throughout the orbit. The majority of the noise occurred when the setpoint was not optimal leading to exaggerated changes of the solar cell voltage as compared to the control signal. The total integrated power for the Fixed Voltage Controller is 188.80 Ws over one orbit (compared with 197.32 Ws for the ideal resulting in an efficiency of 95.7%).
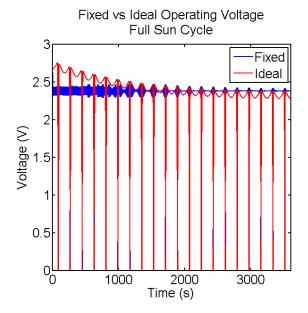
Figure 11: Fixed Voltage vs Ideal Operating Voltage

TC FIXED VOLTAGE

A Temperature Compensated (TC) Fixed Point controller operates like the Fixed Point Controller except that the voltage reference changes with temperature. The nominal operating point as well as the relationship between the temperature and the optimal operating point must, be empirically determined and, any error in characterization has a direct impact on solar array operation. The model described below uses a voltage reference modulated by a temperature transducer.

Modeling Temperature Compensation

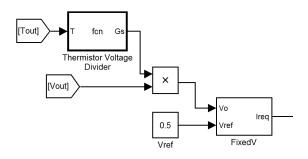Figure 12 shows the Simulink Implementation of the TC Fixed Voltage Solar Array Controller.

Figure 12: Implementation of TC Fixed Voltage Controller

This controller uses a temperature transducer to adjust a voltage divider that modifies the Solar Array Voltage

that is input into the Fixed Voltage Controller as described above. The temperature transducer and voltage divider values were chosen to match the temperature response of the solar cell based on the manufacturer's specs.[12] The temperature transducer modeled is a Vishay Resistive Temperature Detector.

Performance of TC Fixed Voltage Operation

Figure 13 shows the response of the TC Fixed Voltage controller. This controller tracked the ideal operating voltage with noise at high incidence angles corresponding to low irradiance. However, this controller does not follow the ideal as it does not compensate for changes in irradiance. As discussed earlier, this does not cause much inefficiency. The total integrated power of the TC, Fixed Voltage controller is 195.82 Ws over one orbit (compared with 197.32Ws for the ideal resulting in an efficiency of 99.2%).
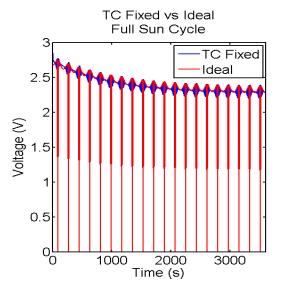

Figure 13: TC Fixed Voltage vs Ideal Operating Voltage

DIRECT ENERGY TRANSFER

In a Direct Energy Transfer (DET) solar array interface is connected directly to the battery (typically through a diode to prevent discharge through the solar cells when they are not illuminated). In this system, the battery voltage sets the operating point of the solar array which varies based on the state of charge on the battery. While this interface requires the least components, the simplicity comes at some cost. Because the solar array voltage is set by the battery voltage the solar array will not operate at its optimal point at all times (e.g., when the voltage changes based on state of charge of the batteries). Finally, a DET system directly couples the

solar array design with the battery design in terms of their respective chemistry and series string length in order to match the operating voltage.

Modeling Direct Energy Transfer

The DET interface consists of a direct connection of the solar arrays to the battery through a protection diode. The Simulink model is shown in Figure 14.
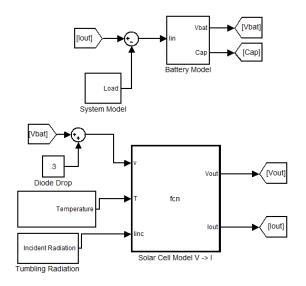

Figure 14: Implementation of DET

The above implementation differs slightly from the other design optons. First, it uses a voltage to determine the solar cell current as opposed to using current. This is necessary as the other options use a battery charge regulator that throttles incoming charge current making *I* the independent variable in the solar cell model. With DET, the battery sets the voltage and the solar arrays operate as a current source making *V* the independent variable in the solar cell model. The protection diode is modeled as a constant voltage added to the battery voltage which sets the solar array operating voltage as:

$$V_S = V_{Bat} + V_D \qquad (2)$$

Where V_S is the solar array operating voltage, V_{Bat} is the battery voltage, and V_D is the forward voltage drop of the diode. Finally, the power calculation uses the solar cell current and the battery voltage, as opposed to the solar array voltage, so as to not include the forward voltage of the diode which would overestimate the amount of power available to the satellite system.

As seen in (2), the operating point of the solar arrays depends on the battery voltage and the battery voltage varies as a function of the current into and out of the

battery. A battery and system load model was created and implemented to simulate this behavior.[11]

Performance of Direct Energy Transfer

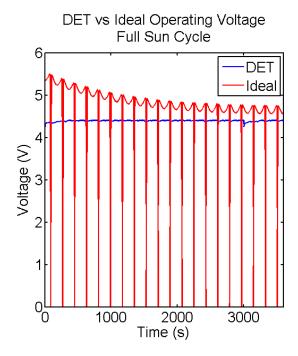Figure 15 shows the system response to the DET system.

Figure 15: DET vs Ideal Operating Voltage

One difference between this graph and the others is that this simulation modeled two solar cells in series, as opposed to one, so as to match the voltage of the battery. This was accomplished by dividing the sum of the battery voltage and diode voltage by two in the function of the solar cell model. To compensate for this, the power calculations made for this simulation have been halved so they can be compared to the other interfaces.

Also while it may seem that by increasing the diode forward voltage drop one could more closely match the ideal operating voltage. It must be noted, however, that the power across the diode is lost and the value of merit is the current flowing into the battery which is decreased at higher voltages. Therefore, a low drop diode, or an active ideal diode, is wanted. Finally, this simulation assumes the battery starts at an 85% Depth of Discharge. The equivalent total integrated power, calculated for a single cell, for the DET system is 170.6 Ws over one orbit (compared with 197.32Ws for the ideal resulting in an efficiency of 86.5%).

DISCUSSION

Comparison of Solar Array Interface Topologies

Table 1 gives the efficiencies for all the solar array interfaces studied with the Fractional Controller and the TC Fixed Voltage Controller performing the best. DET, the simplest interface, performed reasonably well, with the top performer only supplying 13% more power. There are, however other factors that affect the operation of solar array interfaces including the battery charge regulator efficiency, rotation rate, and radiation which will be discussed in the following.

Table 1: Overall Solar Cell to Battery Efficiencies

Solar Interface	No BCR	With Expected BCR Efficiency		
	Spin 1°/s, No Radiation	Spin 1°/s, No Radiation	Spin 20°/s, No Radiation	Spin 1°/s +Radiation
Fractional	99.1%	84.2%	67.9%	84.1%
P&O	98.6%	83.8%	52.6%	83.9%
dP/dV	98.9%	84.1%	46.7%	84.0%
Fixed	95.7%	81.3%	51.2%	57.2%
TC Fixed	99.2%	84.3%	29.1%	66.4%
DET (No BCR)	86.5%		86.5%	91.0%

Battery Charge Regulator Efficiency

All of the solar array interface controllers suited, except DET, must use a battery charge regulator to adjust the operating behavior of the solar array. The effect of battery charge regulators reduce that amount of power available to the satellite system. A survey of commercially available, switching battery charge regulators that are suitable for small spacecraft found optimal efficiency of 90% with a typical expected efficiency of 85%.[11] As shown in Table 1, the efficiency of the BCR dominates the overall efficiency of the system resulting in performance comparable to DET.

Effect of Rotation Rate

All of the simulations above assumed a one degree-per-second rotation rate with respect to the sun. This is consistent with a passively stabilized small satellite. However higher rotation rates are possible (e.g., used for stabilization). As all the solar array interfaces, except DET, use active control systems, an increase in spin rate leads to degraded controller performance. While this loss may be mitigated with an increase in system control gain, this may not be possible for all implementations. To compare designs for a higher spin rate, the simulations were run with a 20 RPM rate. The results can be seen in Table 1 (under the "w/Spin 20°/s" column).

Effect of Radiation

Radiation damage affects all aspects of the solar cell behavior, open circuit voltage, max power voltage, short circuit current, and max power current. True MPPT interfaces, dP/dV and P&O, continue to operate normally as they do not rely on accurate solar array parameters. Fractional Voltage solar array interfaces also operate fairly well after radiation damage as both the open circuit voltage and max power voltage are reduced equally. However, Fixed Point solar array interfaces can be detrimentally affected by solar array damage.

If the fixed operating point chosen corresponds to the optimal operating point before radiation damage occurs, eventually that point will be above the open circuit voltage of the solar arrays. The controller would then be attempting to force the solar array to operate above its open circuit voltage leading to a power output of zero. To compensate, the operating point must be set to non-optimal point to prevent radiation damage from catastrophically affecting power generation. This leads to a lower efficiency than what was calculated above. The DET System is also affected by radiation damage, though not as much as the other interfaces, as the battery voltage is inherently lower than optimal at beginning of life. Care must be taken, however, to choose a low drop diode to avoid higher operating voltages leading to less power after radiation damage. The effect on DET systems will not be catastrophic either, as the battery voltage varies from 3.0 to 4.2 volts; any affect from radiation damage will only cause the battery to not fully charge as opposed to causing zero power generation.[12]

The solar cell model was modified to simulate damage after 10^{14} MeV electrons/cm^2 total radiation fluence based on the manufacturer's specifications and all the simulations were run again. The results can be seen in Table 1 (in the "w/Radiation" column).

Single Cell Damage

Solar arrays can also be affected by single events, such as localized damage or shading due to offgassing, that can cause a single or multiple cells to perform poorly or to fail. All the MPPT Interfaces can compensate for this and the only effect will be the loss of power from the single cell.

However, with non-MPPT interfaces (Fixed, TC Fixed, and DET), this will cause the power from the entire

string of cells to be lost. There are two ways to compensate for this: adding margin between the operating point and the maximum power point i.e. adjusting the setpoint for Fixed and TC Fixed or using more cells per string that what is needed for DET; and/or using many small strings in parallel.

CONCLUSION

As seen in Table 1, a DET system, the least complex solar array interface, performs as well, and in some cases better, than the more complex Maximum Peak Power Tracking interfaces. When the efficiency of a Battery Charge Regulator, which is needed for MPPT, is taken into account, the best MPPT had a solar array matching efficiency of 84.3%. A DET System has a solar array matching efficiency of 86.5%. Given the increased complexity and relatively low gains, as well as how MPPT's are affected by rotation rate, DET Systems is preferred in small spacecraft.

There are, however, two instances where using MPPT's is necessary in small spacecraft. The first is where the solar array and battery chemistries and string length cannot be designed together and the two designs must be decoupled. The switching converter used in the MPPT allows those two systems to be independent of each other and thus able to be designed separately. In this case an MPPT should be used as opposed to a Fixed Point Controller. This is due to the Fixed Point controller's poor response to radiation and other cell damage events requiring margin to be included in the set operating point which, when combined with the efficiency loss due to the necessary switching converter, leads to a detrimental drop in performance as discussed above.

The other instance is where, due to the solar array and battery chemistries and the system architecture, many parallel, short strings of solar cells are not possible. In this case the possibility of single cell damage taking down an entire string would be very damaging and would most likely cause the mission to fail. An MPPT would be able to compensate for this damage and limit the harm to losing the power of only one cell as opposed to the entire string.

If an MPPT must be used the fractional voltage controller should be used given its high performance, relatively low effect of radiation and spin rate, and relative simplicity. The ratio for the fractional controller must be calculated and determined empirically for the specific mission.

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