EVALUATING THE EFFECTIVENESS OF PEAK POWER TRACKING TECHNOLOGIES FOR SOLAR ARRAYS ON SMALL SPACECRAFT

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EVALUATING THE EFFECTIVENESS OF PEAK POWER TRACKING TECHNOLOGIES FOR SOLAR ARRAYS ON SMALL SPACECRAFT

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering in the College of Engineering at the University of Kentucky

By

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2011

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The unique environment of CubeSat and small satellite missions allows certain accepted paradigms of the larger satellite world to be investigated in order to trade performance for simplicity, mass, and volume. Peak Power Tracking technologies for solar arrays are generally implemented in order to meet the End-of-Life power requirements for satellite missions given radiation degradation over time. The short lifetime of the generic satellite mission removes the need to compensate for this degradation. While Peak Power Tracking implementations can give increased power by taking advantage and compensating for the temperature cycles that solar cells experience, this comes at the expense of system complexity and, given smart system design, this increased performance is negligible and possibly detrimental. This thesis investigates different Peak Power Tracking implementations and compares them to two Fixed Point implementations as well as a Direct Energy Transfer system in terms of performance and system complexity using computer simulation. This work demonstrates that, though Peak Power Tracking systems work as designed, under most circumstances Direct Energy Transfer systems should be used in small satellite applications as it gives the same or better performance with less complexity.

KEYWORDS: Small Satellites, Power Systems, Solar Arrays, Peak Power Tracking, Direct Energy Transfer
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9/13/2011
ACKNOWLEDGEMENTS

I would like to acknowledge the support of Kentucky Space, the Kentucky Space Grant Consortium, the Kentucky Science and Technology Corporation, and the Space Systems Lab at the University of Kentucky. I would like to thank Dr. James Lumpp for his support and mentorship during my graduate studies. I would like to thank my parents for always nodding understandingly when I told them that I was almost done. Finally, I would like to thank Lindsey for getting her Master’s degree before me and making me call her master until I finished mine.
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1.0 Introduction

The ability to generate power is necessary for all but the simplest satellites. While missions with low average power consumption and lifetimes on the order of weeks can survive simply on primary batteries, any mission that must last longer or “work” harder must be able to constantly generate energy or replenish stored energy to be used later. There are many options for power generation that have been successfully used in spacecraft including fuel cells and nuclear-thermoelectric, however, by far the most widely used power generation technology for spacecraft is photovoltaics [1]. Furthermore, given the relative size, design constraints, and expense of the more exotic solutions, photovoltaics are practically the only option for the vast majority of missions.

There are several operating characteristics of photovoltaics that must be considered when designing a photovoltaic system, primarily the non-linear current-voltage relationship of the solar cell. The problem of interfacing with the non-linear relationship is exacerbated by the fact that the relationship is dependent on multiple parameters including total radiation fluence, incident angle with respect to the sun, and temperature. Despite these difficulties there are various techniques that optimize the interface to the photovoltaic system and allow for maximum power generation at the expense of circuit board area, complexity, and, in some instances, decreased overall system efficiency. However, this research shows that, for the majority of small satellite missions, although these techniques work as expected and optimize the interface to the photovoltaic system, they are not necessary and possibly detrimental to the success of
the mission. It also demonstrates that the simplest interface (in terms of component count, active components, and board area), a Direct Energy Transfer System, can perform better than the more complicated interfaces.

This work quantifies the specific parameters that make small satellite missions unique, an electrical model and characteristic equation for solar cells, the effect of the small satellite mission environment on solar cell performance, and the various interface techniques that are commonly used for photovoltaic systems. This research introduces models for the orbital environment generally seen by small satellites, solar cell behavior, and the designs which implement the interface techniques. Results include evaluation and discussion of the performance of the various interface techniques along with average integrated power over one sun cycle, and overall efficiencies relative to the ideal across the varying mission parameters. Conclusions include a recommended photovoltaic interface under certain conditions, design parameters for choosing the various interface designs, and recommendations for further work.

2.0 Background

2.1 Small Satellite Definition

A small satellite is defined as any satellite with a mass of less than 500 kilograms. While mass may be the defining characteristic, there are features which most small satellite missions share which set them apart from the generic commercial satellite typified by large geostationary communications satellite. The low mass of small satellites leads to reduced satellite launch cost which allows for increased risk tolerance which allows for
less redundancy in satellite subsystems. Furthermore, small satellites generally have a one to two year primary mission timeline and are injected into low earth orbit both of which lowers the risk of system failure due to shorter exposure to the space environment; radiation, micrometeorites, etc and due to lower overall radiation environment of low earth orbit as opposed to higher orbits.

Increased risk tolerance allows modern technologies to be used in small satellites which lead to further reduced mass and volume. This trend of miniaturization has allowed fully capable satellites to be developed which have a mass of less than one kilogram. An example of one class of these very small satellites is the CubeSat, Figure 1. The CubeSat standard was developed as a means to provide launch opportunities for student built satellites [2]. CubeSats are 10x10x10 cm$^3$ cubes with a mass of up to 1kg. Recently, CubeSat development has begun to flow out of universities and into government agencies, the military, and industry [3],[4]. Cubesats are used as the primary example throughout this work; however, due to the similarities between all small satellites

![Figure 1: KySat-1, a 1U (10x10x10 cm$^3$) CubeSat](image-url)
missions, the conclusions drawn are directly applicable to many small satellites programs.

2.2 Solar Cell Behavior

Solar cells work by converting electromagnetic radiation, in the form of optical wavelength photons, into electrical energy. They do this by using what is known as the photovoltaic effect, in which a photon transfers its energy to a valence electron which is then able to roam around the lattice of a semiconductor, along with the hole it left behind. The movement of electrons and holes generates an electric current in the semiconductor [5].

While it is important to understand the underlying physics of solar cell operation, that level of detail is not necessary to analyze a cell’s performance under varying conditions. An equivalent circuit model is a convenient and widely used method for evaluating the performance of a solar cell. An ideal solar cell can be modeled as a current source in parallel with a forward-biased diode as shown in Figure 2.

![Figure 2: Equivalent Circuit of an Ideal Solar Cell](image)

The behavior is then governed by the well-known Shockley diode equation given as
\[ I_D = I_o (e^{V_D/(nV_T)} - 1) \]  \hspace{1cm} (1)

Where \( I_D \) is the current through the diode, \( I_o \) is the reverse saturation current, \( V_D \) is the voltage across the diode, \( n \) is the quality factor and \( V_T \) is the thermal voltage, which equals \( k*T/q \) where \( q \) is the fundamental charge of an electron in coulombs, \( k \) is the Boltzmann constant in Joules per Kelvin, and \( T \) is the temperature in Kelvin. Circuit analysis gives the behavior of the solar cell as

\[ I = I_{ph} - I_D \]  \hspace{1cm} (2)

Where \( I \) is the current out of the solar cell and \( I_{ph} \) is the photogenerated current using the process described above. Combining (1) and (2) gives the characteristic equation of an ideal solar cell

\[ I = I_{ph} - I_o (e^{V/(nV_T)} - 1) \]  \hspace{1cm} (3)

Where \( V \) is the voltage across the terminals of the solar cell equals \( V_D \) the voltage across the diode. The Voltage-Current relationship of an ideal solar cell is shown in Figure 3.

![Figure 3: Voltage Current Relationship of an Ideal Solar Cell](image)
Unfortunately real solar cells are not ideal and thus some parasitic elements must be incorporated into the model. These parasitic elements are modeled as two resistors; one in series and one in parallel. The equivalent circuit of a solar cell once these parasitic elements are incorporated in is given in Figure 4.

![Figure 4: Equivalent Circuit of a Real Solar Cell](image)

Incorporating these changes into the characteristic equations gives

\[ I = I_{ph} - I_o \left( e^{(V+IR_S)/(nVT)} - 1 \right) - \frac{V + IR_S}{R_{SH}} \]  \hspace{1cm} (4)

Where \( R_S \) is the parasitic series resistance and \( R_{SH} \) is the parasitic shunt resistance. As can be seen this equation now involves \( I \) on both sides making it a transcendental function with no general solution. Numerical methods must therefore be used to solve the characteristic equation of a real solar cell. Newton’s Method is used to solve the equation and is described in a succeeding section. The Voltage-Current relationship of a real solar cell is shown in Figure 5.
Figure 5: Voltage Current Relationship of a Real Solar Cell

As can be seen from comparing Figure 4 and Figure 5, these parasitic resistances increase the slope in both constant current and constant voltage zones of operation leading to decreased power.

It has been shown that a more accurate model for a solar cell is achieved by using a second diode in parallel with the current source with its own unique parameters [6]. However, the influence of the second diode is only significant in situations with low voltages or low irradiances [7] and, thus, such complexity is not necessary when modeling solar arrays for power generation purposes [8].

The parameters of the characteristic equation, $I_0$, $n$, $R_S$, and $R_{SH}$, cannot be directly measured and they vary for different chemistries of solar cells and manufacturers. As this work is focused on comparing solar array interfaces as opposed to modeling an
actual system, the parameters used in the solar cell model constructed were based on manufacturers specifications and not empirically determined; there are, however, various methods for extraction using empirical methods [9], [10].

As can be seen from the unique shape of the Voltage-Current curve, efficient operation of a solar cell as a power generation device is a non-trivial problem. Figure 6 and Figure 7 shows that optimal power extraction only occurs at a unique operating point, \( V_{MP} \) or \( I_{MP} \), and thus the operating voltage or current can be controlled in order to ensure operation at this optimal point.

![Figure 6: Power vs Voltage](image-url)
However, it is not as simple as just setting the operating point of one of the parameters shown above to its optimal value. Various environmental factors affect the performance of solar cells and these effects must be accounted for if optimal power extraction is to be achieved. The environmental factors and their affect on solar cells are described in the following section.

2.3 LEO Environment and Solar Cell Effects

The environment seen by small satellites in low earth orbit affects the performance of solar cells in various ways. Most notably, solar cells are affected by variations in incidence angle with respect to the sun, temperature variations over the sun cycle of an orbit, and radiation damage over the lifetime of the mission. This section discusses the various aspects of the LEO environment that can affect solar cells; incidence angle, temperature, and radiation, and evaluates how those aspects affect the performance of solar cells.
2.3.1 Incidence Angle

The incidence angle, defined as the angle between the a light source and solar cell normal, affects the performance of solar cells by effectively lowering the total irradiance, equivalent power density of the light source in W/m², projected onto the solar cell. The relationship between incidence angle and output current follows the cosine law given by

$$E_s = E_o \cos(\theta)$$  \hspace{1cm} (5)

Where $E_s$ is the irradiance projected onto the solar cell, $\theta$ is the incidence angle between the solar cell and the light source, and $E_o$ is the solar constant. The solar constant is the power density produced by the sun measured once it reaches earth; it has been measured to vary from 1331 to 1423 W/m²[1]. Lowering the irradiance projected onto the solar cell has the effect of lowering the output current of the solar cell. The effect of this reduced irradiance can be seen in Figure 8.
The relationship between output current and angle of incidence also follows the cosine law approximately, due to the output current being related to the level of irradiance, although it does diverge as the angle of incidence increases beyond 30 degrees. The Kelly Cosine is used to accurately model the solar cell over all incidence angles, example values of the Kelly Cosine are given in Table 1[1].

### Table 1: Kelly Cosine Values over Various Incidence Angles

<table>
<thead>
<tr>
<th>Angle (Degrees)</th>
<th>Mathematical Cosine</th>
<th>Kelly Cosine</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.866</td>
<td>0.866</td>
</tr>
<tr>
<td>50</td>
<td>0.643</td>
<td>0.635</td>
</tr>
<tr>
<td>60</td>
<td>0.5</td>
<td>0.45</td>
</tr>
<tr>
<td>80</td>
<td>0.174</td>
<td>0.1</td>
</tr>
<tr>
<td>85</td>
<td>0.087</td>
<td>0</td>
</tr>
</tbody>
</table>
It can be seen in Figure 8 that over the various illuminations the amount of current available from the solar cell decreases dramatically but the open circuit voltage, $V_{OC}$, of the solar cell is only slightly affected. Figure 9 shows the optimal operating point, as well as the maximum power available, as the irradiance varies.

![Graph of Vmp and Pmp vs Incident Radiation](image)

**Figure 9: Optimal Operating Point and Maximum Power vs Irradiance**

As can be seen in Figure 9 the optimal voltage operating point varies little with respect to the incidence angle, -8.8 μV/W/m$^2$, at irradiances over 200 W/m$^2$; which accounts for 98% of the total integrated available power. The effect of the Kelly Cosine can also be seen by the slight non-linearity of the available power at low irradiances, which corresponds to large incidence angles. The angle of incidence changes in low earth orbits when the satellite cannot actively control the solar arrays to point at the sun, which most small satellites cannot, or when the satellite is not sun-pointing, which only few missions allow, which causes the sun angle with respect to the solar arrays to vary over the orbit.
2.3.2 Temperature

With no atmosphere to hold onto heat there are large temperature swings over relatively short periods in low earth orbit. Standard expected temperature in Low Earth orbit vary from -30 to 50 C over one orbit, a period of approximately 100 minutes [11]. The effect of temperature on solar cells can be directly seen in the characteristic equation of a solar cell, \((4)\), in the thermal voltage. But the more dramatic effect comes from changes in the reverse saturation current. However the exact mechanism that causes temperature to change the behavior of solar cells in not important for this study as this study only needs to model one solar cell to evaluate multiple solar array interfaces. Therefore, the effect of temperature has been modeled to correspond to the solar cell manufacturers specification of a change in the optimal voltage operating point of -6.2 mV/C [12]. The effect of varying temperature on solar cell performance can be seen Figure 10

![I-V Curve over Varying Temperatures](image)

Figure 10: I-V Curve over Varying Temperatures
As can be seen the most dramatic effect temperature has on solar cell performance is on $V_{OC}$ and in turn the optimal operating point of the solar array. Though there is a slight temperature dependence on the output current of the solar cell; this is also modeled empirically to match the manufacturer specification. Figure 11 illustrates how the optimal operating point varies with temperature and shows the -6.2 mV/°C slope specified by the manufacturer for Max Power Voltage. It also shows the slight non-linearity of the available power due to temperatures effect on both voltage and current output.

![Figure 11: Optimal Operating Point and Available Power vs Temperature](image)

2.3.3 Radiation

While the temperature in low earth orbit is constantly changing as the satellite enters and exits eclipse, radiation exposure is a constant and compounding; and, without earth’s protective atmosphere, satellites in orbit are subject to a much greater amount of radiation than they would be on earth. This radiation has an effect on many satellite components including solar cells. Solar cells are affected by a decrease in short circuit
current, defined as the amount current generated at zero volts, due to changes in the diffusion length as well as a decrease in $V_{OC}$ due to increases of the reverse saturation current and quality factor [13].

![Trapped Particle Environment in 650 km 67 deg-inclined Orbit](image)

**Figure 12: Radiation Environment at 650km Altitude and 97 Degree Inclination**

The radiation environment for a typical small satellite mission is shown in Figure 12. Figure 12 was created using SPENVIS [14]. SPENVIS is an assortment of tools used to model spacecraft environmental parameters including radiation, spacecraft charging, magnetic interaction, meteoroids and debris, and others based on a specified orbit. Radiation levels are generally given as total fluence at 1-MeV equivalence corresponding to the sum of the areas underneath the curves shown in Figure 12. Furthermore, SPENVIS uses a tool which weights different energies differently depending on the specific solar cells used and the amount of coverglass used; known as Solar Cell Damage Equivalence. More information about Solar Cell Damage Equivalence and 1-MeV equivalence can be found at [13], [14].
For most small satellite missions radiation damage to solar cells can be ignored. For the relatively low altitudes and short mission lifetimes, the damage done to the solar cells is not significant. Figure 13 shows solar cell behavior after radiation damage. As can be seen the radiation, as it accumulates, affects both the open circuit voltage and the short circuit current. The open circuit voltage is affected more in the beginning and tapers off at the end while the short circuit current is affected more at the end.

According to the manufacturers specifications the solar cells modeled do not begin to have any noticeable degradation until the fluence reaches $1 \times 10^{14}$ MeV/cm$^2$. With one mil of coverglass the total equivalent fluence is $\sim 9 \times 10^9$ MeV/cm$^2$ per day; at which rate it would take 30 years to reach $1 \times 10^{14}$ MeV/cm$^2$ total fluence. However, if no coverglass is used the total equivalent fluence per day is $\sim 8 \times 10^{11}$ MeV/cm$^2$ which after two years gives
a total fluence of $5.8 \times 10^{14}$ MeV/cm$^2$, which would lead to a significant change in solar cell performance. Also, if the orbit varies greatly from that described above, the radiation environment could be vastly different. Therefore, a discussion is included in the results section on how each solar array interface responds to a radiation damaged solar cell.

2.4 Solar Array Interface

As discussed above there are many factors in low earth orbit which affect the performance of a solar cell. Temperature and incidence angle are constantly changing throughout an orbit while radiation causes a constant slow decline. Therefore, in order to optimally generate power from solar cells they must be operated carefully. To reach that end, various control schemes have been designed, called Maximum Power Point Trackers (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 situated between the solar arrays and load. The switching converter acts as a load transformer causing the solar array to always “see” an ideal load no matter the state of the actual load. A battery, or other energy storage device, is then placed in parallel to account for load transients. An MPPT also adjusts the ideal load to account for changes in solar cell performance due to environmental factors such as those described above and shown in Figure 8, Figure 10, and Figure 13. Furthermore, the use of a switching converter between the solar arrays and the rest of the system decouples the two designs allowing the solar arrays and the battery/load to be designed with little regard to each other.
3.0 Modeling

Solar arrays operate differently depending on the environment that they are in and, as shown above, that environment is constantly changing in low earth orbit. Furthermore, there are ways to interface to the solar arrays which adjust the operating point of the solar arrays to extract optimum power. The solar array interfaces used in this study (described below) were implemented in hardware for baseline testing and validation, Figure 14, however as low earth orbit is a unique environment and hard to replicate on earth and as it may be prohibitively to test multiple solar array interfaces on orbit, an orbital simulation engine incorporating incidence angle and temperature, a solar array model, a battery and system load model, and solar array interface models is used to compare the effectiveness of solar array interfaces. The simulation also allows for precise control of parameters giving the opportunity to conduct precise, repeatable testing.

Figure 14: Hardware Implementation of Solar Array Interfaces
3.1 Simulink® Based Model

The solar array interfaces described above, as well as other orbital parameters, were implemented in Simulink® in order to model their behavior in an orbital environment and compare their behavior against each other. Simulink® is MATLAB-based tool for graphical modeling and simulation of time-varying dynamic systems. It is used here as a convenient tool for developing differential models and implementing controller designs while combining all of these different elements quickly which eases development and debugging. As Simulink® is, in essence, a differential equation solver it gives the option of using different solvers which can trade accuracy for speed, etc. As used here, all the designs were tested over multiple solvers to ensure stability and accuracy while the same solver, ode45 Dormand-Prince Method, is used for comparisons. More information can be found in the Simulink® documentation [15].

3.2 Orbital Parameters

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 [16]. This orbital period is similar for all low earth orbiting satellites; for this simulation it primarily affects the temperature range experienced by the satellite. It is also used to model the radiation environment. The effects of radiation are discussed in the conclusion. The rotation rate is standard for passively stabilized CubeSats, though the effect of faster rotation rates is discussed in the conclusion.
3.2.1 Rotation Rates

Cubesats generally utilized body mounted solar cells to generate power. This means that the incidence angle between the solar cells and the sun is dependent on the attitude of the entire spacecraft. As most CubeSats use only passive attitude control, as opposed to spin stabilized or three-axis control, a slight rotation is modeled for the solar cells. This rotation rate was determined to be one degree per second for an uncontrolled 1U CubeSat [17]. Figure 15 shows the Simulink® Implementation.

The rotation is modeled using the absolute value of a sine wave that is changing at one degree per second. This corresponds to a double sided solar array spinning on an axis perpendicular to the sun normal. While this is fairly unrealistic, it is sufficient to compare the effectiveness of solar array controllers. The sine wave is then multiplied by the solar constant and finally modulated by a square wave to simulate eclipse.

It is important to note that as these solar array interfaces are dynamic controllers and thus have a response time associated with them. This effect is not apparent at the...
moderate rotation rate used here but must be taken into account for faster rotations. Further discussion of this effect can be found in the Conclusions section of this thesis.

3.2.2 Temperature

As stated above, a CubeSat in low earth orbit has been shown to vary from -30 to +50 degrees C but, due to the unique environment of low earth orbit, this variance is not linear and therefore must be modeled. Several assumptions are used in the development of the temperature model including: infinite conductivity, zero Kelvin sink temperature, and constant absorptivity, emissivity, and specific heat capacity. The temperature model is created by first calculating the net thermal power of the system given as:

$$P_{\text{net}} = APD - APG + q_s \times \alpha \times A \times VF - \varepsilon \times A \times \sigma \times T^4$$ (6)

Where $P_{\text{net}}$ is the net power in watts, $APD$ is the average power dissipated, $APG$ is the average power generated, $q_s$ is the incident radiation in W/m$^2$, $\alpha$ is the absorptivity, $A$ is the total area in m$^2$, $VF$ is the view factor, $\varepsilon$ is the emissivity, $\sigma$ is the Stefan–Boltzmann constant, and $T$ is the temperature in Kelvin. Of course this equation is different depending on whether or not the satellite is in eclipse. While in the sun $q_s$ is the sum of the Earth’s infrared radiation, solar radiation, and solar radiation reflected off the Earth known an albedo. While in eclipse $q_s$ is equal to only Earth’s infrared radiation and $APG$ is equal to zero.

The net power is then integrated with respect to time to determine the total thermal energy of the system in joules.
\[ E = \int_{t_o}^{t} P_{net} dt \]  

(7)

Where \( E \) is the total thermal energy of the system and \( t-t_o \) is the fundamental time step of the system. The total energy is then used to determine the system temperature using the specific heat capacity as follows:

\[ T = \frac{E}{mc} \]  

(8)

Where \( m \) is the mass of the system and \( c \) is the weighted average specific heat of the system given as:

\[ c = \frac{\text{SpecificHeat}(1) \times \text{Mass}(1) + \ldots + \text{SpecificHeat}(n) \times \text{Mass}(n)}{\text{TotalMass}} \]  

(9)

The temperature calculated in (8) is then fed back into (6) for the next net thermal power calculation.

The implementation designed for this model, Figure 16, uses a function to determine the net thermal power and to factor in the mass and weighted specific heat. This value is then integrated to give the overall temperature in Kelvin. This reversal of (7) and (8) is valid as the mass and specific heat are considered constant and thus can move into the integral in (7) without any problems. Finally, the temperature is converted into degrees Celsius. The square wave, labeled orbit, is used to determine when the satellite is in eclipse. The integrator is set to an initial value representing the temperature of the satellite just as it leaves eclipse. This was determined by choosing a reasonable guess...
and then running the model over multiple orbits until it settled into equilibrium. The model gives a range of -32.25 to 42.42 degrees Celsius with a profile shown in Figure 17. This agrees reasonably well with what was found in previous CubeSat missions as described above.

Figure 16: Implementation of Temperature Model

![Temperature Model Diagram](image)

Figure 17: Modeled Temperature Profile

![Temperature Profile Graph](image)
3.3 Solar Cell Model

The behavior of a solar cell is modeled using (4) and either a voltage or current set by the solar array interface and then solving for the corresponding current or voltage respectively. Though as (4) is a transcendental equation, involving the solar cell current I on both sides of the equation, a numerical method is used to solve the equation. As time to convergence is not much of a factor for these simulations Newton’s Method is used.

Newton’s method is a method for finding successively better approximations of the roots of a function; given a function f(x), it’s derivative f’(x), and initial guess x₀, where n=0, Newton’s Method gives the next guess, xₙ₊₁, as:

\[ x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \]  

In order to use Newton’s Method to solve (4), it must be transformed into a different function so that the solution to (4) is the root of the new function. This is done simply by subtracting I from both sides giving:

\[ f(x) = 0 = I_{ph} - I_o \left( e^{(V+IR_s)/(nV_T)} - 1 \right) - \frac{V + IR_s}{R_{SH}} - I \]  

This function can now be used with Newton’s Method to solve for V or I given I or V, respectively, once the respective derivative, f’(V) or f’(I), is found. This function converges fairly quickly, approximately five iterations, but, as run time is not critical, ten iterations are used for safety.
Real solar cells, as part of a full mission simulation, would have to be modeled using the operating parameters, $R_S$, $R_{SH}$, $I_O$, and $n$, would have to be empirically determined; however, as this research is concerned with comparing solar array interfaces as opposed to modeling a real system the parameters $R_S$, $R_{SH}$, $I_O$, and $n$ were not determined empirically using a physical solar cell. They were, however, determined to closely match a manufacturer’s specification of Improved Triple Junction Solar Cells.

A MATLAB function, seen in Figure 18 as the Solar Cell Model block, is the solar cell model in the simulation which takes the requested voltage or current, temperature, and incident radiation as inputs and outputs the solar array current and voltage.

### 3.4 Battery Charge Regulator Model

A battery charge regulator is, as its name implies, a power regulator, either switching or linear, which conditions incoming power to charge a battery with a certain profile specified by the battery chemistry. The battery charge regulator modeled is a current mode switcher which allows for input current programming. This means that the regulator operation is determined by the input current which can be adjusted by an external circuit. This is modeled, as seen in several figures below, as a single gain labeled as $V_{fb} \rightarrow I_{req}$, which translates the solar array interface control signal into the input current of the battery charge regulator and thus the output current of the solar cell.
3.5 Solar Array Interface Models

Figure 18: Generic Interface Model

Figure 18 shows the generic setup used in the simulations. The solar array controller outputs the requested current which is, along with the temperature and incident radiation, inputted to the solar cell model which then outputs the solar cell voltage and current. The outputted voltage and current is then fed back into the solar array controller which uses those parameters to determine the next requested current. The temperature and incident radiation changes with respect to the simulation time and also fed into the solar cell model. Finally voltage and current profiles over time along with the total integrated power is saved to the workspace.
3.5.1 MPPT

While there are many MPPT controllers there are only a few major designs with the rest being derivatives off of those; this study only looks at the major designs but more can be found in [18]. The MPPT controllers described, modeled and compared for this work are known as: Fractional Voltage, Perturb and Observe, and dP/dV. For comparison, a Fixed-Point and Temperature-Compensated Fixed-Point controller are developed and modeled. Finally these are all compared to the simplest solar array interface, connecting the solar arrays directly, with diode protection, to a battery known as Direct Energy Transfer.

3.5.1.1 Fractional Voltage

The theory of operation for the fractional voltage MPPT controller relies on the fact that there is a near linear relationship between the \( V_{OC} \) and the maximum power voltage, \( V_{MP} \), of a solar array [19], [20]. 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 using a pilot cell, an independent cell which is of the same type as that of the array and subject to the same environmental parameters which is left open and used as the reference. While this ratio does vary slightly over different environmental parameters, the change is very slight; Figure 19 and Figure 20 show the relationship between the ratio and the environmental parameters.
Over temperature, the slope of the ratio is $3.9 \times 10^{-4}$ parts per °C accounting for a total change of 0.03 and over irradiances, from 200 W/m$^2$ and above, the slope of the ratio -
3.9e-5 parts per W/m$^2$ accounting for a total change of 0.04. While these numbers are applicable only for the particular solar cell modeled, the general idea remains the same. Herein, though, lies one of the weaknesses of the fractional voltage method; the optimal ratio is solar cell dependent. Therefore, each array must be independently characterized to set the optimal ratio which ensures optimal performance. Also, as this is not a “true” MPPT controller, mistakes in characterization have a direct impact on power generation.

Figure 21 shows the Simulink Implementation of the Fractional Voltage Solar Array controller.

![Fractional Voltage Controller Diagram](image)

Figure 21: Implementation of Fractional Voltage Controller

The heart of this controller is a timer which outputs a 10 millisecond pulse once a 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 the 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 error integrator forces the difference between the operating voltage and the determined operating voltage to zero by adjusting the control value which is input to the Battery Charge Regulator model as described above.

3.5.1.2 Perturb and Observe

A Perturb and Observe (P&O) controller works by coupling a perturbating signal onto the solar cell voltage which induces a change in the 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 $V_{MP}[21]$. 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 the control voltage as opposed to directly on the solar cell voltage which, in practice, accomplishes the same thing and so, for this research, these techniques are considered to be the same. A P&O controller is a “true” MPPT controller and, thus, can be used as generic controller without regard to solar cell type and mistakes in characterization.

Figure 22 shows the Simulink Implementation of the Perturb and Observe Solar Array Controller.
The implementation used here is based on a design published in the *Electronic Design Newsletter* [22]. The power out of the solar array is calculated and the value is then put through a passive differentiator modeled as a derivative through a fixed gain. The derivative is then passed through a synchronous demodulator. The synchronous demodulator is controlled by a +/- 0.5 amplitude square wave; it is this synchronous demodulator which 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 slight rise in the control voltage out of the integrator. If this slight 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 slight 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. Basic operation of this principle can be seen in Figure 23. The blue curve represents the integrator output of only the square wave.

**Figure 22: Implementation of Perturb and Observe Controller**
The red curve represents the integrator output behavior with a positive derivative and the green with a negative derivative. Therefore, if the initial rise in the control signal leads to an increase in power, the control signal, the integrator output, tends to rise. Likewise if the initial rise in the control signal leads to a decrease in power the control signal tends to fall. This causes the control signal to oscillate around the optimal operating point.

![Figure 23: Perturb and Observe Basic Operation](image)

3.5.1.3 \( dP/dV \)

The theory behind a \( dP/dV \) is one of the simplest to understand. Power is locally maximized at whatever operating voltage causes \( dP/dV \) to equal zero. And, as can be seen in Figure 6 there is only maximum, thus ensuring maximum power when \( dP/dV \) equals zero. While the implementation of this system is a somewhat less
straightforward, the design used for this work is described below, though there are others [23], [24]. A dP/dV controller is also a “true” MPPT controller and, thus, can be used as generic controller without regard to solar cell type and mistakes in characterization.

![Figure 24: Implementation of dP/dV Controller](image)

This controller was implemented using a function and some memory blocks to model how this would be implemented on a microcontroller. The output of the controller block is a fixed value but the sign is swapped based on the comparison of two power values. The current power is computed and compared to the previous power after a fixed amount of time, simulating the Analog to Digital Conversion time of a microcontroller. If the current power is greater than the previous power the sign of the output remains the same. If the current power is less than the previous power the sign of the output is swapped. The output is fed into an integrator which gives the final control signal to the Battery Charge Regulator model. The operation of the dP/dV
controller is similar to the operation of the Perturb and Observe controller in that it causes the control signal to oscillate around the optimal point.

3.5.2 Non-MPPT

The following solar array interfaces are not MPPT, or pseudo-MPPT, controllers, however, they do allow an optimal operating point to be set. They also decouple the solar array and battery/load designs.

3.5.2.1 Fixed Voltage

As the name implies, 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 mistake in characterization has a direct impact on solar array operation. Figure 25 shows the Simulink Implementation of the Fixed Voltage Solar Array Controller.

![Figure 25: Implementation of Fixed Voltage Controller](image)

This controller consists of an empirically determined reference setpoint and an error integrator to force the solar array voltage to equal the setpoint. The unity gains were empirically determined to give consistent results over multiple solvers.
3.5.2.2 Temperature Compensated Fixed Voltage

A Temperature Compensated Fixed Point controller operates just like the Fixed Point Controller except that the voltage reference is set in such a way that it changes with temperature. As can be seen by comparing Figure 9 and Figure 11, temperature has the greater impact on the solar array operating point and so, by compensating for temperature, the optimal operating point can be estimated. The nominal operating point as well as the relationship between the temperature and the optimal operating point must, again, be empirically determined and, again, any mistake in characterization has a direct impact on solar array operation. The model described below uses a static voltage reference modulated through a voltage divider which utilizes a Resistive Temperature Detector (RTD) as the temperature transducer. There have been other studies which yielded promising results using a p-n junction diode, under the same temperature conditions as the solar cells, as both the reference voltage and temperature transducer [25]. Figure 26 shows the Simulink Implementation of the Temperature Compensated Fixed Voltage Solar Array Controller.
Figure 26: Implementation of Temperature Compensated Fixed Voltage Controller

This controller uses a temperature transducer to adjust a voltage divider ratio which modifies the Solar Array Voltage that is input into the Fixed Voltage Controller as described above. The reference voltage is also different but this was only done for realism as 0.5 volt references are common. The same reference could be used in the Fixed Voltage Controller by applying a fixed voltage divider ratio to the solar array output voltage. The temperature transducer and voltage divider values were chosen to match the temperature response of the solar cell as seen in Figure 10. The temperature transducer modeled is a Vishay Resistive Temperature Detector.

3.5.3 Direct Energy Transfer

The simplest solar array interface is connecting the solar array directly to the battery, though usually 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 is the simplest interface, there are some drawbacks. As the solar array voltage is set by the
battery voltage the solar array will not operate at its optimal point at all times. Also, as the battery voltage changes based on state of charge, the operating point varies with it. However, the relatively linear discharge curve, Figure 27, of modern lithium batteries alleviates this problem slightly. Finally, a Direct Energy Transfer system directly couples the solar array design with the battery design in terms of chemistry and series string length for both systems.

![Lithium Battery Discharge Curve](image)

Figure 27: Lithium Battery Discharge Curve

The Simulink Implementation used can be seen in Figure 28.
The above implementation differs slightly from the other Solar Array Interfaces. First, it uses a given voltage to determine the solar cell current as opposed to the others which uses a given current to determine the voltage. This is necessary as that the other interfaces use a battery charge regulator that throttles incoming charge current making $I$ the independent variable in the solar cell model whereas, with Direct Energy Transfer, the battery sets the voltage and the solar arrays operate simply as a current source making $V$ the independent variable in the solar cell model. The same equations and
methods were used, the only difference is using Newtons Method to solve for $I$ as opposed to $V$. This was tested and verified to give very similar results. The added protection diode is modeled as a constant voltage added to the battery voltage which sets the solar array operating voltage as:

$$V_S = V_{Bat} + V_D$$  \hspace{1cm} (12)

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 is made using 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 (12), the operating point of the solar arrays depend on the battery voltage and, as seen in Figure 27, the battery voltage, while relatively linear, is dependent on the state-of-charge of the battery. The battery behavior must therefore be modeled to accurately reflect the behavior of the solar arrays during a real mission.

3.5.3.1 Battery Model

The battery model used is based on [26] which develops a model capable of simulating the dynamic behavior of lithium batteries at runtime. The equivalent circuit used to model a lithium battery, developed in [26], can be seen in Figure 29. Runtime behavior is modeled using parameters based on the current state-of-charge of the battery, determined by the integrated current into and out of the battery. The parameters used are the open-circuit voltage, the series resistance, and two RC networks, one
corresponding to a short term transient response and the other to a longer term transient response.

![Battery Circuit Model](image)

Figure 29: Battery Circuit Model

The relationship between the SOC and the parameters has to be empirically determined for any battery. For a full mission simulation, the actual battery being used would have to be evaluated and the relationships discussed above empirically determined, however any generic lithium battery model is sufficient for evaluating solar array interfaces therefore the relationships developed in [26] is used. Methods for extracting these parameters for a given battery are available [27].

For implementation in Simulink, the circuit model in Figure 29 was transformed into an ordinary differential equation use state variable methods, with the battery current as the input and the battery voltage as the output. Figure 30 shows the Simulink implementation of the battery model with a function used to calculate the relevant parameters given the state of charge.
3.5.3.1 System Load Model

As can be seen from the circuit model of the battery, the actual battery voltage is dependent on the current system load. As the solar array voltage is set by the battery voltage, the system load current must be modeled in order to accurately model the transient nature of the battery voltage. Figure 31 shows the battery voltage given different load currents over time with the blue line and left axis showing the battery voltage and the green line and right axis showing the load current.
Figure 31: Transient Battery Response Based on Load

Figure 32 shows the Simulink implementation of a system load model. It consists of a constant current which is summed together with different load currents that are duty-cycled based on parameters set by a script. The loads used were determined to reflect an actual satellite behavior while maintain a positive power budget.
The solar array interfaces described above were simulated over the sun portion of one orbit corresponding to 62 minutes of simulation time incorporating environmental parameters described above; one degree per second rotation and the modeled temperature profile. For the Direct Energy Transfer interface the battery and system load model were also incorporated. The results for each interface compare the simulated operating voltage and the ideal operating voltage. The total integrated power
for each interface is also given along with the matching efficiency; calculated as the total integrated power divided by the ideal total integrated power.

4.1 Ideal

Figure 33 shows the ideal operating behavior of the modeled solar cell over the sun portion of one orbit. The blue line represents the solar cell voltage corresponding to the maximum power generation and the green line represents the maximum power available. The total integrated power available given the modeled solar cell and the modeled environmental parameters is 197.32 Ws.

![Figure 33: Ideal Operating Voltage](image)

4.2 Fractional Voltage

Figure 34 shows the response of the fractional voltage controller and the modeled system. The blue line represents the voltage of the solar arrays as modulated by the fractional voltage controller and the green line shows the ideal operating voltage as shown in Figure 33. As can be seen, the blue curve has two distinct sections; the upper portion corresponding to the system determining 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 very noisy sections correspond to very large inclination angles. This is due to the ideal ratio being very different from the set ratio, as shown in Figure 20, which causes the performance of the controller to degrade. The performance of the controller degrades because it is an Integrator Controller which has a poor dynamic response. This is not a problem, though, as discussed above, there is not much power to be extracted at those large incidence angles. The total integrated power for the fractional voltage controller system is 195.66 Ws giving an efficiency of 99.1%. The noise could possibly be improved by incorporating a Proportional term into the control signal, however any gains would be minimal due to the high efficiency of the present system.

Figure 34: Fractional Voltage vs Ideal Operating Voltage
4.3 Perturb and Observe

Figure 35 shows the response of the Perturb and Observe controller and the modeled system. As above, the blue line represents the actual solar array voltage and the green shows the ideal. Also, as above, the blue line has two distinct portions. This is due to the oscillating nature of the Perturb and Observe controller as discussed above. Besides the oscillations, the Perturb and Observe controller, as seen, does a very good job of tracking the ideal operating voltage. The total integrated power of the Perturb and Observe controller is 194.64 Ws giving an efficiency of 98.6%. Finally, the odd shapes towards the end of the graph are simply sampling artifacts.

Figure 35: Perturb and Observe vs Ideal Operating Voltage
4.4 dP/dV

Figure 36 show the simulation results using the dP/dV controller. As seen, the controller works very well, though it does suffer from the same noise as the Fractional Controller around the extremes of irradiance value; the cause of this noise is the same as before and while the response may be improved any gains would be minor. The total integrated power for the dP/dV controller is 195.10 Ws giving an efficiency of 98.9%.

![Figure 36: dP/dV vs Ideal Operating Voltage](image)

4.5 Fixed Voltage

Figure 37 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 caused, as before, by using an Integrator Controller. The total integrated power for the Fixed Voltage Controller is 188.80 Ws giving an efficiency of 95.7%.

![Fixed Voltage vs Ideal Operating Voltage](image)

**Figure 37:** Fixed Voltage vs Ideal Operating Voltage

### 4.6 Temperature Compensated Fixed Voltage

Figure 38 shows the simulated response of the Temperature Compensated, Fixed Voltage controller. This controller tracked the ideal operating voltage very well with only similar noise at high incidence angles corresponding to low irradiance. Looking closely, however, it can be seen that this controller does not follow the ideal exactly as it is incapable of compensating for changes in irradiance; however, as discussed above, this is slight and does not cause much inefficiency. The total integrated power of the Temperature Compensated, Fixed Voltage controller is 195.82 Ws giving an efficiency of 99.2%.
4.7 Direct Energy Transfer

Figure 39 shows the system response to the Direct Energy Transfer system.

Figure 38: Temperature Compensated Fixed Voltage vs Ideal Operating Voltage

Figure 39: Direct Energy Transfer vs Ideal Operating Voltage
One difference between this graph and all 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 simply 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 simply been halved so they can be compared to the other interfaces.

Also of note, by looking at the graph it seems that because the solar array voltage is simply the battery voltage added to a diode drop, by increasing the diode drop we could more close match ideal operating voltage. It must be remembered, however, that the power across the diode is lost and the battery is using the solar cell as a current source; therefore, the goal is to maximize the current output of the solar cell, this is done by lowering the operating voltage. The performance of the Direct Energy Transfer systems, as compared to the other solar array interfaces, is helped by the parasitic elements of the solar cell due to the slope of the “constant current” section of the IV-Curve as can be seen in Figure 5. Finally, this simulation assumes the battery starts at an 85% Depth of Discharge. Total integrated power for the Direct Energy Transfer system is $170.6 \text{ Ws}$ giving an efficiency of 86.5%.

5.0 Conclusions

Table 2 gives the efficiencies for all the solar array interfaces described above calculated as the total integrated power for each interface divided by the ideal total integrated power. As can be seen, all the solar array interfaces operate as expected and give very
good interface efficiencies with the Fractional Controller and the Temperature Compensated Fixed Voltage Controller performing the best. Direct Energy Transfer, the simplest interface (in terms of component count, number of active components and board area), performed reasonably well, with the top performer only supplying 13% more power.

Table 2: Solar Array Interface Efficiencies

<table>
<thead>
<tr>
<th>Solar Interface</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractional</td>
<td>99.1%</td>
</tr>
<tr>
<td>Perturb and Observe</td>
<td>98.6%</td>
</tr>
<tr>
<td>dP/dV</td>
<td>98.9%</td>
</tr>
<tr>
<td>Fixed</td>
<td>95.7%</td>
</tr>
<tr>
<td>Temperature Compensated Fixed</td>
<td>99.2%</td>
</tr>
<tr>
<td>Direct Energy Transfer</td>
<td>86.5%</td>
</tr>
</tbody>
</table>

There are, however other factors that affect the operation of solar array interfaces.

5.1 Battery Charge Regulator Efficiency

In order to operate, solar array interface controllers must use a battery charge regulator to adjust the operating behavior of the solar array. Battery charge regulators, as non-ideal devices, have efficiencies associated with them which reduce that actual amount of power available to the satellite system. A survey of commercially available, switching battery charge regulators that are suitable for small spacecraft show an optimal efficiency of 90% with an expected efficiency of 85%. Furthermore, the efficiency of the Direct Energy Transfer System was affected by a voltage drop across a protection diode. This can be replaced with an ideal diode, a comparator and a MOSFET, in order to lower
the voltage drop to approximately 20 mV. Table 3 gives these modified solar array interface efficiencies; optimal and expected efficiencies for the battery charge regulator interfaces and the Direct Energy Transfer efficiency incorporating an ideal diode as opposed to a Schottky Diode.

Table 3: Modified Solar Array Interface Efficiencies

<table>
<thead>
<tr>
<th>Solar Interface</th>
<th>Optimal Efficiency</th>
<th>Expected Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractional</td>
<td>89.2%</td>
<td>84.2%</td>
</tr>
<tr>
<td>Perturb and Observe</td>
<td>88.7%</td>
<td>83.8%</td>
</tr>
<tr>
<td>dP/dV</td>
<td>89.0%</td>
<td>84.1%</td>
</tr>
<tr>
<td>Fixed</td>
<td>86.1%</td>
<td>81.3%</td>
</tr>
<tr>
<td>Temperature Compensated Fixed</td>
<td>89.2%</td>
<td>84.3%</td>
</tr>
<tr>
<td>Direct Energy Transfer</td>
<td>89.0%</td>
<td>89.0%</td>
</tr>
</tbody>
</table>

As can be seen, the efficiency of the battery charge regulator has a drastic effect on the overall efficiency of the solar array interface system. Only two of the active interfaces outperform the Direct Energy Transfer System, and only slightly, and none of the active interfaces outperform the Direct Energy Transfer System when considering the expected efficiency.

5.2 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, especially if purposely induced for stabilization. A typical spin-stabilized spacecraft utilizes spin rates between 20 and 90 RPM [16]. As all
the solar array interfaces, except Direct Energy Transfer, use active control systems, an increase in spin rate leads to degraded controller performance. At 20 RPM, all the solar array interfaces except for Direct Energy Transfer, experienced a 20-40% decrease in performance as seen in Table 4.

Table 4: Percent Decrease of Total Integrated Power when Rotation is Increased from 1 to 120 Deg/s (20 RPM)

<table>
<thead>
<tr>
<th>Solar Interface</th>
<th>Percent Decrease at 120 Deg/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractional</td>
<td>19.5%</td>
</tr>
<tr>
<td>Perturb and Observe</td>
<td>37.3%</td>
</tr>
<tr>
<td>dP/dV</td>
<td>44.4%</td>
</tr>
<tr>
<td>Fixed</td>
<td>37.1%</td>
</tr>
<tr>
<td>Temperature Compensated Fixed</td>
<td>65.5%</td>
</tr>
<tr>
<td>Direct Energy Transfer</td>
<td>0%</td>
</tr>
</tbody>
</table>

This decrease may be able to be compensated with an increase in system control gain but that would have to be investigated on a case by case basis.

5.3 Effect of Solar Cell Damage

Due to the extreme nature of the Low Earth Orbit environment, solar cells are subject to possible damage; most commonly, radiation damage, which affects all the cells similarly, and micro-meteorite damage or shadowing, which would affect a single cell. Radiation causes a constant slow degradation of solar cell performance while micro-meteorite impacts are single events that physically damage a solar cell. Shadowing happens when a deployable, or some other part of a satellite, causes less light to fall on a single cell thus changing its behavior with respect to the other cells. These events cause a
permanent change to the solar cells negatively affecting their performance. The probability of damage increases with increased mission time, therefore most of these effects can be discounted for short mission times. However, to ensure mission success, the possible consequences of radiation or single cell damage must be investigated.

5.3.1 Radiation

Figure 13 shows the behavior of solar cells after being damaged by differing amounts of radiation. As can be seen, 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 are able to compensate and do not rely on accurate solar array parameters to operate. Fractional Voltage solar array interfaces also operate fairly well after radiation damage as both the open circuit voltage and max power voltage are reduced relatively equally. However, Fixed Point solar array interfaces, both temperature compensated and not, can be detrimentally affected by solar array damage.

As can be seen in Figure 13 if the fixed operating point chosen corresponds to the optimal operating point before radiation damage occurs, it will not be long before that point is 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 Direct Energy Transfer 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 or to use an ideal diode to avoid higher operating voltages leading to less power after radiation damage. The affect on direct energy transfer 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 zero power generation.

Table 5 shows the percent decrease of total integrated power based on total radiation fluences of 1e14, 5e14, and 1e15. As can be seen the MPPT interfaces track the ideal fairly closely, the non-MPPT interfaces fail catastrophically at higher radiation levels, and the Direct Energy Transfer System is the least affected by increasing radiation.

<table>
<thead>
<tr>
<th>Solar Interface</th>
<th>1e14 MeV/cm2</th>
<th>5e14 MeV/cm2</th>
<th>1e15 MeV/cm2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal</td>
<td>5.4%</td>
<td>10.3%</td>
<td>14.3%</td>
</tr>
<tr>
<td>Fractional</td>
<td>5.6%</td>
<td>10.6%</td>
<td>14.5%</td>
</tr>
<tr>
<td>Perturb and Observe</td>
<td>5.4%</td>
<td>11.4%</td>
<td>15.4%</td>
</tr>
<tr>
<td>dP/dV</td>
<td>5.5%</td>
<td>10.4%</td>
<td>14.4%</td>
</tr>
<tr>
<td>Fixed</td>
<td>33.5%</td>
<td>67.0%</td>
<td>75.32%</td>
</tr>
<tr>
<td>Temperature Compensated Fixed</td>
<td>25.5%</td>
<td>75.0%</td>
<td>98.8%</td>
</tr>
<tr>
<td>Direct Energy Transfer</td>
<td>0.5%</td>
<td>2.3%</td>
<td>5.6%</td>
</tr>
</tbody>
</table>
5.3.2 Single Cell Damage

Solar arrays can also be affected by single events, such as localized damage or shading due to offgassing, that cause one cell in a string to not operate or to operate poorly. All the MPPT Interfaces can compensate for this and the only affect will be the loss of power from the single cell. However, with non-MPPT interfaces, this will cause the power from the entire string of cells to be lost. There are two ways to compensate for this, oversizing solar cell strings and using lots of small strings as opposed to a few long strings. As these single events should be rare, oversizing solar cell strings is not practical or efficient for small spacecraft, therefore the best method for compensating against single events while still maintaining a high efficiency is to use the smallest string length and the maximum number of strings possible.

5.4 Discussion

As demonstrated above, a Direct Energy Transfer system, the simplest solar array interface (in terms of component count, the number of active components, and board area), performs as well, and in some cases better, than the more complex Maximum Peak Power Tracking interfaces. Even when the optimal efficiency of a Battery Charge Regulator (90%) is taken into consideration the best MPPT had a solar array matching efficiency of 89.2%. A Direct Energy Transfer System, using an ideal diode (the optimal solution for Direct Energy Transfer), has a solar array matching efficiency of 89.0%. Given the increased complexity and relatively low gains, as well as how MPPT’s are
affected by rotation rate, Direct Energy Transfer Systems should be used in small spacecraft.

If an MPPT must be used, e.g. if the spacecraft must be able to survive single solar cell failures and short string lengths are not possible, the fractional voltage controller should be used given its high performance, the relatively low effect of radiation and spin rate, and relative simplicity. The ratio for the fractional controller must be calculated and determined empirically but can easily be changed in a design by substituting two resistors making up a voltage divider. Given their low performance and the large effects rotation and radiation have on them, fixed point solar array interfaces should not be used for small spacecraft.

<table>
<thead>
<tr>
<th>Solar Interface</th>
<th>No BCR</th>
<th>With Expected BCR Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spin 1°/s, No Radiation</td>
<td>Spin 20°/s, No Radiation</td>
</tr>
<tr>
<td>Fractional</td>
<td>99.1%</td>
<td>84.2%</td>
</tr>
<tr>
<td>P&amp;O</td>
<td>98.6%</td>
<td>83.8%</td>
</tr>
<tr>
<td>dP/dV</td>
<td>98.9%</td>
<td>84.1%</td>
</tr>
<tr>
<td>Fixed</td>
<td>95.7%</td>
<td>81.3%</td>
</tr>
<tr>
<td>TC Fixed</td>
<td>99.2%</td>
<td>84.3%</td>
</tr>
<tr>
<td>DET (No BCR)</td>
<td>86.5%</td>
<td>86.5%</td>
</tr>
</tbody>
</table>

One possible criticism for this research is it only focused on one chemistry of solar cells and one chemistry of batteries. While the chemistries used represent the current state of the art of both batteries and solar cells (lithium-polymer and ultra triple junction respectively) a discussion concerning other chemistries is warranted. As stated, the only
requirement for Direct Energy Transfer systems to work is that the battery voltage and the solar array voltage be matched. The technologies modeled not only represent current state of the art but also the highest current nominal voltages; lithium batteries at 3.7v nominal, 4.2v max and triple junction solar cells at \(~2.3v\) @ max power. Therefore, if legacy technologies are used, all that must be considered is if their nominal voltage is a close multiple of the technologies modeled. Commonly used batteries for small spacecraft, besides lithium chemistries, are Nickel-Cadmium and Nickel Metal-Hydride. The voltages for both of these chemistries are 1.2v nominal and 1.4v max which means that a series string of three of these batteries will give 3.6v nominal and 4.2v max which matches very closely to the batteries modeled. The discharge curve for these batteries are different than the lithium technologies modeled, however the difference is slight enough that it should not matter.

Two commonly used solar cell chemistries for small spacecraft are multi-junction and silicon solar cells. Multi-junction (double- and triple-junction, the latter of which was modeled for this work) have similar performance characteristics as described above. Silicon solar cells have a max power voltage of a little less than 0.5 volts which, when arranged in a series string of 5 cells gives a max power voltage of 2.5v which approximately matches the multi-junction performance; if arranged in a series string of 9 cells gives a max power voltage of 4.5v which is a good match for lithium batteries. Given the smaller nominal voltages of silicon solar cells and nickel-based batteries arranging them to match each other or the other technologies modeled is a semi-trivial
task. As an example the CubeSat mission mentioned before that achieved a 90% matching efficiency used Lithium-Ion batteries and Double-Junction solar cells.

Another possible criticism is that only one cell or two cells in series were modeled as opposed to modeling full arrays. However, while there may be some differences due to individual characteristics of actual solar cells (which can be mitigated by careful selection of cells) there is no inherent reason that arrays should behave any differently than single cells, besides the increase in voltage or current due to series or parallel strings respectively, given proper blocking and bypass diode protection is used. As discussed above, the only thing necessary when using arrays as opposed to single cells is to still match the battery and solar cell voltages. Finally, it must be noted that when combining chemistries and array sizes in order to match battery and solar array voltages the error should be on the side of greater solar cell voltage. When using Direct Energy Transfer the solar cells serve as a current source for the batteries and, given the IV-curve of solar cells, if the batteries are sized 0.1v (for example) above the solar array voltage the power loss will be fairly severe when compared to the power loss from sizing the solar array voltage 0.1v above the batteries.
6.0 Bibliography


    http://www.spenvis.oma.be/


7.0 Vita

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Publications