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Comparison of Maximum Power Point Tracking Techniques in Electrical Power Systems of Cubesats

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ABSTRACT

This work compares different maximum power point tracking (MPPT) techniques to find which is more efficient in a 3U Cubesat. The comparison is between an active searching algorithm, perturb-and-observe (P&O), and a voltage-feedback technique, Linear Reoriented Coordinates Method (LRCM). Even if previous work showed evaluations of MPPT techniques, these studies were based mainly on simulations with few details on the power converter topology. We employ mathematical models that describe the electrical behavior of solar cells and power converters. By using the space environment characteristics we obtain the efficiencies of each one of the MPPT methods to determine which one is the best technique for the given conditions. The results showed that both techniques have equivalent results.

INTRODUCTION

Libertad 1 was the first picosatellite developed in Colombia, which was launched in 2007. In order to improve the performance of Libertad 1 and the aerospace research of the country, the Universidad Sergio Arboleda has initiated activities related to the design, implementation and launch of its second Cubesat, which is called Libertad 2. This is a three unit (3U) Cubesat nanosatellite capable of capturing images, and temperature and irradiance data. Libertad 2 is going to be operating at the LEO orbit (Low Earth Orbit) which is located at 700 Km from the earth.

The development of the electrical power system (EPS) is one the most important goals of the Libertad 2 mission. EPS are needed to supply the power required for the operation of the Cubesat components. As an energy source the EPS usually has photovoltaic (PV) cells, which are connected to compose a solar panel[1]. Since PV cells have a particular current-voltage relationship, they generally require an interface to be used efficiently. The PV cell current-voltage curve and its relationship with the temperature and irradiance are described in the first section, where the problem of operating without interface to the loads is also presented.

The interface between the PV panel and load is commonly a power converter, which can vary the operating point over the PV current-voltage curve for extracting the maximum power as shown in Figure 1. However, an MPPT technique is needed for driving the power converter. Reviews of the different MPPT techniques can be found in the literature[2,3]. Due to the reduced space of Cubesats and the need of efficiently using the PV cells, a careful selection of the MPPT must be done during the design of the EPS. Evaluations of different MPPT methods have been done before[4,5]; however, this paper presents results for different conditions on 3U Cubesats. The MPPT techniques compared in this paper are Perturb and Observe (P&O) and Linear Reoriented Coordinates Method (LRCM). The second section describes the MPPT techniques operation.

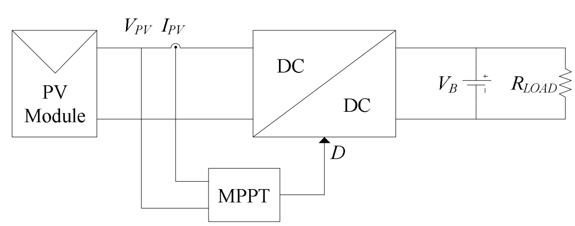

Figure 1: Block diagram of a MPPT technique

The MPPT uses a dc-dc power converter as a regulator. The efficiency of this converter could decrease the total power that is fed into the charge, making the MPPT needless[4]. For this reason, an optimal design of the power converter is critical when an MPPT is implemented, especially at low power as in the Cubesat case. The third section describes a simplified model for dc-dc power converters and the main losses of the Buck converter.

The rapid changes in solar irradiance impact the performance of searching MPPT techniques, such as P&O[6]. According to the American Society for Testing and Materials (ASTM), at one astronomical unit the accepted value of solar irradiance is 1366 W/m^2, which is also known as the solar constant[7] . However, this value is the irradiance at normal incidence; but, as the incidence angle changes due to the Cubesat attitude variation, the irradiance absorbed by the solar panel is proportional to the cosine law[8]. In the fourth section we present the irradiance and temperature conditions that are used to evaluate the MPPT performance.

Once the temperature and irradiance conditions are established and all the components are modeled, we use software simulations to obtain the maximum power that can be generated by the solar panels. In the same way, the MPPT techniques are integrated to the simulation to calculate the produced power for each technique and evaluate its behavior. These results, which are very helpful during the design of the EPS and the power budget, are presented in the last section.

ELECTRICAL BEHAVIOR OF PHOTOVOLTAIC CELLS

The utilized mathematical model describes the electrical behavior of a photovoltaic cell according to a current I - voltage V relationship given by

$$I = \frac{I_x}{1-\exp\left(-\frac{1}{b}\right)}\left[1 - \exp\left(\frac{V}{bV_x} - \frac{1}{b}\right)\right] \quad (1)$$

where I_x and V_x are the short-circuit current and the open circuit voltage, respectively; these values depend on the temperature (T) and the irradiance (E_i) and they are given by

$$I_x = \frac{E_i}{E_{in}}\left[I_{scn} + TC_i(T - T_n)\right] \quad (2)$$

$$V_x = TC_v(T - T_n) + A\left[\exp\left(B\frac{E_i}{E_{in}}\right) - \exp\left(C\frac{E_i}{E_{in}}\right)\right] \quad (3)$$

the constants b, A, B, and C are calculated as described [9,10], where the model is fully described. I_{scn} is the short circuit current at the test conditions specified on the datasheet for irradiance (E_{in}) and temperature (T_n). TC_i and TC_v are the temperature coefficients for the short circuit current and the open circuit voltage, respectively; which are also specified in the datasheet. The accuracy of this model to describe the current - voltage relationship of high efficiency photovoltaic cells have been validated[11].

The used photovoltaic cells are high efficiency triple junction (GaAs/GaInP/Ge) space solar cells from Azur Space; their parameters are listed in Table 1. The cell area is 30.18 cm^2, thus, a solar panel of 10 cm x 10 cm (1U) is composed of two cells, and the solar panel of 30cm x 10cm (3U) consists of six cells.

Table 1: Parameters of Azurspace 3G30C solar cells datasheet[12]

Parameters at 28°C and 1367W/m2	Value
Open circuit Voltage (V_{ocn})	2669 mV
Short circuit current (I_{scn})	525 mA
Voltage at maximum power (V_{mpp})	2379 mV
Current at maximum power (I_{mpp})	505 mA
Temperature coefficient (TC_v)	-6.0 mV/°C
Temperature coefficient (TC_i)	0,32 mA/°C
Characteristic Constant (b)	0.0333
Calculated Constant A	2.3023
Calculated Constant B	0.1478
Calculated Constant C	-15.5481

MPPT TECHNIQUES

The main goal of an MPPT technique is to find the current and voltage where a PV module provides the maximum power; this is called the maximum power point. In addition, it is necessary to vary the duty cycle of a power converter until the PV module operates at that point. The difference between the two analyzed methods is the way that they discover the voltage for the maximum power.

The P&O technique looks for the maximum power continuously, by perturbing the power converter and observing the changes in the power. The perturbation consists of increasing or decreasing the duty cycle of the power converter in order to increase the power; if the power increases then the perturbation applied must be kept; otherwise, the perturbation must be inverted[13].

The other MPPT technique is called Linear Reoriented Coordinates Method (LRCM), which approximates the voltage at maximum power (V_{mpp}) by using the open circuit voltage V_x [14]. This is similar to fractional open circuit voltage[3]; but it determines the constant of proportionality by using the characteristic constant of the model b. This method was experimentally validated[15], by approximating the voltage at maximum power to V_{ap}, given by

$$V_{ap} = V_x + bV_x \ln\left[b - b\exp\left(-\frac{1}{b}\right)\right] \quad (4)$$

POWER CONVERTERS

The selected model for the buck converter is shown in Figure 2. The semiconductor devices are modeled by an ideal switch in series with the on-resistance. In the case of the diode, it is also considered the on-voltage. The passive devices are modeled by an ideal element in series with their equivalent series resistances.

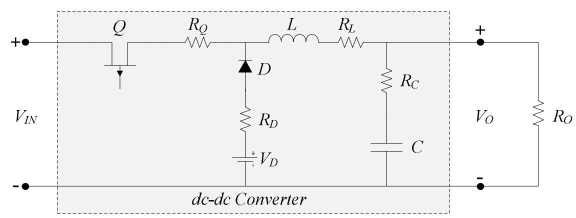

Figure 2: Buck converter model including device losses

While considering non-ideal elements, the output voltage of the buck converter can be expressed as:

$$V_O = \frac{DV_{IN} - (1-D)V_D}{1 + \frac{R_D + R_L}{R_O} + D\left(\frac{R_{ON} - R_D}{R_O}\right)}, \quad (5)$$

The improved performance of the semiconductor devices available in the market allows a buck converter to have efficiencies above 90 percent. The converter efficiency could be improved even more by implementing the synchronous configuration[16].

IRRADIANCE AND TEMPERATURE CONDITIONS

The considered case for the evaluation of MPPT is sun-synchronous low Earth orbit (LEO) at 710 km. The Cubesat orbital period (T_0) can be calculate by using Kepler's third law

$$T_0^2 = \frac{4\pi^2 a^3}{\mu} \quad (6)$$

where a is the semi-major axis of the satellite orbit and μ is the gravity constant of the Earth, which is μ =3.986 x 10^5 km^3/s^2 [8]. From the former equation we obtain a period of 99 minutes, although the eclipse is less than 50% of the period, this simulation takes a simplified scenario where eclipse and sunlight period are equal to 49.5 minutes.

In this case, we assumed an attitude control that keeps a Cubesat side oriented to the Earth as illustrated in Figure 3. According to the cosine loss, the irradiance absorbed by the solar cells on side number 4 are proportional to the sine θ ; in this way, the solar constant (1367W/m^2) is completely absorbed when $\theta = 90°$ and zero irradiance at $\theta = 0°$ and $\theta = 180°$ on side number 4. A similar analysis would obtain the irradiance on the sides 1 and 3 as show on Figure 4.

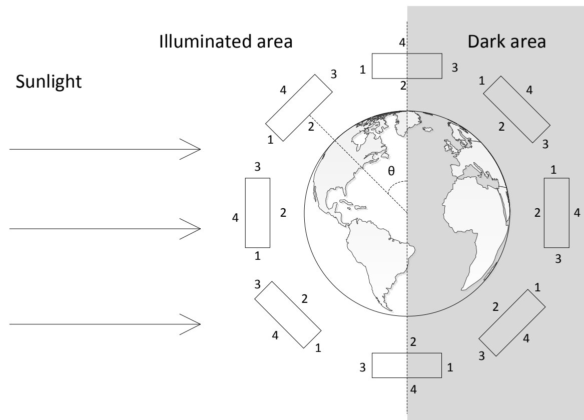

Figure 3: Simplified orbit of a 3U Cubesat

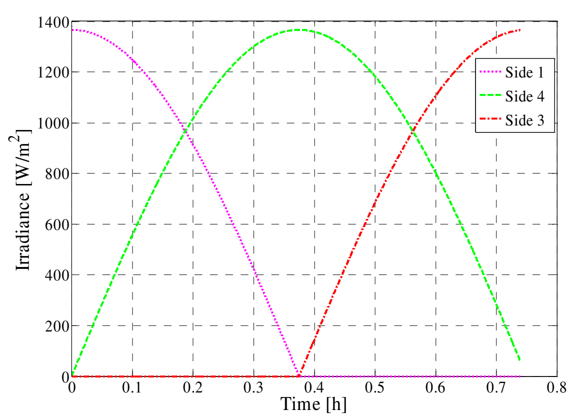

Figure 4: Absorbed irradiance on the solar panels

Regarding the temperature, Cubesat CP3 data show all the sides have a similar temperature value, which varies between -30°C and 20°C with a period of 90 minutes approximately[17]. For this simulation, a first order model that represents a variation from -32°C to 42°C is used. This is very close to the thermal model that shows a variation from -32.25°C to 42.42°C[18]. Figure 5 illustrates the temperature behavior during the sunlight period.

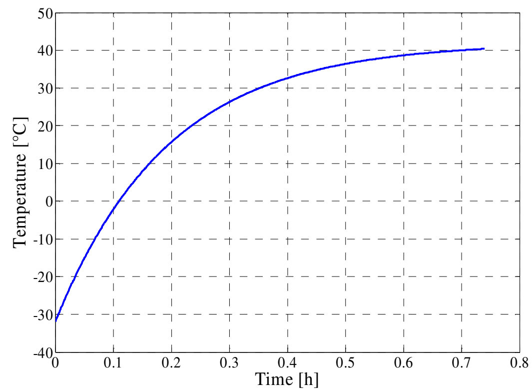

Figure 5: Temperature on the solar panels

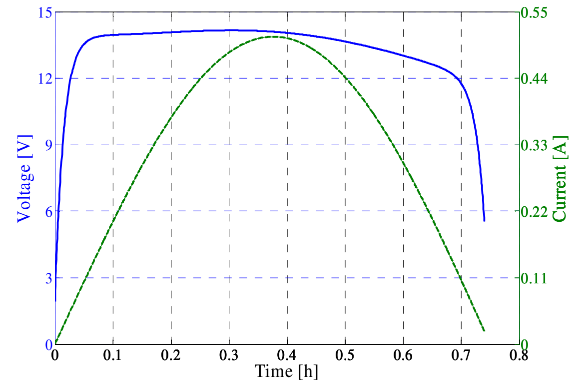

Figure 7: Voltage and current at maximum power of side 4 solar panels

RESULTS

Figure 6 shows the maximum power that can be extracted from the solar panels at the temperature and irradiance conditions in space. Even though sides 1 and 3 are exposed to the same irradiance, the power produced by each side is different because the temperature conditions are not the same for each one (see figures 4 and 5). The integral of the power over the time is the provided energy. Side one produces 0.57 Wh, side three 0.52 Wh and side four 3.33 Wh. The comparison of the MPPT algorithms is accomplished by analyzing only the PV panel of the side 4, since its produced power is higher than the others.

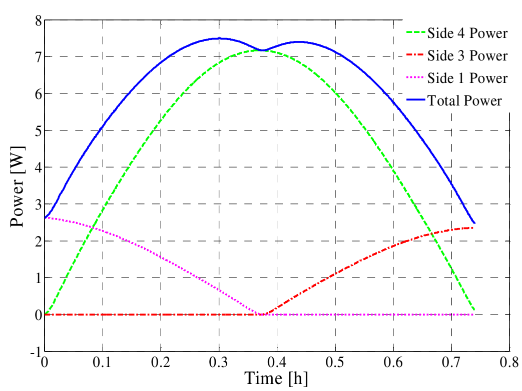

Figure 6: Ideal power for the solar panels

Figure 7 presents the output voltage and current at the maximum power point for the PV panel of the side 4. The voltage varies between 12 and 15 V and is smaller at the end of a solar period because there the temperature is higher. Since the considerably stable output voltage, this is used as the controlled variable for the MPPT algorithms.

Figure 8 displays the power extracted from the solar panel on side 4 for the P&O (blue) and LRCM (green) algorithms compared to the ideally maximum power that could be extracted (red). Since the LRCM uses the open circuit voltage V_x to develop its control actions, the PV module is disconnected from the dc-dc converter producing zero power each time V_x is measured. Figure 9 shows a zoomed version of Figure 8 where it is possible to see the oscillations of the P&O, which are inevitable due to the functioning of the method. The efficiencies obtained for the P&O and LRCM methods are 99.8% and 99.7%, respectively

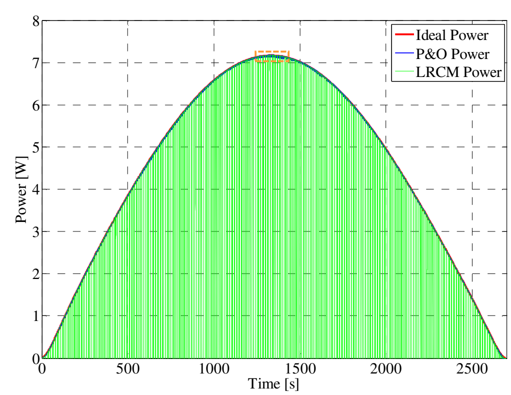

Figure 8: Obtained PV power using P&O and LRCM

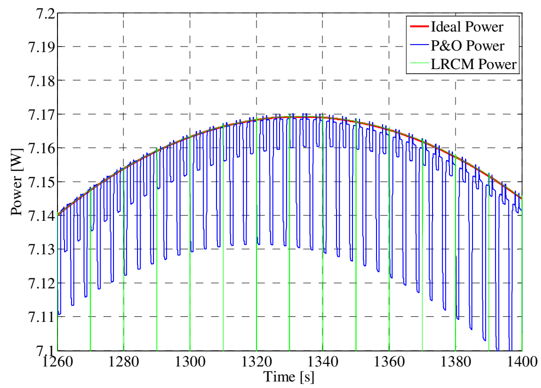

Figure 9: Zoomed version of Figure 8

CONCLUSIONS

The power produced by the solar cells over a large side of a 3U Cubesat was used to compare the performance of the maximum power point tracking techniques. Irradiance absorbed by the solar cell was approximated by the cosine law, and temperature effect was also considered. The ideal operating point of the PV cells was estimated during the orbit sunlight period to be used as a benchmark for the MPPT comparisons.

Both MPPT methods presented a similar performance over an entire sunlight period. An effective operation of LRCM requires precision in the mathematical model of the PV panel. In the case of P&O method, a careful selection of the sampling time and the step size must be done for its correct operation.

As the CubeSat uses temperature and irradiance sensors, LRCM could be implemented without the disconnection of the PV panel, because sensor could be used to calculate the V_x using the model of the solar cells.

The showed results were in a case where the attitude of the Cubesat was successfully controlled. However, different situations without attitude control are being analyzed to know the performance of the MPPT techniques if the attitude control fails.

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