EVALUATION OF TECHNIQUES FOR POWER REGULATION ON NANOSATELLITES

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ABSTRACT

We evaluate two power regulation techniques to find which is more efficient in a 3U CubeSat nanosatellite. The comparison is between maximum power point tracking (MPPT) technique and direct energy transfer (DET). Previous work showed the effectiveness of MPPT techniques; however, the efficiency of the power converter topology must be considered, especially at low power as nanosatellites. We employ mathematical models that describe the electrical behavior of solar cells and power converters. By using the space environment characteristics, we obtain the delivered power to the load in order to determine which one is the best technique for the given conditions. Simulation results show that both techniques have similar performance for nadir aligned 3U CubeSat. Therefore, DET should be used since it is easier to implement than MPPT.

1. INTRODUCTION

Among small satellites, three-unit (3U) CubeSats are becoming more attractive for military, research and commercial applications. Due to their size (30cm x 10cm x 10cm) and weight ($<$ 4 kg) the cost of these missions is low, bringing a new opportunity for the satellite industry. However, their dimension is also a disadvantage when the power generation system is designed. The reduced size prevents from including a large amount of photovoltaic (PV) cells and batteries. Therefore, to provide enough power to accomplish the nanosatellite mission, the efficiency of the electrical power system becomes a critical requirement that must be considered in the selection of the power regulation technique.

There are mainly two power regulation techniques: direct energy transfer (DET) and peak power tracker (PPT) [1], also known as maximum power point tracker (MPPT). In a DET system the battery is directly connected to the PV cells; therefore, the operating voltage of the PV cells is determined by the battery. In contrast, an MPPT system uses a dc-dc converter for matching the load to the PV cells, in such way the maximum power can be obtained [2]. Section 2 describes how these techniques are modelled for the evaluation of their performance.

Nanosatellites mainly use photovoltaic (PV) cells as energy source for the electrical power system (EPS), and lithium-ion batteries as energy storage [3]. In addition, electronics circuits such as dc-dc power converters are required for power regulation [4]. The mathematical models for these components that are used for evaluating the power regulation techniques are summarized in section 3.

Most of the CubeSats have implemented MPPT [5]. Previous work has evaluated the performance of power regulation techniques for small satellites. In [6] an MPPT system for a small satellite is compared to a DET system for the same condition. It claims that there is an increase in 25% of energy output when MPPT is employed. However this work did not considered the efficiency of the dc-dc converter. Reference [7] presented a study for the EPS of one unit (1U) CubeSat, where several MPPT methods are compared to a DET system. Contrary to what is expected, DET presented the best performance. These contradictory results motivated the study for a 3U CubeSat with body mounted PV cells.

This study presents the power that is extracted from the PV cells for DET and MPPT systems. In the same way, this paper presents the actual power that is delivered to the load when the interface losses are considered. In the case of DET the diode that prevents reverse current is included, while in MPPT the efficiency of the converter is calculated according to the operating point. These results are shown in section 4 and the conclusions are presented in section 5.

2. POWER REGULATION TECHNIQUES

There are three categories in power regulation: controlling the solar array, regulating bus voltage, and charging battery. We focus on the first one, which is also known as solar array regulator; this is responsible of transferring the solar power during sunlight to the power bus [1]. There are two main power system architectures: DET and MPPT. These are described below.

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2.1. Direct energy transfer

In DET system there is no series regulator between the PV cells and the batteries. However, a shunt regulator is usually connected for dissipating the excess of energy. Moreover, a diode is used as interface for preventing the PV cell behave as load during eclipse. For the simulation of DET the PV cells are connected to the series connection of a diode and the battery; in such way the PV voltage is determined by the battery voltage plus the forward voltage of the diode. We do not consider the shunt regulator since we are evaluating when the power is required. This is shown in Fig. 1 (b).

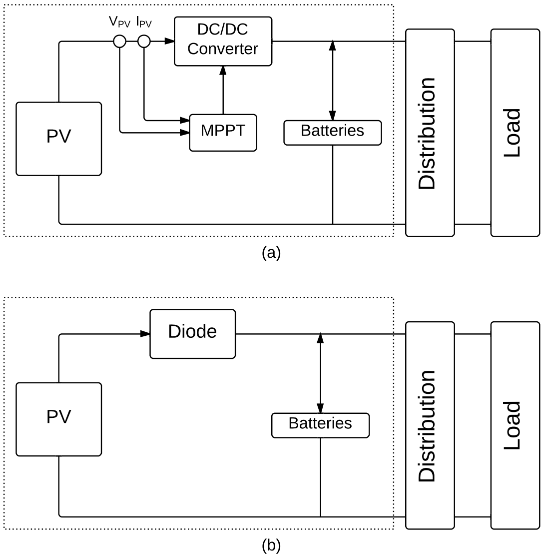

Figure 1. Power system architecture. (a) MPPT (b)DET

The voltage of maximum power of one PV cell is about 2.37V. On the side of a 3U CubeSat six PV cells can be located; then, the voltage for maximum power for the PV panel is about 14V. Since Li-Ion batteries present a nominal voltage of 3.7V, the number of batteries in series connection must be three, in this way the operating voltage of the battery is close to the optimal voltage.

2.2. Maximum power point tracking

In MPPT the power converter is used as interface as shown in Fig. 1 (a). The PV panel considered has the characteristics described before: six PV cells series connected. Therefore a step-down converter or buck dc-dc converter is the selected topology. Two cases are evaluated according to the number of batteries: one battery (3.7V) and two batteries (7.4V).

There are several techniques for MPPT implementation [8]. However, it has been shown that these MPPT techniques have a similar good performance [9]. Therefore, Linear reoriented coordinates method (LRCM) MPPT method with 99.7% of efficiency is considered. The focus is not only the MPPT method but the overall performance when the efficiency of the dc-dc converter is considered.

3. MODELING THE POWER SYSTEM COMPONENTS

3.1. Photovoltaic cells

The mathematical model describes the electrical behavior of a photovoltaic cell according to the current - voltage (I - V) relationship given by Eq. 1

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

where b is a characteristic constant of the PV cells, 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 are fully described in [10].

3.2. Power converters

The series power converter used as interface between the PV cells and the battery is a buck dc-dc converter. There are some losses that affect the efficiency depending of the parasitic of its components. Fig 2 shows the buck converter circuit including these parasitic components. Then, the power loss P_{LS} is given by Eq. 2

$$P_{LS} = P_{r_{DS}} + P_{SW} + P_D + P_{rL} + P_{rC} \qquad (2)$$

where $P_{r_{DS}}$ is conduction losses of MOSFET, P_{SW} is switching losses, P_D is diode losses, P_{rL} is inductance resistance losses and P_{rC} is capacitor series resistance losses [11]. When efficiency, η, is considered, the relation between the output voltage and the input voltage of a buck converter can be expressed as Eq. 3.

$$\frac{V_o}{V_i} = \eta \cdot D \qquad (3)$$

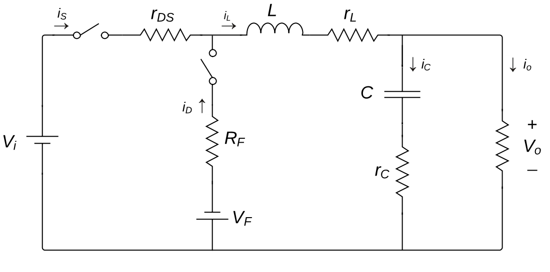

Figure 2. Buck dc-dc converter

Power converter efficiency also depends on the operating point, which is determined by the duty cycle, D, and the load, and was derived in [11]. Switching losses are negligible for low frequencies and this is the considered case in this work. Therefore, the efficiency is described by Eq. 4

$$\eta = \frac{1}{1 + \frac{D r_{DS} + (1-D) R_f + r_L}{R_L} + \frac{(1-D) V_f}{V_o} + \frac{r_C R_L (1-D)^2}{12 f^2 L^2}} \tag{4}$$

where r_{DS} is the drain-source internal resistance of the MOSFET, V_f and R_f are the forward voltage and the forward resistance of the Schottky diode, r_L and r_C are the internal resistance of the inductor and internal resistance of the capacitor respectively, L the inductance, f_s the frequency applied and R_L the load resistor of the converter.

From Eqs. 4 and 3 the dc voltage transfer function is given by Eq. 5.

$$\frac{V_o}{V_i} = \frac{D}{1 + \frac{D r_D + (1-D) R_f + r_L}{R_L} + \frac{(1-D) V_f}{V_o} + \frac{r_C R_L (1-D)^2}{12 f^2 L^2}} \tag{5}$$

3.3. Batteries

The electrical battery model was proposed in [12] and is shown in Fig 3. The mathematical expression that describes the battery voltage V_{Batt} in accordance with the present components is given by Eq. 6.

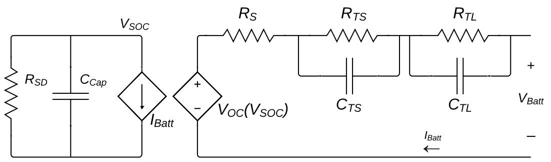

Figure 3. Electrical battery model [12]

$$\begin{aligned} V_{Batt} &= V_{oc} - R_S . I_{Batt} + \frac{1}{C_{TS}} \int I_{C_{TS}} \cdot dt \\ &+ \frac{1}{C_{TL}} \int I_{C_{TL}} \cdot dt \end{aligned} \tag{6}$$

where $I_{C_{TS}}$ and $I_{C_{TL}}$ are the current through capacitors C_{TS} and C_{TL} and are given by Eqs. 7 and 8

$$I_{C_{TS}} = \frac{-1}{R_{TS} . C_{TS}} \int I_{C_{TS}} \cdot dt - I_{Batt} \tag{7}$$

$$I_{C_{TL}} = \frac{-1}{R_{TL} . C_{TL}} \int I_{C_{TL}} \cdot dt - I_{Batt} \tag{8}$$

4. RESULTS

Both DET and MPPT architectures were evaluated during the sunlight period of a CubeSat with sun-synchronous low-Earth-orbit, which is nadir aligned. Due to the CubeSat attitude the incidence irradiance has a sinusoidal form; in the same way the temperature varies from $-32°C$ to $42°C$ as in [9]. The sunlight period takes about 49 minutes.

In the following subsections, the simulation results are presented for DET, MPPT with voltage bus of 3.7V (One battery) and MPPT with voltage bus of 7.4 V (Two batteries). The ideal PV power is the maximum power that can be extracted from the PV cells and this is compared with the actual obtained PV power. In addition, the total power delivered to the load is also estimated for each one of the cases.

4.1. Simulation of DET

DET system was simulated for the conditions already described. Fig. 4 shows the PV cells power during the sunlight period. As was expected, the actual PV cell power (red) was lower than the maximum PV power (green).

As already mentioned, the diode conduction losses were also calculated. Fig. 5 shows the efficiency of a DET system. This efficiency was calculated as the ratio between the delivered power and the ideal PV cells power. Therefore, we can see a peak efficiency when the ideal PV power is zero. This happens both at the beginning and at the end of the simulation when there is not enough irradiance, but the mathematical model is not valid in these regions.

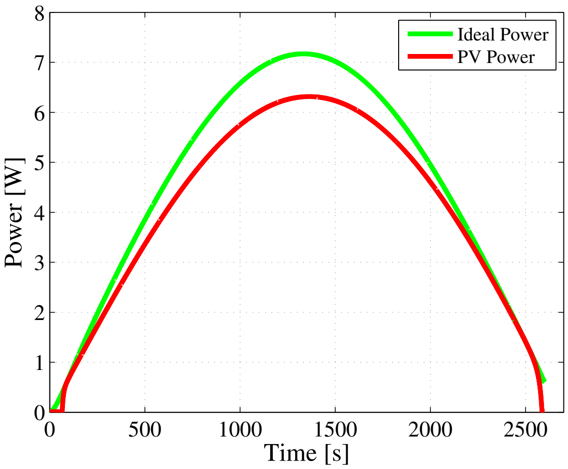

Figure 4. Comparison between Ideal PV power and actual PV power in DET

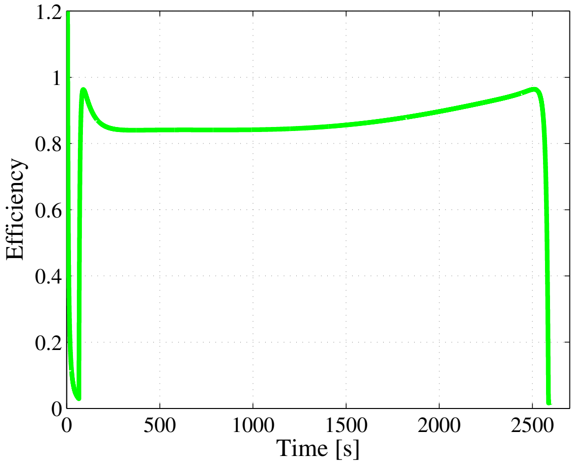

Figure 5. Efficiency of DET system

4.2. Simulation of MPPT for Vbat=3.7V

In this case an MPPT is considered where only one battery is connected to the output of the power converter; therefore, the unregulated voltage bus is about 3.7V. Fig. 6 shows the ideal maximum power (green) and the actual PV power (blue). Due to the effectivity of the MPPT method, the actual PV power is equal to the ideal maximum power, hence, only one line can be seen.

Although the PV cells are providing the maximum power, this is not the power delivered to the battery due to the power converter losses. Fig. 7 shows the efficiency (green) of the power converter during the sunlight period. The efficieny is under 80% most of the simulation time. Fig. 7 also shows the duty cycle that was generated by the MPPT method to obtain the maximum power of the PV cells.

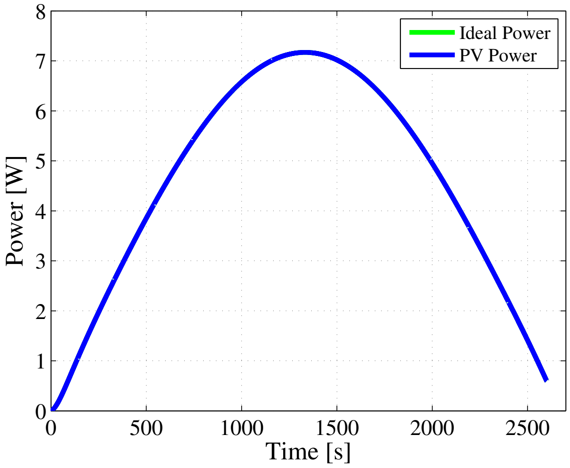

Figure 6. Ideal PV power and actual PV power

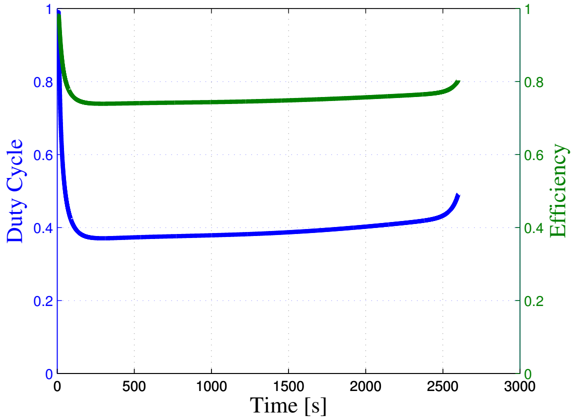

Figure 7. Efficiency and duty cycle for voltage bus of 3.7V

4.3. Simulation of MPPT for Vbat=7.4V

In the case that two batteries are connected to the output of the power converter, the nominal voltage bus is about 7.4V. The MPPT is still successful and the maximum PV power is obtained. In such way, the ideal maximum power and the actual PV power is similar to the one battery case (Fig. 6). However, the duty cycle and the efficiency are different as shown in Fig. 8. The efficiency is above 80% and close to the DET efficiency.

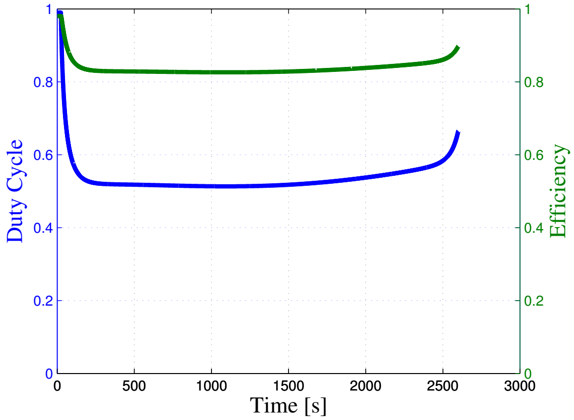

Figure 8. Efficiency and duty cycle for voltage bus of 7.4V

4.4. Comparison of delivered power

DET is compared to both MPPT cases, when all the losses are considered. Fig. 9 shows the delivered power to the battery by the MPPT (1-Battery) and the DET system. In the same way, Fig. 10 shows the comparison between DET system and MPPT (2-batteries).

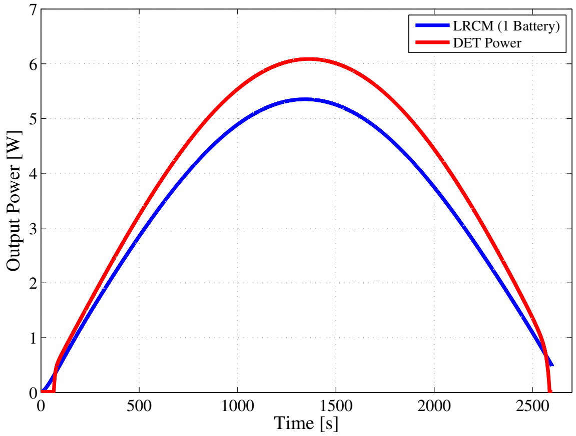

Figure 9. Comparison between DET and MPPT (one battery)

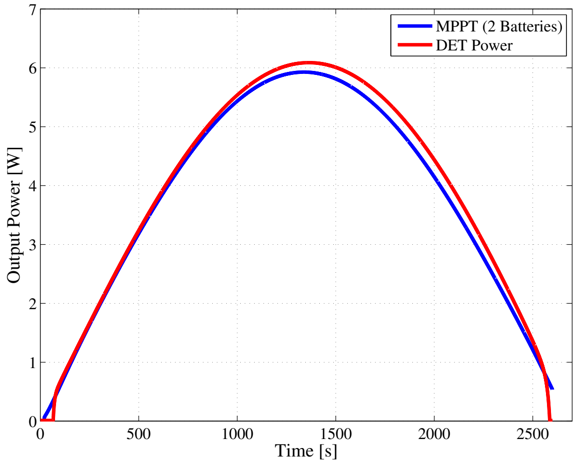

Figure 10. Comparison between DET and MPPT (two batteries)

5. CONCLUSIONS

Comparison between MPPT and DET systems was performed by simulation of mathematical models for a 3U CubeSat in a sun-synchronous low-earth orbit nadir aligned. For the MPPT system two cases were evaluated. One of them with voltage bus of 3.7V and the other with voltage bus of 7.4V. These correspond to one battery and two batteries, respectively.

According to the simulation results, the MPPT technique extracts more power from the PV cells than DET; however, when the efficiency of the power converter is considered, the total power produced by using the MPPT is not provided to the load. The total power provided to the load is similar for both MPPT and DET, but DET is easier to implement. For that reason, DET should be used.

Experimental evaluation by implementation of the power converter and the MPPT should be realized as future work.

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