Cube Satellite Battery Charger Regulator Design

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Abstract: Battery Charger Regulator (BCR) circuit used on spacecraft power systems, are usually switching regulators to provide maximum power for current operation mode and fixed voltage for voltage mode. In this article, we present detailed design procedures for BCR implemented on Cube-satellite. We will show small-signal analysis of a battery charger, to perform the control loop design of the maximum power point detection step and also voltage mode control loop to detecte battery Endof- charge. We present also a simulation of tow loops to verify our design.

Keywords: Cube Satellite, Power system, Battery charger, Lead-Lag Controller.

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1. Introduction

Spacecraft power system autonomy has two levels, hardware and software. The hardware is to ensure power conversion and stabilization from solar panels to the power storage part (Battery) and then distribute to the other subsystem. The software levels are to control and supervise all functionality of the power system, charge a battery with more efficiency and also detect the anomaly and act to solve the problem. Electrical power power used in small-satellite is usually produced from photovoltaic cells through the conversion of solar energy to electricity, further for the eclipse period we use power stored in a battery using BCR [1]. Depending on the mission criteria, there are two basic types of power system configuration for small-satellite. Unregulated or Regulated power bus [2], [3]. The first configuration means that the system obtains the power directly from solar cell panels, this configuration is simple to implement and presents an advantage which is low mass and less expensive. This type of structure presented in Fig.1 ("Fig.1a") is more practical and effective for the mission which has relatively few eclipse periods like Geostationary Earth Orbit (GEO) mission [4].

In regulated bus configuration, we can find several variations as a shunt regulator. These second configurations implement a Maximum Power Point Tracker (MPPT) between battery and solar panel is presented in Fig.1 ("Fig.1b"). This configuration characterized more efficiency for spacecraft with large eclipse periods as Low Earth orbit spacecraft (LEO) [5], [6], [7]. The regulated structure has two working modes. Current mode assured with Maximum Power Point Tracking, and voltage mode assured with converter output voltage regulation.

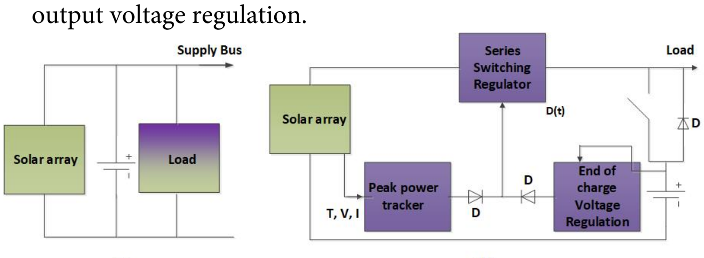

Fig. 1: (a) Unregulated Configuration (b) Regulated Configuration.

In literature, we can find a lot of MPPT's techniques. For small satellites, the most popular MPPT used is Perturb and Observe technics which usually uses Microcontroller [7]. Depending on solar panel characteristics variation with temperature and radiation this algorithm tray to keep the solar array working at its maximum point by measuring voltage and current for power calculation and then comparing with old measured values to generate an adequate Duty Cycle on transistor gate of DC-DC converter [7]. "Fig. 2" shows an Analog battery charger regulator (BCR) system. This structure uses DC-DC switching converter between solar panels and bus distribution. The role of the DC-DC converter is to control the panel output voltage at the maximum power point (Vmpp) until the battery reaches a nominal value of 8.4 V. then the system automatically swings to the second mode which keeps the battery voltage constant. The system is designed around TL494 Pulse Width Modulation control IC and IRF9540 P-channel as switching transistors. The current mode is activated when the battery is discharged; the principle of this mode is based on the accuracy of panel array temperature sensing and compared with the predicted Panel VMPP point. Then this temperature is measured, conditioned, and amplified using operational amplifier circuits. Voltage mode uses a feedback system and battery voltage to keep the voltage constant.

2. System Modeling

As described above, our system consists of two independent closed loops, first for buck converter input voltage regulation,

TABLE I: Different parameters of system

Model characteristics	Values
Vin	21 V
Vout	8.4 V
C	100µF
L	130 µH
D	0.4
Fswi	100khz

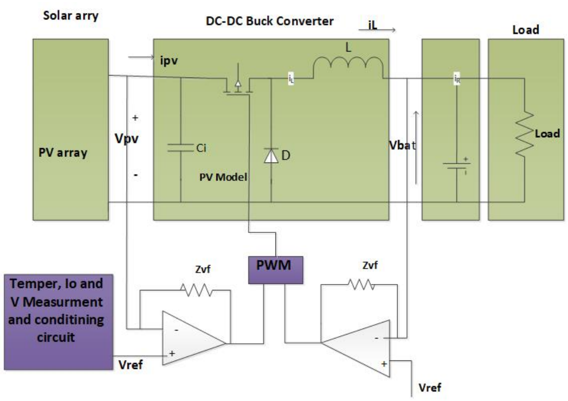

Fig. 2: Analog Batteru Charger.

and second to regulate the output voltage of DC-DC converter. So for modeling our system, we will take into account two approaches. In the first l oop s tudy, w e w ill c onsider Buck converter output as voltage constant in order to control the muximum power point voltage (Vmpp) in the input of the Buck converter. Therefore, for second loop control, we will regulate Buck converter output voltage considerring the input voltage as constant. The different parameters of our system are presented in Table I.

2.1 Modeling the Pv Array

"Fig. 3"shows a simple PV array Model, Where Ip is PV current, RS and Rp represents shunt and series resistance respectively [8].

In this work, we will consider solar cells which operate as a current source in current mode and a voltage source in voltage mode as presented in "Fig.4a" and "Fig.4b" [9], [10] ("Fig. 4").

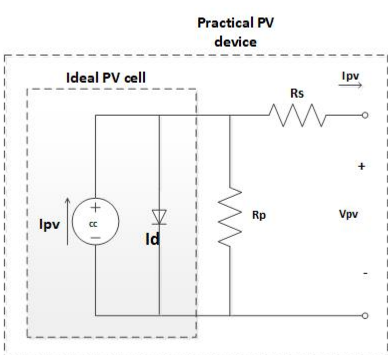

Fig. 3: Simple PV array model.

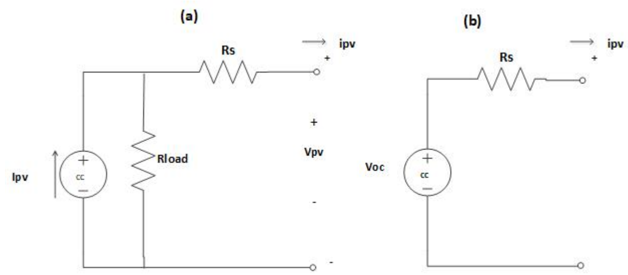

Fig. 4: PV linear equivalent circuit. (a) Current Mode, (b) Voltage source mode.

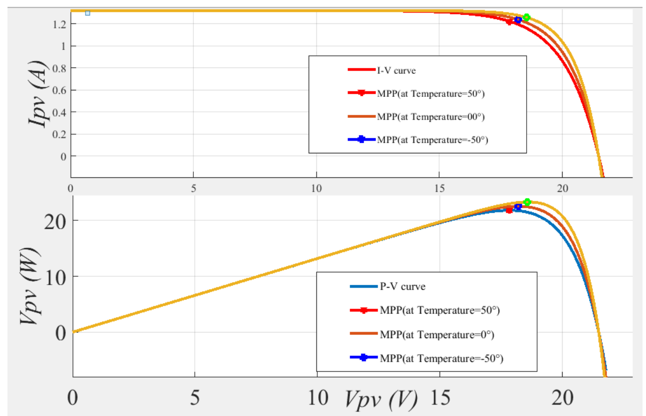

Fig. 5: Effet of temperature on cell I-V and P-V characteristics at 1000w/m2.

"Fig. 5" illustriate a simulated I-V and P-V cahracteristics, theis figure show that Vmpp shift with temperature variartion. as mentionned above, our MPPT command is based on this priciple for Vmpp traking with temperature variation.

2.2 Buck Converter Modeling and Controller Design

1) Input voltage regulation: In this paper, we have adopted a DC-DC Buck converter as shown in "Fig. 6". We assume that the output voltage is relatively constant battery voltage. Therefore, for this first step, the objective of converter modeling is to obtain small-signal transfer function which describes the buck converter input voltage with the duty cycle variation.

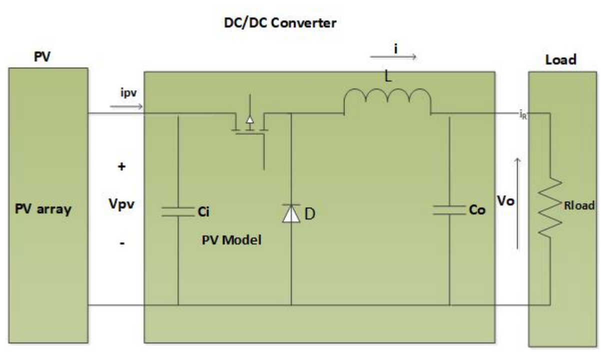

Fig. 6: DC-DC Buck converter.

To model DC-DC converter we consider two switch states of the transistor (on and off). According to the control system signal applied on the Gate transistor. “Fig.7a” present the state when the transistor is closed during the time interval (d*T). “Fig.7b” present second state when the transistor is open for a time interval (1-d)*T.

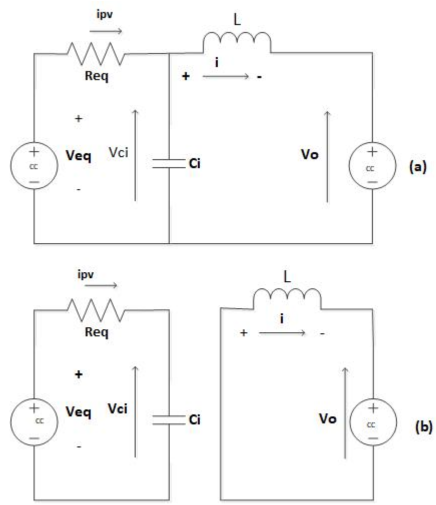

Fig. 7: (a) on switch step (b off switch step).

In the next step, we combine on/off capacitor and inductor state equation we get:

$$\begin{cases} \frac{di_L}{dt} = \frac{1}{L}\left(dv_{ci} - V_0\right) \\ \frac{dv}{dt} = \frac{1}{c_i}\left(-i_L d - \frac{v_{ci}}{R_{eq}} + \frac{V_{eq}}{R_{eq}}\right) \end{cases} \quad (1)$$

Then, to get the small-signal model we write the average variables as a sum of DC and AC variation [10].

$$\begin{cases} v_{ci} = V + \widehat{v_{ci}} \\ d = D - \hat{d} \\ i_L = I + \widehat{i_L} \end{cases} \quad (2)$$

In “equation (2)”, the steady stat elements are represented by capital letters, also small AC disturbances are represented with symbol ∧ hat. During current mode, PV panel work as a current source, thus from equivalent Thevenin circuit of “Fig.4a”, $R_{eq} = I_{pv} * Rp$ and $R_{eq} = Rp + Rs$ .where Req and Veq are respectively resistance and voltage of equivalent Thevenin circuit and Ipv, Rp, Rs are respectively panel open circuit current.

Using equations “(1)” and by neglecting the nonlinear terms and also transform Laplace applying, we can obtain the transfer function of Buck converter represented by the variation of PV voltage and Duty-Cycle d with “(3)”. This small signal transfer function describes the dynamic behavior of the input voltage of the converter.

$$G_{vd}(s) = \frac{\widehat{v_{cl}}(s)}{\hat{d}(s)} = \frac{R_{eq}(VD + sLI)}{s^2 R_{eq} L C_i + sL + D^2 R_{eq}} \quad (3)$$

“Equation (3)”contains additional Zero comparing with control to the output transfer function of a simple buck converter. With I and V are represented as follow:

$$I = \frac{V_{eq} - V}{R_{eq} D}, V = \frac{V_o}{D} \quad (4)$$

2) Closed loop control system: “Fig. 8”, present feedback closed loop used to control converter input voltage V. The compensator $C_{vd}(s)$ employed is Lead-Lag PID compensator, the Lead compensator add a zero to the loop gain at crossover frequency to help improve margin, which will improve dynamic response and stability. The Lag compensator is used to increase low-frequency loop gain [10].

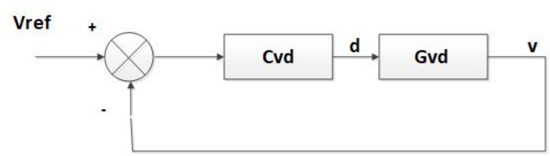

Fig. 8: Input voltage control system feedback.

The Bode plot of the open-loop system and the uncompensated loop can be seen in “Fig. 9”. After closing the loop without a compensator, the uncompensated loop gain becomes negative with a very low phase margin. The Lead compensator should improve the phase margin, so to get loop gain at the crossover frequency of 7 Rad/s, the lead compensator should have a gain of a 41.6dB. And to improve low-frequency gain, a Lag PI compensator has been added,

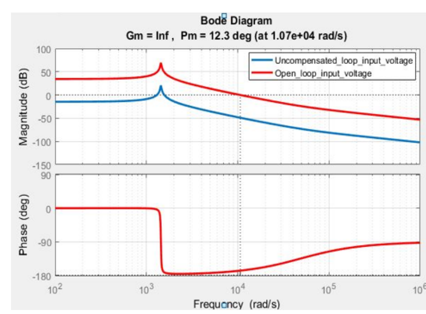

Fig. 9: Bode plot of open and uncompensated loop.

“Fig. 10” below shows a Bode plot of a closed-loop with a Lead-Lag compensator. From the bode plot of the closed-loop we can see a shift of 67°of phase margin around crossover frequency of 7 Rad/s, also improving low-frequency gain.

3) Output voltage regulation: When the battery is relatively charged the Buck converter can work as a current charge controller. To achieve this function the system uses a second closed loop to control Buck converter output voltage. So, our goal is to get a small-signal transfer function describing the variation of output voltage with Duty-Cycle control d considering input voltage as constant. “Fig. 11” shows (a) On the state of a buck converter (b) off the stat of a buck converter.

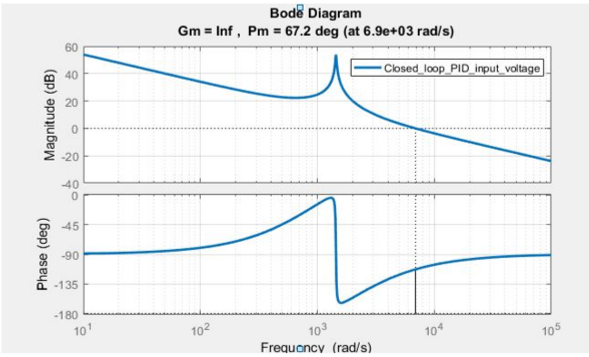

Fig. 10: Bode plot of closed loop with Leag-Lag compensator.

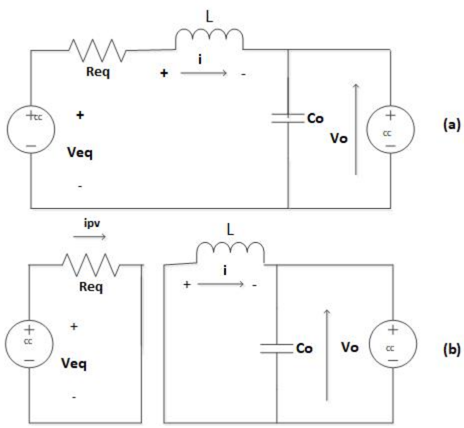

Fig. 11: (a) on switch step (b off switch step).

Using the same modeling method as above, we get equations “(5)”.

$$\begin{cases} V_{in} + \widehat{V_{in}} - V_c - V_c - L\frac{d\hat{i}L}{dt} = 0 \\ I_L + \widehat{i_L} - \frac{V_c}{R} - \frac{\widehat{V_c}}{R} - C\frac{d\widehat{V_c}}{dt} = 0 \end{cases} \quad (5)$$

Combining these two equations we obtain control to output transfer function represented by variation of converter output voltage and Duty-Cycle d. The small-signal transfer function Gvd(s) is presented by “(6)”.

$$G_{vd}(s) = \frac{v_c(s)}{\hat{d}(s)} = \frac{V_{in}}{D}\frac{1}{s^2LC + \frac{sL}{R} + 1} \quad (6)$$

“Fig. 12” shows a Bode plot of the open and uncompensated loop system. After closing the loop without compensation, we notice a decrease in loop gain and also we get a very small phase margin. So to get a desirable phase margin the Lead compensator should have 20dB at the crossover frequency of 6.58 rad/s.
“Fig. 13” shows closed-loop Bode plot with emprouve an improvement in a phase margin and small-frequency region gain.

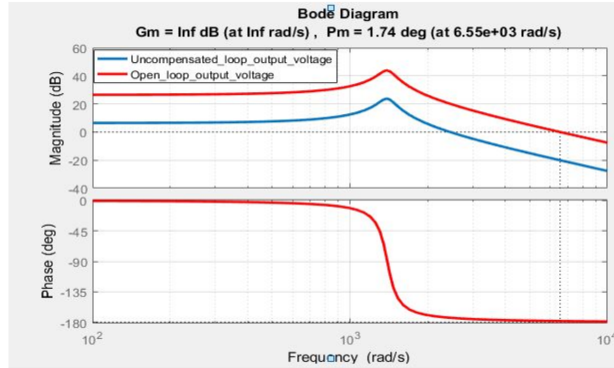

Fig. 12: Bode plot of open and uncompensated loop.

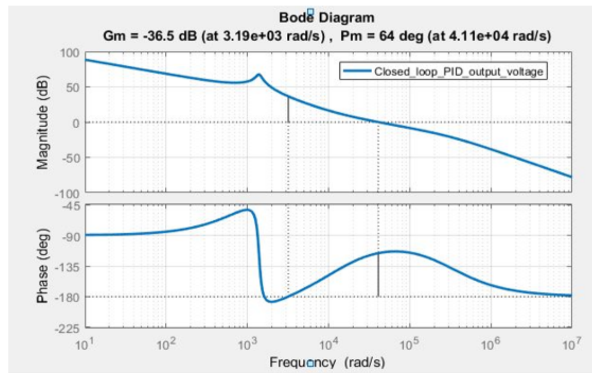

Fig. 13: Bode plot of feedback closed loop.

3. Results

To verify the response of Buck input voltage control of the small-signal model proposed. Matlab/Simulink model has been built to simulate control of input voltage with step transient in Reference (Panel Temperature). “Fig. 14” shows the Simulink Model proposed.

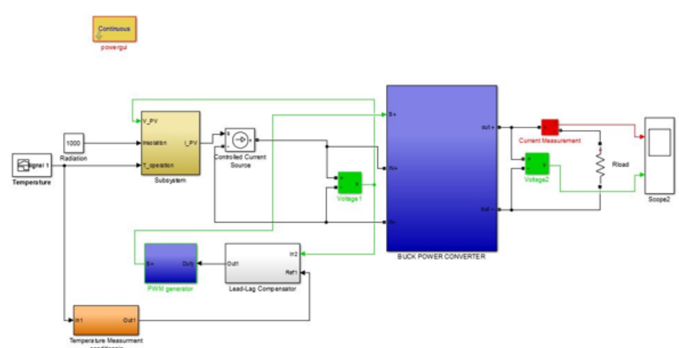

Fig. 14: MPPT controller simulink model.

“Fig. 15” shows a variation of input voltage from 18V which corresponds to low-temperature measurement on panel solar to 18.5V which mean an increse in temperature of the panel. From this figure, we can see the Input voltage of Buck converter track the reference variation with small overshoot and settling time (stabilisation time of 270μs).

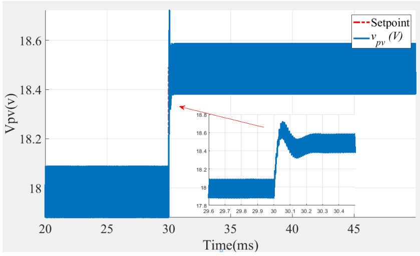

Fig. 15: Response of buck intput voltage due change in Refference.

we also presented in “Fig. 16” the step-up response of panel current and power against the variation of reference.

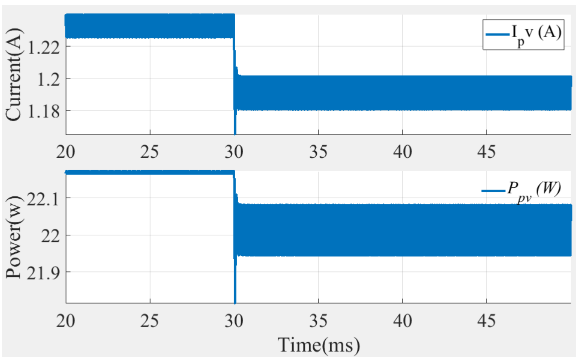

Fig. 16: Variation in buck intput Current and Power due change in Refference.

Matlab/Simulink model has been built to simulate control of output voltage with step transient in load charge to verify the response of the system.

“Fig. 17” and “Fig. 18” represents respectively the response of Buck output voltage and inductor current against load charge variation.

4. Conclusions

In this paper, a Battery Charger Controller BCR design is proposed for the Cubesat power sub-system. For controller design for two modes of charging, the small-signal transfer function from buck converter input voltage to the output voltage and the input voltage controller is obtained. Two analog Lead-Lag controllers for the Buck converter are designed with stability analysis. We made modeling of switching Buck converter for both, input to output transfer function to control and stabilize an output voltage of our system, and also transfer function for Buck converter input voltage controller. Transient

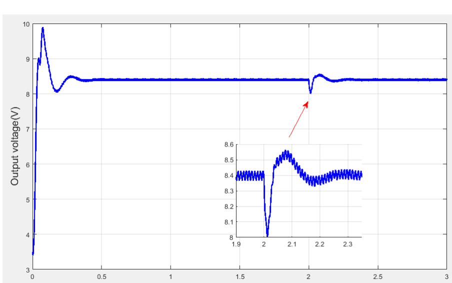

Fig. 17: Resepnse of buck output voltage with the load charge variation

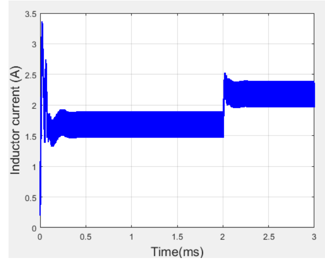

Fig. 18: Response of buck inductor current with charge variation.

load test simulation gives a good result for response time for both closed loops buck converter controllers.

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Conflicts of Interest

The author(s) declare no potential conflicts of interest concerning the research, authorship, or publication of this article.

Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

The author(s) contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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