# MC²: A POWER CONDITIONNING AND DISTRIBUTION UNIT FOR STRATOSPHERICS BALLOONS

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## ABSTRACT

For long duration scientific missions with stratospheric balloons (objective of 3 month duration), renewable energy is used. Solar panels with mono crystalline silicon solar cells are mounted on both scientific and avionic gondola. A power conditioning board with Maximum Power Point Tracking (MPPT) is designed and currently tested. This board is called MC²: Communicant Conditioning Module. It allows controlling a Li Ion battery charge through PWM regulators. Moreover, outlets ON/OFF commutations associated to overcurrent's protections are implemented in this board. The battery active thermal control is made by MC² autonomously. The main design drivers are mass, costs and efficiency. A CAN Bus between MC² and On Board Computer allows to have a commandability and observability of MC² through OBC. The overall avionic gondola is designed to be Single Points Failure free by using two segregated chains in order to be compatible with safety rules. The nominal chain is the main chain and use MC² with renewable energy. The secondary chain uses a primary electrochemical cell which feeds loads in case of undervoltage of the main chain. This overall architecture allows both chains to be designed without SPF free constrains. This paper describes the overall requirements and the design of MC². The main innovation described in this paper is the way to implement MPPT: the MPPT algorithm is performed at the output of the power converter. This MPPT extracts maximum power of both solar panel characteristics and power converter. The main advantage is that this MPPT uses only one existing sensor (output current of boost converter) instead of using current and voltage sensor of each solar panel.

## 1. INTRODUCTION

### 1.1. Missions Objectives

The scientific mission called STRATEOLE 2 [1] is a campaign dedicated to advance the knowledge of coupling processes between the troposphere and the stratosphere in the deep tropics, and foreseen in 2020-2021 and 2023-2024. The goal is to study the stratospheric dynamics and ozone chemistry in the southern hemisphere by a set of instrumented drifting balloons (objective is 30 balloons) during 3 month between 18km to 20 km of altitude.
Avionics gondola is in charge of balloon flight control (control, localisation, communication…). CNES (French Space Agency) is responsible of the development and control of this gondola. This gondola is a kind of platform in spacecraft vocabulary.
Likewise, scientific gondola corresponds to the payload gondola. In order to save developments costs both scientific and avionic gondolas shall use the same MC² and solar panel cells and packaging technologies.

### 1.2. Previous mission and experience: Concordiasi

A previous mission was successfully achieved in 2010 to validate infrared measurements made by spacecraft and to improve meteorologic and climate models. Moreover, additional aims were to improve the forecast of chemical transient on stratosphere (upper Antarctic) and to understand the behaviour of ozone evolution in stratosphere during winter and spring.
This mission was composed of 20 balloons which evolved near south-pole during a mean time of 70 days. The solar panels mounted on the avionic gondola of this mission use polycrystalline silicon cells, which were previously cut from standard size cells. A picture of a scientific gondola used during Concordiasi campaign is presented on *Figure 1* .

*Figure 1: Concordiasi avionic gondola with cuts solar cells*

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The main advantage of using cut cells is to have a serial connection of cells for a small solar panel surface with an open circuit voltage always upper than battery voltage. A simple circuit which connects to or disconnects from solar panels (8 in total) battery was used. This kind of control is usually called DET: Direct Energy Transfer.

Nevertheless, the main drawback is the low efficiency of the power conditioning. Indeed, the number of cells in series is determinate so as to have the maximum power point always upper than the battery voltage for a temperature range inside [-90°C; +110°C]. *Figure 2* shows an example of the working point of the solar panel in case of DET. The battery imposes the polarization voltage of the solar panel and the working point imposed by Vbat could be far from the MPP (depending on solar panel temperature).

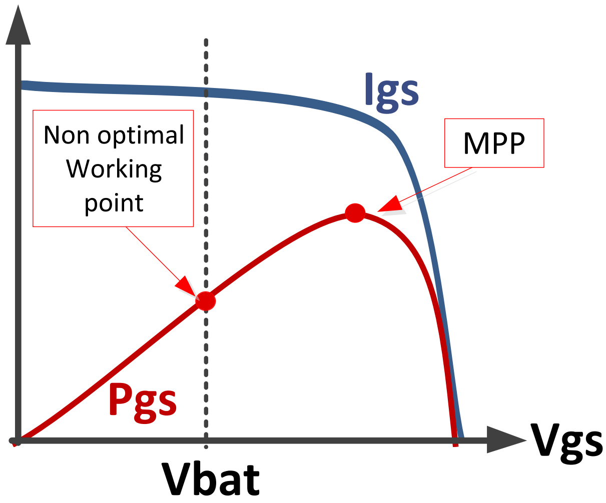


*Figure 2 : Concordiasi power conditioning*

## 2. MC² REQUIREMENTS

The first and the main technical requirement is that MC² shall be used for both scientific and avionic gondola.

### 2.1. Avionic gondola requirements

The preliminary design of avionic gondola is shown in *Figure 3*.

An energetic simulation allowed to determine that the minimum number of solar cells is 9 per solar panel for an overall power consumption of 10W (mean value). These solar cells are associated in serial. The loads to supply by the MC² in this gondola are Inmarsat and Iridium modems, radar transponder, flashing light (for aerial security), pressure and temperature sensors, on board computer and MC². Moreover, outlets uses for thermal control (heaters) are necessary. The overall need is to have 12 outlets ON/OFF controlled with overcurrent protections.

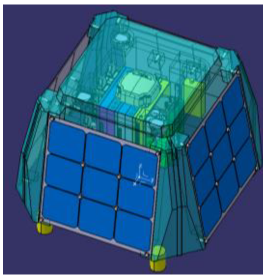

*Figure 3 : Avionic gondola preliminary design*

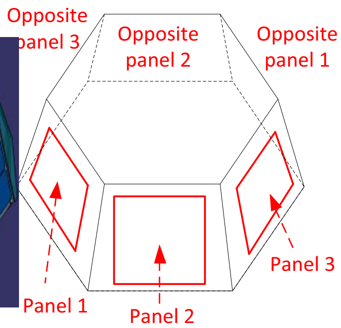


*Figure 4 : scientific gondola preliminary design*

### 2.2. Scientific gondola requirements

The preliminary design of scientific gondola is shown in *Figure 4*.

This gondola needs six solar panels with 12 solar cells associated in serial for each solar panel. This gondola needs 12 outlets ON/OFF as the avionic gondola.

### 2.3. Solar cells characteristics

The solar cells used in both scientific and avionic gondola are monocrystalline silicon cells C60Jp manufactured by SUNPOWER [2].

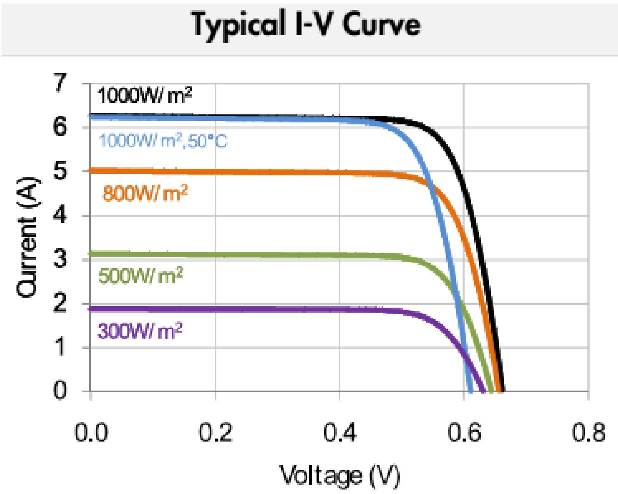


*Figure 5 : solar cells electrical characteristics*

These cells are usually used at 1000W/m². A dedicated experimental gondola launched in July 2016 from Aire sur l'Adour in France allowed recording the electrical characteristics of this solar panel in real conditions (flux and temperature). *Figure 6* shows the electrical characteristics Solar panel current IGS and voltage VGS on the top graph and solar panel power: PGS vs VGS on the bottom one. The solar panel temperature for a normal solar flux of 1368W/m² is 90°C. The main electrical data for 90°C are:

- Voc=5.1V
- Icc=7.8A
- Vmp=3.75V
- Imp=7A
- Pmp=26.5W

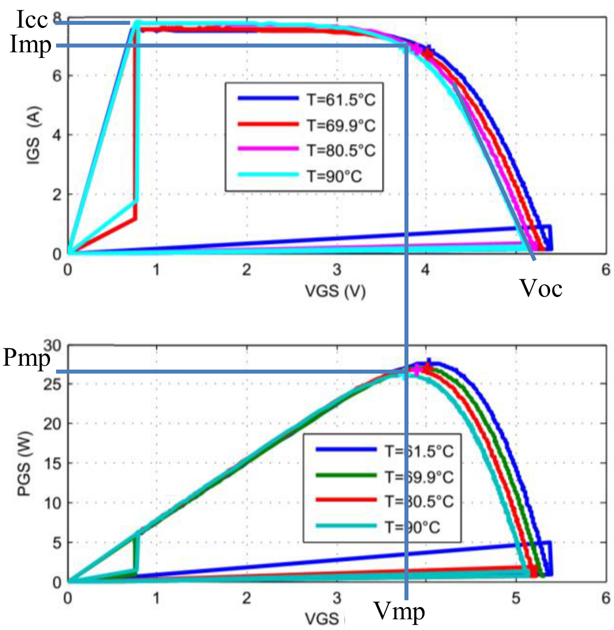


*Figure 6: Experimental data of solar pannel 9S versus temperature*

The conditioning circuit shall be designed in order to work with a good efficiency for low voltages (3.75V) and high currents (7A).

### 2.4. Battery interface cells characteristics

Usual loads are already designed and work properly in a supply voltage range [10V - 20V]. A battery with 4 LiIOn cells [3] associated in serial is used. The voltage of this battery (depending on the state of charge) is in the range [10V – 16.8V] which is compliant to the supply voltage range of loads. Consequently, an electrical architecture with an unregulated bus (battery directly connected to the distribution bus) is used.

### 2.5. Mass and volume constrains

The complete board (PCB, components, connectors) mass shall not exceed 700g for the avionics gondola and 900g for the scientific gondola. Volume restrictions are an area lower than 183*183 mm with a thickness lower than 25mm.

## 3. PRELIMINARY DESIGN OF PROTOTYPE

### 3.1. Boost regulator

According to the electrical architecture defined in §2.4 and the solar panel electrical characteristics §2.3, a voltage elevator power converter shall be used between solar panels and battery.

### 3.2. Power multiplexor

Moreover, the energy analysis already presented in §2.1 and §2.2 assumes a worst case illumination. This worst case considers only a direct solar flux of one panel and neglects the albedo flux which can provide some energy on other panels. This assumption is especially verified during flight over ocean without cloud cover. This case is a realistic case and solar cells number is determinate by considering this case.
According to this assumption, it is not necessary to have two opposite panels simultaneously connected to MC². An innovative solution which consists in using two (or three depending on the gondola) power multiplexers between solar panels and powers converters is chosen. It allows a mass optimization by combining input filters and power converters for two opposite panels. It means that scientific gondola uses 3 inputs filters and power converters, and avionic gondola uses only 2 inputs filters and converters.

### 3.3. PCB

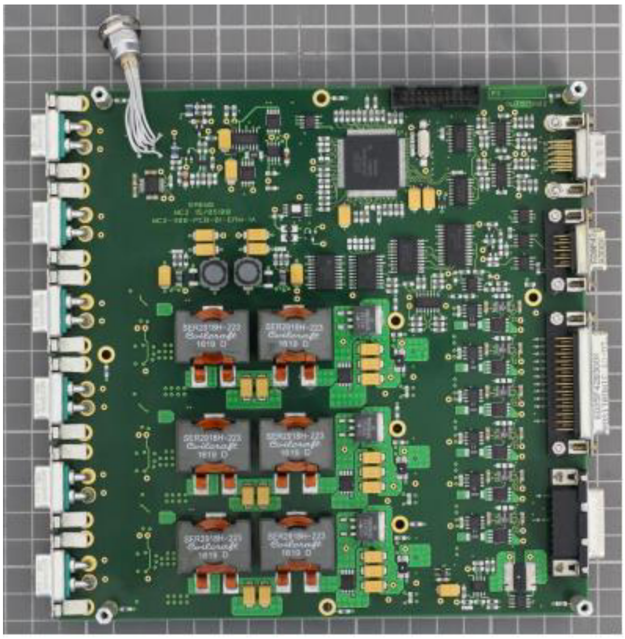

*Figure 7 : Printed Circuit Board prototype designed by EREMS. Top face*

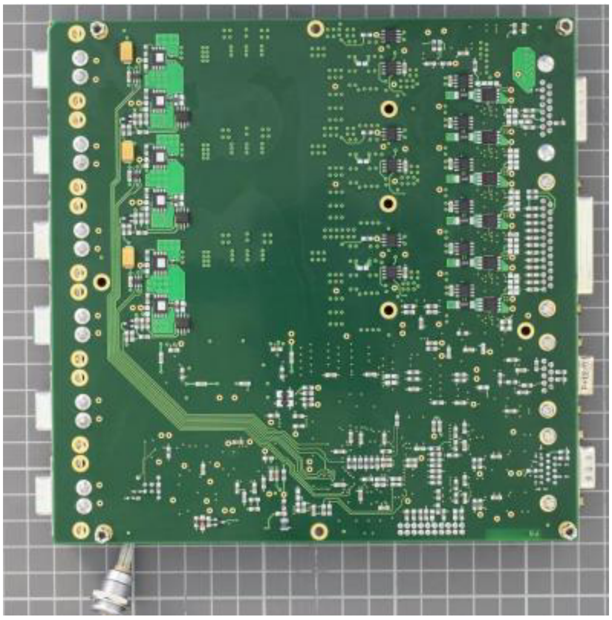

*Figure 8 : Printed Circuit Board prototype designed by EREMS. Bottom face*

This PCB is currently tested in EREMS facility's for electrical functioning purpose. CNES has no experimental results at this time, which is why this paper is focussed on simulation results. On left side of *Figure 7*, are the 2W2 connectors which will interface with the 6 solar panels. On the left side of the bottom face in *Figure 8*, the power multiplexors are visible. The differential filters (sized for few volts and 8 amps) are presented in the middle of the top face.

## 4. OVERALL ARCHITECTURE OF MC²

The overall architecture of MC² is shown *Figure 9*.

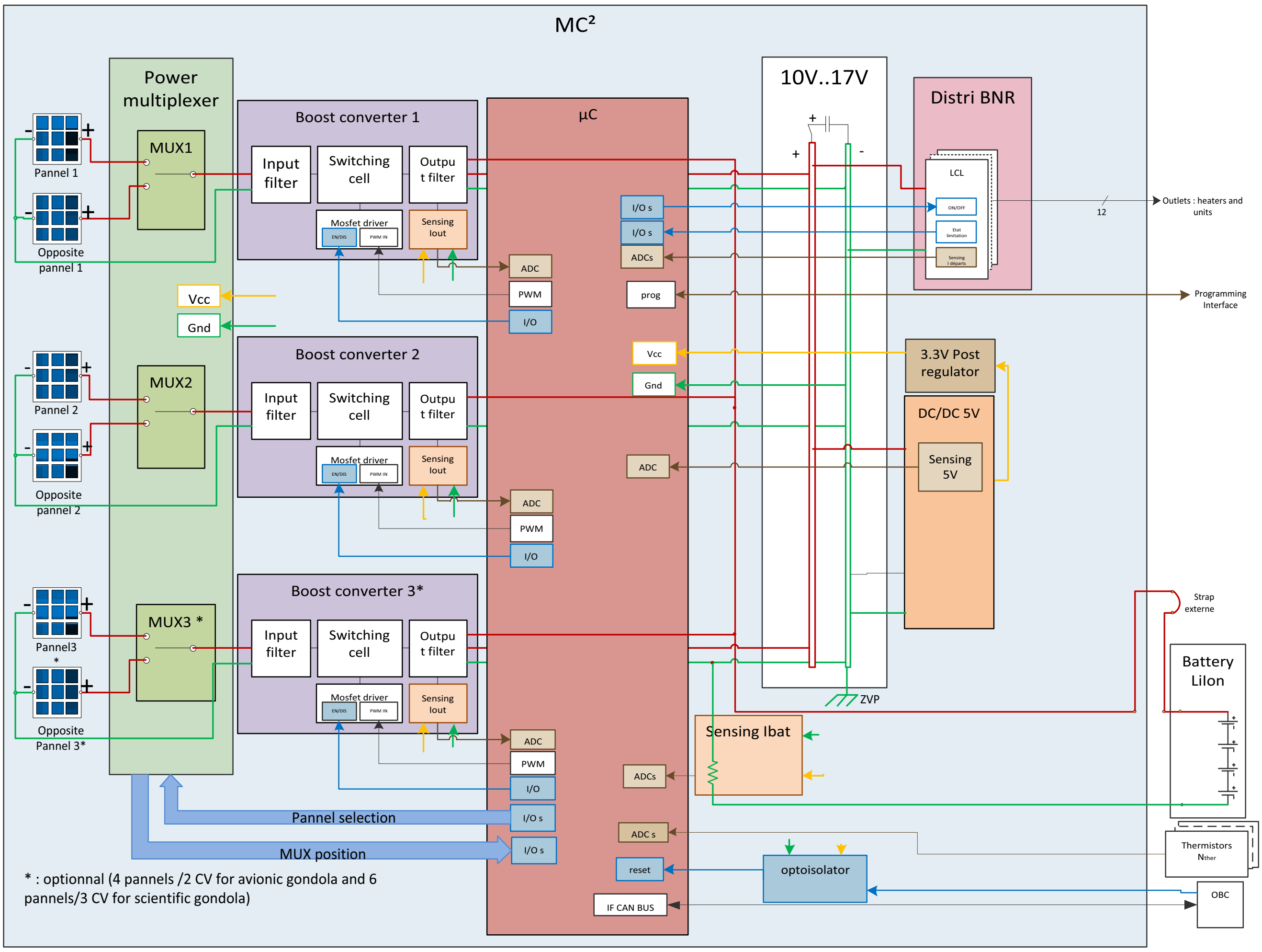


*Figure 9 : Overall architecture of MC²*

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## 5. POWER CONDITIONNING REGULATION

### 5.1. MPPT algorithm

The usual way to implement a MPPT controller is a perturb-and-observe method. The perturbation comes from a working point change, and the observation comes from measurement of solar panel current and voltage.
The main idea presented in this paper is to observe the boost converter output current as presented *in Figure 10.*
A duty cycle =1 means that the MOSFET is permanently ON and short circuit the solar panel. A duty cycle =0, means that the solar panel is connected to the battery if the rectifying diode is correctly polarized.
**As the output voltage of boost converter is imposed by the battery, the maximum output power is reached for maximum output current of the converter.**
*Figure 11* shows the solar panel electrical characteristics: IGS vs VGS on the first graph. The next graph shows the output current of the boost converter vs the duty cycle. Clearly, this graph shows a maximum current value which is reached at the MPP working point of the solar panel. The two graphs in the bottom are the solar panel current vs duty cycle and the solar array voltage vs duty cycle.

So, to explain the MPPT operation in this application, the MPPT disturbance comes from an increment of boost duty cycle provided by the PWM output of the microcontroller. This duty cycle increment is directly linked to the clock frequency and PWM bit scaling of microcontroller. The output current evolution of the boost converter is analysed and a tracker acts on PWM duty cycle in order to find the maximal output current.

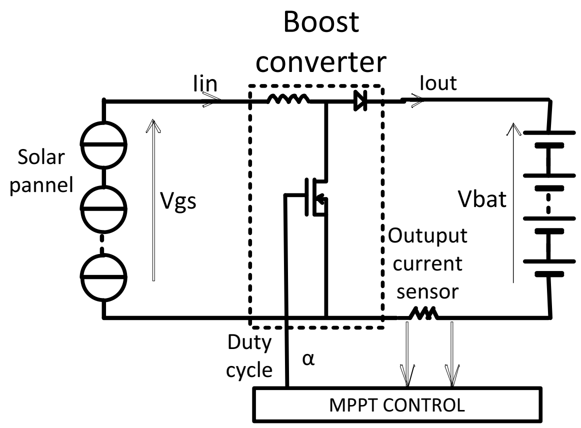


*Figure 10 : Sensor and boost converter*

It means that only one current sensor at the output of converter is sufficient to implement a MPPT. The disturbance comes from a positive or negative increment on boost converter duty cycle and the observation is the output current of the converter.

The output current sensor is already necessary for boost converter regulation. So, using this existing sensor for MPPT allows to supress (2) 3 solar panel current sensors and (2) 3 voltage sensors (2 for avionic gondola).

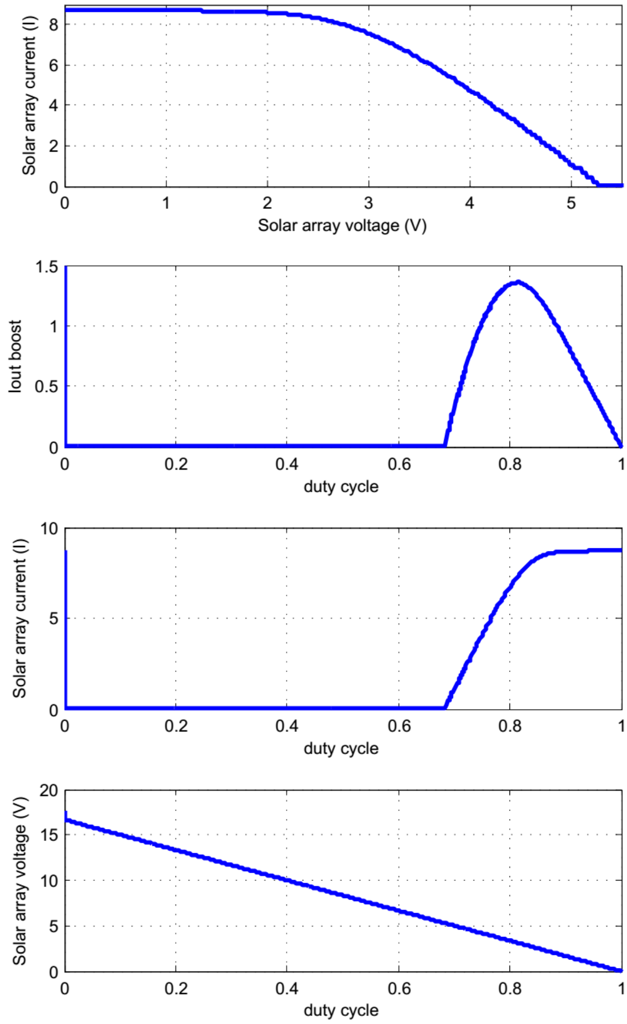


*Figure 11: boost converter output current and voltage vs duty cycle.*

### 5.2. Power Multiplexor control

If there is enough power at converters output to supply loads and to charge the battery according the profile shows in *Figure 12*, the power multiplexor keeps the present state.

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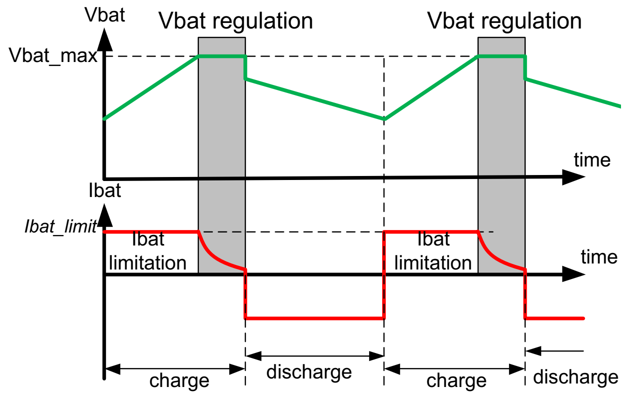


*Figure 12 : charge/discharge profile of battery*

Nevertheless, if the battery current or voltage are lower than programmed references (Vbat_max or Ibat_limit), it means that the power needed by the gondola is upper than the solar array power. In this case, the power multiplexors are switched one after the other until power at converters output becomes sufficient.
So it means that the control scans sequentially all the pairs of opposite solar panels, and selects the panels which give the more power. This power multiplexor algorithm is based on periodic timers with 120° phase shifts between each other's. In this case, the timers trigged the research of the most powered panel between one panel and its opposite panel, as explained in *Figure 13*.

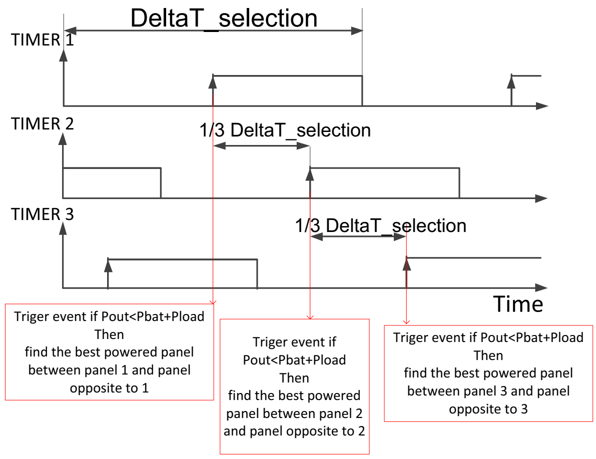


*Figure 13 : Power multiplexor timers*

5.3. Overall regulation algorithm

The overall regulation is shown in the block scheme.
First, the battery reference voltage is compared to the battery voltage at sensor output.
The voltage error goes to a Proportional Integral corrector to define the battery current reference.

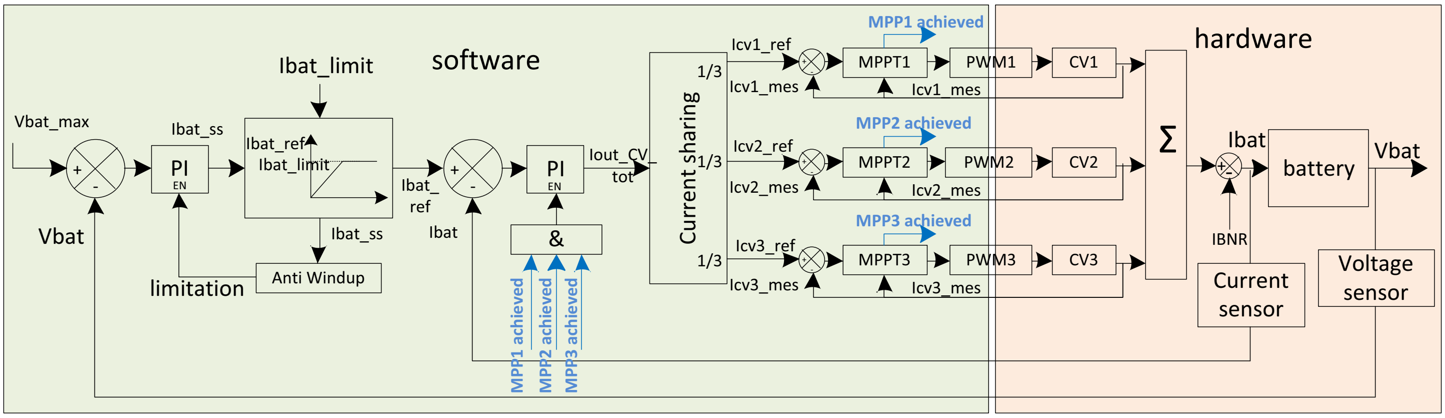


*Figure 14: Block scheme of the power conditionning algorithms*

Then this battery current reference is limited to the maximum charge rate of the battery. An anti-windup is implemented in this loop to reduce time response in case of saturation. Then, the battery current is regulated by a PI loop. The Integral action of the current could be disabled in case all MPP (1 to 3) are achieved. Indeed, it is not necessary to try to increase the total output currents of converters in case of power deficit between solar array power and power consumption of the gondola. The current sharing is balanced between the 3 converters. Then an independent MPPT algorithm is implemented on each converter.

## 6. MODELING AND SIMULATION

6.1. Introduction

A model in Matlab/Simulink was developed. This model allows simulating MPPT algorithms behaviour and power conditioning control made by MC². The hardware models are the solar arrays and their solar flux, the power multiplexors, the boost converters, the battery and loads. The software model is a

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representative sampled function. The power conditioning algorithm is representative of the software implemented inside the microcontroller for the real power conditioning. In order to test the algorithms robustness, noises have been added to converter outputs currents measurements. This simulation is focused on avionic gondola architecture (4 solar panels). All the simulation results presented hereafter are for a MC2 configured for avionic gondola architecture.

6.2. Simulation results

*Figure 15* shows the MPPT response. The algorithm starts at 0.1s and the convergence is achieved in few ms.

An internal variable shows the achievement of MPP. This variable is used for the software as explained in 5.3.

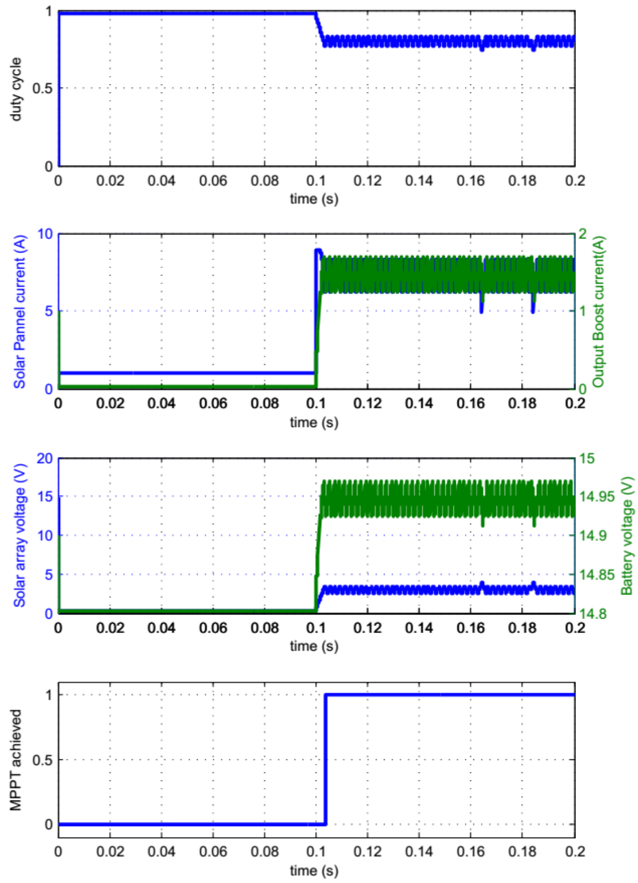


*Figure 15 : MPPT response*

Duty cycle format is 10 bits and the increment of duty cycle around the MPP is +/-30 Low Significant Bits, which is equal to +/-3% of duty cycle increment. This increment value depends on the capability of the microcontroller (depending on its clock frequency, and PWM frequency). +/-3% of duty cycle ripple leads to a solar panel voltage ripple of 1Vpp and a current ripple of 2Amps. On battery interface, the current ripple is 0.5A. This value of +/-3% of duty cycle ripple is a worst case obtained by a PWM with 5.1 equivalent useful bits, which is a very low granularity value.

The power multiplexor test is presented in *Figure 16*. Remember that avionic gondola architecture with only 4 solar panels is presented. The graph (a) simulates the solar flux view by solar panels (according to *Figure 9*). When the power multiplexor connects the panel to the converter, relative flux become a bold line. The graph (b) shows the current at multiplexor output. Depending on the value of the variable sampling mux (shows in (d) and defined in *Figure 13*), the currents have some transients. Indeed, during this transients, the other panel is temporary connected to the boost converter and the MPP of this panel is found. If the MPP of this panel is lower than the previous one, then the power multiplexor goes back to the previous position. During the temporary connection of another panel, if the MPP becomes upper than the previous MPP, then the power multiplexor keeps this position.

In (c), the variable MPP achieved is showed. Each time the variable sampling MUX is equal to 1, another panel is connected and the MPP is found.

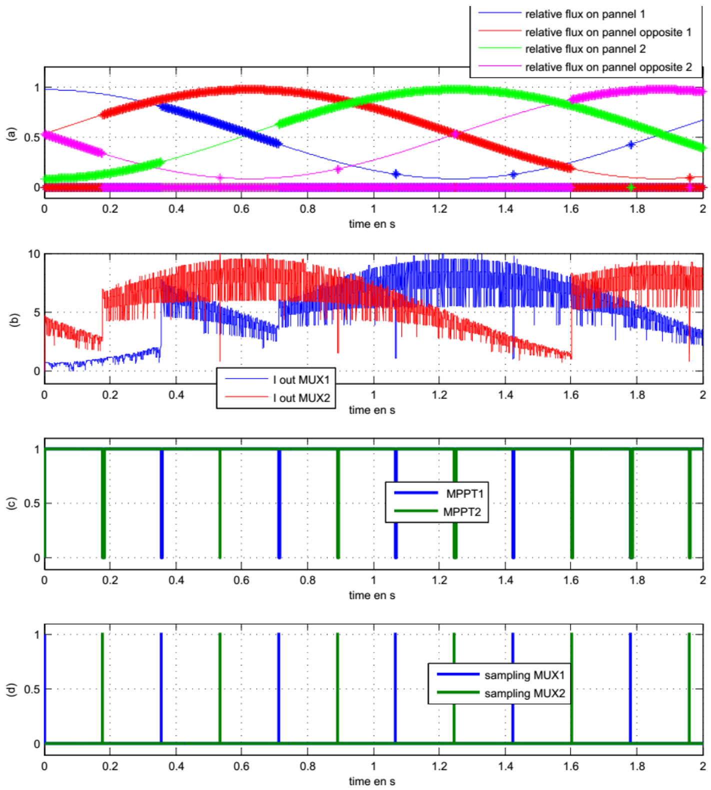


*Figure 16: Power multiplexor test*

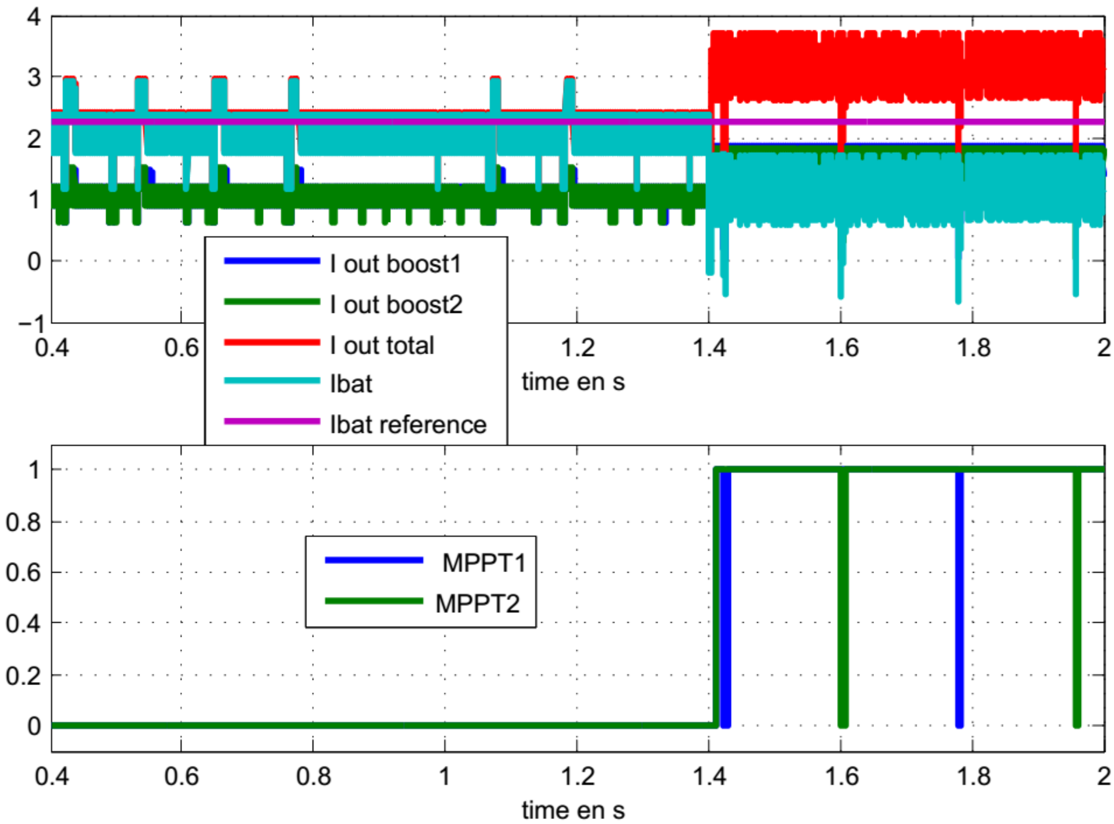


*Figure 17: Battery current regulation loop test*

Regarding the battery current loop, *Figure 17* shows the behaviour of the regulation. The reference current is equal to the battery capacity divided by 3. At 1.4s, the load current goes from 0.05A to 2A, in order to see the transient response of the loop. With a load of 2A, the solar panel power is not sufficient to maintain the battery current equals to the reference. The battery current goes to 1A, and both MPPT variables 1 and 2 go to 1. It means that the power conditioning is in MPPT mode, and all the available power at solar panels is converted by the boost converters.

## 7. CONCLUSION

This paper presents a power conditioning and distribution board for stratospheric balloons. Renewable energy is used and power conditioning algorithms using a MPPT are implemented and simulated.
A dedicated architecture based on power multiplexor allows to select 2 among 4 (or 3 among 6 depending on gondola) solar panels. The multiplexor state depends on the maximal extracted power of the opposite solar panel. Priority connection is given to the solar panel which gives the more power.
A new Maximum Power Point Tracker is implemented and associated to a boost converter. This MPPT uses the output current of the converters which is proportional to the power (the converter output is connected to a battery constant DC voltage). Simulation results are presented and the behaviour of the algorithms is showed. The board is currently in test in EREMS facilities. Experimental results could be presented during the oral session.

## 8. REFERENCES

1. Stratéole-2, a long-duration balloon campaign at the equator, 22nd ESA symposium on European rocket and balloon programmes and related research, june 2015, Tromso.

2. SUNPOWER C60Jp monocrystalline silicon solar cells : datasheet available at http://eshop.terms.eu/_data/s_3386/files/1379942540-sunpower_c60_bin_ghi.pdf

3. SAFT MP 176065 Integration cell. Datasheet Available at : http://www.saftbatteries.com/force_download/MP_176065.pdf