Electrical Power System (EPS) for Nanosatellites based on SuperCapacitors and Lithium-Ion Batteries

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***Abstract*—This paper is summarizes the research carried out at the NanoSatLab of the Universitat Politècnica de Catalunya - Barcelona Tech. Its main objective is to study and validate a design of a Electrical Power System for Nanosatellites using Supercapacitors technology as a source for systems that require high currents for a short time, together with Lithium-Ion batteries. The system is planned to be used in a 12U nanosatellite with a motor that deploys a reflector antenna.**

***Index Terms*—EPS, Nanosatellites, Supercapacitors, Lithium-Ion, DC-DC, PV Cells, MPPT, Efficiency, PCB.**

I. Introduction

THE requirements for a nanosatellite system are very varied and depend on the mission, lifetime, orbit, power budget, etc. The system must have DC-DC converters to supply from the photovoltaic (PV) system and storage systems to the different subsystems such as the On-Board Computer (OBD), the payload, the Attitude Determination and Control System (ADCS), and the Communication.

While in the orbit any satellite undergoes two cycles: the sunlight period, and the eclipse period. When satellites are in sunlight, the PV panels power the whole system, and for the eclipse a storage system is needed which will be charged by the PV panels in the sunlight. Therefore, a system for storing the energy and its corresponding charging system is necessary for the design.

We differentiate between two types of energy storage depending on the subsystem requirements. There will be systems that need high peak currents during short times, and others that need high energy density to supply during the whole eclipse period. The main objective of this project is then the use of supercapacitors for high peak currents, together with Lithium-Ion batteries for long duration consumption.

II. Validation of prework

The work has continued a first version of the design of an EPS using supercapacitors and lithium-ion batteries started in [1]. The system is divided into three main blocks, the charger block for the batteries and supercapacitors, the DC-DC converters, and distribution block and the microcontroller block.

The system was studied and analyzed for electrical and functional validation corresponding to the design. Some problems were found both in the design phase and in the PCB.

A. Footprints

There were some components with an incorrect footprint relative to the data sheet information. The incorrect components were:

1) the switch between the different DC buses, and
2) the current sensor at the system input.

B. Missing connections and subsystems

On the other hand, some connections between subsystems and access to program the µC were missing. The missing elements were:

1) the connection between the PV and battery switch with the input of the DC-DC converters,
2) the connection between the PV and supercapacitor switch, and the DC-DC converter input,
3) a connector for programming the µC, and
4) the converter subsystem with the Maximum Power Point Tracking (MPPT) algorithm for PV cells which increases performance.

After analyzing the problems and the design, some selection criteria were followed to improve the EPS designs and solutions for the problems encountered. Thus, it was decided to redesign a new EPS with improved systems and technology.

III. Requirements and Sizing

The requirements for the design are mainly the energy budget, which includes the sizing of the PV panels, batteries and supercapacitors, and the converters for the rest of the systems and for the performance of the PV cells. Table I summarizes the main power requirements, and Table II the main power requirements for the batteries. There are also requirements for system logic and control.

A. Power Budget

The power budget corresponds to the continuously required power for the different systems of the nanosatellite. The requirements must be met in the sunlight period, and in the

TABLE I
SUBSYSTEMS POWER BUDGET

System	Voltage	Current	Power
Batteries + PV			
COMMS	12 V	1.1 A	13 W
EPS	- - -	- - -	2.41 W
OBC	3.3 V	0.75 A	2.5 W
Payload	5 V	2.4 A	12.09 W
ADCS	3.3 V	0.75 A	2.46 W
TOTAL	- - -	- - -	32.46 W
SuperCap + PV			
Reflector Deployer	12 V	0.1 A	1.2 W
TOTAL	- - -	- - -	1.2 W

TABLE II
REQUIRED BATTERIES ENERGY

System	Voltage	P_{out}	Effcy. (ρ)	P_{in}	Energy
OBC	3.3 V	2.5 W	94%	2.66 W	1.33Wh
Payload	5 V	12.09 W	97%	12.46 W	6.23Wh
ADCS	3.3 V	2.46 W	94%	2.64 W	1.32Wh
TOTAL	- - -	17.05 W	- - -	17.76 W	8.88Wh

eclipse phase as well. Thus, the system has to supply the required power in sunlight and, at the same time, store power for the eclipse.

The nanosatellite has two distinct lines, the Lithium-Ion batteries and the SuperCapacitors. This distinction is due to the high current peak requirements of some systems and the high power capacity of others.

Therefore, the EPS requires four power lines for the different systems. Two 12 V lines, one for the Reflector Deployer for minimum 100 mA and powered by the SuperCapacitors and another line for the communication system with a minimum of 1.1 A powered by the Lithium-Ion batteries. The On-Board Computer and the ADCS require a 3.3 V line, capable of supplying a minimum of 1.5 A. The final line is for the 5 V and 2.4 A for the payload.

B. Lithium-Ion Batteries

The sizing of the batteries depends on the systems to be supplied and their duration. The orbital period for LEO satellites is about 90 minutes, of which 60 minutes approximately correspond to the sunlight period and the remaining to the eclipse period.

The systems that will always be powered by the batteries are the OBC, the payload, the ADCS, and the COMMS systems, which will only be operated in sunlight.

The nanosatellite consumes 17.76W in 30 min eclipse orbit. The mission lifetime is 3 years, so the required cycles for the batteries are [2]:

$$\mathbf{Cycles} = \frac{24h}{day} \cdot \frac{cycle}{1.5h} \cdot \frac{365days}{year} \cdot 3years = \mathbf{17520\ cycles} \quad (1)$$

To increase the lifetime of Lithium-Ion batteries, and to be able to achieve 17520 cycles, the Deep-Off-Discharge (DOD) must be reduced to 10% [2]. Then, the battery should be able to store:

$$\mathbf{Energy} = \frac{8.88Wh}{DOD} = \frac{8.88Wh}{0.1} = \mathbf{88.8\ Wh} \quad (2)$$

The Lithium-Ion batteries used are the **PANASONIC NCR1860**, and have 2.9Ah capacity, and 3.7V each, so 10.73Wh. [3] Finally, for this system, and this configuration, the number of cells that will be necessary is:

$$\mathbf{Cells} = \frac{88.8Wh}{10.73Wh} = 8.28 \approx \mathbf{9\ Battery\ cells} \quad (3)$$

C. SuperCapacitors

The size of the supercapacitors will depend on the system to be powered, and for how long. In this case, the system that needs a power supply capable of providing high currents peak for a short time are the motors that deploy the nanosatellite antenna for the communications antenna. The capacity is computed as:

$$C \geq \frac{I_{max}}{V_{max} - V_{min}} \cdot T = \frac{1A}{5.2V - 4V} \cdot 200sec = 166.67\ F \quad (4)$$

The supercapacitor and configuration used are the **XV3560-2R7407-R** with a capacitance of 400 F and a operating voltage of 2.7V, and therefore two of these capacitors will be used in series to obtain 200F with a total operating voltage of 5.2V. [4]

D. PV Cells

The number of PV cells required to power all systems depends on the total current required by the nanosatellite and the current provided by each cell.

From the Table I, the required power of all nanosatellite subsystems is 34W. This power is required in all phases of the orbit, therefore, the PV cells must be able to provide this power to the subsystems, while charging the energy storage systems during the sunlight period.

$$P_{in} = P_{in\,sunlight} + P_{in\,eclipse}, \quad (5)$$

$$I_{in} = \frac{Input\ Power}{PV\ Cell\ Volatge} = \frac{P_{in}}{V_{PV}} \quad (6)$$

$$Number\ of\ Required\ PV\ cells = \#_{PV_{cells}} \quad (7)$$

$$\#_{PV_{cells}} = \frac{Input\ Power}{PV\ Cell\ Current} = \frac{I_{in}}{I_{PV_{cell}}} \quad (8)$$

IV. BLOCK DIAGRAM

The system must include the converter stage, the storage systems and their corresponding chargers, and a monitoring and control logic for the different subsystems in the different periods of the orbit.

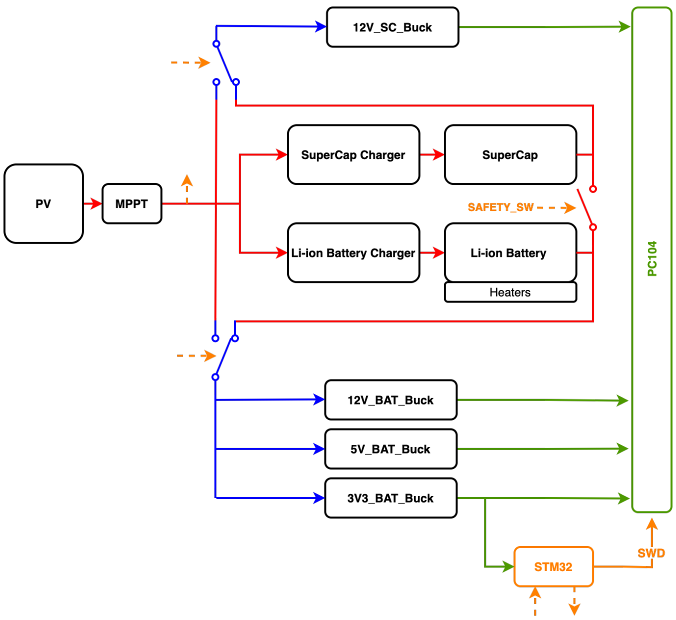

Fig. 1. EPS Block diagram.

V. EPS Design

The system design criteria depend on the requirements listed in the previous section, always aiming for the highest possible energy efficiency and to extend the lifetime of the system, as well as the lifetime of the nanosatellite.

A. PV Cells and MPPT

The efficiency of the PV cells is relatively low, around 30%. To maximize the power efficiency conversion, a power converter implementing a Maximum Peak Power Tracker (MPPT) algorithm is used. It consists of varying the resistance presented to the cells, to match the load and obtain the maximum power. [5]

Satellites typically use the 30% Triple Junction GaAs Solar Cells providing a current of ∼500 mA, and an open circuit voltage of 2.7V. Since the cell voltage is low, in order to reduce the number of cells needed and simplify the converter stage, the cell configuration is 2 cells in series to increase the voltage to 5.4V, and as many cells in parallel as needed to provide the required current. [6]

Taking into account the requirements mentioned in section *III-D: PV Cells*, the number of cells needed to supply all the systems is:

$$I_{in} = \frac{34W \cdot 2}{5.4V} = 12.6\ A \tag{9}$$

$$\#_{PV_{cells}} = \frac{I_{in}}{I_{VP_{cell}}} = \frac{12.6A}{500mA} \approx 26\ PV\ cells \tag{10}$$

For the selection of the MPPT converter, a market study has been conducted taking into account the characteristics of the converters such as the size, since the dimensions of the CubeSat board are standardized, the maximum current it can handle is limited. The converter chosen is the **SPV1040** from **STMicroelectronics**, which supports up to 1.5 A, and an input voltage range from 0.3 V to 5.5 V. [7]

As the converter chosen supports up to 1.5 A, three pairs of series cells can be connected in parallel to each converter.

Parallel and series connections between different cells can cause some issues, and even failures. With the series configuration, if a cell is not illuminated, it can behave as an open circuit. In the parallel configuration, if a cell is not illuminated, it can behave as a short circuit. Therefore, to avoid these problems, diodes are added in series, or in parallel to the cells. [2]

The final configuration of the PV cells that complies with the requirements of this design is as shown in the Figure 2. As can be seen, each cell block is duplicated due to the ±X/±Y/±Z architecture which consists of mounting identical panels on both sides of each axis. In this way, the incidence of sunlight will not depend on the orientation of the nanosatellite, i.e. it does not depend on which side of the satellite receives the sunlight.

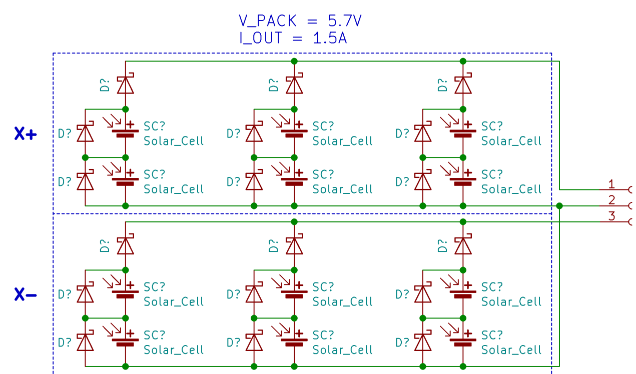

Fig. 2. PV Cell Array Configuration.

Finally, each pair of cell blocks is connected to the input of the MPPT converter to obtain the maximum power, and regulate the output of the MPPT converter to a constant voltage of 5V. To achieve the power budget, 9 blocks with their respective converter are connected to each other at the output with a protection diode. Fig. 3 shows the connections of the boost converter with the necessary components to apply the MPPT algorithm. [8]

B. Power Switch

A system is needed to switch between the power lines of the sunlight period and the eclipse period, so that all subsystems remain powered for the whole orbit without interruption.

The most common analog switches are the Mosfets and relays. The need a driver and a logic part that controls the

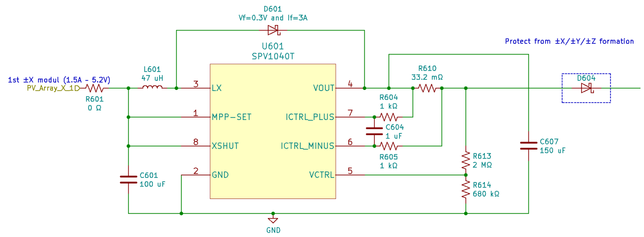

Fig. 3. DC-DC Converter with MPPT Algorithm.

selection with some criteria of which input signal to connect to the output. A system is also necessary to ensure that the power supply is uninterrupted due to switching operations, such as a capacitor at the output.

Integrating different circuits and systems to do the switching can result in an unrobust and less fault tolerant system. For this purpose an IC is used which has all the above mentioned functionalities and an autonomous control with a programmed criterion by external components. This IC is the **TPS2121** from **Texas Instruments**. [9]

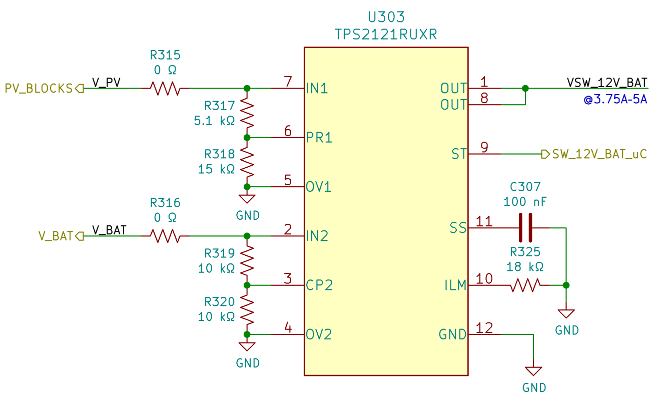

Fig. 4. Analogic Switch Circuit.

The criteria followed by the chip are as follows:

- The highest priority power supply is from the PC cells, when the nanosatellite is in the sunlight period.
- The Fast Switchover mode is enabled when the CP2 pin is higher than the internal reference voltage.
- The output should switch to the secondary input (batteries or SuperCaps) when the PV cell voltage drops below 3.7 V. However, the cell voltage drops drastically to 0 V when there is no sunlight
- The current also is limited to 5.4 A by a 18k resistor in the ILM pin.
- The chip also has the option of a Soft Start by adding a capacitor to the SS pin.

C. DC-DC Converters

The nanosatellite needs converter stages to transform and adapt the voltage of the power supplies to match the power supply voltages of the different systems of its composition. As indicated in Table I, it is necessary converters for 12 V, 5 V and 3.3 V.

The selection has been made with the criterion of maximum efficiency in order to reduce the losses and thus the energy required from the power supplies.

The converters that depend on Lithium-Ion batteries have an input voltage range between 3 V and 5 V, depending on the PV cells voltage and the battery voltage.

Two types of converters are needed, the boost converter for the 12 V and 5 V lines. And a buck-boost converter for the 3.3 V line.

For the boost converter, the **TPS61288** IC from Texas Instruments [10] has been used. And as buck-boost converter, the **TPS630242** chip, also from Texas Instruments [11]. All converters have an efficiency between 94% and 97%.

The current required for the PV cells is 6.55 A, as well as, 8.5 A for the Lithium-Ion batteries. And finally, 250 mA for the SuperCapacitors.

D. Lithium-Ion Batteries Charger

The charging of Lithium-Ion batteries is very critical as it can be dangerous, and it can cause damage to other systems if not correctly done. Batteries must be charged up to the maximum voltage and current to prevent them from heating up and eventually exploding due to their chemical composition.

The charging rate must also be controlled to extend the life of the batteries, as the number of cycles stresses them and causes the maximum capacity to decrease. The battery charging voltage also affects the longevity of the batteries, reducing the charging voltage will reduce the stress on the batteries. [12]

The charging of the batteries must follow a profile to optimize the charging and thus obtain higher efficiency. Specifically for Lithium-Ion batteries, the constant current-constant voltage (CC-CV) charging algorithm is used [13].

The figures shows the different charging stages with their respective values:
To manage the charging of the system's batteries, the **LTC4013** charger from **Linear TECHNOLOGY** has been used, capable of configuring the battery type, charge rate and charge voltage. It also has protections against overvoltages and overcurrents that would cause the battery a irreparable damage.

The Figure 6 shows the schematic of the batteries charger:

E. Supercapacitor Charger

The charging of supercapacitors must be safe and protected against overvoltage, as this will cause their destruction. In

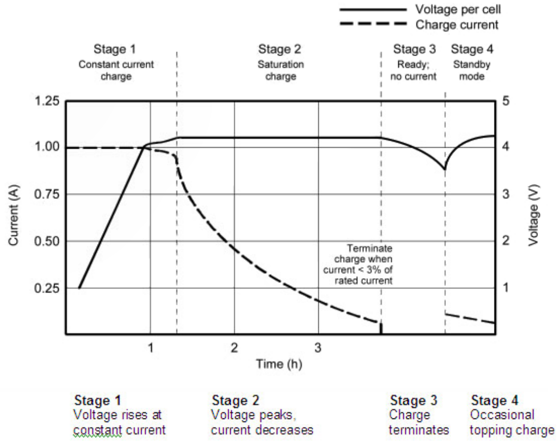

Fig. 5. Lithium-Ion Batteries Charge Profile. [13]

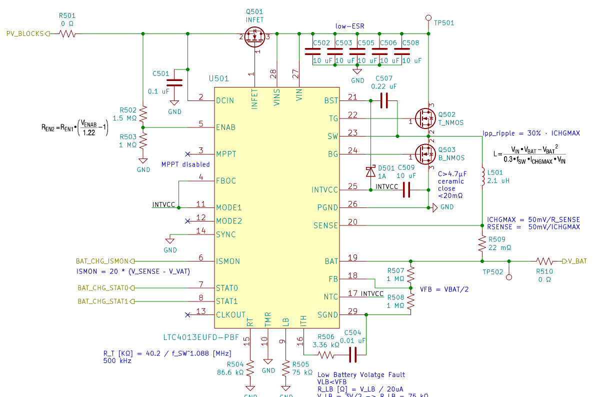

Fig. 6. Lithium-Ion Batteries Charger Circuit.

addition, when different supercapacitors are used in series, the charging must be balanced to improve efficiency and extend lifetime.

The advantage of using supercapacitors is that charging is less complex than Lithium-Ion batteries and that their lifetime is virtually infinity. They can be charged at any rate and can also be discharged at a DOD of 100% without affecting their performance. [14]

The charge of the supercapacitors is conducted using the **LTC3125** integrated circuit from **Linear TECHNOLOGY**, which allows balancing them with a very accurate input current limiter.

The charging current can be up to 3 A, and fixed during charging. In this case the charging current is 1A to reduce the power budget as the charging time is more than enough. The charge current limit is set through the combination of a resistor and a capacitor on the PROG pin of the charger.

The charging voltage of the supercapacitors is the most critical factor, since a high value could lead to their destruction. According to the manufacturer's datasheet of the supercapacitors [4], the maximum voltage they can withstand is 2.9 V. By means of a resistor connected externally to an internal current source the charger compares the voltage of the supercapacitors with the voltage drop across the resistor (maximum voltage), and regulates the charging voltage.

The Figure 6 shows the charger schematic:

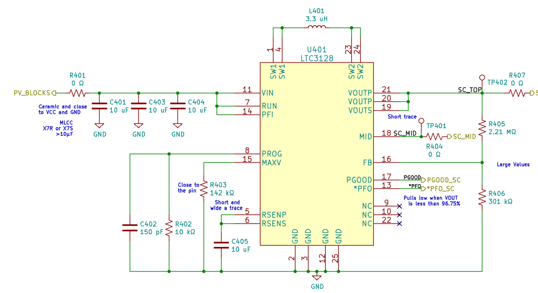

Fig. 7. SuperCapacitors Charger Circuit.

F. Microcontroller

A logic system monitors and controls the different stages and ensures the proper functioning of the ensemble. For this purpose, the L4 microcontroller (µC) family of STMicroelectronics is used, specifically the STM32L412C8T6, because of the low power consumption, and improved efficiency.

A watchdog is also used to control and protect the µC in case it fails or stops responding.

The µC also monitors the status of the different EPS systems through digital signals connected to its GPIO ports. The option of having communication buses, such as i2c or SPI or UART, between the EPS, and the other nanosatellite systems has also been considered.

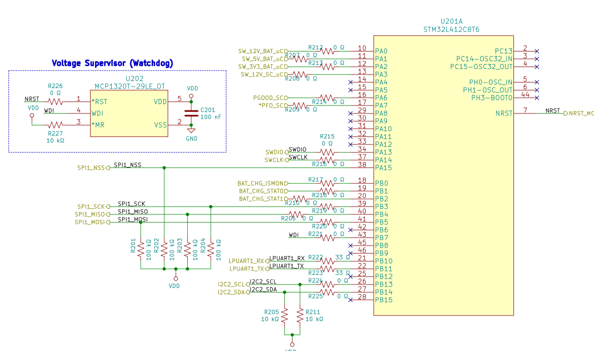

Fig. 8. Microcontroller Circuit.

VI. PCB Design Considerations

The most important requirement for PCB design is compliance with the PC104 standard. This standard defines the dimensions and connector position of the PCBs that form the CubeSats. [15]

To place the components the rule followed consists of placing the circuits of the same block as close as possible. The decoupling capacitors have also been placed as close as possible to the power supply pins to avoid and filter noise.

For the thermal efficiency of the board, the width of the traces has been calculated as a function of the current flowing through them by means of the following formulas:

$$Area\ [mils^2] = \frac{I\ [Amp]}{k \cdot {T_{rise}}^{b}\ [^{o}C]}^{1/c}, \tag{11}$$

$$Width\ [mils] = \frac{Area\ [mils^2]}{Thickness\ [oz] \cdot 1.378\ [mils/oz]}, \tag{12}$$

where, following IPC-2221 standards [16], k = 0.024, b = 0.44, c = 0.725 for internal layers and k = 0.048, b = 0.44, c = 0.7 for external layers.

The design has taken into account the validation phase by adding 0 Ω (short-circuit) resistors at different points of the circuit to enable block sectioning and isolate them from each other for individual validation and also to have test points to measure the signals.

The resulting PCB is shown in Figure 9:

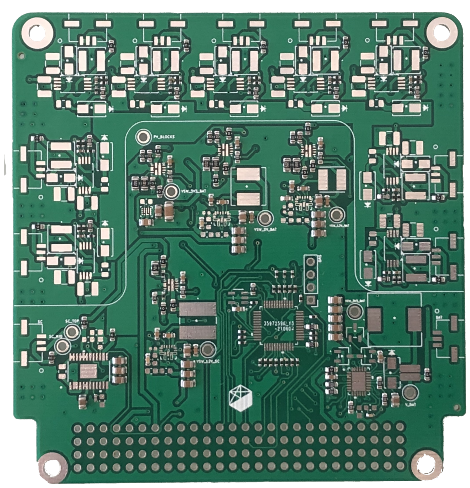

Fig. 9. EPS board manufactured.

The PCBs have been manufactured and some passive components have been assembled with the company JLCPCB, and the remaining components will be assembled in the NanoSat Lab.

VII. Future Work

A. Heat System

An interesting future line of work is the implementation of a heating and temperature control system for the batteries. With this system it would be possible to achieve optimal working conditions for the batteries and thus increase their lifetime.

B. Auxiliary System

To increase the resilience and robustness of the system it would be interesting to add a circuit and algorithm that would allow to use the SuperCapacitors as the main power source in case the batteries die and thus increase the lifetime of the mission.

C. Customized Design

As seen throughout the paper, this design is a generalized system for different missions. To increase the efficiency of the system and its sizing, the values of the power budget and requirements should be redesigned specifically for each mission.

VIII. Conclusion

A robust electrical power system has been designed according to the power budget and functionality requirements of the project. It has been a challenging task due to the complexity of integrating numerous systems and components in a reduced space such as this board, but at the same time it has been motivating to work on a project for nanosatellites and especially for NanoSatLab - UPC.

A complete validation of the design and its functionality will be performed. It will be performed voltage measurements on the outputs of the power converters and MPPT converters, the operation of the analog switcher, the operation of the chargers as well as the charging and discharging time of the Lithium-Ion batteries and the SuperCapacitors.

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