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Designs and Implementations for CubeSat Colombia 1 Satellite Power Module

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Abstract

This article contains the results of the research process, analysis, and EPS (Electrical Power Subsystem) design for the small satellite CubeSat Colombia 1, Project CubeSat UD, Telemedicine and Telemetry, of the Universidad Distrital Francisco José de Caldas. Initially, a theoretical Preliminary Design of the Power Module was established, determining components and topologies of the Module; after the Version 1 of the Critical Design was completed based on the first implementation of the Preliminary Design, the results led to the Final Version of Critical Design. Electrical and physical tests were performed on the Printed Circuit Boards (PCBs), manufactured by specialized companies, with designs of students and teachers in Altium Designer software. For tests, it was necessary to use power supplies, multimeter, oscilloscope, scales, among others. Due to these electrical tests, it can be stated that the Final Version of the Critical Design is reliable; however, it is still important to adequately validate the delivery of the necessary power to the users in orbiting conditions, for future works.

Keywords: Power Module, CubeSat Colombia I, Preliminary Design, Version 1 of Critical Design, Final Version of Critical Design.

INTRODUCTION

After the starting of the space age on October 4th, 1957, with the launch of Sputnik 1, the high costs of space projects has limited the real access to space of many nations and international agencies. To counteract this trend, many global institutions are developing small satellites with Very Large Scale Integrated Circuits (VLSI)[1]. It has been possible for almost all university in the world to develop its own satellites, thanks to the CubeSat Standard[2]. The CubeSat Standard emerges from the CubeSat Project began in 1999, and seeks to reduce the costs and time of development of picosatellites, increase the accessibility to space and allow frequent launches to be sustained[3].

The CubeSat launch began on June 30th, 2003 aboard the Rockot spacecraft from the Plesetsk Cosmodrome, Russia. The rocket contained the Danish satellites AAU CubeSat and DTUsat, the Japanese CubeSat XI-IV and CUTE-1, the Canadian CAN X-1, and the triple US CubeSat Quakesat. After this launch, there was a great participation of students from different universities of the world; by the year 2015, we can talk about more than 230 CubeSat launched by different universities around the world, and several future projects that will allow to establish the capacity of the CubeSat Project, when it will be used as satellite constellations [4]. In Colombia, for example, on April 17th, 2007, CubeSat Libertad 1 was placed in Earth orbit, which was acquired and adapted by the Sergio Arboleda University of Colombia and it is the first object in the orbit of the Earth by a Colombian institution [5]

In [3], the CubeSat satellite is defined as a 10 cm edge cube, with a mass of up to 1.33 kg and the requirements of a CubeSat are shown. To its deployment there is a standardized system, the Poly Picosatellite Orbital Deployer (P-POD) from Cal Poly University, a system that serves as an interface between the CubeSat and the Launch Vehicle (LV) [6]. During launch, the satellites must be turned off through of a disconnect switch. Once the satellite is deployed in space, the switch will be activated and the satellite will begin to operate [7]. On the other hand, the cards that compose the CubeSat, must be stacked vertically, according the PC104 Standard, that is based on 104 contacts on two bus connectors (64 connections on P1, and 40 connections on P2) [8]. In the PCB specifications for the CubeSat, the PC104 bus are named CubeSat Kit Bus [9].

The CubeSat, like other satellites, can be visualized in each of the following parts and subsystems: structure, communications subsystem, position control subsystem, power subsystem, command and data management subsystem, thermal control, propulsion subsystem and payload [4]. One of them, the satellite's Electrical Power Subsystem (EPS) has the purpose of providing, storing, distributing and controlling the spacecraft's electrical energy [10]. The basic EPS components include a primary power source, power regulation, rechargeable energy storage, power distribution and protection, and power loads [11].

A common source of primary energy are solar panels, made up of semiconductor photovoltaic cells that transform the energy of light into electrical energy; the photovoltaic cells just like the panels are interconnected in series (to obtain more output voltage, with the same current) or parallel (to obtain more output current, with the same voltage)[12]. Multi-junction cell panels, can achieve greater efficiency than those with single junction cells, because they can convert energy into a wider light spectrum [13], which includes albedo radiation and terrestrial infrared radiation [14]. In order to protect the panels from the shadows that can be generated in the solar cells, the bypass diodes are used [15]; at the same time, the use of the blocking diodes is necessary, to avoid the return of currents to the panels, fact that can occur in the absence of sunlight [16].

During the eclipse periods, the secondary batteries must provide the satellite the energy stored in electrochemical form, for long duration missions. [11]. Types of secondary batteries include those made from: nickel-cadmium (NiCd), nickel-metal hydride (NiMH), nickel-hydrogen (NiH2), lithium-ion and lithium polymer Li-po) [17], [18]; Lithium-based secondary batteries, are commonly used in portable electronic devices, because of their low weight and high energy [17]. In [18], a comparative study is made between some types of batteries, and it is mentioned that the Lithium Polymer- Ion battery cells possess only between 16% and 17% of the size of Lithium Ion batteries; however, they have a smaller capacity of charge storage. To mitigate this disadvantage, the load capacity is increased by performing parallel cell arrays.

Power Management and Distribution (PMAD) Systems control the power flow to the spacecraft's subsystems. For example, many manufacturers of EPS (Electrical Power Systems), can distribute a regulated voltage of 5 V and 3.3 V to several subsystems [17]. The part of the regulators is necessary, because it must provide conditioned energy to the electrical systems of the satellite properly [19]. Therefore the energy of the batteries or panels must be regulated for the power supply of the loads or users of the Power Module, and must be provided by fuses or protection circuits [19].

The CubeSat Colombia 1 satellite, is expected to be in a synchronous circular orbit LEO (Low Earth Orbit), between 600 km and 800 km in height [20]. In LEO, the satellite is exposed to high vacuum, ultraviolet radiation, thermal cycles, charged particles, electromagnetic radiation, micrometeorites and space junk[21]. The pressure in the LEO orbit is close to vacuum (near to 10^{-5} Torr at 200 km or less, as the height increases), and the thermal cycle can vary between -150 ° C and 150 ° C, according to[21]. The temperature for a CubeSat in LEO, according to [7], [22], can vary between -40 °C and 80 °C, although data collected by the CP3 show a variation between -30ºC and 20ºC [23]. In [24], EPS must operate at temperatures between -10 ° C and 60 ° C under vacuum.

In space, the satellite will pass through illumination and eclipse periods, which in LEO orbits represent about 36% of the orbit [25]; it means that the batteries must contain at least 5000 charge and discharge cycles for one year [18], [26]. The irradiance on the CubeSat varies according to its distance from the sun; in this sense, it is estimated that the irradiance can vary between 1328.66 W / m^2 and 1421.06 W / m^2 on Earth and the satellites orbiting around this, due to the translation movements[27]. Many tests for CubeSat are made with the constant Solar Zero Mass (AM0), which is 1366.1 W / m^2 ±7 W / m^2 according to [28]. According to [29], the effective irradiance absorbed by the CubeSat decreases, depending on the variation of its angle of incidence

This article discusses a methodical development of the Power Module (equivalent to EPS) of the CubeSat Colombia 1 of the Universidad Distrital. The design process of the Power Module begins with a Review of the Preliminary Design and ends with the Review of the Final Version of the Critical Design, which is the most reliable version for the results obtained in the tests performed.

CONFIGURATION AND IMPLEMENTATIoN OF THE PRELIMINARY DESIGN FOR CUBESAT COLOMBIA 1 POWER MODULE

The preliminary design of the Power Module was carried out by Augusto Chaves Garcia [30], therefore, to explain this part his thesis is taken as a source. To establish the best topology of the Power Module and the most appropriate devices, a SWOT analysis was performed. The SWOT analysis is one of the many possible tools of strategic planning used to evaluate the Strengths, Weaknesses, Opportunities, and Threats involved in a project, or any other situation that requires a decision[31]. Topology selection is vital, since through it, the organization of each of the subsystems of the Power Module is established, and its peripherals. The chosen topology is in Figure 1, this consists of different devices such as the charger device batteries, DC/DC regulators, power supply, a MSP430 microcontroller and protection circuitry switches to the user. The microcontroller is intended to perform an OBC (on board computer) or subsystem command and data management procedures. The latter receives, validates, decodes and distributes orders to other subsystems of the satellite[1].

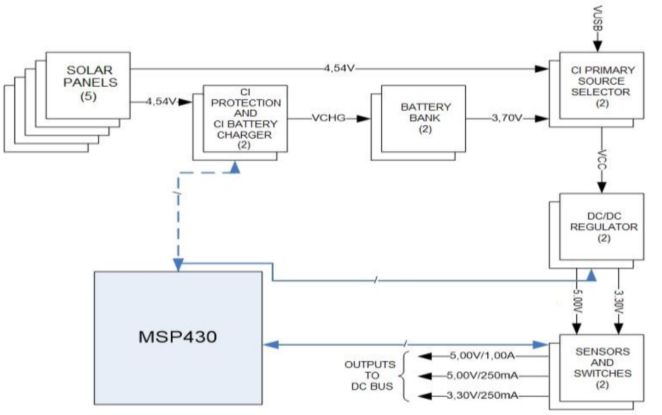

Figure 1: Block Diagram for topology of Preliminary Design.

The regulators implemented are of two types, with fixed voltage outputs from 3.3 and 5.0 Volts. The regulators are designed to perform soft interruption and low emission, so is that there is no interference between the communications and telemetry modules. The numbers under the labels correspond to the number of items that are used, for example, the use of two banks of batteries is observed.

A. Battery Charger Design

BQ24010 device by means of SWOT analysis was chosen for the battery design charger. For the implementation of the device it was necessary to establish components such as resistors, capacitors and a thermistor, which are implemented taking into account the thermal characteristics that should be charging the batteries, and according to the datasheet of the IC (integrated circuit)[32]. It is important that the charging of the batteries occurs inside temperatures of 0 to 50 degrees Celsius. The thermistor used was the NTC's reference NCP18WM474J03RB from Murata manufacturer[33], whose characteristics are: resistance value at 25° C of 470 kΩ, resistance value at 0° C of 1794,358 kΩ, and resistance value at 50 ° C of 146,215 kΩ. The schematic diagram of the implementation is located in Figure 2.

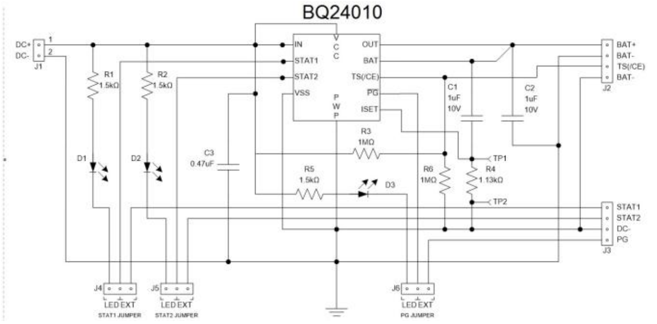

Figure 2: Schematic for battery charger.

B. Design of DC / DC Power Regulators.

Here, two independent regulators adjusted 3.3 V and 5.0 V were established. The regulator 3.3 V takes the tension panels (maximum of 4.54 V) or battery (maximum 3.7 V) to establish a constant level of 3.3 V. The 5 volt regulator is a voltage lift, considering it takes the tension of the selected source and elevates it to a constant level of 5.0 Volts. The TPS601XX device was chosen by means of analysis SWOT. The external components of the device were established with the information from the datasheet [34], [35]. For the actual assembly a charging current of 400 mA was determined for the regulator from 3.3 V, and charging currents of 900 mA for 5.0 controller V. because of this it was necessary to locate two regulatory circuits of 3.3 V in parallel and 3 regulatory circuits of 5.0 V in parallel. The Implemented circuits are observed in Figure 3 and Figure 4.

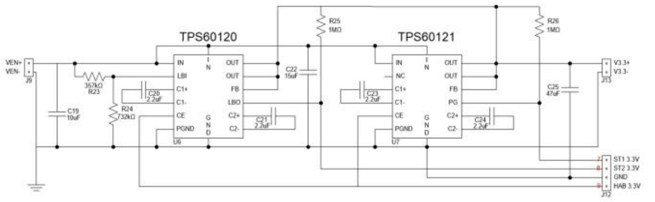

Figure 3: Diagram of regulators for 3.3 V.

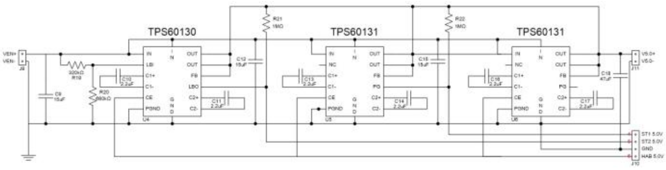

Figure 4: Diagram of regulators for 5 V.

C. Design of the Primary Source Selector and User Protection.

The primary source selector is in charge of selecting between solar panels and batteries as power system when the satellite is in flight. This selector must make a soft interruption and at the same time instant, among the power sources. For ground tests, three types of sources were established: solar panels, batteries, and USB voltage. By means of analysis SWOT was chosen the device TPS2111, whose description is found in[36]. Figure 5 shows the diagram of the primary source selector circuit which was implemented with two TPS2111 devices for the selection of three types of power supplies.

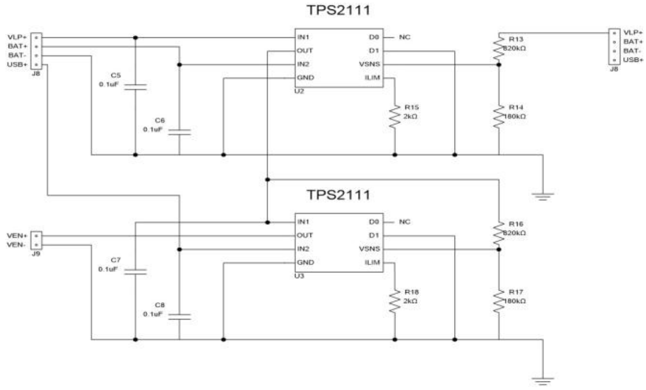

Figure 5: Diagram of the primary source selector.

By means of analysis SWOT was chosen the TPS20XX device, which is a "hot-plug" or hot-plug device manufactured by Texas Instruments. The TPS2062 is useful for connecting users with 5.0V/1A switches, the TPS2092 is useful for connecting users with 250mA/5.0V and 3.3V/250mA switches. The devices also feature limitation of current, and thermal protection and short circuit[37], [38].

D. Implementation of the Preliminary Design of the Power Module.

From the specifications shown in the Preliminary Design the first assembly and implementation of the Colombia 1 satellite Power Module was carried out [39]. In this assembly, the following modifications to the original design were made: only a selector device of primary source was implemented that commutes between the Bank of batteries and solar panels; on the other hand, a battery charger was only with its corresponding battery bank. In this implementation, no tests were performed with the control of the MSP430 microcontroller. Figure 6 shows the implementation of the Preliminary Design made up of: the IC BQ24010 labeled IC1; The IC TPS60120 labeled IC2 and the IC TPS60121 labeled IC3; The IC TPS60130 labeled IC4 and two IC TPS60131 labeled IC5 and IC6; The IC TPS2111 labeled IC7; Three IC TPS2062 user protection, labeled IC8, IC10 and IC12; And three user protection ICs TPS2092, labeled IC9, IC11 and IC13.

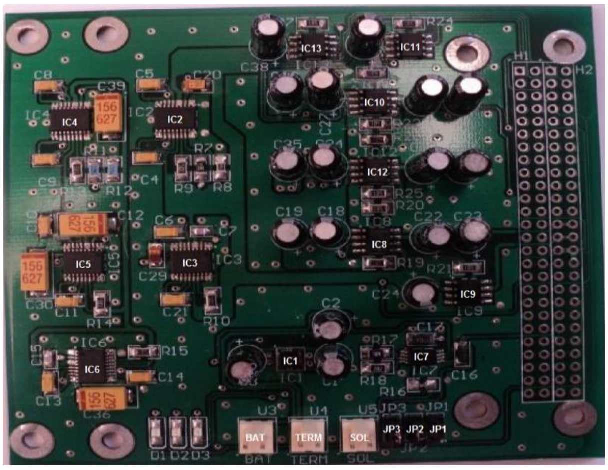

Figure 6: L Implementation of Preliminary Design of CubeSat Colombia 1.

E. Testing for the Implementation of the Preliminary Design

Testing included printed card shown Power Module in Figure 6, 2 NiMH batteries brand BESTON 1.2 V with a capacity of 3000 mAh each[40], resistors of carbon 470kΩ and 47 kΩ, an adjustable DC source, a multimeter and an analog oscilloscope. Tests consisted of supplying printed card Power Module with the source DC adjustable via the SOL terminal card, to simulate the input of the panels.

In early testing, the discharged batteries were connected in series to the BAT terminal and in the terminal TERM, individual resistors were placed. First a 470kΩ resistor and then another one of 47 kΩ, representing the values of resistance at 25 ° C and 90° C thermistor NTC NCP18WM474J03RB[33], in both tests three LEDs showing the State of battery charge and was measured with a multimeter the current delivered to the batteries. The currents measured were 100 mA in the first test and 0 mA in the second test. According to these tests, the battery charger can deliver pre-charge current if thermistor is at a temperature of 25 ºc to charge the batteries; in the event that the thermistor is at a temperature of 90° C there will be no power to the batteries.

Tests were also conducted with the primary selector to set which voltage was selected at the output from different input voltage values. For almost all cases greater voltage to the input value is selected as expected, except when one of the input voltages were very low and the other was null. In the latter case, out of the selector was observed a zero voltage, which indicated that the input voltage was below the threshold of input voltage. With respect to the tests with power regulators on the oscilloscope, it was observed that the voltage level at the output of the 5 V regulator had a negligible kink, while the output voltage of the 3.3 V regulator had a kink from 3.2 to 4.7 V above the DC level of 3.8 V. In the Protection Circuits test users, using a multimeter, it was observed that when the enabling terminal was grounded, the DC voltage of the regulators was displayed at the output, as expected, nonetheless, when it was in an open circuit state unexpected voltage levels were displayed.

VERSION 1 OF CRITICAL DESIGN OF POWER MODULE FOR CUBESAT COLOMBIA 1

The first version of the Critical Design of the CubeSat Colombia I Power Module was developed by Javier Castro and Alfredo Grajales, to explain this work, it is used as a source[41], [42]. The scheme of the initial Critical Design of the Power Module is located in Figure 7, which does not differ much from Chaves design, however, modifications in the reference of the charging battery devices, DC/DC regulators, and user protection circuits were made. New Input regulators were implemented within the solar panels as well as battery charging circuits, for each pair of opposite panels one of these input controllers were implemented. A microcontroller was established to allow the autonomous operation of the Power Module, this microcontroller communicates with the OBC.

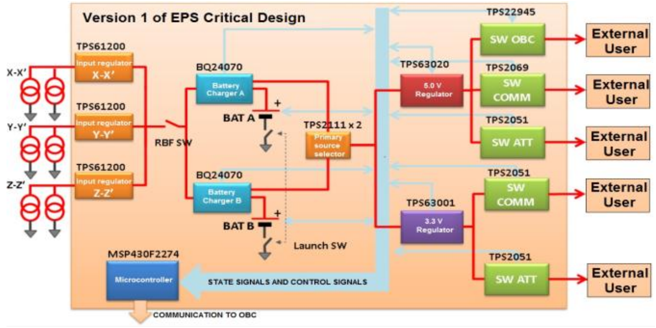

Figure 7: Schematic of version 1 of the Critical Design of Power Module in CubeSat Colombia 1.

Figure 7 shows the users that connect to the module (green boxes), on which are the references of the protection and distribution switches of each one. There are also the blue lines that refer to signals, status and control. The description of each of the components is as follows: 3 regulators TPS61200 entry to deliver an appropriate level of voltage to battery chargers; 2 BQ24070 battery chargers; 2 multiplexer TPS2111 in parallel in order to handle more power to regulators; a TPS63001 controller for the 3.3 V bus; a TPS 63020 controller for 5.0 V bus; 3 integrated TPS2051B for control of the power of 5.0 V and 3.3 V of attitude control module, and 3.3 V of the communications module; 2 integrated TPS2069 for control of the power of 5.0 V of the communications module and battery heaters; an integrated TPS22945 for OBC module power control of 5.0 V; microcontroller MSP430F2274 which monitors signals of State and control via the General Purpose Input/Output (GPIO) terminals. The I2C communication port for temperature sensor data, battery electrical power, and communication of the status of the EPS with the OBC using Serial Peripheral Interface(SPI) are used.

A. Specific Description of Modified or Aggregated Components

For version 1 of the Critical Design the batteries of Lithium Ion Polymer of high energy density of the manufacturer DANONICS of reference DLP 375388-01 were established, some main features according to[43] are: single cell, rated at 1.7 Ah, nominal voltage of 3.7 V, maximum charging voltage of 4.2 V, minimum discharging voltage of 3.0 V. Connectors are used to establish the set of batteries of coupling manufacturer SAMTEC, whose female connector is SEML-105-02-03.0-H-D reference for the EPS, and the male connector is TEML-105-02-03.0-H-D reference for the set of batteries. The printed circuit board and the assembly of the components were made by Sequoia Space Company. Heaters battery reference KHLV-103/5 p, the integrated circuit INA209 were also added to the monitoring voltage, current and power of the battery through the I2C Protocol. In addition, three temperature sensors LM75 were established to monitor the temperature inside the satellite and each battery. A TPS2069 reference current limiter of 1.5 A was incorporated, and led indicators were included as reference for status signals·[43].

Input controllers are responsible for providing a voltage level of constant 5V circuits for battery chargers. A regulator was established by each pair of opposite faces of the CubeSat, whose panels are connected in parallel. The device that was chosen as input controller was the TPS61200, according to the datasheet, it is a DC/DC converter which is suitable for one, two or three cell alkaline batteries, and it is also useful for Li-Ion or Li-Polymer batteries in a cell. This circuit is able to work with voltages coming from the panels between 0.3V and 5.5V, and provide a fixed output voltage of 5V[44].

For the battery charger circuit the BQ24070 was used, some of the functions of the device according to the datasheet,: the device is capable of allowing the delivery of power to the system and charging batteries simultaneously through the administration of the power path (DPPM), it supports a total current up to 2A, thermal regulation by charge control, protection reverse current, short circuit and temperature[45].

For the 3.3V bus, the reference TPS6012X was replaced by the TPS63001 reference. Also for the 5.0V bus the reference TPS6013X is replaced by the reference TPS63020. Among some of the functions of the TPS63001 device according to the feature sheet, we have that it is a device with a typical value of current limit on their switches of 1.8A, it is able to provide a current of up to 800 mA with the voltage of 3.3V in elevator mode, it can provide an efficiency up to 96%[46]. According to the feature sheet of the TPS63020 device, the maximum average current limit on their switches has a typical value of 4 A [47].

B. Evaluation Cards and Final Card of the Critical Design Version 1.

Evaluation cards were designed in the computational tool Altium Designer. Initially, tests were performed within the range specified by the manufacturer and then were conducted under conditions of over-consumption of power. In general, the results were according to the data from the manufacturer except for the TPS2111 which provided current management less than the manufacturer established[43]. After testing the circuits on their respective evaluation cards, the Critical Design Version 1 final card was built and assembled. A card was manufactured with the CIDEI Company and the other one with Microemsamble. See Figure 8.

Figure 8: Implementation of version 1 of Critical Design of Power Module in CubeSat Colombia 1.

C. Tests with the Version 1 of the Critical Design Power Module.

Results and adjustments are summarized in the following way: The battery chargers operated correctly, but they had problems overheating. This is attributed to a design problem in the dissipation planes. The power multiplexer had a critical failure due to it burned during a test with moderate current, since this stage was replaced, the failure persisted; the ultimate test was done with a charge of 6.9 Ω measuring at the output of the OBC user of 5.0 V with an output current of 0.8 A before burning the component. In addition there were never switching between sources. In the 5.0 V bus controller, there was a troubling ripple of 1 Vpp voltage, it also had the same disadvantages of temperature in the battery charger. The 3.3 V regulator had trouble in the inductor, buzzing and overheating. The user switches had a good performance. The microcontroller did not work, not even after replacing it and the reason for the failure could not be determined. There was the need for resistors pull up for Chargers enabling signals, by which adjustments were made. Due to the failure of the microcontroller, wires had to be welded to manually activate the integrated circuits for testing. There was a deficiency in the design of land planes and voltage levels. The routing of the tracks established was complicated, with many paths crossed between the two layers of the PCB. There was a critical error in selecting the connector of the battery pack and it was necessary to use an adapter to make the connection.

FINAL VERSION OF CRITICAL DESIGN OF THE POWER MODULE.

To explain the Final Version of the Critical Design of the Power Module, the degree works of Andrés Moreno and Javier Castro are used as sources. As it was already seen in the results for the 1.0 version of EPS different types of problems were as switching between sources (batteries and solar panels), temperature problems, and problems in the PCB, among others. Due to the errors it was necessary to make a second version of the EPS in which MOSFET transistors are incorporated to solve the switching error between sources. The Version 2 of the Critical Design had problems of construction due to the distribution of the roads in the PCB and the use of MOSFET transistors that were not able to provide the necessary current. Finally, the versión 3.0 of the Critical Design of the Power Module was performed, whose changes basically were: a main board and an assistant one were implemented, because of the need of a good temperature dissipation plane. In the latter, some changes of components were made, due to the need for the connection of the light sensors I2C with attitude control module, it was decided the implementation of tracks in the Power Module to transport these signals by means of PC104 bus, thus avoiding the use of cable directly to the attitude control module, 2 terminals on the bus were CubeSat Kit to the I2C (SDA and SCL). A new version of the set of batteries was made. The schematic diagram of the version 3 is located in Figure 10, which shows the distribution of the CI implemented and the new used components which are detailed later.

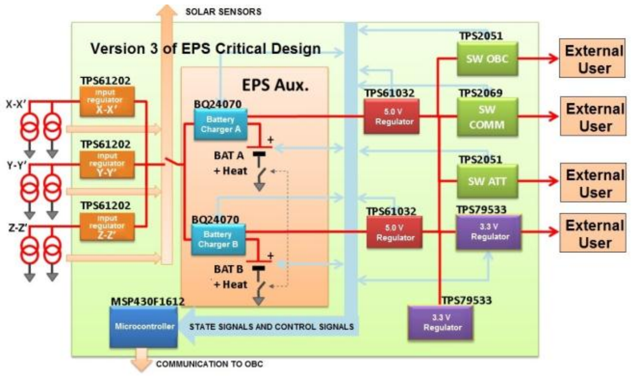

Figure 9: Schematic of version 3 of Critical Design of Power Module in CubeSat Colombia 1

The main board is responsible for regulating and managing power, where the connectors for solar panels (Figure 11) can also be observed. In the auxiliary board we find battery charging circuits, the circuits that control battery heaters and battery connectors.

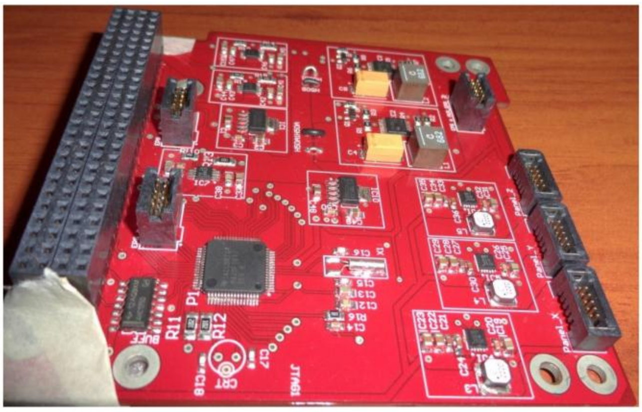

Figure 10: Principal board implemented of version 1 of Critical Design of Power Module in CubeSat Colombia 1.

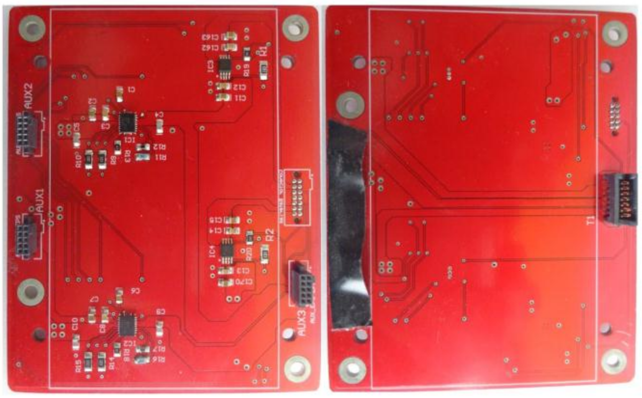

Figure 11: Top View and Bottom View of Auxiliary Board implemented for Version 1 of Critical Design of Power Module in CubeSat Colombia 1.

For the connection of the solar panels to the main board, the TFM-105-01-SD-WT connector was used, this connector has 10 terminals and has a coupling system to be attached to the Power Module, giving greater security at the time of launching. One connector is used for each pair of opposing panels.

A. Specific Changes in the Boards and Set of Batteries

Changes in components were as follows: The reference of the input regulators TPS61200 was replaced by reference TPS61202, which are capable of delivering 5.0 V to 600 mA each. The stage of multiplexer, which selected among the voltages of battery chargers was removed, since they did not withstand much current and a regulator of 5.0 V in series to each battery charger was implemented. The reference 5.0 V regulator TPS63020 is replaced by the reference TPS61032, considering difficulties arose in the dissipation of heat by the ground plane design, also the type of encapsulation was difficult to manipulate. The 3.3 V regulator was replaced with reference TPS63001 for the TPS79533 reference, since that component was used to supply low-power microcontrollers, it was not necessary to use a complex circuit for this purpose. With the new controller reference, two 3.3 V buses were implemented: a bus controlled by EPS, and another one for the EPS power supply, the microcontroller, and associated sensors. The 3.3 V switch is eliminated, and the enabler/disable feature of the CI TPS79533 is used. The TPS22945 switch is replaced from the OBC 5.0 V by the TPS20XX which handles most current. The connector of the battery set is replaced by the TFM-107-01-S-D reference, which is located on the auxiliary board. Version 1 of the microcontroller is changed, the MSP430F2274 by reference MSP430F1612, considering the microcontroller did not work for unknown reasons, the new reference was chosen also since it had been used in other working groups, and it is also the reference that comes in the CubeSat Kit development board, when this latter is being teste in the development board it ran well. The MSP430F1612 is a microcontroller with ultra-low consumption power, CPU RISC of 16-bits, two 16-bit integrated timers, a 12-bit A/D converter, two communication interfaces serial USART[48].

A new version was made out of the set of batteries, called version 3, seeing that, the version 1 had a mistake in the selection of the connector, had damage on the battery by physical-mechanical drilling[18]. In the implementation of the Critical Design of the EPS version 1 there were physical problems, because the set of batteries clashed with the components of EPS by the height of the connector, the new auxiliary board is also developed to raise battery, acts as a heat sink, and relieves the complex routing. For the new design, the indicator leds and any device bulb were eliminated, thus avoiding the explosion in the vacuum of space and the accelerated degassing. Batteries that were used for this version were the same as the version 1, but they have a sleeve containing the batteries together with lids additionally. The heaters are also the same. The reference to the connector located on the auxiliary board of the EPS is TFM-107-01-S-D-A (male connector), and the reference of the connector of the battery set is SFM-107-01-S-D-A (female connector), each connector has 14 terminals[18]. The LM75A configured for typical application was used for temperature measurement [49]. The INA209 was replaced by the INA219 for the monitoring of voltages, currents, and power, since the INA209 has unnecessary functions and terminals for the application[43]. The INA219 was configured for Shunt Bus and Voltage Measurement[50].

B. The Software Development.

The architecture of the code was performed through interruptions which allows to operate at low power, this due to the fact that the device remains asleep until it reaches a breakpoint. 3 types of outages were handled: periodic interruption: it has to do with checking the status of the Power Module, the sensor readings are taken by the I2C, the status signals of the subsystems are checked, the EPS_Reg registry data are modified, and the state in which the EPS should be located is chosen the State in which the EPS; communication interruption: It is done from the flight (OBC) module to indicate to the EPS any operation or to take telemetry data to the OBC by SPI; external interrupts: are 3 interrupts originated in ports of states of bus switches for the OBC, COMM (communications user) and ATT (User Control attitude), instructs the EPS an event of overcurrent in any of those modules and which should be disabling the module, and perform the recovery from failure. The developed codes are found in the annexes 9 to 12 in.

C. Testing With The Final Version of the Critical Design.

Physical, electrical and software tests were conducted. In the physical tests the characteristics were assessed of the boards implemented in the structure and the results are compared with the standard for the CubeSat. The electrical tests focused on regulators, battery chargers and connections to users. In the implemented software testing the microcontroller is programmed to perform some functions of the Power Module.

a) The Physical Tests

For these tests the physical dimensions of the boards were evaluated, the weight of the Power Module, and the integration of the Power Module to the structure and flight (OBC) module was performed. For the measurement of the dimensions of the boards a 0.05 mm precision millimeter calibrator was used. The weight measurements were performed using a digital scale with a capacity of 30 kg, accuracy of ±5 gr, Texon Technologies brand measurement. The results of this test are seen in Table 1 avaliable in [43]

Table 1: Results of Physical Tests.

Board	**Height (mm)**	**Area (mm^2)**	**Weight (gr)**
Principal EPS		95.6 x 90.0	56
Auxiliary EPS		91.0 x 73.0	25
Batteries Set		90.0 x 73.5	118
Total			199
Principal EPS + Auxiliary EPS	13	With margin of error:	199±5
***Principal EPS + Auxiliary EPS + Batteries Set**	27		
Distance allowed between module and small satellite module:	↑	The height of the module should be either 15mm, or 25mm, or 30mm, or 40mm, which are the combinations of the PC-104 connectors. It is observed that the maximum height of the EPS * is 27mm.Two 15mm PC-104 connectors /adapters can be fitted. This height represents 30% of the height of the CubeSat.	
Height	15		
Height	25		
Height	30		
Height	40		

From the Table 1 we have that the main board measured 95.6 mm x 90 mm, the auxiliary board measuring 91 mm x 73 mm, the height of the two boards including the set of batteries is 27 mm. The weight without batteries set is 81 grams; this weight is a good result, because on average the boards come to weigh more than the double of the board developed in the research group. In addition, when performing the test on the functioning of the RBF and LSW (release or deployment switch) switches due to international regulations and requirements, the correct operation of these switches was checked in [43].

b) The Testing of Panels.

Initially, each pair of panels are tested independently, this is done by setting the connection of only one of the panels connectors, the results are as follows. X panels: the controller runs between 0.3 V and 5.5 V input and generates a stable output of 5 V. Y panels: The controller operates between 0.28 V and 5.5 V input and generates a stable output of 5.003 V. Z panels: The controller works between 0.78 V and 5.5 V input and generates a stable output of 5 V. The results are good for the three controllers, however, a larger input voltage of the Z panels is required for correct operation.

Then tests were performed with two types of panel connections and the voltage delivered by the regulators was checked. XY connection: From the 0.38 V at the output of the regulators, there is a stable output voltage of 5 V. XZ connection: with an input voltage in the 0.34V regulators, an output of 4.99V was obtained, the minimum supply voltage was 4.95 V. YZ connection: With an input voltage of 0.45 V a voltage of 5V was obtained at the output.

c) Test of Voltage delivered by the Battery Chargers.

The voltage measurement on the chargers was only possible on the B charger and not on the A charger, due to physical characteristics of the implementation of the PCB. Then, the system was fed with the X panels whereby an output voltage was obtained in the B battery charger of 4.382V (4.4 V was expected). A measurement was also made on buses A and B, with the following results: Bus output voltage of 5.0A was 5V. Bus output voltage of 5.0B was 5V. Due to the output buses, the functioning of A and B battery chargers is checked. A measurement was conducted in Vsys and Vbus3.3 buses; the first one refers to the power supply of some EPS circuits such as the microcontroller and I2C sensors. The second bus focuses on the power supply of the microcontrollers of the communication modules and the OBC, although the OBC has its own regulator for safety reasons. The values obtained with a test current consumption of 40 mA are as follows: Vbus3.3 = 3.333V. Vsys = 3.325V. The tension measurements are also adequate and therefore the results are good.

d) Individual Efficiency Test of each Input Regulator with Load Variation.

In this test the efficiency of the input regulators is estimated by supplying them with batteries instead of the solar panels and varying the charge for each of the regulators. The results are shown in Figure 12.

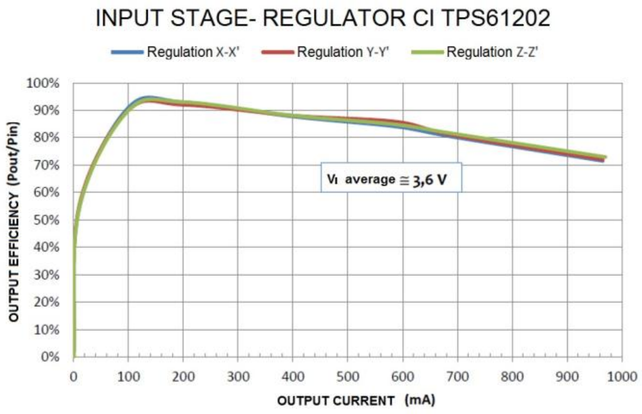

Figure 12: Efficiency of each input regulator separately.

In the obtained results it is observed that as the amount of current provided by the regulators increases, the efficiency tends to decrease, however, not too much. Actually, each pair of opposing faces may provide approximately 500 mA at maximum current, therefore, the efficiency obtained for that expected current is still good, being about 85%.

e) Test with Loads on Connections to Users.

In order to determine the current that can be delivered to the other users, a variable resistor with 100Ω maximum resistance was used as a charge in the connections of the different users. In Figure 13 the procedure is illustrated [42].

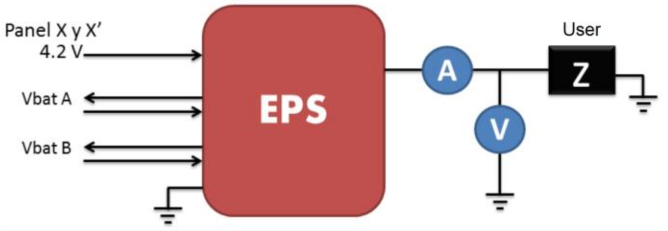

Figure 13: Diagram of tests with load as one user.

The voltages for the users are shown in Table 2. For this experiment, the X connection of the solar panels with the connected batteries A and B was used, in which adequate voltage levels were observed for each user.

Table 1: Voltages for the users.

USER	Voltage [V]
V_OBC	4.99 V
V_BUS3.3	3.33 V
V_ACT	4.99 V
V_COM	4.98 V

For each user a charge variation was performed to increase the amount of current to be delivered to the user. The EPS was designed to provide a current of up to 1A for the communications module, however, because of over-dimensioning issues it is capable of delivering up to 2A. The EPS is also capable of delivering 1A for the ADCS although it was initially designed for 500 mA, it can deliver 1A for OBC although its consumption is not greater than 300mA, and it can deliver up to 500 mA for the 3.3V bus user. The tests for each of the users are in Table 3, Table 4 and Table 5, and Table 6 in which the current was increased to verify the supply of EPS.

Table 2: Test for COM user.

Load [Ω]	Voltage [V]	Current [mA]
100	4.99	49
46.1	4.985	108
9.5	4.95	519
5.4	4.9	900
4.8	4.88	1006

Table 3: Test for ADCS user.

Load [Ω]	Voltage ADCS [V]	Current ADCS [mA]
100	4.99	49
49.8	4.986	100
19.7	4.985	253
9.8	4.954	502
8	4.94	614

Table 4: Test for OBC user.

Load [Ω]	Voltage ADCS [V]	Current ADCS [mA]
100	4.988	49
49.5	4.9	99
33	4.99	151
24.9	4.98	200
12.4	4.944	398

Table 5: Test for bus of 3.3V users.

Load [Ω]	Voltage [V]	Current [mA]
100	3.33	33
66.6	3.33	50
33.2	3.32	100
22.1	3.32	150
16.6	3.32	200
13.2	3.32	250
11	3.31	300

In addition to the above, a short was also provoked to prove that the EPS would react by stopping the power supply and protecting the system. In Table 7 there is a summary of measurements with high currents for each user, these tests were made by taking as a power source the batteries, taking the case that the satellite is in flight and in an eclipse.

Table 6: Test with loads and batteries as power source.

	Load [Ω]	Voltage [V]	Current [mA]
COM	6.604	4.92	745
	4.676	4.873	1042
ADCS	9.57	4.948	517
	8.081	4.938	611
OBC	16.25	4.958	305
	11.83	4.936	417
BUS 3.3	15.596	3.322	213
	10.98	3.318	302

f) Software Checks.

An ON/OFF code was implemented in the microcontroller to enable and disable the integrated circuits related with the user switch of 5.0 V and 3.3 V of the EPS. As it was at the beginning that the user switch are found disabled, in the check it was found that there was no power. Once the microcontroller is programmed the connections are then able for the users. Working with the communication group a code was developed with the program CrossWorks for MSP430 to check the sensors I2C and contribute this way the telemetry data of the Power Module, for this the check is made with the sensors and then with the EPS program. Then, the registers and the variables are checked in the debug of the program. The data of the temperature and the current is collected of the sensors I2C and no problem was found. The data of the temperature and power are packed for being used in telemetry.

DISCUSSION

The Preliminary Design was a model that was developed with enough care and from which the main features of next designs were established. These features are the topology organization of the EPS; the regulators selection that will not cause interference with other users of the CubeSat; the tension levels required by other users of the satellite equivalent to 3.3 V and 5V; the establishment of a temperature range between 0ºC and 50ºC for the battery charge. The implementation of the Preliminary Design as it was expected produced many electric errors in devices such as the main source selector, the user protection circuit and the regulator of 3.3 V. However, there was also some good results such as the functioning of the regulator of 5 V and the battery charger, validating somehow part of the model developed.

In the first version of the Critical Design new components were included like the temperature sensors and the current limiters to interact with the EPS microcontroller; also, a battery heat was added and a new set of more convenient batteries were implemented. For the CubeSat, along with better components which indicated a bigger model. Yet, there was an over-heat problem, and the regulator 5V did not work adequately for this model, which seem to be a regression in the design. It seemed to be good to put the Power Module apart from the other CubeSat modules, establishing its own microcontroller, however, this never worked for it was also not a good real possibility to make software checks and microcontroller administration.

Before the final version of the Critical Design a draft version was made and the idea was to solve the commutation problem between sources, this problem had not been solved since the first design. For this, transistors MOSFET were implemented, but finally it failed. This last one seems to be a stuck in the model, however, the next effort was the one that finally succeeded.

In the Final Version of the Critical Design, changes in terms of component reference were made, in the implementation of the EPS, in the implementation of set of batteries and in the topology of the Power Module. The thermic problems were treated establishing two cards, one for the set of batteries and the other for all the rest of the components of the EPS, which solved the track routing, and the disposition of the components. Additionally, the reference of the regulator 5V was changed which solved the regulation problem, changes in the bus CubeSat setting were made for the reception of the signs of the light sensors, also the reference of the microcontroller was changed for a most trustful one, which worked and permitted the administration checks of the microcontroller. When the electric and physical checks were made an adequate Power Module was achieved in terms of standard accomplishment and electric functioning. In addition, it was important the fact that software checks were made with the microcontroller successfully.

CONCLUSSIONS

In the Preliminary Design version of the Power Module the theoretical basis were established for the real implementation of the module, from it several component changes were taken into account, changing the references of the components to be used, changes in the structured itself of the Power Module scheme, in which finally some input regulator changes were established, the independence of the Power Module through its own microcontroller, and not to use the multiplexor for each battery in the final version. It was implemented evaluation cards and the cards of the modules for different versions of the Power Module until reaching the final Critical Design version. It all resulted in the obtaining of a trustful Power Module for flying, from it the theoretical and practical basis were established to design Power Modules.

In the electric checks made good results were obtained in terms of tension levels, efficiency and current of some components. In the physical checks it was found results within the CubeSat standard, including the good functioning of the switches RBF and LSW. In the software checks, simple tests were made through the programming of the microcontroller satisfactorily. Despite the good results there were some checks that were not made such as the in vacuum check and the vibration and that was because the university does not have the resources. Also, it is still necessary to do checks with the other real modules in relation with the Power Module because the checks were made with loads that simulated those modules which implies not having full confidence in the power launching module, yet it is expected to make these last checks for the total validation of the module.

Finally, it is expected that this developed work along with the other CubeSat UD projects, facilitate and promote the Aerospatiale research in the Universidad Distrital F. J. C and other universities in Colombia. Also, we hope that in the future these projects allow the development of the Aerospatiale industry in Colombia.

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