Satellite Electrical Power System

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Abstract—The Electrical Power System (EPS) is an electronic circuit board that is designed to supply and manage the energy in an efficient way. This paper describes the design architecture and circuits involved for an EPS deployed in the ISTsat ONE nano-satellite project. The EPS generates energy through the solar panels which is stored in the battery, and then using DC-DC switching voltage regulators, convert to the final voltage of ±3.3 V and ±5 V, supplying these voltage rails for rest of the subsystems of the satellite. This architecture meets the performance and size requirements of Cubesat architecture. It implements Maximum Power Point Tracking mechanism to achieve maximum efficiency in the conversion the solar energy, a 20.8 Wh battery, solar panels and redundant circuitry that ensures power supply to the satellite. The EPS is a subsystem of the ISTsat ONE and as such it communicates with other subsystems present in the satellite, by sending data logs, error warnings as well as receiving commands.


Man has put satellites on orbit to address the ever growing necessity of connecting every part of the world. The Satellites have various purposes such as telecommunication, space exploring, military purposes, weather forecast, among others. The ISTsat ONE is a nano-satellite standard 10 cm cube and its main purpose is to support the Automatic Dependent Surveillance Broadcast system (ADS-B) via satellite, receiving the identification and position of the airplane broadcasted by the plane and relay it back to a ground station on Earth. This solution addresses the issue of the airplanes loosing contact with the ground stations, and so failing to report their position, leading to missing airplane cases [1][2].

This project is inserted in the Fly Your Satellite Program from European Space Agency, which it’s main purpose is to provide the opportunity to students in the university to develop and launch a satellite, at the same time providing a mission service.

The ISTsat ONE is divided into subsystems, namely the Attitude Determination and Control System (ADCS) which is responsible for determining in real time position and satellite framework with the Earth; Communications (COM) which is the system responsible for all digital communications between the satellite and the ground stations; Command and Data Handling (CDH) that performs the processing of data provided by the on-board components, the responsibility to maintain the proper functioning of the satellite; Telemetry Tracking and Command system (TT&C) gathers all the relevant information of the satellite (position, attitude, systems status, and more…) and sends the collected data through a dedicated frequency back to the Ground Station; and the EPS. These subsystems perform full control of the Space-Craft (S/C), an additional sub-system is deployed to perform a scientific experiment or a specific mission called the Payload.

There are many risk factors in space that can jeopardize the S/C: space debris can hit the S/C, damaging the PV cells or internal circuitry, solar radiation, electromagnetic wave; and because there is no service or repair in space for a nano-satellite due to the incapability of fetching the satellite once deployed, the EPS must assure that power never fails under any circumstance. This feature is addressed with redundant circuitry and energy optimized operation modes.

The design chosen to the EPS electric circuit is divided in four sections: the converters use to regulated power supply collected by solar panels, the architecture used to distribute or store the energy collected in the battery, the power distribution module that converter energy in regulated outputs use for power in all nano-satellites and the section devoted to the microcontroller used to collect measurements and carry out the monitoring of all EPS.

1. FIRST EPS VERSION FOR ISTSAT ONE

The presented project is based on the first EPS prototype (Figure 1) that was developed for the ISTsat ONE. At that time it accomplished the power supply requirements of the ISTsat ONE.

![Figure 1 – ISTsat ONE first EPS developed prototype [3].](image)

This EPS features connection to five solar panels with three MPPT converters a battery charger, a boost converter to achieve 12 V, two Single Ended Primary Inductor Converters (SEPIC) to achieve 5 V and 3.3 V. This EPS also features redundancy for the final regulation. The implementation for this redundancy is by step-down the voltage supplied from higher voltage buses, as shown in Figure 2.
The MPPT and SEPIC converters pulses are controlled by the microcontroller. The boost and the buck has a dedicated Integrated Circuit (IC) that controls and drives the circuits. The linear voltage regulator offers more redundancy in terms of regulation, if all other converters fail. The battery charger is a linear circuit and also features its own IC controller.

This EPS is functional, however the ISTsat ONE electrical and design specifications have changed since then and therefore this new project aims to meet the new requirements. For instance this version of the EPS does not feature individual supply to each of the sub-systems, the microcontroller does not have a dedicated power supply, nor does the battery feature heaters. There are other new requirements which this EPS does not meet. This new project also focus in improving this architecture efficiency by using switched power converters, and minimizing the number of conversion stages to achieve final regulation while maintaining and redundancy features. One of the aspects that can be improved the fact that the MPPT is able to charge directly the battery, because it does not employ bidirectional switches nor does the MPPT converter perform the charging profile or regulates the output voltage.

In terms of satellite functionality it is necessary that the new EPS features a Remove Before Flight Cut power cut off pin, and deployment switches. The new EPS must also feature I2C communication with other sub-systems.

II. EPS ARCHITECTURE

The ISTsat ONE electrical power subsystem uses five triple junction solar panels, a battery with two lithium cells in series, an in-house designed controller and a supervisor system. A charging port will be available to recharge the battery while the satellite is grounded. The blocks diagram in Figure 3 presents the different stages of energy processing and indicate the power flow of the EPS architecture.

The solar panels are mounted on each face of the satellite associated with the respective axis (X,Y,Z). The solar panels are arranged in opposite faces of the cube (-X / +X, -Y / +Y axis and one panel is mounted on +Z, -Z face is reserved to accommodate the Payload subsystem antenna). With this arrangement the MPP of each individual solar panel can be tracked, mind that when +X is light, the -X is in the dark side. The panel that is in the dark is not producing energy, and so the tracking is made only by the panel that is light.

The system voltage regulation is achieved in a two-stage process. In the first power processing stage, the input voltage coming from the solar panels is converted to an intermediate voltage using a MPPT. At this point the voltage will vary between 4 V and 15 V depending on the energy produced by the solar panels. The second stage involves the output voltage regulators and current limiting systems that will feed all the satellite subsystems.

A dedicated microprocessor is responsible for the EPS management. It controls and monitors key currents and voltages points within the EPS, handles communication with the OBC, controls the power lines that supply other sub-systems and if necessary engages redundant circuitry. The microcontroller also implements the MPPT algorithm controlling the MPPT switching. This system is able to furnish all details of the available voltages, current consumption, available energy on the batteries and on the solar panels, and State of Charge (SoC).

This design also takes into consideration redundancy circuitry so that, in case a component should fail, the power at PC104 connector is guaranteed at all times, although decreasing efficiency. The above proposed architecture allows for the energy that is coming directly flowing from the solar panels to be fed directly to the output voltage regulators through the power multiplexer, without involving the battery.

A SEPIC converter was selected as a battery charger considering its ability to both step up and down the voltage, which is necessary due to the MPPT profile. It also performs the charging profile required to charge the battery. The charger also accomplishes the charging while the satellite is not launched through a service port.

As referred, for redundancy purposes, the final 3.3 V regulator is repeated so that in case one should fail, the other should provide the power. In normal operation the power load between the final regulators is evenly distributed. The EPS architecture will work with solar panels (without battery). If the microprocessor fails the solar panels output power will be available to generate the output regulated voltage of 3.3 V.

The EPS also features a latch memory circuit that stores the initialization state of the satellite. This serves the purpose of the satellite being resettable with the RBF pull pin, and at the same time hold the initialization state if the system power fails. The latch is set after the initialization procedure is complete.

Regarding commercial standards, and compatibility purposes, the PC104 connector pin out and its functions were mapped in accordance.
III. HARDWARE CIRCUITRY & COMPONENTS

A. Solar Panels

The solar panels are triple junction solar cells InGaP/GaAs/Ge, with two 2 cells connected in series in each panel. These panels efficiency can go up to 29.5%. The solar panels are commercial panels and are suited for nano-satellites or cube applications with the standard size 1U (10 cm x 10 cm). Each solar panel generates 4.66 V in open circuit, and 0.517 A in short circuit, and the maximum power output is 2.4 W. Due to the solar characteristic curve I(V) of the solar cells the maximum power is obtained only for a specific current and voltage, as shown in Figure 4.

![Figure 4 – Characteristic curve (Current vs Voltage) of the solar panel for different incident radiation angles.](image)

B. Maximum Power Point Tracking converter

This converter keeps tracking the maximum power that can be extracted from the solar panels emulating a specific load on the affecting the solar panels conductance, thus forcing them to work at maximum efficiency. This converter is controlled by the micro-controller, meaning that the algorithm is performed within the micro-controller as well as the measurements and the gate PWM signal. The circuit of the MPPT is based on a boost converter as shown in Figure 5.

![Figure 5 – Maximum power point tracking circuit, boost converter](image)

The relation between the duty cycle and the input and output voltages for the Continuous Current Mode for a boost converter is given by

\[
\frac{V_{\text{OUT}}}{V_{\text{IN}}} = \frac{1}{1-D} .
\]

The algorithm used is based on the Incremental Conductance MPPT [6]. Because the power curve has only one maximum point, in every perturbation it is possible to find the evolution of the curve and thus perform the MPPT. Analyzing the power diagram, it can be verified when the power reaches its maximum value (1),

\[
\frac{dP}{dv} = 0 .
\]

The power is given by the product of current and voltage,

\[
P = V \cdot I ,
\]

Combining (1) with (2) it comes to

\[
\frac{dl}{dv} + \frac{l}{V} = 0 \leftrightarrow \frac{dl}{dv} = -\frac{l}{V} .
\]

Finally the condition for which the maximum power is achieved is verified if (15) is valid. As the software is not able to compute derivative, it is necessary to make an approximation as

\[
\frac{dl}{dv} \approx I(V_2) - I(V_1) .
\]

According to (1), incrementing the duty cycle the output voltage increases. But the current supplied from the solar panels is limited, limiting also the power, this means that increasing the duty cycle the current from the solar panels also increases up to its limit, which in turn the output of the solar panels starts to decrease. Hence if (1) is above 0 and if the power curve maintains it is necessary to decrease the duty cycle, and if (1) is below 0 then it is necessary to increase the duty cycle.

The algorithm is presented in the flowchart in Figure 6.

![Figure 6 – Incremental Conductance MPPT algorithm.](image)
This algorithm also has the advantage of increasing the PWM between iterations of the algorithm, by calculating the derivative of the power, it is possible to predict the next PWM duty cycle required, which translates into a faster convergence. The MPPT converter also charges the battery. When the MPPT converter is charging the battery, the battery dominates the output voltage of the converter with its correspondent voltage charge. When the output voltage of the converter reaches to 8.25 V, it means that excess energy is produced and so the MPPT converter instead of tracking the MPP of the solar panels, now tracks the output voltage to stabilize 8.25 V which corresponds to the end of charge voltage of the battery.

C. Battery Pack

The battery is composed by four Varta LPP5037598HH Lithium Ion cells. Each cell has 5.2 Wh of energy capacity, nominal voltage of 3.7 V and the maximum discharge current is 2 A. These cells come with an embedded NTC temperature sensor and Protection Circuit Module (PCM) for protection against over discharge (below 3 V), over charge (over 4.32 V) and over current (over 2 A). The batteries configuration is a two series and two parallel cell connection (2S2P) (Figure 7) which has a total of 20.8 Wh and generates 7.4 V nominal voltage. This arrangement has some advantages: it allows extracting higher current; but more important it divides the current through the parallel of each pair of battery series. This way the cells charge and discharge rate is reduced helping to maintain the battery state of Health (SoH). The cells must not be charged if their temperature is below 0 ºC, because it could affect the cell’s performance. The heat within the battery dissipates to space. So in order to the temperature above 0 ºC the battery pack features heaters to heat the cells.

As stated the battery pack also features cell charging balance, preventing the cells being over discharged due to charge unbalancing between each cell. There are four cells, yet only two balancing circuits are necessary, because each cell series shares the same voltage node, and the charge between the cell series will balance automatically. So the charging balance circuit is only needed between the cells in each series. The charging balance method is achieved by dissipating energy in the cell that has the most. During this process the battery loses energy, so it should only be done while charging the battery. The IC that performs the cell balance (BQ29200 from Texas Instruments) also has an overvoltage protection.

There are two heaters that are controlled by the EPS microcontroller, which are ON when the battery’s temperature falls below 1.5 ºC and OFF when the temperature goes above 6.5 ºC. The power of the heaters is controlled by PWM and the maximum heat power is 510 mW. The heaters consist on resistance developed and designed on a double sided PCB. It generates heat by dissipating energy of the tracks on the PCB.

Another important aspect is the determination of the State of Charge, as it provides the information of how much charge is left in the battery and how long it lasts until the battery is depleted. The method used to determine the SoC is based in the association of the percentage of charge with the Open Circuit Voltage (OCV) of the battery [8][12]. The voltage at the battery terminals is not used due to the voltage drop under heavy loads. So, if the load is constantly varying, the voltage of the battery is also varying. But the OCV of the battery does not depend on the load that is applied. It only depends on the energy that is stored. The voltage drop upon a load happens because of the internal resistance in the battery. One method to determine the internal resistance of the battery is to measure the OCV of the battery, and then apply a load to the battery immediately followed by the measures of the battery voltage and of the current that is being drawn. Figure 8 shows the circuit schematic and points out the measurements taken. Note that the cell model presented is only valid for DC measurements.

\[
V_{OC} = R_i I + V_{load}
\]  

(6)

To determine the OCV, the \( R_{load} \) must be very high or even disconnected from the circuit. With this setting \( V_{OC} = V_{load} \). Then, adding the \( R_{load} \) with a value between 1 \( \Omega \) to 10 \( \Omega \), the current that flows through the battery is the same as the load current. This approximation is valid because the impedance of the voltmeter is high enough so that the current leaking through the voltmeter is negligible. Thus the internal resistance of the battery is obtained through

\[
R_i = \frac{V_{OC} - V_{load}}{I}
\]

(7)
As stated, the SoC of the battery is determined through a Look-Up Table (LUT) containing the discharge profile of the battery. The LUT establishes the relation between the OCV and the charge percentage. Measurements of both current and voltage of the battery are taken. As for the internal resistance of the battery, the EPS has this value registered in memory, and through (7) it determines the OCV. Then, by comparison with the LUT it finds the respective percentage of the SoC.

The internal resistance of the battery varies with the SoC and with the temperature mostly [13]. It also varies with the SoH of the battery, but in this type of batteries this effect is negligible for this application, due to the reduced life time (6 months). Due to this, various measurements of the internal resistance over the discharge cycle are made at different temperatures. With these measurements a relation between the temperature and internal resistance is established. To determine the internal resistance of the battery a matrix reference table establishes the relation between the internal resistance, temperature and SoC. The determined internal resistance is then used for calculation of the OCV. So in order to obtain the SoC the EPS follows the flowchart presented in Figure 9.

E. Multiplexer Circuit

The multiplexer allows the EPS to manage the power source to the final regulators. Both ports are bidirectional, note that this MOSFET arrangement (back to back connected sources of the MOSFETs) places all the substrate diodes against any current flow, and only when MOSFET is ON the current flows. This also allows the EPS to switch ON both sources at the same time, which can result in the charging of the battery.

F. RBF and Deployment Switches

The Remove Before Flight (RBF) switch is a mechanical contact, normally open, pull pin spring switch and serves the purpose of cutting all the power of the satellite, actuating MOSFETs that cut off the power feed. The RBF pull pin is integrated in the solar panels and it connects directly to the EPS board. There are two MOSFETs that are connected in series with the MOSFETs that control the multiplexer switch, featured in the previous section.

G. Latch memory circuit

The latch memory circuit (Figure 13) is dedicated to store the information of the initialization state of the satellite when
the power fails, whilst being able to reset through the RBF pull pin. The latch is set by the micro controller. This information is a 1 bit value and it is stored in the capacitors. If the voltage in the capacitors is above the threshold voltage of the MOSFET, then output is active. By default, the latch is not set, meaning that the battery of capacitors shown in Figure 13 are discharged and the N MOSFET is OFF. Note that because the memory of the latch is held by the capacitors, it is required to refresh the charge periodically. Although the impedances connected to the capacitors are very high, it is expected to have a lower current leakage.

\[
V_{\text{Final}} = V_{\text{Initial}} \left(1 - e^{-t/RC}\right)
\]

where \(R\) is the total resistance connected to the capacitor’s terminals, \(C\) the total capacitance, \(t_{\text{OFF}}\) the time of discharge, \(V_{\text{Final}}\) the final discharged voltage value and \(V_{\text{Initial}}\) the maximum capacitor’s charging voltage value. As the threshold voltage of the N MOSFET is 2.3 V (max.)[7], the capacitors voltage, when discharged should be higher, hence \(V_{\text{Final}} = 3\) V. \(V_{\text{Initial}}\) is set to 6.2 V, which is the voltage when the battery is discharged, and the discharge time minimum is the eclipse time which is approximately 2460 seconds. But in order to guarantee that the latch does not lose its state the discharge time used is 5400 seconds (approximately 1 orbit). From (8) the total capacitance is 68.7 \(\mu\)F.

**H. 3.3V Regulator**

The final regulation is done using a Synchronous buck converter. The main difference from a regular buck is the absence of the diode, which is replace with MOSFET in its stead (transistor mounted in parallel). These type of converters are more efficient, especially in micro power systems, and low voltages, due to the low drop voltage across the transistor. While diodes usually have a forward voltage of 350 mV (Schottky diodes), which represent approximately 10% in energy losses. Because this type of converter uses two MOSFETs additional control is needed. The LT8610a is a monolithic integrated circuit which does the control of these switches, as well as monitoring the voltage and current at the output.

### I. Power Distribution Module

After the voltage regulation it is necessary to distribute and supply the satellite subsystems. This module purpose is to control the power supply individually to each one of the subsystems, and offer redundancy by being able to choose between Bucks 2 and 3, and also to offer complementary voltage regulation if necessary. Another feature of this module is current limiting for the subsystems output. Figure 15 presents the blocks diagram of the power distribution module.

**J. Software**

The software developed for the microcontroller manages the EPS. It periodically monitors the internal voltage and current signals as well as the operation signals from converter’s controllers. This method detects any fault on the hardware, by doing this measuring it can pinpoint the fault and try to solve by engaging redundant circuitry. Besides the system monitoring, the EPS also communicates with the OBC, receiving commands for data logging, diagnostics and power control of other subsystems. The EPS also reports single events, errors, change of operation mode. Along with the power control and measurement routines, the microcontroller will also have an algorithm to drive the MPPT.

### IV. EPS Prototype

**A. Prototype**

The EPS prototype is designed to meet the commercial standard designs for cubesats, featuring the PC104 connector the connectors for the solar panels as well as the PCB dimensions.
The EPS prototype is presented with the battery mounted in Figure 17.

**B. Electrical Characteristics**

This prototype is designed to meet all the requirements for ISTsat ONE. However, some requirements are flexible and only specify a minimum or a maximum goal. Besides of meeting these objectives the EPS design supports higher tolerance in terms of power consumption and power generation, leaving some margin to expand this EPS design into future projects. The electrical characteristics are presented in

**TABLE I. POWER CONSUMPTION OF THE SATELLITE**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min</th>
<th>Typical</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Panels X,Y,Z inputs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage Input</td>
<td>0</td>
<td>6</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Current Input</td>
<td>0</td>
<td>1</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>+3.3V (H2.27, H2.28)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage output</td>
<td>3</td>
<td>3.6</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Current Draw</td>
<td>3.3</td>
<td>3</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>VCCx (H1.47; H1.48; H1.49; H1.50) outputs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage Output</td>
<td>3</td>
<td>3.6</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Current Draw per output</td>
<td>3.3</td>
<td>1.5</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Current Draw all outputs combined</td>
<td>6</td>
<td></td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>VCHARGE (H1.23)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage Input through the charging port</td>
<td>5</td>
<td>9</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Current Draw</td>
<td>0.23</td>
<td>0.5</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>VBAT (H2.45, H2.46)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery Output Voltage</td>
<td>6</td>
<td>8.4</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Current Draw</td>
<td>2.4</td>
<td></td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Power Consumption (OFF)</td>
<td>0.9</td>
<td></td>
<td>mW</td>
<td></td>
</tr>
<tr>
<td>Power Consumption (Active)</td>
<td>100</td>
<td>150</td>
<td>mW</td>
<td></td>
</tr>
</tbody>
</table>

V. ENERGY BUDGET

The satellite is at orbit and with a spin of its own, leading to a constant variation in light radiated to the solar panels. Figure 18 illustrates a scenario where the satellite has permanently the same face heading towards the Earth.

In this scenario the power is generated with only two panels light. The power generation with no eclipse is represented by the Figure 19. In this case the mean of the power generated is 3.05 W. The satellite movement can take other forms, but this case is the minimum mean power that can be generated in an orbit, as this is the worst case where the Z panel is not light.

During eclipse there is no power generation. In an orbit the satellite is 61% of the time exposed to the sun and 39% in the eclipse zone, the orbit has 92.7 minutes. So this scenario (Figure 20) the average power generation is 1.87 W, hence the energy generated in an orbit is 2.88 Wh.
consumption some assumptions were made following the most probable scenarios and some unfavourable situations. TABLE II. presents the estimate values of power consumption for different ISTSat ONE subsystems under normal and safe modes, it also displays the peak power and the estimated average power consumption for each subsystem when active. As for the energy losses it is assumed that the efficiency is 70 %.

TABLE II. POWER CONSUMPTION OF THE SATELLITE

<table>
<thead>
<tr>
<th>Module</th>
<th>Peak [mW]</th>
<th>Average [mW]</th>
<th>Normal [mW]</th>
<th>Safe [mW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTC Rx</td>
<td>400</td>
<td>300</td>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>TTC Tx</td>
<td>2000</td>
<td>750</td>
<td>83</td>
<td>60</td>
</tr>
<tr>
<td>Beacon Tx</td>
<td>300</td>
<td>175</td>
<td>66</td>
<td>66</td>
</tr>
<tr>
<td>OBC</td>
<td>500</td>
<td>320</td>
<td>64</td>
<td>60</td>
</tr>
<tr>
<td>COM</td>
<td>1500</td>
<td>750</td>
<td>156</td>
<td>60</td>
</tr>
<tr>
<td>Payload</td>
<td>1000</td>
<td>900</td>
<td>150</td>
<td>60</td>
</tr>
<tr>
<td>Magnetorquers</td>
<td>775</td>
<td>775</td>
<td>39</td>
<td>0</td>
</tr>
<tr>
<td>EPS</td>
<td>200</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Energy losses</td>
<td>3594</td>
<td>2178</td>
<td>373</td>
<td>189</td>
</tr>
<tr>
<td>Total</td>
<td>10269</td>
<td>6223</td>
<td>1066</td>
<td>600</td>
</tr>
</tbody>
</table>

TABLE III. presents the energy budget for the ISTSat ONE, taking into account that the battery has 20.8 Wh of energy capacity, energy losses, and an orbit time of 1.54 hours.

TABLE III. ENERGY BUDGET OF THE SATELLITE

<table>
<thead>
<tr>
<th>Energy Figures</th>
<th>S/C in Safe Mode</th>
<th>S/C in Normal Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Generated per Orbit [Wh]</td>
<td>2.88</td>
<td></td>
</tr>
<tr>
<td>Consumed Energy without Losses per Orbit [Wh]</td>
<td>0.758</td>
<td>1.194</td>
</tr>
<tr>
<td>Energy Losses per Orbit [Wh]</td>
<td>0.325</td>
<td>0.512</td>
</tr>
<tr>
<td>Consumed Energy per Orbit [Wh]</td>
<td>1.083</td>
<td>1.705</td>
</tr>
<tr>
<td>Energy budget per Orbit [Wh]</td>
<td>1.797</td>
<td>1.175</td>
</tr>
</tbody>
</table>

On normal operation mode the S/C is self-sustained, as the energy budget is positive, which means that 1.175 Wh can be directly stored in the battery. This means that if necessary the S/C can perform extra events. Considering the event of the satellite being constantly draining the average power continuously for each subsystem (see TABLE II.), the S/C is already not self-sustained, but it can maintain this operation during 2 orbits, and then it has to switch back into normal operation. If quick battery charging is necessary the S/C goes into safe mode operation, as this is where the energy budget is higher (1.797 Wh), taking up to 7.5 orbits to fully charge the battery.

In an extreme case if ISTSat ONE solar panels fail, the S/C can remain operational up to 19.2 orbits (29.6 hours) in safe mode operation, and 12 orbits (18.5 hours) in normal operation mode. Another extreme case is the battery failure. In this case the S/C can only operate while it is out of eclipse.

VI. EPS RESULTS AND CHARACTERIZATION

A. MPPT Converters

When this converter was designed it was taken into account the power that it would be generated, making sure that the converter has enough excursion, in terms of duty cycle versus power, and that it should remain within the Continuous Conduction Mode (CCM), since this mode is more efficient. The minimum power for the converter to be in the CCM is 246.5 mW. The current passing through the inductor presents a ripple of 140 mA of amplitude. Note that the tests conducted did not have the battery connected to the output, so although the ripple is propagated to the output voltage, is not problematic because this converter is connected directly to the battery, acting as huge capacitance value and therefore the output voltage is stable. While in MPPT mode the microcontroller has to able to process the MPPT algorithm as fast as it can, meaning that the duty cycle adjustment period must be able to keep up with the light variance on the solar panel, and thus affecting the MPP. The MPPT algorithm is processed, on average 330 times per second and is directly tied to the software complexity and the number of tasks. This is also true while the converter is in Boost mode. In order to see if the control implementation is fast enough and finds the MPP, the algorithm convergence was tested and power transients were applied at both output and input the MPPT converter, Figure 21 presents the test results.

The MPPT algorithm and converter work as it should, it finds the MPP and keeps adjusting the PWM accordingly to the maximum available power on the solar panel. The MPP is tracked in less than 250 ms.

Figure 22 presents a uniform input voltage sweep variance with the battery fully charged (8.35 V), in this case the converter is in Boost mode and the battery is disconnected in order to not influence the output voltage. The converter has enough excursion for the input voltage to be as low as 1.150 V to maintain the output regulated, below this value the duty cycle reaches its maximum value of 88.6 %. When the output is regulated, the ripple reaches up to 400 mVpp.
The input voltage variance test with the MPPT in Boost mode is presented in Figure 22.

Figure 23 presents the power efficiency for the MPPT converter with the input voltage set to 5 V and a maximum current of 1 A.

As expected at low power, the MPPT is less efficient proving the purpose of applying bursts of pulses in order to obtain higher peak power, rather than low average power. Overall the efficiency results are good, with an expected efficiency of approximately 88.5% at 2.4 W (solar panel MPP).

### B. Battery Charger

To ensure that the controller detects the maximum charging voltage as well as limiting the charging current, a variable load is applied to the output setting various steps and sweeping the output voltage. Figure 7.9 presents the waveform results for this test.

The results are as expected. The maximum voltage obtained is 8.224 V, and the maximum current is 635 mA. This test also validates its charging profile which meets the battery requirement, constant current when the voltage is below the maximum charging voltage and constant voltage when it reaches the charging voltage.

The maximum voltage threshold of the MOSFET which the manufacturer guarantees is 2.3 V, for which the time of discharge for the capacitors to reach this voltage is 119 minutes.

### D. Buck Converters

The power efficiency of the buck converter 2 is presented in Figure 27. The efficiency of the converter can reach as high as 92%. Note that the converter has higher efficiency for higher power outputs, which is also favourable because for lower power output, the solar panels may be producing power in excess and so this excess is stored in the battery, hence less energy is wasted.

The electrical characteristics measured for each converter are presented in TABLE IV.

<table>
<thead>
<tr>
<th>TABLE IV. POWER CONSUMPTION OF THE SATELLITE</th>
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<tbody>
<tr>
<td>Buck Converter</td>
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<tr>
<td>Nominal Voltage [V]</td>
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<tr>
<td>Measured OCV Voltage [V]</td>
</tr>
<tr>
<td>Measured Min Voltage [V]</td>
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<tr>
<td>Output voltage Ripple [mV]</td>
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<tr>
<td>Peak Current [A]</td>
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<tr>
<td>Switch Frequency [kHz]</td>
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The EPS efficiency is displayed in Figure 28. Note that during this experiment the MPPT remains in Boost mode, because the maximum power is not required, and so the MPPT is able to regulate to 8.25 V. The overall efficiency of the EPS is good, considering that two converters in series are used to achieve the necessary power output and with the efficiency reaching as high as 82%. As expected the curve is similar to the efficiency graphs from the previously studied converters and because they are in series it can be confirmed that the overall efficiency is the product of both MPPT and Buck converters efficiency curves.

VII. CONCLUSION

A first version of the EPS for the ISTsat ONE was made but due to new features and requirements of the ISTsat ONE, a new EPS has been designed in order to comply with all requirements.

The MPPT algorithm converges in less than 250 ms allowing the EPS to perform the tracking even if the satellite is tumbling heavily. In the case of the satellite being launched and forced into low power mode, the de-tumbling system is not engaged but still EPS is able to keep tracking of the MPP and efficiently charge the battery. The battery charger is working properly and can charge the battery reliably even if the power input is lower than expected. The Power Mux module (RBF and deployment switches, Latch, battery and solar power switches) is working well, meaning that the Latch can hold the initialization state for more than one orbit time if there is a power failure. The RBF and deployment switches switches mechanism proven to work and perform the intended logic.

All the Buck converters regulate the voltage in any circumstance, and the PDN monitors the outputs and offers protection to the EPS and to the other subsystems, by limiting the output current and even offering protection against short circuits. The extra regulators available in the power distribution module offer redundancy for the power regulation if the buck converters should fail.

Regarding the EPS as a whole, it can manage the power between the battery and the solar panels whilst supplying power to the subsystems. It manages to recharge the battery, if the solar panels harvest enough energy, or the battery supplies the power to the satellite. All this happens seamlessly to the subsystems. The overall efficiency is good reaching up to 82%.

A study was made on the energy budget for the ISTsat, in order to predict if the energy harvested from the solar panels is enough, if the battery charge capacity is adequate or simply analyze the overall power consumption of the satellite. The conclusion was that the with the ISTsat ONE architecture, the satellite is self-sustained producing enough energy to power itself and store enough energy in the battery so that during the eclipse the satellite is able to maintain its normal operation. This study assumed that the EPS energy harvesting and power distribution would have an efficiency of 70%, however the EPS performance results proved that the EPS efficiency is higher than expected, thus increasing the energy budget reinforcing the energy stability of the satellite.

Comparing this new design with the first version of the EPS, this new EPS is more efficient, offers individual power outputs with voltage and current monitoring for power consumption, overcurrent protection and redundant circuitry to ensure that the power output never fails. It also meets the updated requirements for the ISTsat ONE.

REFERENCES