On-board power and battery sytem for small satellites

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ON-BOARD POWER AND BATTERY SYSTEM FOR SMALL SATELLITES

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Advances in contemporary space mission design allow for the development of more and more miniaturized spacecrafts with short development time. Most of the attention in the previous years was focused on small satellites around 1-5 kg, while now many missions are shifting towards 10-50 kg satellites. To support the two markets ISIS - Innovative Solutions In Space B.V. and SystematIC design B.V. jointly started the development of a versatile and scalable power system. Since Electronic Power Systems are crucial in satellites and are reported as one of the main causes for failure in several small satellite missions, reliability has always been the most important goal of the design. This paper presents the newly designed EPS and it will focus on the design phases and qualification methodologies applied to achieve reliable power storage by means of commercial Lithium-Ion batteries. Battery technology was carefully evaluated to achieve the previously mentioned performances & characterization procedure. Extensive characterization is being performed to achieve confidence on the battery lifetime estimation. Suitable thermal design has been also carried out to ensure safe operation of batteries at optimal temperature. The main advantage of the newly developed system is flexibility and scalability, which can be achieved also to commercial batteries. The EPS has been developed with COTS components leading to cost effective mass production. Yet the system is qualified for space flight in LEO. Particular attention was paid to avoid Single Point Failures and to have a redundant system capable of tolerating faults. To properly address such a wide market a scalable design was selected, allowing fitting the system for 2U CubeSats with only body mounted cell up to I2C CubeSats with deployable panels. If higher redundancy level is required, the power system can be counted in a hot/cold redundant setup. This solution also allows further widening applications range to 20-5- kg satellite. The development of this new line of products takes advantage of the synergy between the partners, with different backgrounds but all focused to improve the performance of current space systems to fit highly demanding small satellite missions.

I. INTRODUCTION

Over the last 20 years there has been a remarkable development in electronics which has enabled smaller and compact devices that we see around us today. This development has also enabled building of much smaller satellites with increasing capabilities and more useful missions which were previously possible with only larger satellites. Consequently new terminology for these small satellites started to emerge [1]:

- Microsatellites: Satellites less than 100 Kg
- Nanosatellites: Satellites less than 10 Kg
- Picosatellites: Satellites less than 1 Kg

This work deals with the development of a CubeSat EPS but it serves right to give a broader view of the system we are dealing with to enhance our understanding. The cubesat, or Nanosat class satellites, have traditionally used highly integrated Electrical Power System (EPS) electronics designed to optimize for power. For the cubesat to become a mainstay bus used for real world missions, the EPS must not only be efficient but flexible. The ideal EPS design is one that meets the power requirements of a specific mission, and can then be used multiple times in different mission scenarios, without having to be redesigned for each mission. Distributive architectures are flexible. They have enable modular designs that result in greater design reuse, while still meeting system requirements of varying satellite payloads and spacecraft configurations. In this regard, there is a need for commercial EPS product which can be used with greater flexibility depending on design requirements & class of satellite.

II. SYSTEM REQUIREMENTS

As a first step towards design process a set of system requirements are formulated. Following are some of the high level system requirement for the proposed system:

i. EPS shall be applicable to Nano-satellites but can be customized to be able to use for satellite of mass up to 50 Kgs with life time of 3 years
ii. The size of the EPS board together with 1 battery unit shall not exceed 96 x 96 x 40 mm (WxLxT) and be compatible with cubesat bus
iii. The EPS shall be designed to provide overall power efficiency of 85% to 90%
iv. The EPS shall provide energy to the satellite through multiple power buses according to load requirements with maximum voltage & current protection
v. The EPS shall be able to store energy onboard through secondary batteries and must be scalable according to load requirements
vi. The EPS shall support the use of a battery heater to maintain programmable temperature range and shall operate automatically.
vii. EPS shall handle minimum of 30W to maximum of 60W of solar power in its basic configuration
viii. The mass of the EPS board together with 1 battery unit shall be lower than 250 g
ix. EPS shall be designed to provide its telemetry on continue bases to satellite computer with accuracy of at least 5%
x. Radiated EM noise should not alter receiver noise floor by more than 3 dB

III. DESIGN & SYSTEM TRADEOFFS

This section covers the preliminary design of the EPS system architecture by proposing several tradeoffs in the design to identify the most suited solution. This section will start with the description of the overall building blocks.

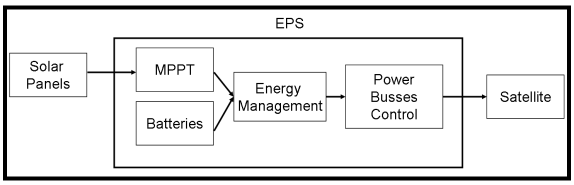


Figure 1. EPS high level block diagram

Solar panels are considered as external components, as it is the rest of the satellite. In principle, the depicted power connections are the only necessary interconnections with the satellite: for simplicity, no digital control signal has been added. All these components should be integrated into a Cubesat satellite, which requires the EPS to be compliant to the Cubesat standard. The main design goal is to reduce system size, aiming at fitting everything on a single PC-104 board. From first estimations, this will not be possible, so it is envisaged the use of a main board and some further boards to build the EPS system, each connected together.

III.I MPPT

The Maximum Power Point Tracker block is used to extract maximum power from the solar panels. This is usually achieved by matching the solar panel impedance with a switching mode power converter. Given the non-linear characteristic of solar cells, a control unit should be used to properly track the solar cell maximum power point. As per the requirements, every solar panel should have its own MPPT controller to harvest most of the available solar power. Also the MPPTs should be able to fit different solar panel size (number of cells) to achieve a flexible EPS system.

III.I.I Variable Solar Panel Number

As per the design requirements, the EPS shall be able to handle at least 4 solar panels up to at least 8 (EPS.P.03 and EPS.P.04). This high flexibility required can be a problem for the design since some of the MPPTs will never be used in small missions.

The best approach to solve this problem is making the system modular: when more MPPTs are needed, they can be simply to be "plugged" on the system. According to this concept, it is best to design the board to fit the minimum required number of MPPTs and then add a second board to meet the other requirement, as depicted in below figure.

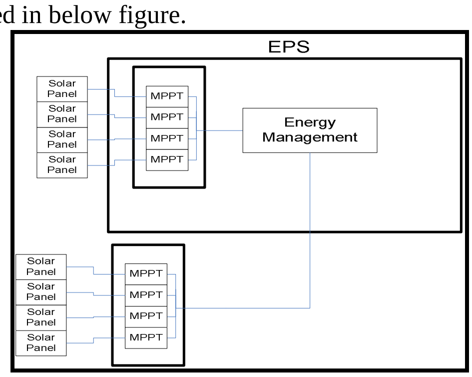


Figure 2. Multiple MPPT boards

Using this approach it is possible to create a flexible system, without increasing too much the complexity. It is easy to note that fitting 8 MPPT blocks on the same board would have made it too big and non-efficiently used on small systems. This architectural solution requires a proper mechanical and electrical interfacing between the main board (hosting most the EPS systems) and a smaller daughter board hosting the MPPT controllers. It is also possible to add further MPPT daughter boards by stacking them vertically one on top of the other. This would make the system even more flexible without increasing too much the complexity. The main downside is that the EPS system will become thicker due to these daughter boards but this is not in general a big issue since the basic unit is kept quite thin (which is extremely important since the basic unit is going to be fitted in small 2U Cubesats) while the other units will be thicker (without this being a big problem since they will be fitted in 3U, 6U or bigger systems).

	Circuit Complexity	PCB design complexity	Board Thickness	Modularity
Integrated MPPT	Simple	High	Good	Low
MPPTs on pluggable module	Simple	Low	Worse	High

Table 1. MPPT Trade-Off

According to above table, the best solution for achieving MPPT modularity is the use of pluggable modules which add further MPPT controllers to the EPS. One group of 4 MPPT should be embedded in the basic EPS (according to requirements) while the other can be on a separate pluggable board. For simplicity, it is envisaged the use of a common solution for the MPPT (on the EPS and on the pluggable boards) to increase design reuse and minimize recurring costs in the development.

III.I.II Variable Solar cells number

The MPPT controllers should be capable of handling from a minimum of 2 Triple Junction solar cells up to 8. The next table shown the main characteristics of AzurSpace Triple Junction 28% efficiency solar cells.

Solar cell parameter	**Value**
Short circuit current @ 28°C (Isc)	506 mA
Open circuit voltage @ 28°C (Voc)	2.667 V
Maximum power point current @ 28°C (Imp)	487 mA
Maximum power point voltage @ 28°C (Vmp)	2.371 V
Short circuit current temperature gradient (dIsc/dT)	0.32 mA/K
Open circuit voltage temperature gradient (dVoc/dT)	-6.0 mV/K
Maximum power point current temperature gradient (dImp/dT)	0.28 mA/K
Maximum power point voltage temperature gradient (dVmp/dT)	-6.1 mV/K

Table 2. AzurSpace 3J solar cells parameters

According to Table 3-2, the minimum MPPT input voltage would be 4 V while the maximum voltage should be 24.6 V. Furthermore, the MPPT should stand a maximum input current of 525 mA.

Given the wide input voltage range, the MPPT controller can require a complex switching converter to accommodate it. Since the EPS is going to be used on a 2U platform (no platform smaller than that one is envisaged), there is a minimum use of low solar cells count panels. In particular they should only be fitted on the Top and Bottom side of the satellite while the other faces will be at least 4 cells each. This consideration may help defining a sub-set of the input voltage dynamic.

Out of the 4 MPPTs on the EPS (as it was decided in section 3.1), one can be dedicated to low voltage solar panels, actually running with as few as 2 cells, while the other 3 MPPTs will always be used with more than 4 solar cells. Since the most common platform for the EPS should be a 2U Cubesat, it should be still possible to use 4 2U solar panels (so with 4 cells): this consideration helps in defining the actual voltage range for the low-voltage MPPT before mentioned to a maximum of 4 cells or 12.3 V.

To sum up, on a minimum-configuration EPS, the 4 MPPTs should support the following voltage ranges:

MPPT	**Voltage Range**	**Solar Cells**
1x	3.5 ÷ 12.3 V	2 ÷ 4
3x	7 ÷ 24.6 V	4 ÷ 8

Table 3. MPPT input voltage range

Further MPPTs (those employed on daughter boards in high performances configurations) are required to support high size solar panels, so they should have again an input voltage ranging from 8 to 24.6 V. This configuration was selected for AzurSpace solar cells: it would be advantageous if the MPPT could support also other cells. This in particular translates in a slightly wider voltage input range. To be fully compliant with other solar cells it would be necessary that the low-voltage MPPT could also run as low as 3.5 V. The same applies for the high-voltage MPPT which should be able to run from as low as 7 V.

The previous mentioned configuration is not a strict requirement: is it is possible to design a switching converter covering the whole voltage range without performances degradation or high complexity, this solution is absolutely accepted. The proposed solution with 2 different MPPTs may be used to simplify the design and reduce complexity.

III.I. III MPPT architecture

The MPPT block is a critical component of the EPS since it is responsible of harvesting the maximum amount of power from solar cells. As specified in [ISIS.EPS.REQ], a real MPPT is required: no solution based on a model of the solar cells can be used since this will require having a fixed type of solar cells and also in case of solar cells degradation, the performances of the EPS will be degraded. A real MPPT is based on the measurement of the input power and on a control loop trying to optimize the power transfer between solar cells and the rest of the system. A simplified block diagram is represented in Figure 3-2. The connection between the solar panel and the switching converter is used to carry power while the MPPT controller is sampling voltage and current. The MPPT controller will then have to set a control signal to steer the switching converter to track the maximum power point. This last connection is likely an analog signal.

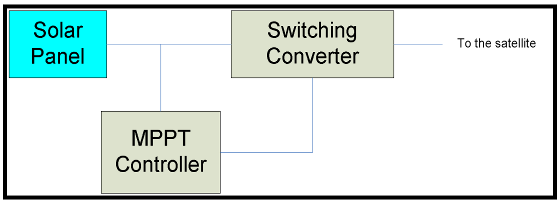


Figure 3. MPPT block diagram

The MPPT algorithm for computing the solar cell maximum power is quite simple in principle but involves non-linear operations (computation of average power). This operation can easily be implemented with an analog circuit, but this would require a high number of components while a software implementation requires one micro-controller and less components. Furthermore, a software implementation has higher flexibility in the selection of the optimum tracking algorithm.

Starting from the conclusions of Section 3.1, the MPPTs will be grouped in units of 4: this means that every solar panel will have his own switching converter and MPPT controller. Given the fact that the controller will be implemented as a software block, this means that every MPPT will have his own controller task computing the actual maximum power point.

This opens up two main implementation possibilities: using one MCU per single MPPT or sharing many MCU tasks on a single microcontroller. Each of the two solutions presents several advantages and disadvantages so a proper trade-off is required.

Considering the requirements, every MPPT should be responsible of acquisition of solar panel current, voltage and temperature. The first two parameters are used to compute actual input power while temperature is used for telemetry. Beside this, every MPPT should monitor the output of the MPPT controller to avoid overdriving the loads (in case the satellite is drawing less than the total produced power). This means that every microcontroller requires 4 analog inputs.

Furthermore, 1 output line is required to set the proper control voltage for the power switching. This can be achieved in several ways: a DAC, a PWM line, etc…

III.I.IV Single MCU per MPPT

PROs:
- Simple MCU design: there is one single task running on the MCU tracking the MPPT
- Requires a small MCU: 4 analog input lines and 1 analog output
- MCU clock can be quite slow (the task is not computationally intensive)
- No single point of failure in the controller
- Common mode errors prone (since the design is one, if there is an error or due to components degradation, all should be affected)

CONs:
- Many MCU will be used, thus making communication between them more complex
- More components on the board

III.I.V Single MCU per 4 MPPT

PROs:
- Complex MCU design: there are 4 tasks running on the MCU tracking the MPPT
- Requires a bigger MCU: 16 analog input lines and 4 outputs
- Single point of failure for a group of 4 MPPT

CONs:
- Simple inter-processor communication
- Analog multiplexer probably needed (due to the high number of analog lines)

III.I.VI Power Busses control

Power is provided to the satellite by means of the power busses: the bus controller is responsible of monitoring power consumption on the busses and switching them on and off according to satellite commands. As specified in [ISIS.EPS.REQ], the switch should have a slew-rate controller to avoid current peaks and a fast switch-off in case of short circuits

III.I.VII Energy Management

The Energy Management block is responsible of managing the available power (solar generated or battery stored) and provide it to the satellite. The main task of this block is the decision which power source to use (solar panels or batteries) based on power availability (eclipse, status of charge).
In case a higher power than needed is generated, the Energy Management system can decide to start storing this energy in the batteries for future use.

III.II Overall General Architecture

This section will address the preliminary design of the ISIS EPS. Since this is a quite complex system, it is better to start with a high level analysis listing the main components to better focus later on every component. As can be seen from Figure 2.2, several components are present on the board. Energy generation is achieved by means of solar panels (not included in the EPS) and solar energy conversion is handled by the MPPTs. Energy storage is granted by the batteries, which are connected to an energy management system controlling their charge / discharge process.

The energy converges in a central node (identified by the switch block in the centre) which is responsible of power sharing. This node should also select which is the proper energy source to satisfy satellite power requirements. This central node is critical for the system since it may be a single point of failure.

This central node can also receive power from an external source (external battery charger) which can be used to charge satellite batteries when the satellite is already integrated. Furthermore, upon satellite release from the deployment mechanism, a separation sensor can trigger a general power on for the satellite.

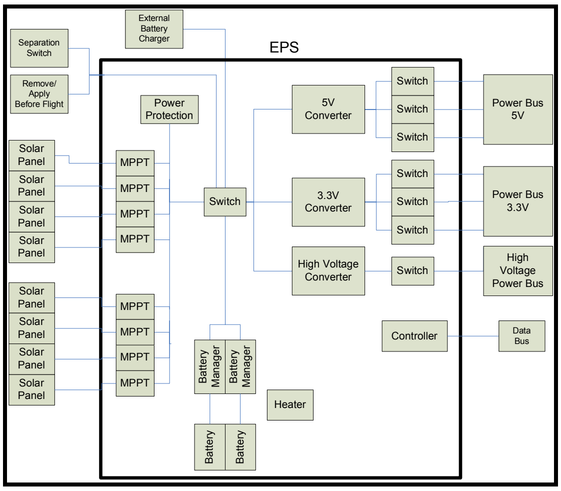


Figure 4. EPS system Architecture

The internal switch node (which still also be considered as the internal power bus) will not be directly connected to the power buses, but it will probably require some switching converters to match the required voltage (one of those can be skipped if the internal power bus matches one of the external ones, even if this is not envisaged). Controlled power switches are required between the previous mentioned switching converters (or the internal power bus) and the output power buses. These switches should be protected against over-current and they should also have a limited slew-rate, as required by the system requirements.

A power protection block is required to ensure that, even if no power is drawn from the satellite and full power is available on the solar panels, the board cannot be damaged.

As can be seen in Figure 2-2, the EPS should have a central control unit (a programmable device, like a microcontroller of similar) to execute the commands and control the system. This central unit should be single (it may be redundant for fault tolerant purposes, but it is not a distributed system). This unit should represent the main interface between the EPS system and the satellite through the data bus. If multiple MCU (or other type of programmable devices) are used inside the EPS, they should be connected to the central unit. No direct exposure of other controller on the satellite bus should happen to avoid interferences or high bus traffic. Data storage should be performed on this central unit because the other "peripheral" units can be switched off for power saving, while this one should always be available.

III.III Modularity and scalability

As specified in [ISIS.EPS.REQ], the EPS shall be able to handle a variable number of solar panels input and batteries. This cannot be easily accommodated using a single board design. One board would be extremely inefficient in terms of space usage and probably it will not fit all the required components. The suggested approach is therefore the use of multiple boards, in particular the use of a main board with attached daughter boards. The main unit should host the central controller and the connection to the satellite bus, while the MPPTs and batteries (which should be scalable) can be hosted on stackable daughter boards.

Two different types of daughter boards can be produced hosting the MPPTs on one and the battery manager on the other one. This solution gives high flexibility and scalability but it requires the design of two separate boards which could increase the lead time and development cost.

A different solution could be to develop only one daughter board housing both batteries (and the battery management) and MPPTs. This solution will require a more complex PCB but is simpler for production. Batteries can be housed on one side of the board while the switching converters can be on the other side. This solution simplifies the stacking of the boards and increases the fill factor. Further boards can be then easily stacked optimizing the maximum capacity that can be fitted. This last solution is depicted in Figure 2-3.

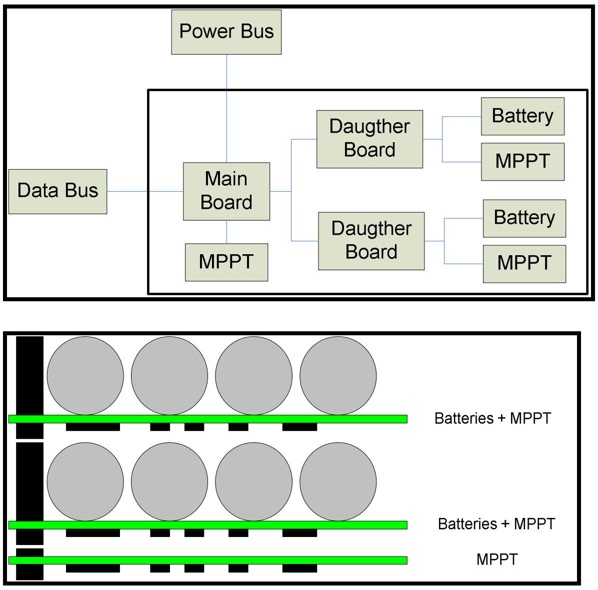


Figure 5. EPS & Battery Stacking

Figure 2-4 depicts a possible solution for stacking the daughter boards, as above described. Different daughter boards can be created by populating only part of the whole board. This way only one daughter board can be designed but two different one can be produced.

IV. Thermal Analysis

The EPS mechanical design is currently based on 4x Sanyo UR18650F cells mounted on a PC-104 type PCB. Consideration for the supporting electronics has not been included in the analysis but it has been noted that they will mostly be placed on the underside of the PCB.

IV.I Mechanical Design

Below is a visual representation of the EPS thermal model set up in ThermXL. The 4 cells are mounted in a battery case which is then assembled to a PCB. Each battery is 64.7mm long with a diameter of 18mm.

Dimensions of Sanyo UR18650F battery cell	
Length	64.7 mm
Diameter	18 mm

Table 4: Battery cell dimensions

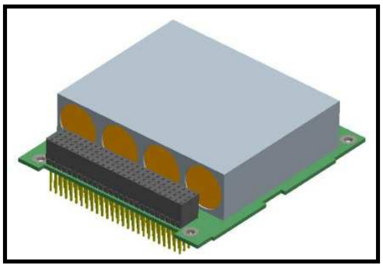


Figure 6. Visual representation of EPS thermal model

As the request was to determine the performance of the EPS in the space environment, the thermal model was expanded to consider the EPS board mounted within a CubeSat structure.

The assumptions of the thermal model were:

- A 1-Unit CubeSat was model mounted with 2 solar cells per panel
- The PCB stack had 4 PC-104 PCBs of which only the EPS board was populated. The remaining PCBs were blank.
- The CubeSat was simulated to be in a midnight-noon orbit with a nadir pointing configuration.
- The EPS board was therefore always on the Zenith pointing side of the CubeSat.
- The batteries had a heat loss of 10%.
- Without data to simulate the chemical reaction of the cells or knowing the

lumped conductivity of the cells, the cells were assumed as being pure Lithium incased in a Stainless Steel casing.

- Radiation only occurs between the external surfaces of the CubeSat to space
- All internal heat interaction is assumed to be by conduction only which is very dominant.

IV.II Material Assignment

Table below lists the material properties assigned to the components of the model.

Components	Material
PCB	Combination of 4 Copper and 3 epoxy layers
Bus Connector	Copper (Pins only, plastic body ignored)
Threaded rods	Stainless steel
STS ribs	Aluminum
STS frame	Aluminum
STS panels	Aluminum
Solar Cells	Germanium + cover glass
Battery cells	Lithium + stainless steel casing
Battery holder	Polycarbonate

Table 5: Material assignment of parts

IV.III. Thermal Inputs

The external heat inputs will be from solar radiation, Earth albedo and Earth IR emissions on the external surfaces of the CubeSat. These are roughly calculated per surface during each time step of the orbit.

As for the internal heat input from the battery cells, information has been provided on the power discharge of a single cell. This data is based on earlier power budget analysis of the Triton satellite. The battery efficiency ranges from 85-90%. The best efficiency was assumed to simulate conditions with minimal internal heat generation.

Orbit phase	Power discharge (W/hr)
Eclipse	0.86
Sunlit	0.93

Table 6. Battery cell power discharge estimation

IV.IV Results of Thermal Analysis

Error! Reference source not found. and **Error! Reference source not found.** display the measured maximum and minimum temperature respectively on the EPS board. **Error! Reference source not found.** shows the temperature variation of a PCB node of the EPS board along with single battery cell and the battery holder. **Figure** shows the temperature variation of the external surfaces of the CubeSat. Without an active heating system, the batteries have a temperature range below 0 °C.

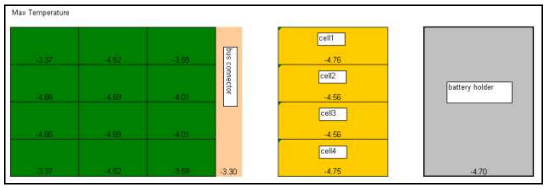


Figure 7. EPS board maximum temperature (°C)

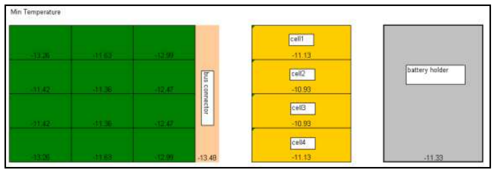
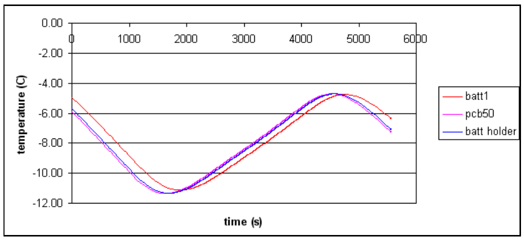


Figure 8. EPS board minimum temperature (°C)



Figuer 9. Internal temperature range

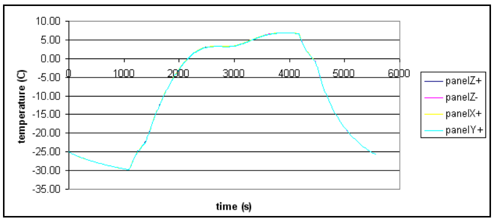


Figure 10. External temperature range

Error! Reference source not found. then shows the temperature profile after assuming battery heating is implemented to the system. The assumption was that 0.6W was added to the existing heat generation per battery cell during the eclipse phase and 0.4W added during the sunlit phase. The battery cell temperatures would then stay above 0 °C.

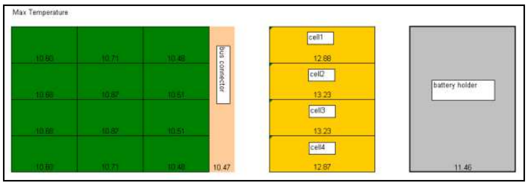


Figure 11. EPS board maximum temperatures (with battery heater)

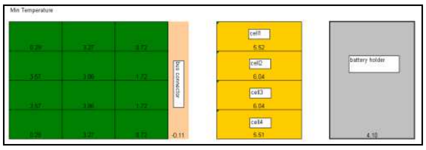


Figure 12. EPS board minimum temperatures (with battery heater)

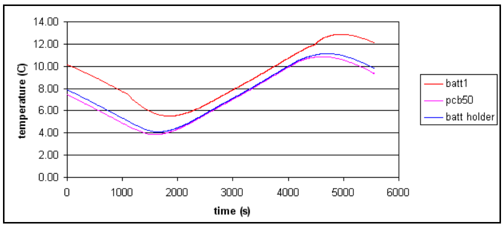


Figure 13. Internal temperature range (with battery heater)

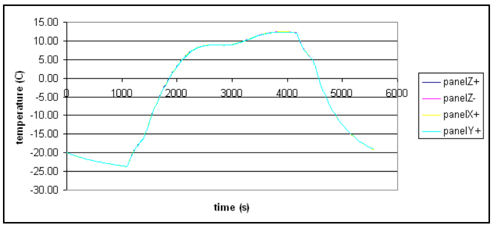


Figure 14. External temperature range (with battery heater)

V. Battery System

Energy storage is achieved by means of secondary (rechargeable) batteries which can use solar generated power to be charged. They are used to provide power to the satellite when it is in eclipse (about 40-60% of the orbit time, depending on the orbit) or when solar panels cannot stand the peak power requirements from the satellite. According to [ISIS.EPS.REQ], the EPS should be able to operate also without batteries: this may be useful if no actual battery is installed in the satellite of when all the batteries failed due to aging.

The battery management system is extremely important for a satellite power system since it can ensure power when other sources (like solar panels) are not available (in eclipse, for example). Given the high variability in the required stored energy, the battery management system should be modular, with pluggable units to increase stored energy. As discussed in Section 2, these modules will probably be stacked one on top of the other to increase the fill factor

V.I Coupling

There are basically three different ways to couple the batteries together: series, parallel and hybrid as shown in the below figure A, B & C respectively.

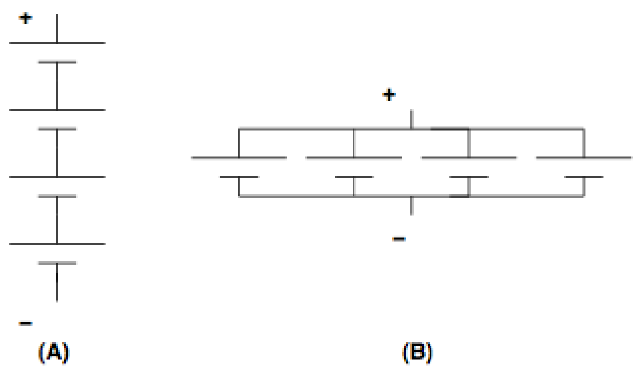


Figure 15. Battery Coupling (A) Series (B) Parallel

Battery Cells in Series V/s Parallel:

1. When connected in series, the cells have to be accurately balanced because the same current runs through all of them and if not completely balanced they will be fully charged at different times. When the first battery is fully charged the other battery charging must be stopped, leaving the other batteries not fully charged. This problem is much smaller when cells connected in parallel. But it should be noted that in either configuration batteries have to balanced properly before connecting to the EPS.

2. Another problem with series connection is that, if one of the battery in the series array fails in open then it leads to failure of complete battery system, which is not the case if cells are connected in parallel.

3. When connected in parallel, the battery system will provide high capacity but with low voltage. The low voltage will be further boosted before supplying it to down convertor at distribution circuit.

In conclusion, considering better efficiency and high reliability it is decided to avoid series connection of batteries, which eliminates coupling configuration A &

C. Therefore the choice falls on parallel connection of all the batteries.

Battery Standard & Number of Cells:

As specified in [ISIS.EPS.REQ], one complete PCB of PC 104 shall be spared for battery system. Considering the mounting requirements & available area, one side of the PCB area shall be dedicated to battery pack. The other side shall be used for required heater, charger and manager/protection circuit. Therefore an area of (85mm*78mm) will be available for battery cells. Also considering the requirement of very low pressure handling capabilities in vacuum it was decided to go for cylindrical Li-Ion batteries.

It was found that by using batteries with 18650 (18.5 mm x 65 mm) standard would lead to highest total capacity and fill factor. Therefore, four 18650 batteries are proposed for the battery system. Highest available capacity cells were considered, which are commercially available. From a systematic tradeoff process it was found that two barriers Samsung's ICR 18650-30A & Panasonic's NCR18650A offers best performance parameter like high capacity and low discharge cut-off voltage. One among these cells will be used for battery system.

V.II. Heater

It is decided to go for flexi-heaters for individual battery cells rather than single heater for complete battery pack because single heater system will consume same power for heating up even if one of the cell dies during the mission. By having individual heater for battery cells, heaters can be switched ON & OFF according to each cell condition/requirement. The heaters shall be rolled over each battery cell for effective heat transfer.

As specified in the 'EPS Thermal Note.doc', each cell will be supplied with a power up to 0.45 W. Following are the specifications of required heater:

Area: 59 mm x 65 mm
Power: 0.45 watts
Voltage: 3.3v or 5v
Current: 136 mA (3.3v) or 90 mA (5v)
Resistance: 24.26 ohm (3.3v) or 55.5 ohm (5v)

It's found that a company knows as 'Minco' provides commercial heaters, which can be custom designed according to our requirement. Further the heaters form 'Minco' can also be customized to have embedded temperature sensors. Also 'Monic' can provide Pressure Sensitive Adhesive (PSA), which will be easy for battery system fabrication instead of using an Epoxy or RTV.

Battery Cell Mounting:

For better mechanical stability a casing will be used to mount the 4 battery cells on PC 104 as shown in figure:

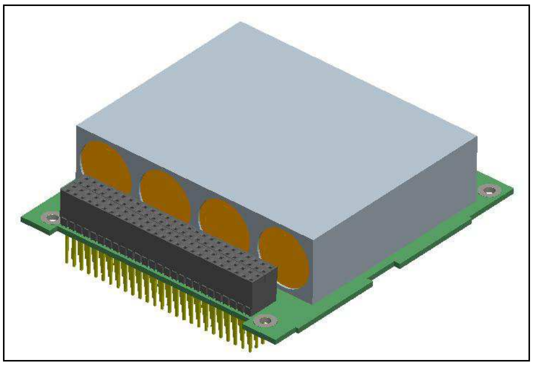


Figure 16. Battery Cell Mounting

Casing Martial:

The casing material of Plastic Fiber is chosen over Aluminum for following reasons:

- Good thermal isolator
- Low cost
- Light weight

V.III Battery & Heater Characterization

The primary objective of this work is to ensure safe operation of Li-Ion Panasonic batteries and heater for small satellite applications. The outcome of this work will influence in deciding the lifetime of the batteries and their sustainability for long duration small satellite missions. The heater characterization results will be a deciding factor for thermal design of iEPS.

Tests & Components Used

After an extensive research and with reference to ESA, ESTEC standards for battery characterization following tests were performed accordingly:

1. Standard Capacity Test
2. Cell capacity with different discharge rates @ ambient conditions
3. Charge characteristics @ ambient conditions
4. Cell behavior in vacuum at +60 degree C
5. Heater Operation
6. EMF Vs SoC
7. Cell Balancing
8. Life Testing

Test Equipments Used:

1. UBA Battery Analyzer
2. Battery Cells: Panasonic NCR18650A
3. Heaters: Minco
4. Temperature Sensors
5. PC
6. Probes

Figure 17. Heater & Batter Cells (left); Battery Holder (right)

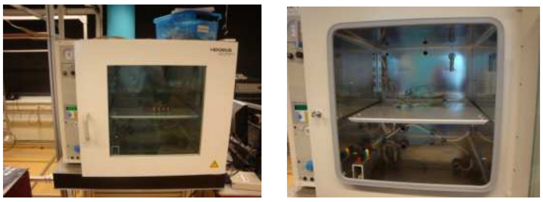


Figure 18. Thermo-vacuum Setup

Following Tests were performed as a part of characterization:

V.III.I Standard Capacity Test

Test Specification:
Temperature: Ambient Condition
Charge Condition: CVCC 3.6 volts; 885 mA
Discharge Condition: Constant current 2950 mA; 2.5 volts cutoff
Data Logging: Every 1 sec
Charge Stabilization: 100 mA @ Charge 0.7 C
Temperature Cutoff: +85 degree Celsius

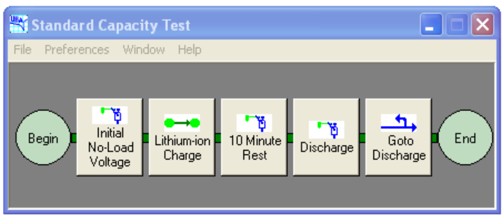


Figure 19. Typical Battery Analyzer Routine

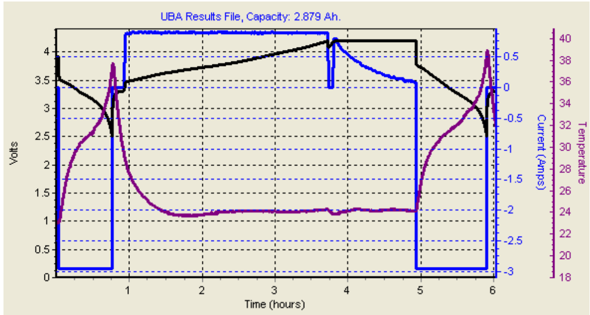


Figure 20. Standard capacity test results

Measured Capacity: 2.879 Ah (92.9% rated). Pass.

V.III.II Cell Capacity at Different Discharge Rates

Specification:
Temperature: Ambient Condition
Charge Condition: CVCC 3.6 volts; 885 mA
Discharge Condition: Constant current C/2, C/5, C/10 and C/50; 2.5 volts cutoff
Data Logging: Every 1 sec
Charge Stabilization: 100 mA @ Charge 0.7 C
Temperature Cutoff: +85 degree Celsius

Following are the measured capacities:

Discharge Condition	**Measured Capacity**
C/2	2.966Ah (94.7% rated)
C/5	2.966Ah (95.7% rated)
C/10	2.990 Ah (96.45 % rated)
C/15	3.033 Ah (97.83 % rated)

Table 7. Cell capacity at different discharge rates

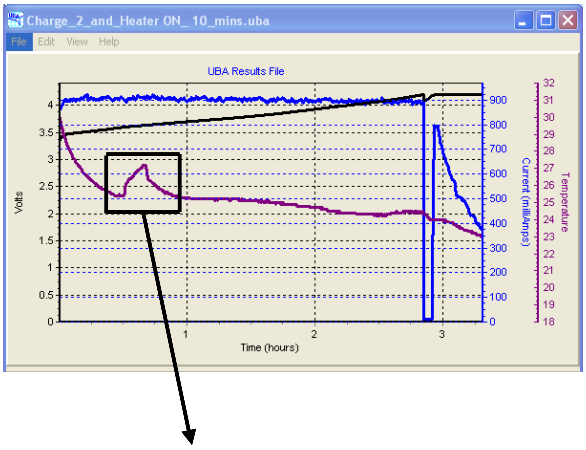
V.III.III Cell Behaviour in Vacuum

Specification:
Temperature: +60 Degree Celsius
Charge Condition: CVCC 3.6 volts; 885 mA
Discharge Condition: Constant current 2950 mA; 2.5 volts cutoff
Data Logging: Every 1 sec
Charge Stabilization: 100 mA @ Charge 0.7 C
Temperature Cutoff: +85 degree Celsius
Measured Capacity: 2.800 Ah (90.32 % rated)

V.III.IV Heater Operation

V.III.IV.I In ambient condition:

Specification:
Heater On Duration: 10 mins
Voltage: 3.3 volts; 60.6 mA



Raise in Temperature

Figure 21. Heater Testing at ambient conditions

A rise of 2 degree Celsius was observed by turning heater ON for 10 mins with 0.2 watts.

V.III.IV.II In Vacuum @ 25 Degree Celsius

Specification:
Heater On Duration: 60 mins
Voltage: 3.3 volts; 60.6 mA and 5.0 volts; 91.92 mA

A rise of 6 degree Celsius was observed by turning heater ON for 60 mins with 3.3v supply and a rise of 11 degree Celsius was observed with 5.0v supply in vacuum.

V.III.V EMF Vs SoC

Specification:
Temperature: Ambient Condition
Charge Condition: CVCC 3.6 volts; 885 mA
Discharge Condition: Constant current C/50; 2.5 volts cutoff
Data Logging: Every 1 sec
Measured Capacity: 3.022 Ah (97.5% rated). Pass.

VI. CONCLUSION

In reference to above discussion a successful design of Electronic Power System (EPS) was carried out. System was made modular in order to be flexible for given class of the satellite.

The thermal results currently are the best approximation of the EPS thermal performance without any active heating. The simulation can be better improved if a more proper thermal model of the battery cell can be simulated. This would required more information of this chemical reaction and material composition. If lumped thermal properties could be found for the thermal conductivity, specific heat capacity and density this would also be a simpler method for modeling.

It can be concluded that battery heaters would be required to provide some heating. Take note that the temperatures seen are still low as other heat generation devices that would be found on a CubeSat or payloads for a specific mission have not been added. This would typically be up to the customer to further simulate. One aspect of the simulation that will be corrected is proper calculation of view factors related to the external heat inputs.

The designed heater was found to provide good heating response. At the end of heater calibration it was decided to implement temperature sensor with feedback to be able to maintain the battery system within required temperature range. Further, the results of battery calibration show that the capacity was consistently measured to be above 95% hence can be concluded to be reliable for satellite operation.

VII. REFERENCES