MINIMUM BATTERY ENERGY IN THE SURVIVAL MODE FOR THE COMS SPACECRAFT

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ABSTRACT ... The MRE (Monitoring Reconfiguration Electronics) board included inside the SCU (Spacecraft Computer Unit) in the COMS (Communication, Ocean and Meteorological Satellite) spacecraft is used to monitor the battery voltage and to detect a battery under voltage (low battery capacity) or a battery overvoltage (overcharge). In case of alarm detection, a reconfiguration is initiated by the MRE board. The MRE configures the overall spacecraft in the survival mode to protect the Li-Ion (lithium ion) battery from overcharge and over discharge. For the EPS (Electrical Power Subsystem) point of view, the survival mode can be trigged from hardware wired thresholds. The aim of this paper to provide and to justify the low and high threshold levels which are associated to the MRE battery voltage monitoring. The MRE trig guarantees minimum battery energy to available for the required 48 hours autonomy duration of the spacecraft after MRE trig in the survival mode.

KEY WORDS: COMS, EPS, Li-Ion battery energy, MRE

1. INTRODUCTION

1.1 Scope

The COMS battery use SAFT VES140S Li-Ion cell (nameplate capacity of 38.5Ah). The maximum cell voltage at 100% state of charge is 4.1V and the minimum critical cell voltage is 4.3V.

The minimum requested energy in the survival mode at is 15%. The criteria for MRE voltage levels is 4.15V to 4.26V for overvoltage and 3.49V (DOD, Depth Of Discharge, of 80%) and 3.57V (DOD of 70%) for under voltage. In eclipse, the battery DOD in the COMS power budget is less than 44% at 10 years end of life in worst case condition with 1 cell module failed. The following items have taken into account to justify the low and high threshold levels of the MRE trig.

- The battery voltage have been computed taking into account SAFT G4 (4th generation cells are the first to be manufactured on a full scale production line) qualification results,
- The battery threshold levels (low and high) associated to MRE alarms are adjusted with a resistor bridge introduced in an accessible and removable plug within the Li-Ion battery,
- The internal battery impedance have been computed for DOD of 70% to 80%, cell module current of up to C/1.35 and an operating temperature of 10°C to 30°C.
- The robustness of MRE alarm has been ensured against spurious trig.

1.2 Overview of COMS Battery

The COMS features 10 cell modules connected in series. These cell modules, together with the associated thermal control and harness are fitted on a dedicated structural panel. The COMS battery is shown in the Figure 1 and the following electrical hardware is installed on a structural panel:

- The 10 cell modules,
- The interconnecting power harness (flat aluminium cables) and signal harness with interface connectors,
- A dedicated power connection between the 9th and the 10th cell module for specific need to MI2U (Meteorological Imager Interface Unit),
- A current sensor by shunt,
- Two relay bracket electronics (RB0358),
- Three plugs,
- Thermal hardware.

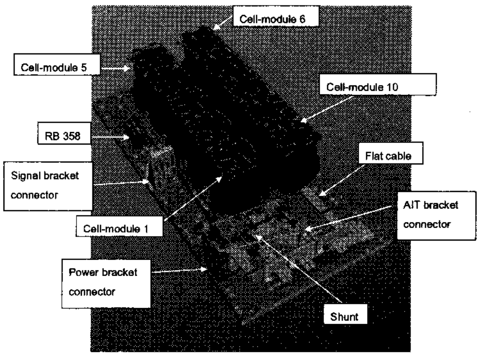

Figure 1. Overview of COMS battery.

The cell module is made of 5 Li-Ion cells connected in parallel to provide required energy, power and voltage. The Figure 2 shows cell module layout for 9P configuration with longer bus bar. The cell module for COMS is 5P configuration with shorter bus bar and each cell module includes:

- Five VES140S cells
- A base plate to support of the cells
- A by-pass device and a by-pass support
- A bus bar for positive power

- Negative power wires
- A BSM Mk2 (Balancing System Module Mark 2)
- A thermistor for cell module 3, 6 and 10
- Connectors for low level signals and by-pass commands in the BSM Mk2

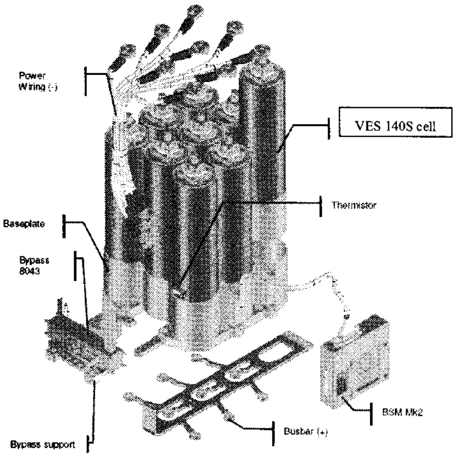

Figure 2. Cell module layout for 9P configuration with longer bus bar.

1.3 Battery Voltage MRE Alarm Interface

The MRE board included inside the SCU is used to monitor the battery voltage and to detect a battery under voltage (low battery capacity) or a battery overvoltage (overcharge). In case of alarm detection, a reconfiguration is initiated by the MRE board and configures the overall spacecraft in survival mode. The battery voltage MRE alarm interface is shown in the Figure 3 and includes with following functions:

- Stage 1: The Li-Ion battery and its charge/discharge current shunt which provide rough battery voltage and battery current shunt voltage signals.
- Stage 2: The PSR (Power Supply Regulator) battery shunt voltage conditioning, this conditioned signal is used to compensate the low/high MRE threshold levels with internal battery voltage drops due to high discharge currents and to the internal battery impedance, the aim of this compensation is to deliver to the MRE a signal proportional to the battery open circuit voltage which is an image of the battery sate of charge.
- Stage 3: The resistor bridge which is used to adapt the battery voltage to the MRE input voltage interface and to combine the battery current signal for compensation. This function is included inside a dedicated plug within the battery.
- Stage 4: The MRE board is in charge of monitoring the good operation of the spacecraft. The COMS use the MRE low voltage level A and MRE high voltage level. The MRE low voltage level B is not used for COMS.
- The ADE5 (Actuator Drive Electronics of 5th generation) and PSR acquire the MRE alarm input voltage in order to provide a ground monitoring. The input impedance is 15.11kΩ for the PSR acquisition channel and 20 to 50MΩ for the ADE5 acquisition channel.

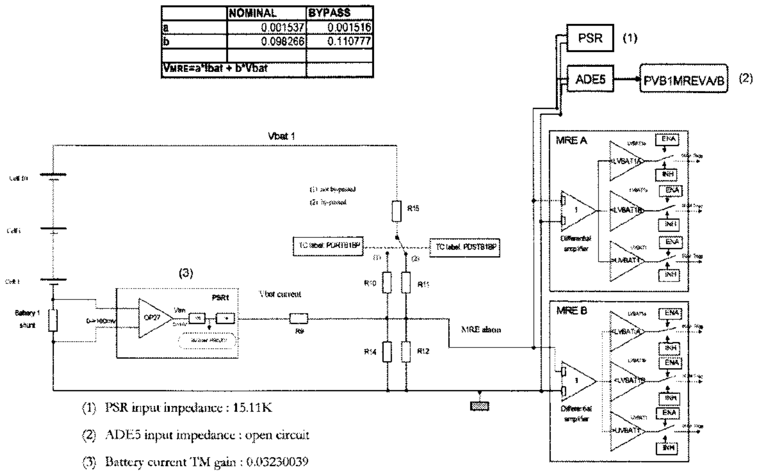

Figure 3. Battery voltage MRE alarm interface.

2. DESIGN DESCRIPTION

2.1 Battery Shunt Current Monitoring

The PSR monitors battery charge and discharge currents with a current sensor included inside the battery. The battery current monitoring in the PSR includes three independent charge/discharge current telemetries issued from a current sensor by shunt. Each telemetry line of positive and return includes a serial resistor as a protection. The discharge current telemetry conditioning circuit is used to compensate the low/high battery threshold levels. The shunt is 0.7692mΩ in 130Amax and provided by the EMPRO. The voltage provided at amplifier outputs in the PSR conditioning circuit is as follows:

- $Vbat\_i > 0$ for a discharge current
- $Vbat\_i < 0$ for a charge current

The common mode voltage is very low at shunt level and is less than 100mV. The amplifier provides output resistors to protect the amplifier in case of output short circuit failure to ground or with regard to sinking currents when the amplifier output voltage is negative in charge mode. The amplifier gain is 0.0323.

2.2 Li-Ion Battery Modelling

The aim is to evaluate the internal resistance of the battery in order to model the battery voltage according to the battery DOD, the battery temperature and the battery operating conditions (charge and discharge, low or high discharge current, low or high charge current), it includes following terms:

- Cell internal impedance based on SAFT measurements,
- Cell module power harness impedance,
- Contact resistance,
- Battery power harness impedance,

Cell impedance

The SAFT was measured cell internal resistance with respect to temperature and current during G4 qualification phase. The equation 1 can be used to take into account temperature effects at a constant discharge current of 22A. The equation 2 can be used to take into account current effects at a constant temperature at 20°C. The equation 1 and 2 are obtained with a polynomial interpolation for the measured values. The temperature and current coefficients can be merged to the equation 3 in order to get an overall cell impedance model which is a function of the temperature and the current. The two factors $coef\_1_0(\Delta T)$ and $coef\_2_0(\Delta T)$ have been computed and are provided in the equation 4 and 5 respectively. The $coef\_1_0$ and $coef\_2_0$ are 56.275 and -0.7488 respectively. The worst case resistance value is obtained for a DOD equal to 80% and a low temperature environment of 10°C and ageing or fading equal to 20% (Rint×1.2) at the end of life.

$$R(T, DoD=80\,\%, Idis=22A)=0.0058\times T^2-0.4731\times T+13.265 \quad (1)$$

$$R(I, T=20°C)=56.275\times I^{-0.7488} \quad (2)$$

$$R(I, \Delta T)=coef\_1_0(\Delta T)\times I^{-coef\_2_0(\Delta T)} \text{ with } \Delta T=20-T \quad (3)$$

$$coef\_1(\Delta T)=coef\_1_0\times(0.0195\times\Delta T+1.0042) \quad (4)$$

$$coef\_2(\Delta T)=coef\_2_0\times(0.0273\times\Delta T+0.9918) \quad (5)$$

Cell module harness impedance

The bus bar resistance calculation is based on the linear resistance of 2.83μΩ×cm considering geometry of the positive bus bar. The aluminum cables are used for the power connections in the negative power side. The aluminum cable resistance calculation is based on the following assumptions:

- Each negative terminal connection to the by-pass includes six AWG16 (American Wire Gauge 16) aluminum cables
- Linear resistor of 23.4Ω/km
- The material used for these cables is aluminum 1050
- For by-pass terminal connection a resistance of 10μΩ added
- The cables temperature is considered to be equal to 40°C

The bypass module of NEA8043 is connected in series with each cell module. The characteristics of the by-pass are as follows:

- Resistance of the bypass is 115μΩ (maximum specified end of life value)
- Two contacts are provided with a 10μΩ

Battery harness impedance

The resistance due to power bus bars and contact resistance have been estimated as follows:

- Bus bars between battery negative connectors and shunt, shunt and cell module 1 negative terminals, cell module 5 positive terminals and cell module 6 negative terminals, cell module 10 positive terminals and battery positive connectors
- Contact resistance for battery positive and negative connectors, shunt terminals, module to module interface

Total battery harness impedance

The total battery harness impedance calculates with respect to temperature and discharge current including Li-Ion cells resistance, cell module harness and battery harness at a DOD of 80%. Taking into account an open circuit voltage of 3.49V for a DOD of 80% and 3.57V for a DOD of 70%, a correlation of the model has been performed at cell level with regard to test results. The results lead to a maximum error less than 1.0% for the complete operating range. The uncertainties for the error in the model are largely covered the temperature uncertainties (+/-5°C) in the battery thermal design.

Battery energy

The battery voltage and impedance models permit to predict the battery voltage and impedance at a fixed DOD, this DOD corresponds to the ratio of the discharged energy at a fixed discharged current and at a fixed temperature with regard to the nameplate energy at 20°C, C/1.5. In survival mode for COMS case, the thermal software regulation is the same as in operational mode. The thresholds values are 13.5°C for transfer orbit and 13.9°C for on-station. The remaining energy after MRE trig is always greater than the remaining energy obtained at the battery temperature during the MRE trig. This energy can be expressed as equation 6 and 7.

$$\text{BOL remaining energy}=(\text{Total energy}(BOL, C/3, 4.1V, T_{MRE\ trig}) - 138Wh\times DOD)\times n_p\times n_s \quad (6)$$

$$\text{EOL remaining energy}=(\text{Total energy}(EOL, C/3, 4.1V, T_{MRE\ trig}) - 125Wh\times DOD)\times n_p\times n_s \quad (7)$$

Where:

n_s: number of cells in parallel per cell module

n_p: number of cells in series per battery

DOD: depth of discharge computed with regard to the nameplate energy (125Wh for EOL conditions and 138Wh for BOL conditions) at 20°C and C/1.5.

Total energy (BOL/EOL, C/3, 4.1V, $T_{MRE\ trig}$): total energy after full charge in BOL or EOL conditions (4.1V) and for the battery temperature at MRE trig. With regard to temperature aspects, SAFT qualification tests have permitted to approximate this mechanism: $E_{cell}=24.13\times Ln(T_{MRE\ trig})+56.72$.

2.3 MRE Threshold Adjustment

The definition of the plug is quite independent from the requested DOD, it mainly depend on the battery configuration (XsYp, cell module s connected in series and cell p connected in parallel). The battery threshold levels have been adjusted to fulfil the following objectives:

- The over voltage detection have to greater than S×Vcell_max, where Vcell_max is 4.15V
- The under voltage detection have to lower than S×Vcell_min, where Vcell_min is 3.49V for DOD of 80% and 3.57V for DOD of 70%
- Vbat=EMFbat+Rbat×Ibat=S×EMFbat_cell+Rbat×Ibat, where the EMFbat is Electro Motive Force voltage of battery

Resistor bridge interface

The resistor bridge is show in the Figure 4 and is used to adapt the battery voltage range to the MRE input interface (battery threshold voltage) and to combine the PSR current shunt signal. The TL12 relay is used to adjust the battery voltage levels (overcharge and undercharge) in normal and bypass configurations. Each relay position corresponds to a different gain thanks to the selection of a different resistor (R10 or R11). The R9 resistor is used to compensate the battery voltage with the battery discharge current acquired by the PSR. The R15, R10 and R11 resistors permit to adjust MRE thresholds in both configurations (nominal and bypass position). The R12 and R14 resistors permit to adjust MRE thresholds in both configurations. The resulting value is chosen as low as possible to avoid a significant effect of the PSR and ADE5 acquisition channel leak current. This MRE voltage can be expressed as equation 8.

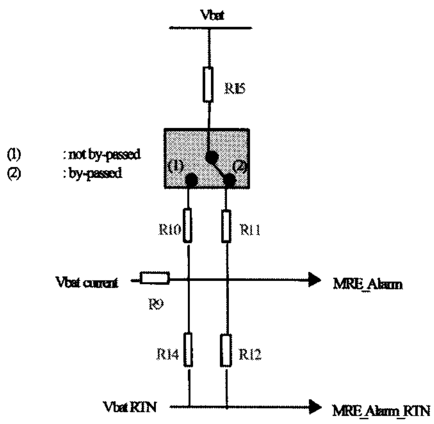

Figure 4. Resistor bridge interface.

$$V_{MRE}=(Vbat\_I\times A)+(Vbat/B) \quad (8)$$

Where:

Ra=R15+R10 for not by-passed (or R11 for by-passed)

Rb=R9, Rc=R14//R12, Rd=Ra//Rc, Re=Rb//Rc

A=Rd/(Rb+Rd), B=(Ra+Re)/Re

MRE alarm adjustment at the SCU level

The low level at the MRE board is specific to a DOD configuration and to the number of cell modules in series per battery. It does not depend on the number of cell in parallel. The high level at the MRE board depends on the number of the cell modules in series per battery.

2.4 MRE Alarm Robustness

The robustness of MRE alarm have to ensure against spurious trig which could lead to a spacecraft reconfiguration in survival mode and by consequence to a temporary mission interruption.

SEU (Single Event Upset) aspects

As the battery, the PSR conditioning circuit and the ADE5 acquisition channels do not include any SEU sensitive components. The only SEU critical points correspond to the LM139 comparator, the FPGA (Field Programmable Gate Array) in the MRE board and the AD584 voltage reference. For LM139 and AD584 cases, a maximum transient duration at the output of each component is less than 5μs. As the comparator is not latched, a SEU will only lead to a transient fault output less than 5μs. This transient will have no effect at MRE level as the FPGA which monitor the alarm includes a numerical filtering of 1 minute.

EMC (Electro Magnetic Compatibility) and ESD (Electro Static Discharge) aspects

For both aspects, the verification of filtering circuits included in each sub-function of the MRE alarm permits to the robustness level of the overall circuit. The PSR conditioning circuit includes a RC filter of cut-off frequency at 100Hz. The battery plug includes one capacitor of 1μF in parallel with the potential divider output (cut-off frequency at less than 10Hz). The output of SCU MRE alarm is directly received by the MRE FPGA which includes a numerical filtering of 1 minute.

3. CONCLUSIONS

The MRE thresholds are adjusted according to the by-pass status of the battery by toggling a relay within the bridge divide inside the battery. The MRE threshold values have been selected considering the worst case conditions (ageing, temperature, discharge current, by-pass status) in order to guarantee a minimum battery energy available. The MRE voltage levels for COMS Li-Ion battery is 3.527V for battery under voltage (low battery capacity) and 4.209V for battery overvoltage (overcharge) at 10 years end of life. These MRE voltage levels are always fulfil the criteria for under voltage and overvoltage without any problem. The lower MRE value is reached in worst case conditions at 33% state of charge (67% DOD) in worst case by-passed condition at 10 years end of life. The minimum requested energy of 15% in the survival mode is always fulfilled.

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