Aviation Battery Monitoring Electronics for Li-Ion Battery Systems in Electrified Gliders and Aircrafts

R. Schwarz[a], R. Waller[a], M. Wenger[a], M. Akdere[a], J. Neureuther[a], M. Gepp[a], S. Koffel[a], V.R.H. Lorentz[a], M. März[a], A. Holtsmark[b], V. Gribov[b], A. Lange[b]

a)
Fraunhofer IISB
Schottkystrasse 10 ; D-91058 Erlangen ; Germany
vincent.lorentz@iisb.fraunhofer.de

b)
Lange Aviation GmbH
Brüsseler Straße 30 ; D-66482 Zweibrücken ; Germany
axel.lange@lange-research-aircraft.com

***Abstract*—This paper presents the hardware and software design of a battery monitoring circuit developed to be used in aviation applications employing lithium-ion batteries in their electrified powertrain. The considered aircraft is a manned glider able to take-off and land by using its electric propulsion system supplied by NCA/Graphite lithium-ion batteries. The battery monitoring electronics was developed with the highest considerations in terms of fail-safe and fail-operational requirements. The electronic design of the battery monitoring circuit integrates the battery busbars and uses new passive balancing components with an innovative busbar cooling solution, thus increasing the reliability and the robustness of the whole battery system. The software also contributes to the high safety level by employing cross-check and plausibility check mechanisms.**

Keywords—Lithium-Ion Battery; Fail-Operational; High-Availability; Redundant Architecture; Electrified Powertrain; Electrical Energy Storage System; Electric Aircraft; Aviation

I. INTRODUCTION

The electrification of the powertrains in road vehicles is well established nowadays, however the electrification of aircrafts is just at its beginning. This paper presents the results of the development of an aviation battery system integrated in an electric glider designed by Lange Aviation GmbH in Germany. The company develops and produces sailplanes with the capability of electric propulsion for climbing as well as for take-off and landing. The Lange Antares 20E is a self-launching 20 m electric glider with a 42 kW DC-brushless motor powered by lithium-ion batteries. It was the first glider with an electric propulsion system obtaining a certificate of airworthiness from the European Aviation Safety Agency (EASA). With a fully charged battery pack, it can climb more than 3000 m purely electrically.

II. OVERALL ARCHITECTURE OF THE GLIDER

The electrical power supply of the Antares 20E consists of 2×12 battery modules located inside the two wings of the glider. Each of the battery modules consists of three NCA/Graphite lithium-ion cells of 41 Ah and includes a battery monitoring circuit (UTM: Voltage and Temperature Monitoring) which communicates via a CAN bus with the battery management system (BMS) of the glider as proposed in [1]; in contrast to a capacitive coupled differential communication between each UTM and the central BMS as proposed in [2]. A schematic overview over the powertrain of the glider is given in Fig. 1.

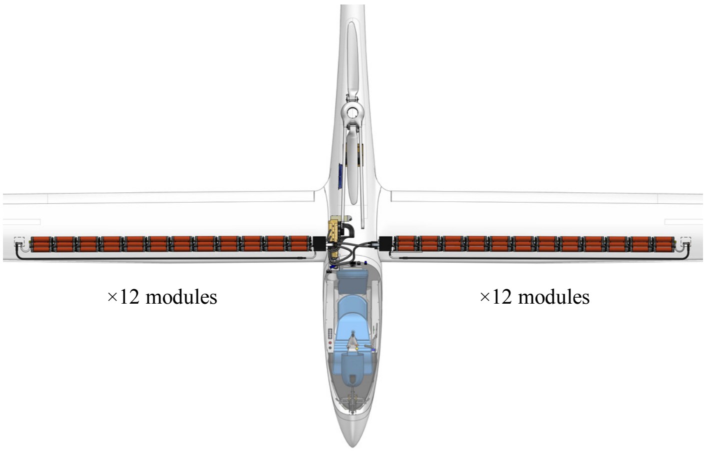

Fig. 1. Global overview of the Antares 20E glider from Lange Aviation GmbH showing its electrical powertrain.

To reach the best level of reliability, safety, maintainability, availability and performance, the monitoring circuit shown in Fig. 2 was developed by considering the following requirements:

- Redundant battery cell voltage measurement
- Redundant battery cell heater control switches
- Three battery cell temperature sensors
- Two independent sensors with integrated over-temperature switches
- Busbars avoiding mechanical and thermal stress on the printed circuit board and providing accurate temperature measurements
- Independent over-temperature shutdown of the battery cell heater and the balancing circuitry, controlled by a microcontroller unit (MCU)
- Separate hardware watchdog circuit (redundant with the microcontroller) to shut down the battery heater and the balancing circuitry

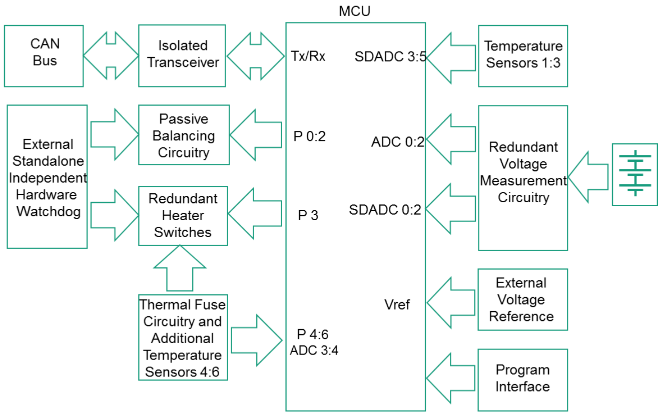

Fig. 2. Block diagram of the battery monitoring electronic circuit sensing the battery cell voltages and temperatures, performing passive cell balancing, and sending the collected data to a central computing unit (CCU) over a galvanically isolated CAN bus.

III. Electronic Design of the UTM

The UTM battery monitoring electronics is mounted between the battery modules and is monitoring the three battery cells of each module. The design and circuit of this electronics is focused on fail-safe operation and robustness in harsh aviation environment. A photograph of a UTM board is shown in Fig. 3.

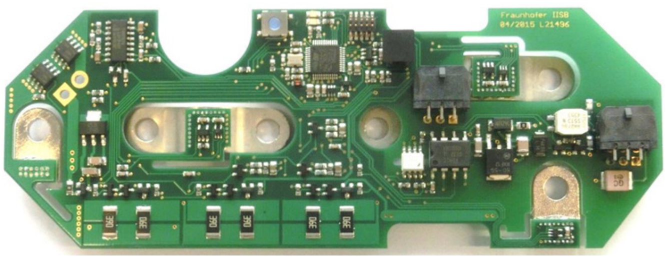

Fig. 3. Battery monitoring electronics showing the busbars directly soldered on the printed circuit board.

The battery monitoring is built around an ARM Cortex-M4 microcontroller unit (MCU) from ST-Microelectronics (STM32). This MCU features high precision 16-bit sigma-delta analog-to-digital converters (ADC) for cell voltage measurements and a CAN interface for the communication between the monitoring electronics and the central computing unit (CCU). The CAN interface is galvanically isolated and supplied by an external power source. To improve the safety level, the complete monitoring electronics may be reset by the CCU, in case, for example, a communication problem has occurred.

To improve the robustness and the availability in harsh aviation environment, the battery cell heating and the voltage and temperature measurements have been designed in a redundant way. The voltage measurement of each battery cell is read by two different ADC types: the measurement of the 16-bit sigma-delta ADC is validated by a second measurement performed with a 12-bit successive approximation ADC, thus failures in battery cell voltage measurements can be detected and communicated to the CCU. In addition, the temperature of each battery cell is measured with two independent integrated circuits (IC), while one of them has a hardware over-temperature output signal that is independent from the MCU. This signal is fed back to the MCU of the UTM to trigger an over-temperature interrupt and furthermore it is used to switch the battery cell heater off in case the over-temperature is generated by a failure of the battery heater control. Further, the cell heater is guarded by an independent watchdog IC, which is shutting the heater off in case the periodic refresh signal from the MCU is missing. These features ensure that the battery heater does not overheat the cells in any failure case.

The temperature measurement of the battery cells is performed by an integrated circuit of type LMT85 from Texas Instruments. The measured temperature is actually the temperature of the busbar. This technique ensures early detection of corrosion of the screwed busbars contacting the battery cells. As a supplement, a sensorless battery temperature estimation circuit may be added to estimate the real inner temperature of the jellyroll [3] [4]. By using this technique, the equivalent cell temperature can be estimated by its impedance behavior. This is especially useful in battery systems using large cylindrical battery cells providing a limited heat extraction surface. In that case, the sensor-based measurement on the outside of the cylindrical cell may have a strong deviation from the real inner jellyroll temperature.

The UTM battery monitoring electronics features also a passive cell balancing circuit for charge equalization. This is needed, as the state-of-charge (SOC) of series connected cells may diverge due to variation of the cell impedance. This is mainly caused by variations during the battery cell production process or inhomogeneous aging of the cells (e.g., due to temperature gradients inside the whole battery pack). While variations of the production process may be minimized by battery cell mass production, inhomogeneous temperature distribution inside the battery module or pack can be reduced by optimized mechanical design and thermal management [5]. The photograph in Fig. 4 shows the arrangement of the battery modules. The UTM boards can be seen between the battery modules.

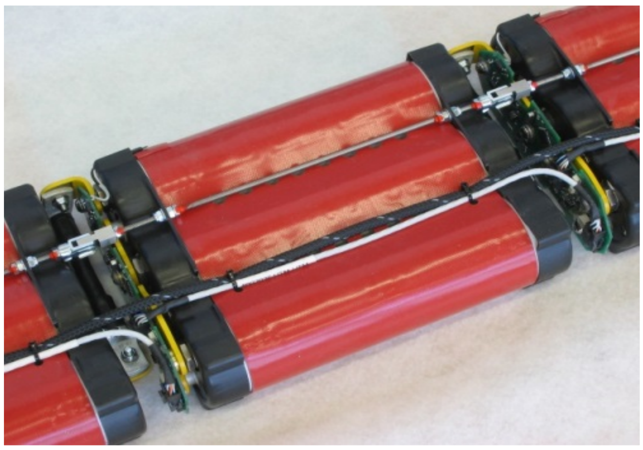

Fig. 4. Battery modules consisting of three battery cells connected in series. The battery monitoring electronics is located between two modules.

IV. Passive Balancing with Busbar Cooling

The circuit for passive cell balancing is designed for rather low balancing currents of approximately 100 mA. Such a low balancing current is sufficient, since aviation applications only afford to use battery cells complying with highest quality standards and providing very low manufacturing process variations. The most likely cause of unbalanced cells in an avionics battery system is therefore to be found in an inevitable inhomogeneous temperature distribution within the battery system, especially during operation. The requirement for high quality cells however results in high cost for the battery system. Due to the long service life of airborne equipment, the battery has to be kept operational over a long time to enable an economic operation of the aircraft. A malfunctioning balancing circuit may jeopardize the intended service life time of the battery system resulting in considerable additional cost for replacement and repair. Although, the cell balancing circuit is not considered a major safety critical part of the battery electronics, it is still vital for economic operation of the battery system over the complete life time. The reliability of the balancing circuit has therefore to be increased: a faulty balancing circuit having a significant leakage current could destroy the whole battery system by deeply discharging one of the cells.

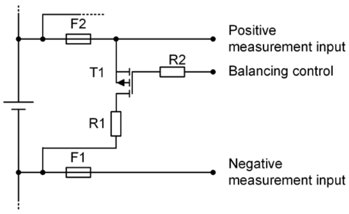

Fig. 5. Passive balancing circuit for a battery cell as part of a series connection of battery cells.

The proposed circuit for passive balancing is shown in Fig. 5. A P-channel MOSFET T1 which can discharge a single cell via the balancing resistor R1 is controlled by a microcontroller or a specific ASIC for battery monitoring and balancing. The resistor is used to dissipate the energy taken from the cell. Together with gate series resistor R2 this circuit consists of 3 components (neglecting Fuses F1 and F2).

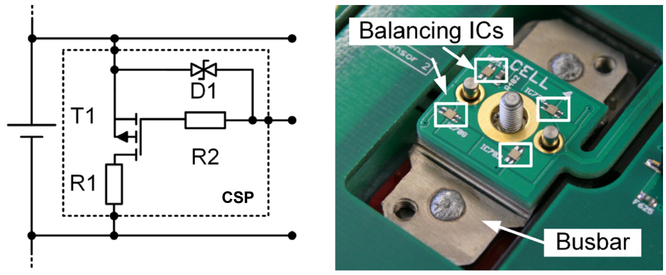

Fig. 6. Left: Equivalent circuit of the balancing IC; Right: chip-size-package (CSP) balancing MOSFET components mounted on PCB. For improved heat dissipation the PCB is soldered to the busbar below.

Due to the high number of series connected cells (i.e., 2×12×3=72 cells in case of the Antares 20E), this adds up to 216 electronic components on the UTMs for the complete battery system. This large number of components increases the system complexity and reduces the system reliability. The use of a single integrated electronic component, regrouping all discrete components that are necessary for balancing a single cell, has therefore been developed in close cooperation with Panasonic Semiconductors. Fig. 6 shows the newly developed passive balancing component (right) and its equivalent circuit (left). The newly developed balancing component integrates a P-channel MOSFET T1, the balancing resistor R1, the gate resistor R2, and a protection diode D1. The component uses a chip-size-package (CSP) and therefore needs only very little space on a PCB (1.2×1.2 mm^2). The CSP enables high power density, but the small size poses a challenge concerning the heat dissipation. The unique design of the UTM battery monitoring PCB with integrated busbars was specifically designed and optimized to dissipate this heat. Fig. 7 shows the cross-section of a busbar connected to the PCB with a CSP on top.

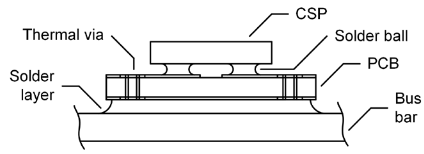

Fig. 7. Cross section of the CSP mounted on a PCB using the battery busbar for improved heat dissipation

The heat generated during the balancing process can be easily transferred to the busbars, to the cell terminals, and to the cells themselves, which have a high thermal capacity. In order to get a worst case estimation of the thermal situation, a simulation using a thermal equivalent circuit as in Fig. 8 is used. Thermal masses of the components can be neglected in this investigation as only the steady state is analyzed. The battery cells are assumed to be ideal heat sinks at 25°C ($T_{battery}$).

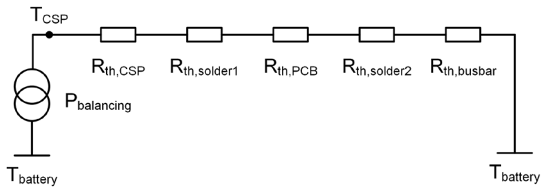

Fig. 8. Thermal equivalent circuit for a worst case estimation of the CSP temperature (T_{CSP}) during balancing.

The balancing power is assumed to be 706 mW, resulting from 168 mA balancing current at cell voltage of 4.2 V. TABLE I. gives the thermal resistances values of equivalent circuit components used in the analysis. The simulation results show that the temperature of the CSP stays below 63°C for steady state balancing action. By using integrated balancing circuits and optimized placement on suitable busbars, the BOM of the battery system could be reduced by 3 components per cell (i.e., a decrease of 216 electronic components for the complete 72s1p battery system), thus increasing the system reliability and also reducing the mounting costs.

TABLE I. Summary of the Thermal Resistance Values Rth Used in the Equivalent Circuit

$R_{th,CSP}$	0.16 K/W	$R_{th,solder2}$	0.02 K/W
$R_{th,solder1}$	0.77 K/W	$R_{th,busbar}$	1.6 K/W
$R_{th,PCB}$	52.27 K/W		

V. Software Design of the UTM

The software integrates several features for a safety-related system design. As shown in Fig. 9, the startup of the system is processed in two different ways: a cold startup, or a warm startup. The former one executes extended system tests and ensures the availability of all diagnostic features. In contrast, a system reset during normal operation starts the system in the warm start up mode with specific diagnostic and recovery functions to keep the system at least partially running. For detecting random or transient hardware faults and systematic software faults, the following methods were implemented:

- A window watchdog and independently clocked watchdog which are integrated in the MCU
- A standalone external watchdog for cell balancing and heat control
- A hardfault exception handler
- A port locking mechanism
- Redundant measurements with plausibility checks

As a part of system monitoring and diagnostic functions, a window watchdog and separate independent watchdogs are triggered by appropriate software tasks. The window watchdog clock is derived from the main clock of the MCU and can be adjusted with fine time resolution. In addition, the external watchdogs are triggered by software, thus ensuring the integrity of the battery heater control and the cell balancing circuit. These features primarily address the detection of software runtime faults. Moreover, failure modes of the clock system in the MCU are detected by a separate independent standalone watchdog IC, which is clocked by a dedicated clock with lower accuracy. Cell voltage and temperature measurements are read redundantly with separate ADC units and reference voltages. Their values are crosschecked and tested on plausibility.

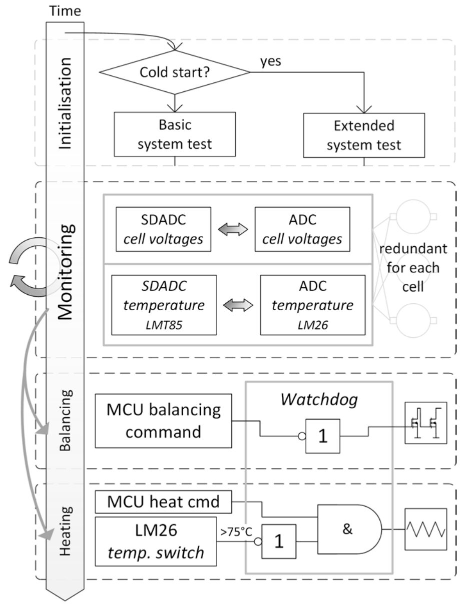

Fig. 9. Overview of the software architecture used in the UTM.

VI. Conclusion

The hardware and software design of a battery monitoring circuit developed to be used in aviation applications employing lithium-ion batteries in their electrified powertrain was presented. Since the targeted aircraft is a manned glider of type Antares 20E from Lange Aviation, the architecture and the design of the hardware and software of the battery monitoring electronics was made in such a way that the safety level allows a pure electric take-off and landing by using the electric propulsion system supplied by NCA/Graphite lithium-ion batteries. To fulfill these requirements, the electronic design of the battery monitoring circuit integrates the battery busbars and uses new passive balancing components in a small CSP package, coupled with an innovative busbar cooling solution, thus increasing the reliability and the robustness of the whole battery system. The software architecture was kept simple to ensure a quick validation by the certification authority (European Aviation Safety Agency: EASA). The design will be validated by a flight by end of 2016.

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References

[1] M. Brandl, H. Gall, M. Wenger, V. Lorentz, M. Giegerich, F. Baronti, G. Fantechi, L. Fanucci, R. Roncella, R. Saletti, S. Saponara, A. Thaler, A. Cifrain, and W. Prochazka, "Batteries and battery management systems for electric vehicles" Design, Automation & Test in Europe Conference & Exhibition (DATE), Dresden, pp. 971–976, 2012.

[2] V. Lorentz, M. Wenger, J. Grosch, M. Giegerich, M. Jank, M. März, and L. Frey, "Novel Cost-Efficient Contactless Distributed Monitoring Concept for Smart Battery Cells," in 21st IEEE International Symposium on Industrial Electronics (ISIE2012), pp. 1342–1347, May 28–31, 2012.

[3] R. Schwarz, K. Semmler, M. Wenger, V. Lorentz, and M. März, "Sensorless Battery Cell Temperature Estimation Circuit for Enhanced Safety in Battery Systems," in 41th Annual Conference of the IEEE Industrial Electronics Society (IECON2015), Nov. 9–12, 2015.

[4] J. Schmidt, S. Arnold, A. Loges, D. Werner, T. Wetzel, E. Ivers-Tiffée, "Measurement of the internal cell temperature via impedance: Evaluation and application of a new method," *Journal of Energy Storage*, vol. 243, pp. 110–117, Jun. 12, 2013.

[5] M. Gepp, R. Filimon, S. Koffel, V. Lorentz, and M. März, "Advanced Thermal Management for Temperature Homogenization in High-Power Lithium-Ion Battery Systems Based on Prismatic Cells," in 24st IEEE International Symposium on Industrial Electronics (ISIE2015), Jun. 3–5, 2015.