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Battery Management System Hardware Design for a Student Electric Racing Car

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Abstract: The paper deals with a complex hardware design of a battery management system (BMS) for a Formula Student electric car. This car, built completely by students, has specific requirements, because while being highly demanding application with high power, high voltage tractive system driven in hot summer conditions, simplicity and reliability are very important. To meet the requirements, two separate PCBs were designed, one being integrated inside the segment of battery box to connect to cell voltages and measure temperatures, the other one being on top of the segment to control the system. The control PCB is based on the STM32 microcontroller and the BQ76PL455A-Q1 integrated circuit intended for BMS applications in automotive. The whole system was manufactured and assembled, and basic hardware test was conducted to evaluate the design and get it completely ready for the subsequent software design.

Keywords: batteries, battery management system, battery box, electric powertrains, electric vehicles, Formula Student

1. INTRODUCTION

The ever-increasing demands of today's world on transport of all kinds combined with its increasingly evident environmental impact mean that mankind must constantly seek solutions for a better, more efficient, renewable, greener energy sources for vehicles. As a suitable alternative for fossil fuels, electricity has become the world's most prominent asset in various aspects. Thus, electromobility becomes more and more widespread worldwide every day, gaining popularity especially in the advanced countries (Longo et al., 2015). However, in order to be able to compete with an internal combustion engine, it is necessary to eliminate or at least decrease the disadvantages of electric vehicle.

Probably the biggest disadvantage of today's electric cars which often discourages their purchase by wider masses of people, are batteries, their slow charging, lifespan and price (Junquera et al., 2016). The solution to this problem is the advancement in the cell chemistries, but their efficient, safe and user-friendly implementation in end-products are equally important. In order to withstand the maximum number of cycles with the highest possible capacity and safety, the Battery Management Systems (BMS) are implemented; they are responsible for batteries' complete life cycle, charging, balancing, and discharging processes (Lu et al., 2013).

The paper deals with development, construction and implementation of a BMS for a high demanding electric racing car – Student Formula. The paper is organized as follows: First, the batteries in general are described, together with BMS and its difficulties. Then, the target application is discussed. Design of the BMS itself is described next, including two separate PCB designs, concluded by basic hardware testing of manufactured BMS.

2. BATTERIES AND BMS

2.1 Battery Characteristics and Requirements

Lithium-based battery cells are the most commonly used not only in the transport but in almost every industry where efficient electricity storage is needed. Compared to competitors, they achieve higher energy density (up to 265 Wh/kg), high power density (up to 676 W/kg), low internal resistance, low self-discharge and long service life when used in proper conditions. On the other hand, their undisputed disadvantages are low temperature tolerance, higher price, but also security risks, which is why complex battery management systems are needed (Li et al., 2018; Liu et al., 2018).

To ensure safety, long life and reliability of a Li-Ion cell, it has always to be kept within recommended parameters whether being used or not. A cell with overvoltage or currents higher than rated is exposed to risk of overheat and explosion, undervoltage can reduce the lifecycle and capacity rapidly. If more cells are connected in series, the problem of imbalance may arise caused by manufacturing differences, slightly different chemical degradation or different operating conditions of each cell; hence, cells can reach different State of Charge (SoC) along the pack resulting to a decreased overall usable capacity. Therefore, it is necessary to implement a BMS that always checks these conditions and takes necessary actions to avoid potential risk of damage (shuts down the charging/discharging, balances the cells) (Liu K. et al., 2019).

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2.2 Battery Management Systems

There are different levels of BMS implementation, from a simple cell monitoring and passive balancing as presented in (Abronzini et al., 2018) to complex highly efficient energy and thermal management as described in (Lopez-Sanz et al., 2017; Rashid et al., 2018), the latter being required in the most advanced commercial vehicles.

With a higher number of cells in series, a BMS with the option of balancing cells, whether active or passive, is required. Active and passive balancing differ mainly in efficiency; while a passive system only dissipates excess energy, the active one effectively moves it from one cell to another which leads to more complex and expensive solutions (Lelie et al., 2018). In this paper, implementation of the passive balancing system is considered, because for the Student Formula application a low number of cycles and long charging times are sufficient and system simplicity and reliability are the main goal.

For effective cell balancing it is necessary to know the SoC of all cells connected in series. The most basic approach on SoC determining is through cell voltages, however this approach brings several restrictions. During the current load, the voltage of the cells varies, so only Open Circuit Voltage (OCV) can be considered. However, due to manufacturing differences, different temperature conditions or different State of Health (SoH), OCVs do not have to provide a reliable information about how much energy can still be acquired from cells. Therefore, various advanced methods of SoC and SoH determination are used, implementing numerical integration, Kalman filters, cell mathematical model or others (Lu et al., 2013).

3. TARGET APPLICATION – “FORMULA STUDENT” COMPETITION VEHICLE

The battery management system was implemented in the electric vehicle SGT-FE18 built within a student project STUBA Green Team. Except a few of off-the-shelf components, it has been completely designed, built and assembled by students within one season of an international engineering student competition called “Formula Student”. The developed electric vehicle (Fig. 1) has a carbon fiber monocoque chassis, suspension rods, a complete aerodynamic package and steering wheel; self-developed two-stage planetary gearboxes, all-wheel-drive with independent motor control, multi-channel telemetry and a custom-designed battery box.

Fig. 1. The SGT-FE18 racing car.

The battery box of the car uses 420 Lithium-Polymer pouch cells (140 series and 3 parallel cells) divided into 10 equal segments connected in series, i.e. each segment contains 14 cells in series, 3 in parallel. Its overall parameters are stated in Table 1. Mechanically, the cells are incorporated into FR-4 glass fibre laminate cases and separated for the cooling air flow by a silicone sponge material keeping the non-flammable, non-conductive and high temperature material requirements fulfilled. The cells are ultrasonically welded to ETP copper custom shaped busbars.

Table 1. Battery Box parameters

Max./nominal/min. voltage	588/518/420 VDC
Continous/peak discharge current	234/312 A
Capacity/energy	15.6 Ah / 8.08 kWh
Internal resistance (cells only)	102 mΩ
Overall weight	56 kg

The fact that the electro-mechanic design of the battery box was also performed by the authors of this paper helped the process of integration, connection and placement of BMS components.

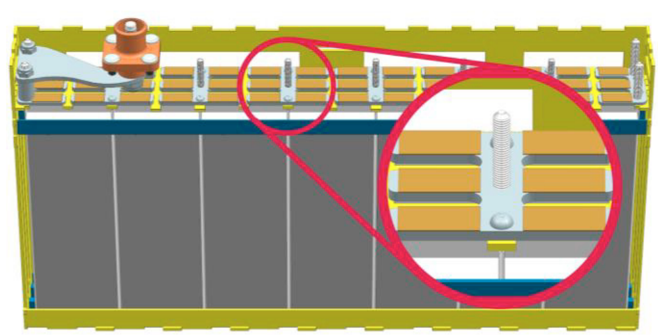

Fig. 2. Visualization of half of the battery segment (zoomed in: ultrasonically welded busbar with a bolt ready for BMS mounting and connection).

4. BMS PCB DESIGN

After the mechanical parts of the battery segment were designed and completed, the BMS itself has been designed. The main objective was to design two auxiliary PCBs built into a sealed segment including only hard-wired, potentially error-free electronics, and providing connection to cell voltages and temperature sensors for main BMS PCB outside the segment. The main advantage of using PCBs instead of any cabling consists in consistency, avoiding mixed connections, and in manufacturing simplification. In this way, a battery box segment is completely closed and equipped with everything needed inside, with two power output connectors and two non-power connectors for cell voltages and temperatures connection. The main BMS PCB can be placed on top of the segment to be easily available for debugging, measurements and quick replacement in case of any faults or design changes.

4.1 *Auxiliary PCB design*

Auxiliary PCB has to provide reliable connection to all cell voltages, appropriate cell temperature measurement, fulfilling the competition rules requirements (temperature sensors in direct contact with a negative pole of 30% of cells, or maximally 10mm away on the bus bar (Formula Student Germany, 2018)). For mounting the PCBs as well as easy voltage measurements, all bus bars in the segment (except the outermost ones) have integrated M3 bolts (Fig. 2). The idea was to put plastic standoffs on the bolts to keep constant offset of PCB from busbars. M3 nuts with integrated washers are used to hold the PCB, and to provide contact with PCB pads and connect the cell voltages to them. The cell voltages connection concept is depicted in Fig. 3.

For temperature measurement, the appropriate temperature sensor has to have body electrically isolated from its contacts to provide a direct contact with the bus bar without short circuit occurrence. Sensor size, electrical output type, availability and price had to be also considered. This led us to searching for a TO-92 package. The Microchip's Low-Power Linear Active Thermistor™ MCP9700A, with 10 mV/°C output and ±2°C @ 0°C to +70°C accuracy was chosen (Microchip Technology, 2014) with linear voltage-temperature output characteristics. One auxiliary PCB has 7 of these sensors, each in contact with one bus bar, so the cells' negative poles are within their reach. Sensors were designed to be reaching from PCB down to the bus bar nearby the mounting bolts. Two identical auxiliary PCBs were placed in one segment, one for each half of it. A CAD model with all parts inside the segment can be seen in Fig. 3 and Fig. 4, and an auxiliary PCB layout in Fig. 6. Segment top view with numbering of cells and sensors as well as connector pinouts is in Fig. 5**.**

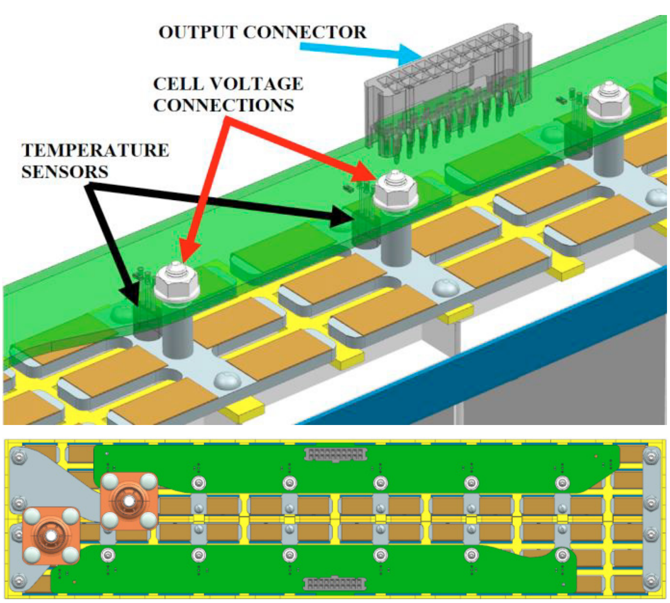

Fig. 3. Auxiliary PCBs integration and details from inside of the battery segment.

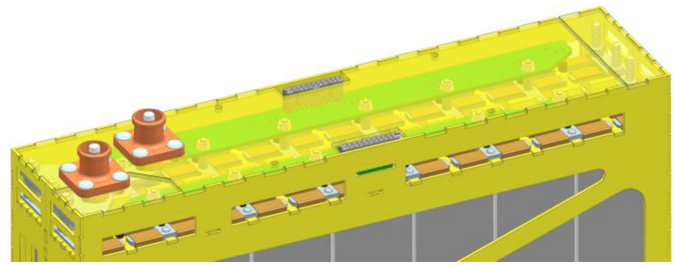

Fig. 4. Enclosed battery segment with auxiliary PCB integrated inside.

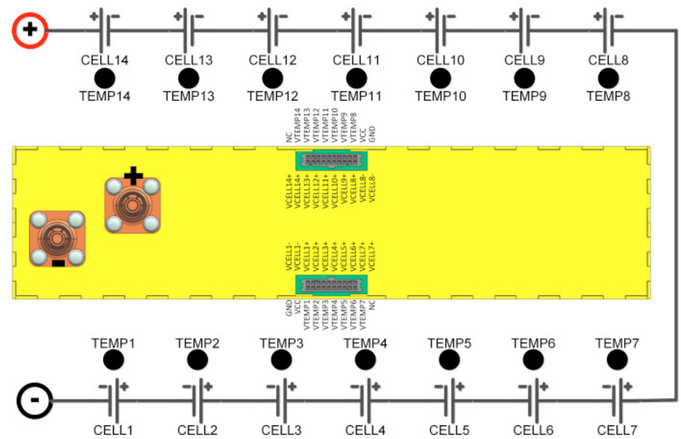

Fig. 5. Segment top view with a cell connection schematic, numberings and connector pinouts.

4.2 *Main PCB Design*

With the battery segment fully designed from inside, we designed the most important part of the BMS – the main control PCB. We wanted the whole system to be controlled by one microcontroller (for easier software development, simplicity and price), able to reliably monitor 140 cells in series divided into 10 segments with a resulting maximum voltage 588VDC, able to monitor 140 voltage inputs representing the cell temperatures, able to communicate on galvanically separated CAN Bus with the rest of the vehicle and be resistant to electromagnetic interference (EMI) present in the battery box.

We decided to look for an integrated circuit (IC) designed directly for BMS use, rather than to design our own solution from general electronic components. The BQ76PL455A-Q1 from Texas Instruments was chosen after the market research. It is the company's most advanced automotive-grade IC intended for use in battery management systems for high power, high voltage battery packs, with 16 cell voltage measurement inputs and 8 auxiliary analog inputs and possibility of use up to 16 units communicating on proprietary differential daisy-chain (to be resistive to EMI). It allows usage of only one microcontroller communicating with the whole stack over Serial Communication and has a lot of features for safety enhancement (Texas Instruments, 2016).

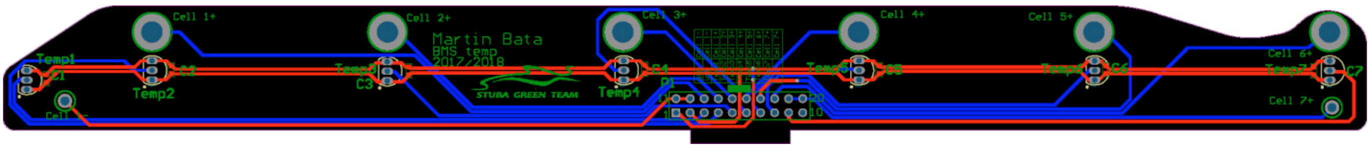

Fig. 6. BMS Auxiliary PCB Layout.

With BMS IC selected, we selected the microcontroller STM32F105RBT6 to control the whole system (STMicroelectronics, 2019); it was a result of considering multiple aspects, specifically good community and company support for STM32 line, use of these microcontrollers widely in whole vehicle and price aspect (sponsorship for these exact controllers in STUBA Green Team). The block diagram of our system in context of the whole battery box and vehicle is in Fig. 7. The BMS is designed with one master + slave PCB, where both BQ76 and STM32 ICs are placed. The whole BMS control software will be running on the PCB and communication with the rest of the vehicle will be controlled. Nine other PCBs of the BMS are slaves, therefore equipped only with BQ76 ICs. Connection of the whole system with the rest of the vehicle consists only of a CAN Bus, low voltage (LV) system power supply for the master part of master-slave PCB, and one analogue binary signal line to indicate FAULT state of the whole BMS. We decided to use the same PCB for all 10 BMS units, however only the first unit will have the master part functional, the rest of them will use only the slave part of the PCB, while the master part will be without components soldered.

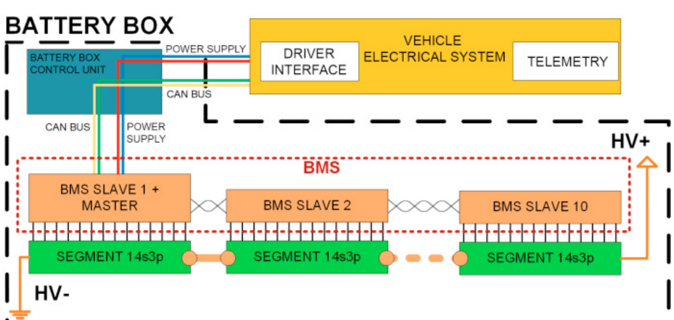

Fig. 7. Block scheme of BMS implementation in the battery box and interaction with the rest of the vehicle.

Besides from the Texas Instruments reference design of PCB schematics, temperature measurements had to be designed. Because each BQ76 is required to measure 14 voltage outputs from temperature sensors but has only 8 auxiliary measurement inputs a multiplexer with a ratio 16:8 was used. It is controlled by two of the six GPIO pins of BQ76 IC and switches between measurement of temperature outputs from two auxiliary PCBs. To connect the master PCB with LV system of the vehicle while keeping the galvanic separation, an isolated DC-DC converter, an isolated CAN Bus transceiver and an optocoupler were used. An additional connector was added for overriding the microcontroller and connecting right to the UART lines, WAKEUP and FAULT pins, which allows connection of the computer with USB-UART converter and Texas Instruments interface, if required for debugging or hardware testing.

The PCB layout was designed with consideration of the battery segment proportions and connectors. At first, all the components were placed on the PCB in logical groups (Fig. 8) to make the traces as short as possible.

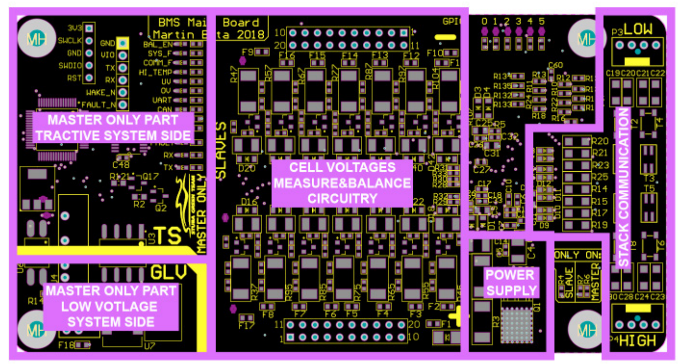

Fig. 8. Layout of electronic components in groups on PCB

After components placement, all the routing and labeling was done and grounded copper polygons were poured over whole TS part of the PCB. Separate copper polygons were also poured under the heat sink of the main power supply NPN transistor to provide cooling surface. Final design of PCB is shown in Fig. 9.

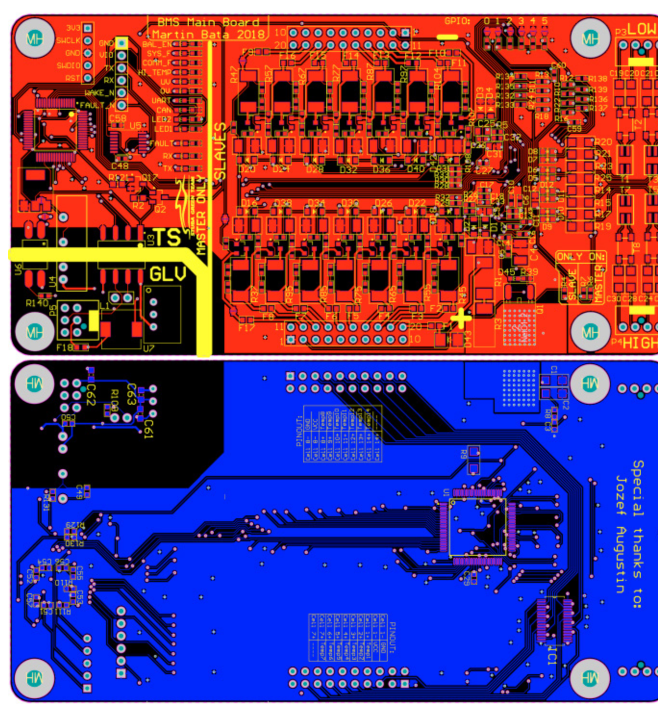

Fig. 9. Top (red) and bottom (blue) layout of the designed PCB.

5. HARDWARE TESTING AND DESIGN EVALUATION

With PCBs designed, we manufactured one main and two auxiliary PCBs to validate the design and test the functionality of the hardware. We placed the main PCB on top of one complete segment with auxiliary PCBs inside. Then, simple software for STM32 microcontroller was developed, just to be able to configure the BQ76, communicate with it and get the cell data from it. The communication was working well, after the initialization done, it was able to send us all the cell voltages. These were all successfully checked by a digital multimeter to be sure they are measured right. Then, we tried the balancing of all the cells, indicated by LEDs on the PCBs and after repairing few cells with bad contacts (caused by hand soldering), the balancing circuits were also working well.

Therefore, we decided to make a test measurement of cell voltages in one segment over time while trying to charge the cells and turn all the balancing circuits on. Voltages has been aquired using STMStudio software, which is able to read the live data from STM32 microcontroller without affecting his functionality, plot the data and log the data. Used sample period was 100ms, as it is small enough to capture all the dynamic changes in voltages. The resulting graph of this test can be seen in Fig. 10.

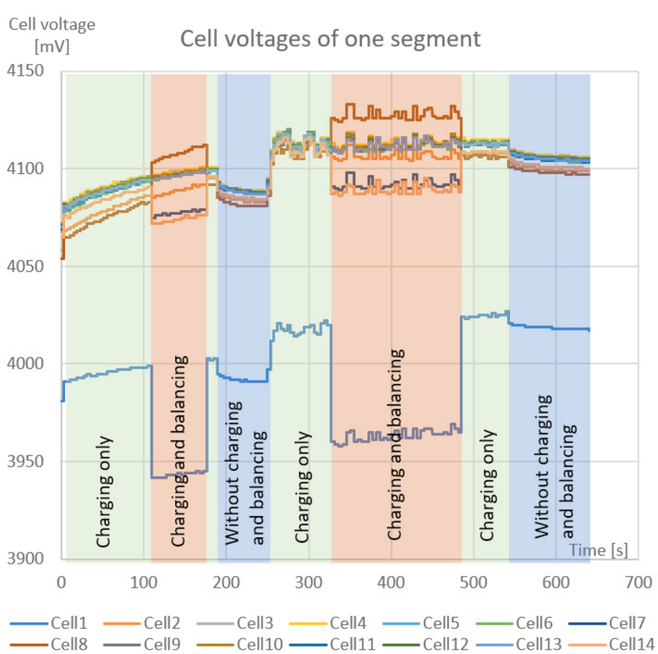

Fig. 10. Cell voltages graph while hardware test of charging and balancing

This test had couple of phases in it, specifically:

1. Charging current 5A was set for aproximatelly 100 sec., where you can see all the voltages rise, while voltage of Cell 1 being lower than others due to small inbalance of the cells.
2. Balancing was turned on, but as long as the balancing algorithm is the subject of future work, for now we turned all the balancing circuits on. It can be seen that cell voltages reacted differently, which is caused mainly by sharing measurement and balancing lines for all the cells – these voltages while balancing will not be considered later in the balancing algorithm, only the OCVs.
3. Charging and balancing was turned off, the cell voltages got into normal values.
4. Charging was turned on again, now with 15A current, which can be seen on the voltage data oscillating a little more due to higher EMI being present on the PCB traces. This can be later filtered by bigger capacity of measurement capacitor placed on PCB, or by software.
5. After turning on the balancing, again, on all the cells, situation was similar as the first time, now with more oscillation. While this phase, unfortunately, charger hit the set voltage limit, therefore it switched to Constant Voltage mode and current started to exponentially decrease.
6. Final phase was with balancing turned off and current slowly decreasing, which can be seen on oscillation being smaller than at 15A.
7. Charging and balancing was turned off and it can be seen that the cell voltages stabilised again.

This test proved the hardware to be working without problems, therefore we manufactured all the PCBs and assembled the whole battery box, seen in Fig. 11. Similar test was then conducted with whole battery box, which can be seen on all the balancing LEDs turned on and the functionality was also without bigger problems. This meant that the hardware of whole BMS system was successfully designed and manufactured, allowing the software development to start, which is planned for future work and publications.

Fig. 11. Assembled battery box while simple hardware test with all the balancing circuits turned on (seen on the LEDs).

6. CONCLUSION

In this paper, we described the hardware design of the battery management system for an electric racing car. At first, general requirements on batteries were formulated and discussed, then the application and a targeted battery box were described.

The integration of BMS started at the mechanical design of the battery segment, because the voltage and temperature measurements had to be accurate, within the rules and reliable, while keeping the manufacturing costs low, and assembly as easy as possible. This was achieved by implementing two pieces of custom designed auxiliary PCB inside the segment, to concentrate cell voltages and temperature voltages in two simple connectors on the top of the segment without the need of any cable work. Next, the main PCB for BMS was designed according to the IC manufacturer design guidelines and battery box overall layout.

All the parts were manufactured, and basic hardware tests carried out by developing a simple software for STM32, to test all the aspects. Hardware proved to be designed well and working without major issues, therefore more advanced software development can start in consecutive work.

ACKNOWLEDGEMENT

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