μPART.CZ

1S3P LTO Battery Pack with BMS

Features

- Battery Chemistry: Lithium Titanate (LTO) for an extended lifespan and extreme temperature resilience.
- Configuration: 1S3P (three LTO 18650 cells in parallel).
- Nominal Voltage: 2.4 V
- Voltage Range: 1.5 - 2.8 V
- Capacity: 3.9 Ah (1300 mAh per cell)
- BMS Features:
  - Overvoltage and undervoltage protection
  - Overcurrent protection
  - I2C communication for real-time battery monitoring (voltage, current, power)
  - User-upgradable firmware (UPDI programming interface)
- Fully open-source firmware, available on github.com under the MIT license

Applications

- LoRa devices like Meshtastic, MeshCore, or Reticulum, . . .
- IoT and battery powered sensors
- HAM radio setups
- DIY outdoor and low-power electronics

General Description

This 1S3P Lithium Titanate (LTO) battery pack is designed for low-power outdoor applications such as Meshtastic nodes, IoT, HAM radio setups, and DIY electronics. It features an integrated smart Battery Management System (BMS) with voltage, current, and energy measurement, along with protection features including under-voltage lockout (UVLO), over-voltage lockout (OVLO), and overcurrent protection (OC). The battery pack communicates via I^2C, allowing real-time monitoring of power parameters.

This project is **partially open-source**, with public schematics, 3D model in STEP format, 3D printable enclosure, bill of materials (BOM), and firmware.

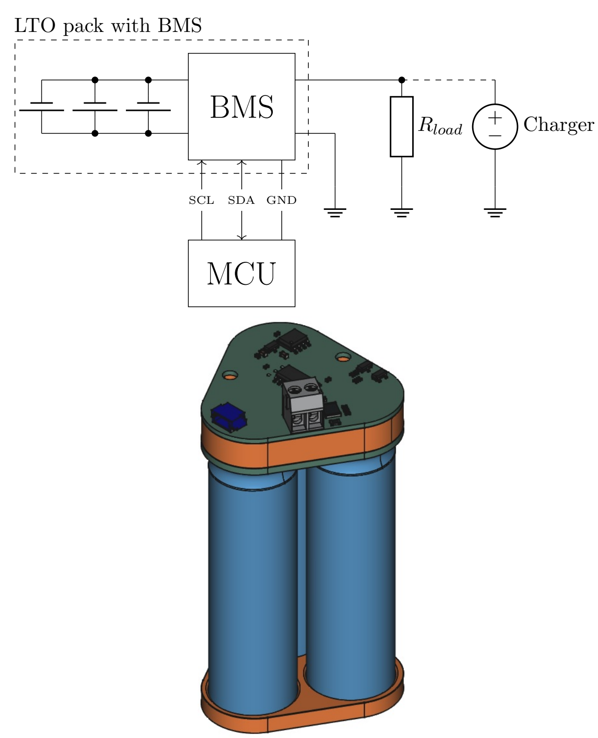


Figure 1: Block diagram (top) and a 3D render (bottom) of the product.

Absolute Maximum Ratings

Table 1: Absolute Maximum Ratings of LTO Battery Pack

Parameter	Rating
Maximum Charging Voltage	2.8 V
Minimum Voltage	1.5 V
Maximum Charging Current	1.0 A (0.25C)
Maximum Discharging Current	1.0 A (0.25C)
Operating Temperature Range	-40°C to +60°C

Note: Stresses above those listed under Absolute Maximum Ratings can cause permanent damage to the device. Charging and discharging currents are limited by the electronics of the BMS, not by the LTO cells itself.

Electrical Specifications

All specifications are in $-40°C \leq T_A \leq 60°C$ unless otherwise noted.

Table 2: LTO Battery Pack Electrical Specifications

Parameter	Symbol	Min.	Typ.	Max.	Unit	Note
Nominal Capacity	C_{nom}		3900		mAh	
Capacity at -20°C	C_{-20}		$\geq$ 90% of C_{nom}		mAh	
Capacity at -40°C	C_{-40}		$\geq$ 50% of C_{nom}		mAh	
Cell Voltage	V_{cell}	1.5	2.4	2.8	V	1
Internal Impedance	R_{int}			18	mΩ	2
Charging Current	I_{charge}		1.0	2.0	A	3 4
Discharging Current	$I_{discharge}$		1.0	2.0	A	3 4
Operating Temperature Range	T_{oper}	-40		60	°C	
Weight	W_{total}		133		g	
Cycle Life ($\geq$ 80% of nominal capacity)	N_{cycles}	5000			cycles	

[1] Typical V_{cell} value is nominal (average) voltage of one LTO cell.
[2] Internal impedance of one LTO cell, not the whole battery pack.
[3] Typical currents can be continuous and are limited by the BMS, not the LTO cells itself.
[4] Maximum currents recommended for $t_{max} = 120s$.

Detailed Description

Lithium Titanate Oxide (LTO) batteries are a distinct category within the rechargeable lithium-based battery family, utilizing lithium titanate ($Li_4Ti_5O_{12}$) as the anode material. This composition gives LTO cells unique characteristics that differentiate them from other lithium-ion chemistries, such as Lithium-Ion (Li-Ion), Lithium Polymer (Li-Po), and Lithium Iron Phosphate ($LiFePO_4$, or LFP) batteries.

LTO batteries present a compelling option for applications requiring long cycle life, operation in extreme temperatures, and rapid charging. However, their lower energy density and higher cost may limit their suitability for applications where space and budget are primary concerns.

An LTO cell typically operates within the voltage ranges shown in Table 3. These voltage ranges are lower compared to other lithium-based batteries, necessitating appropriate system design considerations when integrating LTO cells into the intended application. They are not and cannot be a drop-in replacement for Li-Ion, Li-Po and other types of batteries and cannot be charged by their charging ICs.

With the parameters in Table 3, one can see that LTO batteries are a great fit for battery-powered, low-power devices installed outdoors year-round.

Table 3: Comparison of LTO, Li-Ion/Li-Po, and $LiFePO_4$ Batteries

Parameter	Unit	LTO	Li-Ion/Li-Po	$LiFePO_4$
Nominal Voltage	V	2.3–2.4	3.6–3.7	3.2–3.3
Maximum Voltage	V	2.8–2.9	4.2–4.4	3.65
Minimum Voltage	V	1.5–1.6	2.5–3.0	2.5
Energy Density	Wh/kg	70–110	150–250	90–160
Cycle Life	cycles	4000–7000	500–1,500	2,000–5,000
Charge Rate	C	5–10	1–2	1–2
Discharge Rate	C	10–20	1–10	10–25
Discharging Temp. Range	°C	-40 to 60	-20 to 60	-20 to 60
Charging Temp. Range	°C	-10 to 55	0 to 45	0 to 45
Safety	–	Very High	Medium	High

Advantages of LTO Cells

- **Extended Cycle Life:** They can endure a significantly higher number of charge-discharge cycles, often exceeding 4000 cycles, which is substantially more than typical Li-Ion or $LiFePO_4$ batteries.
- **Enhanced Safety:** The structural stability of LTO reduces risks associated with thermal runaway, making them safer under various operating conditions.
- **Wide Operating Temperature Range:** LTO batteries perform reliably in a broad temperature spectrum, including sub-zero conditions, making them suitable for extreme environments.
- **Rapid Charging:** LTO cells support high charge and discharge rates, allowing for quick charging times. This is less important for IoT and low-power devices which this LTO battery pack with BMS is designed for.

Disadvantages of LTO Cells

- **Lower Energy Density:** They typically offer energy densities between 30–110 Wh/kg, which is lower than that of Li-Ion and $LiFePO_4$ batteries.
- **Higher Cost:** The advanced materials and manufacturing processes contribute to a higher price point compared to other lithium-ion batteries.

Protection Features

The Battery Management System (BMS) includes essential protection mechanisms to ensure safe and reliable operation of Lithium Titanate Oxide (LTO) cells. These mechanisms protect against overvoltage (OVLO), undervoltage (UVLO), and overcurrent (OC) conditions. All protection thresholds are fully configurable by writing new values into the EEPROM memory of the BMS's main microcontroller, an `ATtiny824`.

Overvoltage protection ensures that the cell voltage does not exceed a safe upper limit. When the measured voltage on the LTO cells rises above the configured cutoff threshold (`ovlo_cutoff`), the BMS disconnects the charging path. Charging is only re-enabled once the voltage falls below the defined release level (`ovlo_release`). This protects the cell from overcharging, which could otherwise reduce its lifespan or cause safety hazards.

To prevent **over-discharge** and possible damage to the LTO cells, the BMS continuously monitors the voltage level of the cells and disconnects the load if the voltage drops below the cutoff threshold (`uvlo_cutoff`). The load remains disconnected until the voltage recovers above the release threshold (`uvlo_release`). This functionality helps preserve battery health and avoids deep discharge scenarios.

The BMS also includes **overcurrent protection** on the output. If the current exceeds the `max_current` setting (in mA), the output is disabled. The duration of the overcurrent condition is monitored, and if it persists longer than the configured timeout (`oclo_timeout`, in milliseconds), the output is turned off to prevent overheating or damage to connected circuitry.

All protection parameters can be configured by the user via a Python tool included in the firmware repository. This tool allows writing new settings into the EEPROM of the `ATtiny824` via UPDI programming interface, enabling customization for different applications, usage scenarios, or safety requirements. Their default parameters are in Table 4.

Charging

The charging process of the Lithium Titanate Oxide (LTO) cells is straightforward, thanks to the Battery Management System (BMS), which implements all necessary safety features. Charging can be done simply by connecting a constant voltage source to the load side of the BMS. The recommended constant voltage range is 2.7–2.8 V, ensuring the voltage does not exceed the maximum cell voltage.

The typical charging process is shown in Figure 2, where the constant voltage was set to 2.85 V (slightly above the recommended range to show `OVLO` state in the graph), and the battery's initial state was `UVLO` (Under-Voltage Lockout), i.e., fully discharged. Charging is considered complete when the cell voltage if above 1.7 V or when BMS activates the `OVLO` (Over-Voltage Lockout), which indicates the battery is fully charged.

Table 4: Default BMS EEPROM Configuration

Parameter	Description	Default Value
`serial_number`	Device serial number	0
`temp_offset`	Temperature sensor offset (°C)	0
`ovlo_cutoff`	Overvoltage cutoff threshold (mV)	2800
`ovlo_release`	Overvoltage release threshold (mV)	2700
`uvlo_release`	Undervoltage release threshold (mV)	1800
`uvlo_cutoff`	Undervoltage cutoff threshold (mV)	1700
`max_current`	Maximum output current (mA)	1000
`oclo_timeout`	Overcurrent shutdown delay (s)	10

As seen in the Figure 2, the cell voltage slowly increases from 2.36 V(the voltage immediately after connecting the constant voltage source to the load side) up to 2.8 V. At this point, the BMS disconnects the cells from the load and activates `OVLO`.

The charging current is not limited by the constant voltage source, and thus it starts at over 1.5 A, gradually decreasing to 0.173 A just before the battery is fully charged. The entire 3900 mAh capacity is charged in less than 300 minutes (5 hours).

This charging procedure is simple and effective, as the BMS handles all the necessary protections for the cells. A simple Low Dropout Regulator (LDO) or a DC/DC converter can be used to provide the constant voltage for the battery, making it easy and cost-effective to integrate into the user's project.

However, this method is still not ideal. Charging the battery with high current when deeply discharged can lead to slight degradation of the cells, shortening their lifespan and reducing the number of available charge cycles.

A slightly more advanced version of this setup uses an LDO or DC/DC converter with a current limiting circuit. In this case, the output voltage is still set to 2.7–2.8 V, but the current is limited, for example, to 0.5 A. This limits the charging current at the beginning of the process, when the battery is deeply discharged and most sensitive to high currents. This approach offers better cell protection while maintaining simplicity and low cost.

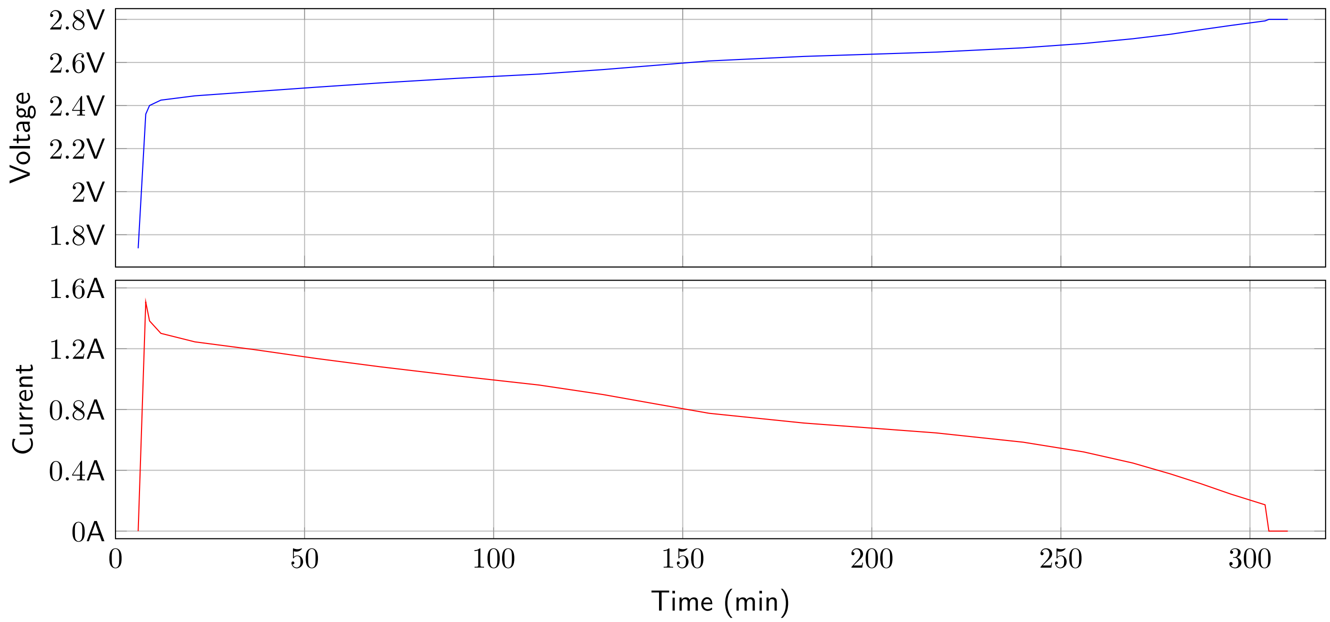
The best, although more complex and costly, solution is to use a *Constant Current / Constant Voltage* (CC/CV) charger specifically designed for LTO batteries, such as the CN3795 IC.

UART Interface

The BMS outputs a detailed log containing the internal state and measurements of the system every minute (this interval can be configured at compile time in the firmware). This log is transmitted via the UART's `TXD` pin and uses the **InfluxDB Line Protocol**, making it convenient to capture and store the data in an InfluxDB instance.

An example of this log is shown in Listing 1, while the meaning of each field is summarized in Table 5, and the possible values of the `state` field are listed in Table 6.

Figure 2: Charging of deeply discharged LTO battery with BMS by a constant voltage.



The UART interface provides a single `TXD` (transmit) signal and operates at a baud rate of 9600. Please note that the BMS does not support receiving data via `RXD`; it only transmits log data. The format of the transmitted log is demonstrated in Listing 1.

Listing 1: UART Output Example

```
lto-bms,id=0006
  uptime=3261420i,v_batt=2768i,v_load=2813i,current=-260i,E_dis=8163i,
  E_chg=15176i,charge=-2530i,temp=296i,gain=8i,state="BMS_STATE_CHARGING"
```

Table 5: UART Log Fields Description

Field	Unit	Description
`uptime`	s	Number of seconds since the last restart.
`v_batt`	mV	Battery voltage.
`v_load`	mV	Voltage present at the load side of the BMS.
`current`	mA	Current through the shunt resistor. Negative values indicate charging.
`E_dis`	Wh	Energy discharged from the battery.
`E_chg`	Wh	Energy charged into the battery.
`charge`	Ah	Total amount of charge in the battery.
`temp`	K	Internal temperature sensor reading.
`gain`	–	ADC gain setting for current measurement.
`state`	–	Internal BMS state. See Table 6.

Table 6: Possible BMS States in the UART Log

State	Description
`BMS_STATE_INVALID`	Invalid state.
`BMS_STATE_UVLO`	Under-voltage lockout.
`BMS_STATE_OVLO`	Over-voltage lockout.
`BMS_STATE_OVLO_ACTIVE`	Over-voltage lockout active.
`BMS_STATE_OCLO`	Over-current lockout.
`BMS_STATE_CHARGING`	Charging.
`BMS_STATE_DISCHARGING`	Discharging.
`BMS_STATE_IDLE`	Idle.
`BMS_STATE_ERR`	Error state.

I^2C Interface

The battery management system (BMS) features an I^2C interface for communication with external devices such as the Meshtastic firmware. This allows the user to read power, current, and voltage information from the battery without requiring any firmware modification on the Meshtastic side, as it already supports the INA260.

This interface supports standard modes of communication and adheres to the INA260 register structure, ensuring compatibility with Meshtastic firmware and ease of integration into existing systems.

The I^2C interface of the BMS mimics the INA260's register set. The communication protocol and register mapping are identical to that of the INA260. Table 7 is a summary of the available registers.

Calculating Returned Values

The least significant bit (LSB) sizes for the *Bus Voltage Register*, *Current Register*, and *Power Register* are fixed, as shown in Table 8. To calculate any of the values for current, voltage, or power, take the integer value returned by the device and multiply that value by the corresponding LSB size.

For example, the LSB for the bus voltage is 1.25 mV/bit. If the device returns an integer value of 9584 (0x2570), the value of the battery voltage is calculated as:

$$V_{battery} = 1.25 \text{ mV} \times 9584 = 11.98 \text{ V}.$$

Since the system supports current measurements in both directions, the returned value for negative currents (battery charging, current flowing into the LTO battery) is represented in two's complement format. The returned power values will always be positive, even when the current is negative.

This table summarizes the calculation of the returned values for current, voltage, and power. When working with the returned data, it is important to multiply the raw register value by the appropriate LSB size to obtain the correct measurement in either volts, milliamps, or milliwatts.

Table 7: Register Set Summary

Address	Register Name	Function	Power-on reset		Type[1]
			Binary	Hex	
0x00	Configuration Register[2]	All-register reset, shunt voltage and bus voltage ADC conversion times and averaging, operating mode.	01100001 00100111	0x6127	$R/\overline{W}$
0x01	Current Register	Contains the value of the current flowing through the shunt resistor.	00000000 00000000	0x0000	R
0x02	Voltage Register	Voltage of the battery cell.	00000000 00000000	0x0000	R
0x03	Power Register	Contains the value of the calculated power being delivered from the battery.	00000000 00000000	0x0000	R
0xFE	Manufacturer ID Register[3]	Contains unique manufacturer identification number.	01010100 01001001	0x5449	R
0xFF	Die ID Register[3]	Contains unique die identification number.	00100010 01110000	0x2270	R

[1] Type: **R** = Read-only, $\mathbf{R}/\overline{\mathbf{W}}$ = Read/Write.
[2] This register is present only for the compatibility with INA260 and is ignored by the current firmware.
[3] These registers and their values are the same as those of the INA260 to mimic the interface.

Self-Consumption

The Figure 3 shows the approximate power consumption of the BMS circuit at different battery voltages. These measurements are indicative and will likely change as the firmware is further optimized. There are still many areas in the code that can be optimized.

Based on a typical cell voltage (see Figure 4), we know that the LTO battery maintains a voltage of around 2.45 V during low discharge currents, and this voltage is sustained for most of the discharge cycle. The voltage starts to drop significantly only when the battery is nearly fully discharged. Therefore, we can estimate the average power consumption of the BMS circuit to be 67.45 µAh. If a single 1300 mAh cell is connected to the BMS without load, it will discharge in approximately 19,000 hours, or roughly 2 years.

Table 8: Calculating Current, Voltage, and Power

Register Name	Address	LSB	Example		Note
			Integer Value	Result	
Current Register	0x01	1.25 mA	0x02F8	0.95 A	
Voltage Register	0x02	1.25 mV	0x0898	2.75 V	
Power Register	0x03	1.25 mW	0x082A	2.6125 W	

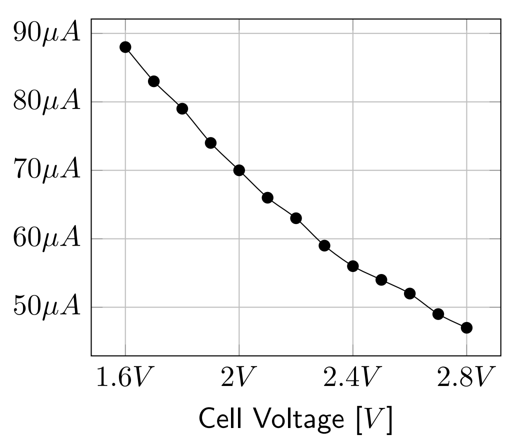


Figure 3: Average self-consumption vs. battery voltage

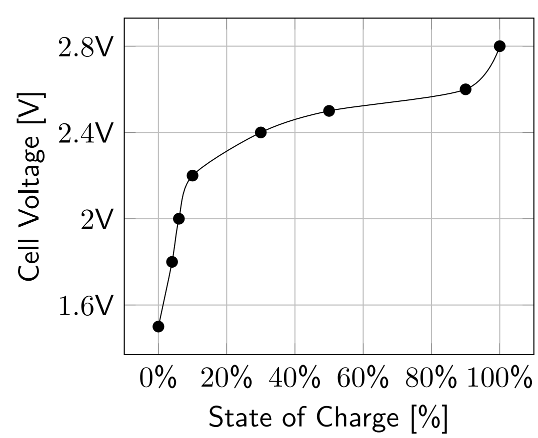


Figure 4: Typical LTO cell voltage vs. state of charge for a small discharge currents ($< 1C$).

Schematics

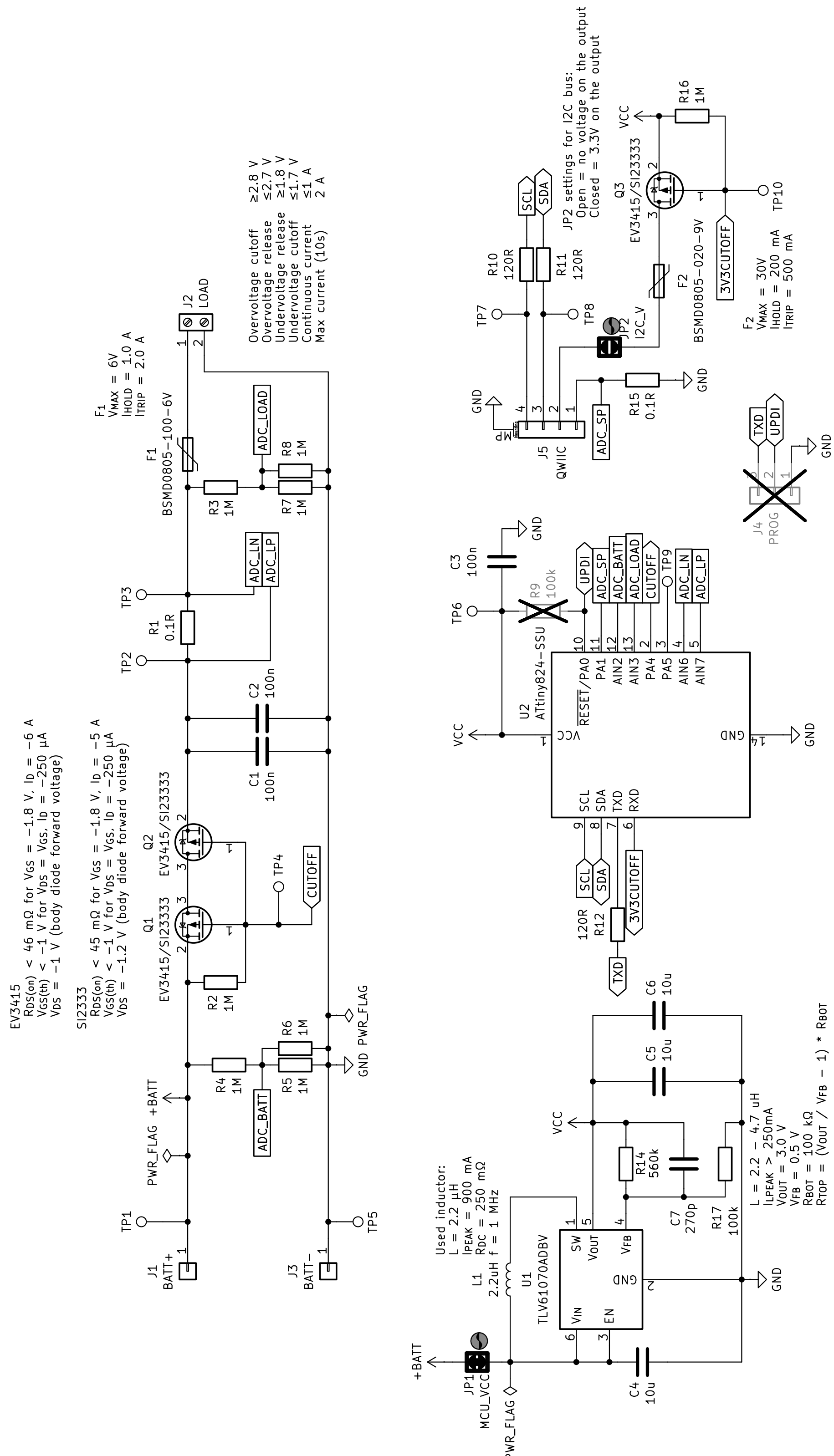


Figure 5: Schematics of the battery management system (BMS) used in the 1S3P LTO battery pack with BMS.

Mechanical Dimensions

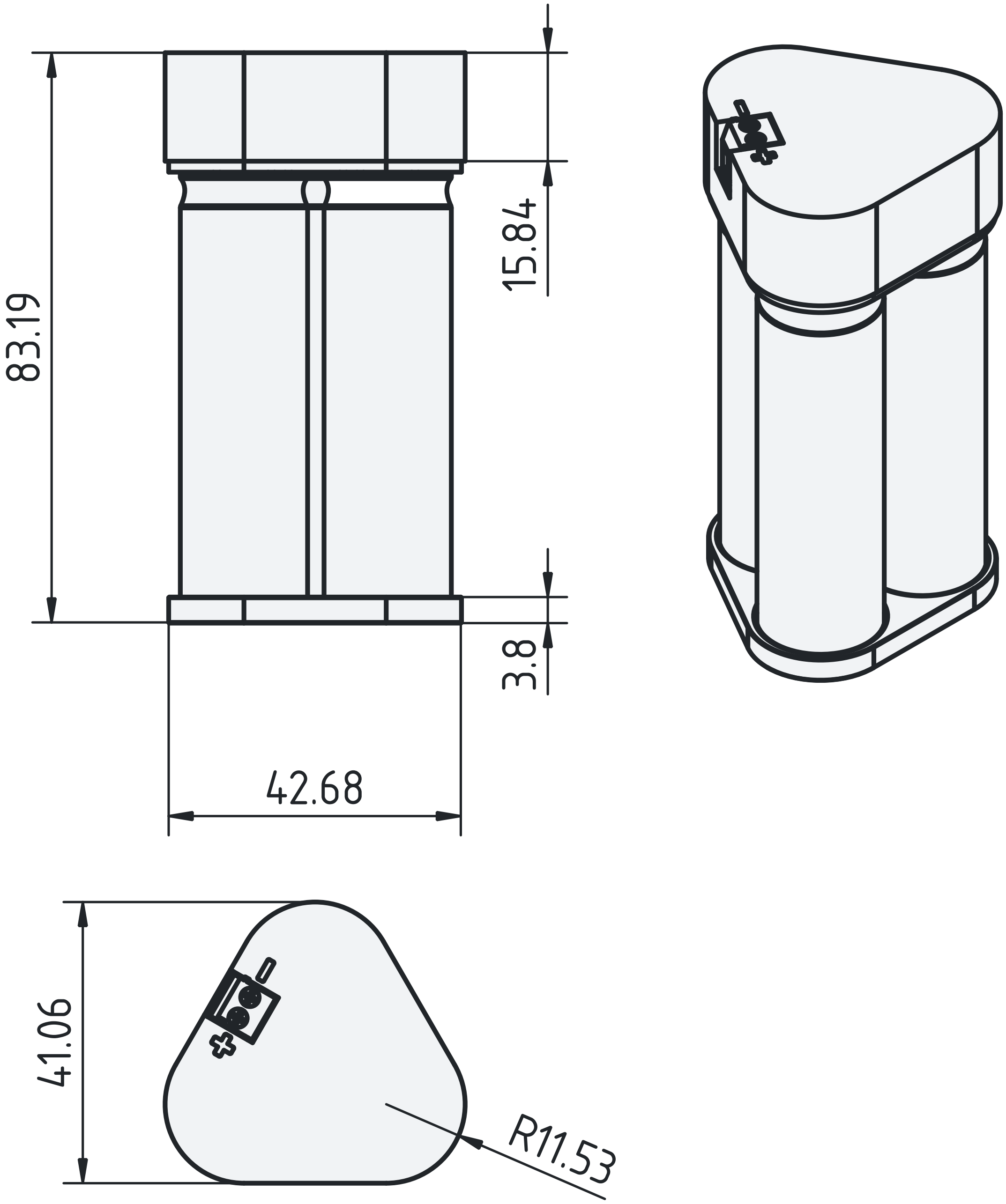


Figure 6: Mechanical dimenstions of the 1S3P LTO battery pack (using 3 × 18650 cells) with the BMS and 3D printed enclosures. Dimensions in mm.