Optimizing Battery Management in High Voltage Energy Storage Systems

WHITE PAPER

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INTRODUCTION

The rechargeable battery industry has experienced significant growth and is expected to continue to grow into the future. Most of this growth is expected to be propelled by next-generation high voltage energy systems for electric vehicles, and marine and home storage applications that use series-connected battery packs. The most popular batteries for these applications are lithium-ion or nickel metal hydride batteries that require battery management systems (BMS) to monitor and maintain the cells in good condition so as to maximize output power. Analyst firm *Markets and Markets* confirms the huge expected growth, estimating that the battery management system market will grow from 1.98 billion USD in 2015 to 7.25 billion USD by 2022, at a CAGR of 20.5 % between 2016 and 2022.

Another important function of a BMS is to help enhance the life expectancy of battery cells and protect them from damage. To achieve maximum efficiency and long battery cell life, the BMS needs to determine the state of charge (SOC) to govern the capacity remaining in the battery, and also to control the rate of charging or discharging.

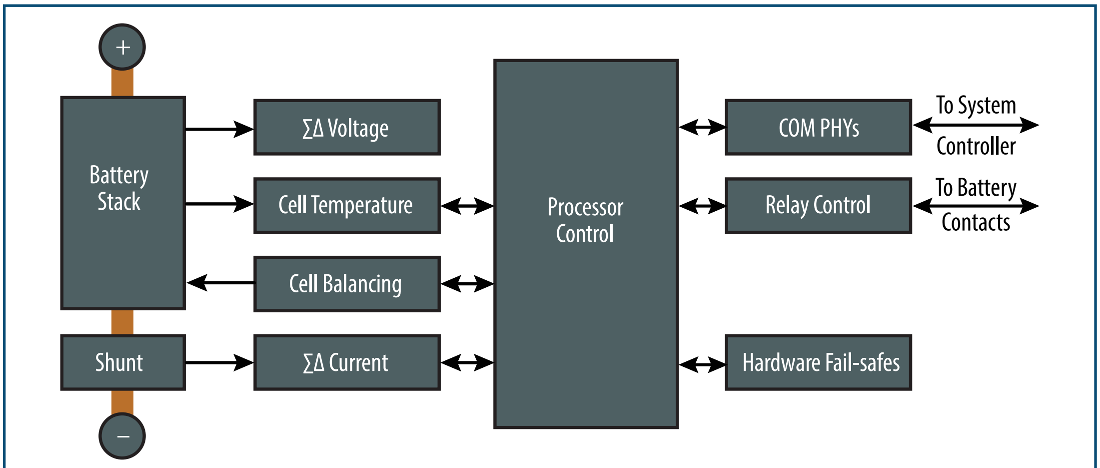

Figure 1. Block Diagram of a BMS

This paper reviews the trends in the BMS market and challenges that designers of BMS face. It focuses on the isolation of communications and transient protection challenges, and introduces isolated sigma delta converters with dynamic ranges less than 200 mV. The attractiveness of shunt-based current measurement for BMS is also reviewed.

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OVERVIEW OF BATTERY MONITORING CIRCUITS

Figure 1 shows a functional block diagram of a BMS for industrial and automotive applications. The left side of the diagram shows the battery cells, current sensing and data acquisition functions. This area of the BMS design is where one integrated Circuit (IC) or separate discrete ICs perform the SOC measurement, temperature and current measurement.

The trend in automotive electric vehicles and marine applications is for the number of cells in stacks to increase beyond 100S (100 cells) and working voltages to approach 1000 V. Such BMS systems will have several cell voltage monitoring modules networked together using two-wire interfaces like CANbus, Ethernet or SPI. The communications line has galvanic isolation using an Ethernet LAN transformer. The isolation barrier prevents the hazardous voltage from jumping onto low voltage lines, although the level of isolation (basic, supplementary, double, and reinforced) is not specified by any standard and is left to each manufacturer's safety engineer to evaluate the environment and determine the required safety level.

Each cell has its voltage checked by the monitoring system with typical tolerances of 0.1 % (to the order of millivolts) to determine the state of charge of each cell. This allows those cells that are overcharged to be bled off (passive balancing), which would prevent other cells with lower capacities from being charged. Active balancing redistributes the charge between over and undercharged cells.

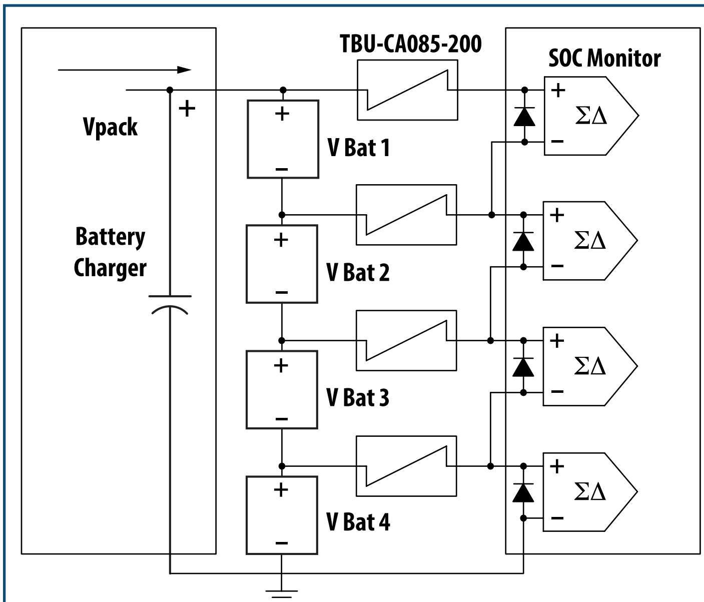

Figure 2. | Block Diagram of BMS IC with Protection on A/D Inputs

Integrated protection from short transients that many times can occur during the handling and wiring of the cells can be provided by Zener or TVS diodes. However, the junctions in these diodes are not typically designed to handle the amount of energy in a transient created by the sudden disconnection of the battery stack busbar. In the event the high current busbar connecting cells together is disconnected, the BMS IC, which is usually connected to the very last cell on the high end of the break, will suddenly go from reading the voltage on a single cell (1S) to reading the entire stack (which could be 100 S or more). This energy may puncture through the protection diodes before control loops can react in time, disconnecting the entire pack. What is needed in this scenario is a high-speed overcurrent protector, such as the Bourns® Model TBU-CA, placed in series with every A/D line. This solution is illustrated in Figure 2 showing how it can protect the IC from catastrophic damage.

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RELIABLE CURRENT MEASUREMENT USING SHUNT RESISTORS

Shunt-based current measurements are well known in the battery industry for monitoring the battery charge and discharge current. One of the drawbacks of shunt-based measurement is power wasted due to ohmic heating by the current being measured. As a rule of thumb, the maximum current with which shunt-based measurement systems work is 50 amperes, although this is now changing with the advent of lower resistance shunts and high dynamic range, high resolution sigma delta modulator technology. Traditionally, Hall Effect sensors measure currents greater than 50 amperes due to the lower power losses incurred. Yet, Hall Effect sensors typically exhibit a wide variation in zero flux output voltage and sensitivity to overtemperature. Temperature compensation circuit solutions are available but can be expensive. By lowering the resistance of the shunt, the power dissipated can also be reduced which allows for higher currents. Shunts have a superior temperature drift characteristic to Hall Effect allowing for higher accuracy with digital sigma delta modulation. Therefore, new developments in signal processing will make the shunt resistor very attractive for future applications that previously used Hall Effect technology.

Designing the circuit to attach a shunt resistor to a sigma delta modulator is straightforward. A simple filter is needed to remove the effects of harmonics from high frequency switching. The equivalent circuit of a shunt resistor consists of a resistor and an inductor in series. At high frequencies, such as harmonics from switching converters or inverters, the inductance changes the response and the voltage across the element will change accordingly. To ensure that the voltage read across the shunt is due to the current itself and not due to inductance, an RC network is added in parallel. The values R_3 and C_1 as shown in Figure 3 are selected according to the following equation:

$$\frac{X_L}{R_3} = \frac{R_1}{C_1}$$

Where X_L and R_1 are the reactance and the DC resistance of the shunt, respectively.

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RELIABLE CURRENT MEASUREMENT USING SHUNT RESISTORS *(Continued)*

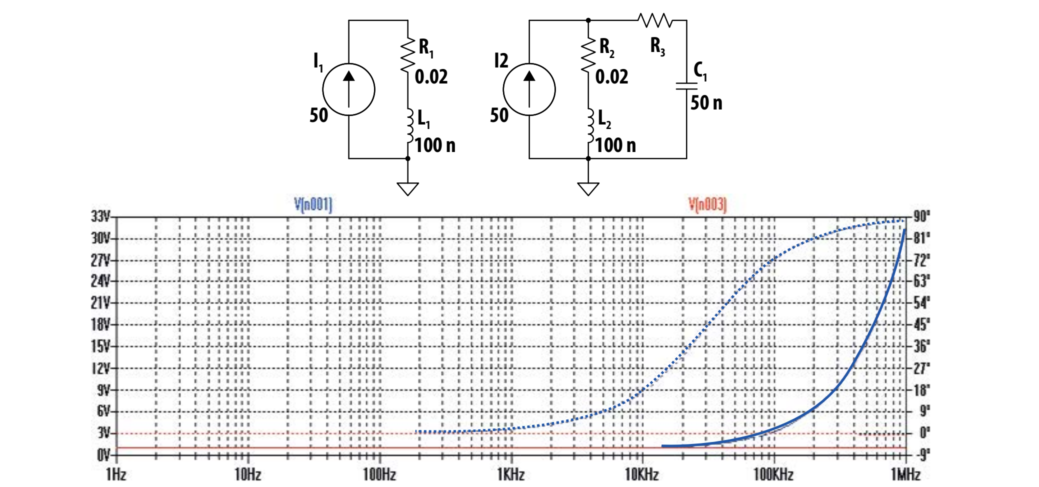
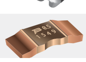
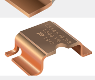
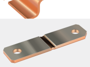
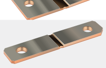


Figure 3. | *Variation of Voltage Across Shunt Resistor Across Several Frequencies*

Figure 3 shows the response of a shunt with (red) and without (blue) a compensation network over a frequency sweep of 1 MHz. The compensation keeps the voltage stable over different frequencies while the voltage grows significantly as the frequency increases beyond 20 kHz.

Table 1. | *Range of Standard High Current Shunt Resistors from Bourns*

Model	Image	Maximum Current (Lowest Resistance)	Voltage at Maximum Current
CST0612		44.7 A	22.3 mV
CSS2H-2512		140 A	42.4 mV
CSS2H-3920		245 A	49 mV
CSS2H-5930		126.5 A	63 mV
CSS4J-4026R		100 A	50 mV
CSM2F-6918		848.5 A	42.4 mW
CSM2F-7036		1000 A	50 mV
CSM2F-8515		848.5 A	42.4 mW

As described on the previous page, the advent of high dynamic range A/D converters in BMS ICs using high-speed sigma delta modulation enables accurate current measurement above 50 amperes with shunt-based technology. Bourns has the capability in a TS16949 facility to manufacture shunts with very low resistance by working with thick high purity copper (up to 3 mm thick). The maximum current-carrying capability increases with the thickness of the copper. Bourns also offers custom designs allowing for direct connection between the shunt and high current busbars.

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HIGH-SPEED PROTECTION OF CELL VOLTAGE LINES FROM HIGH ENERGY

Battery cell monitoring lines in a stack in high voltage systems are vulnerable to hazardous transients and require ultra-fast overcurrent protection to prevent damage to the internal ESD diodes in the event of a hazardous transient. For example, the Bourns® Model TBU-CA085-200 high voltage (850 V) MOSFET device behaves like a resistor until the current reaches its threshold (200 mA) at which point the device will trip. To reset, the voltage across the device must fall below its reset voltage (typically, 15 V). The DC load line characteristics for this device are shown in Figure 4.

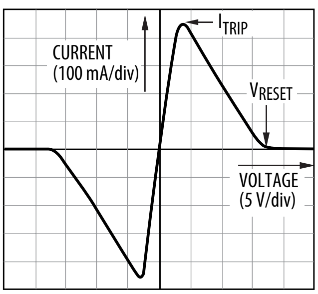

Figure 4. | *DC Load Line of High-Speed Protector*

Figure 5. | *Output from the TBU® High-Speed Protector Evaluation Board for BMS Cell Line Protection*

The Bourns® Model TBU-CA product family offers different combinations of voltage ratings and trigger currents. The device reacts to transients in less than 1 µs. Figure 5 shows the TBU-CA device triggering during a transient event on a demonstration board. The yellow line represents a transient voltage which appears across the device and the blue line shows the current in the device as it trips. The photograph shows the reaction time to be less than 1 µs and total time of 20 µs to extinguish the current. The Bourns® Model TBU-CA085 series has the following advantages:

- **High voltage rating:** In the case of a disconnection of a battery stack busbar, the full output voltage of the charger's bulk capacitor will appear on the A/D input of every cell. The Model TBU-CA085 is able to withstand high voltages up to 850 V.
- **Trip time:** Figure 3 shows a reaction time of less than 1 µs. Relay-based protection is slower (on the order of milliseconds), which can make the difference between experiencing catastrophic damage or protection of the A/D input.
- **Infinite resettability:** Once the high voltage transient is removed, the protector returns to its normal state enabling the IC to monitor the battery cell safely again. This is useful if the battery cell tap lines have been miswired.

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PROTECTION USING GALVANIC ISOLATION

Isolation barriers serve to protect equipment and humans from harmful voltage surges. They also enable communication between a transmitter and a receiver, referenced to very different ground potentials. In the case of battery management ICs connected together in a point-to-point configuration as illustrated in figure 6, two-wire communications designed to operate over an isolation barrier are used. Signal transformers such as Ethernet LAN magnetics are ideal for providing the isolation needed and provide the value-added feature of a common mode choke inside for reducing common mode noise.

For battery stack applications with voltage levels higher than 400 V, it is common to specify reinforced (or double) insulation with hi-pot testing of 4 kV or higher. Reinforced or double insulation both require the use of three layers of insulation. Reinforced insulation consists of triple insulated wire on either the primary or the secondary. Double insulation requires one side of the transformer to have double insulated wire (supplementary) while the other side requires wire with one layer (single insulation). Often times, designers must make compromises to achieve the desired level of safety while maintaining good levels of signal integrity as well as meeting target costs and form factor size goals.

LAN transformers twist the primary and secondary wires together to minimize leakage inductance. However, as the thickness of the insulation used increases, it becomes harder to twist the two together and winding machines experience additional challenges to thread the windings through the toroid. It is often more practical to use double insulation rather than reinforced insulation due to the narrower wires involved. The leakage inductance between the primary and the secondary is proportional to the surface area of the insulation between the coils. Therefore, the thicker the insulation of the wire, the higher the leakage inductance. LAN transformers are also bulkier – not just due to wider cores but also due to their creepage and clearance distances. For example, a LAN transformer with a working voltage of 370 V in a pollution degree 2 environment must have a creepage distance of at least 7.7 mm according to IEC 60950. Consequently, isolated communications with high working voltages using Ethernet magnetics require a trade-off between safety, size, cost and signal integrity.

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PROTECTION USING GALVANIC ISOLATION *(Continued)*

Battery monitoring ICs require stable DC bias voltages. This is typically accomplished using an isolated topology such as "push-pull" or "flyback". By putting an isolation barrier around the power supply, the ground potential difference between the supply ground and the battery IC ground is removed and the risk of the ground potential appearing on signal lines as a common mode voltage is essentially eliminated. Power transformers rely on IEC 61558 for determining the required creepage and clearance distances for the relative working voltage and level of insulation.

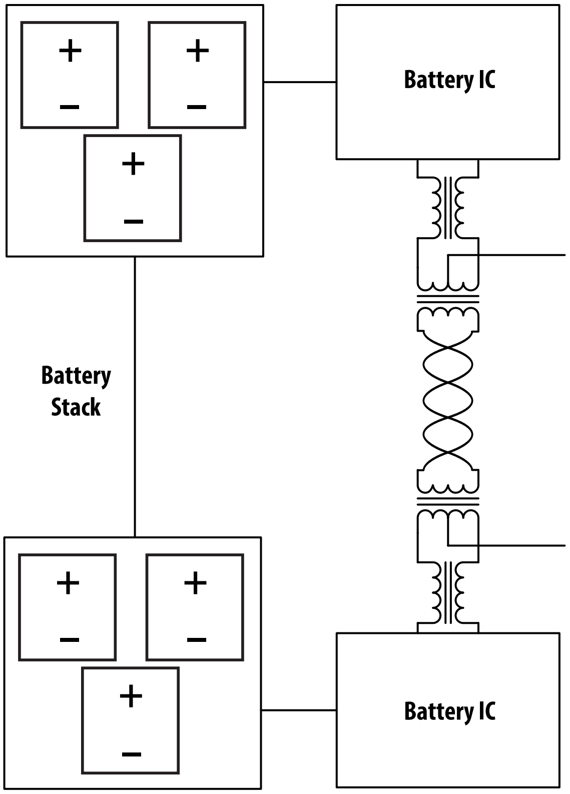

Figure 6. Point-to-Point Connection of Battery Management ICs Over Isolated Interface

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HIGHLY EFFICIENT BMS SOLUTIONS FROM BOURNS

The market for rechargeable batteries and battery management systems is set to grow by double digits over the next five years as high voltage energy system applications in automotive, industrial and marine markets are adopted. Bourns' extensive experience in shunt-based current measurement, signal and power transformers that feature double and reinforced insulation for high working voltages and high-speed battery monitoring solutions provides crucial protection for IC A/D inputs against catastrophic damage.

Bourns' off-the-shelf and custom shunt resistor products and the company's working partnership with select IC manufacturers has led to the development of BMS solutions that utilize the latest in digital sigma delta modulator technology. This enables customers to use shunt based measurement of current levels traditionally reserved for non-contacting sensors with the benefit of higher accuracy thanks to the lower temperature drift of shunts and the high resolution of the sigma delta converter. Bourns also provides custom designs of power and signal transformers for isolated DC/DC supplies and point-to-point communications. Bourns' extensive line of component solutions ensures that customers can choose the right protection for their BMS designs.

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