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Research Article

Battery Management System (BMS) Architecture and Cell Balancing Mechanisms

Shubham Kumar [1*], Dr. Y.K. Chauhan [2], Dr. K.S. Verma [3]
[1-3] Kamla Nehru Institute of Technology, Sultanpur, Uttar Pradesh, India

Corresponding Author: *Shubham Kumar

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Abstract

The contemporary electric cars rely a lot on properly developed battery management systems to ensure high-voltage packs will perform safely and efficiently throughout their service period. This paper looks at how a BMS is built and what it actually does—from the hardware that cuts off current in an emergency, to the algorithms that estimate how much charge remains in the pack at any given moment. We especially consider the difference between single-bus and dual-bus layouts in practice, and why Coulomb Counting with a shunt resistor is likely to work better with unpredictable load variations such as those found in traction work, as they frequently occur.

There is also a problem that we get into that all the pack designers must reckon with sooner or later, and that is, cells that do not age or perform the same. This mismatch (also known as the weakest-link effect) diminishes capacity usability in a manner that can be underestimated. The paper then ends with a side-by-side comparison of passive and active balancing, and holds that in spite of the cost-sensitive nature of resistive bleeding, the trend towards greater energy densities is making switched-capacitor architectures look more favourable in the next-generation designs.

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INTRODUCTION

1. What a BMS Actually Has to Do

Lay off the marketing lingo, and a battery management system is, after all, no more than a system that monitors what is occurring within a pack and acts before anything goes wrong. In an electric car, with the pack potentially containing tens of kilowatt-hours and potentially running at hundreds of volts, there is no opportunity to be wrong. The BMS is in between the cells and the rest of the vehicle and constantly measures voltages, currents and temperatures and then uses the results to maintain everything within healthy limits (1).

A BMS basically has three things to get right, as evident in Figure 1. It must be able to monitor the pack live, hence faults are detected before they can go viral. It requires stacked protection systems, which have the ability to disconnect the pack upon reaching a limit. And it must also optimise pack utilisation in order to maximise range and cycle life as opposed to compromising them (2). These are objectives that appear simple on paper, but when you have to execute them inside of a high-current system, where there are noise issues, thermal differences, and component thresholds that are not on your side, these have to be done with a painstaking hardware design and an equally painstaking software.

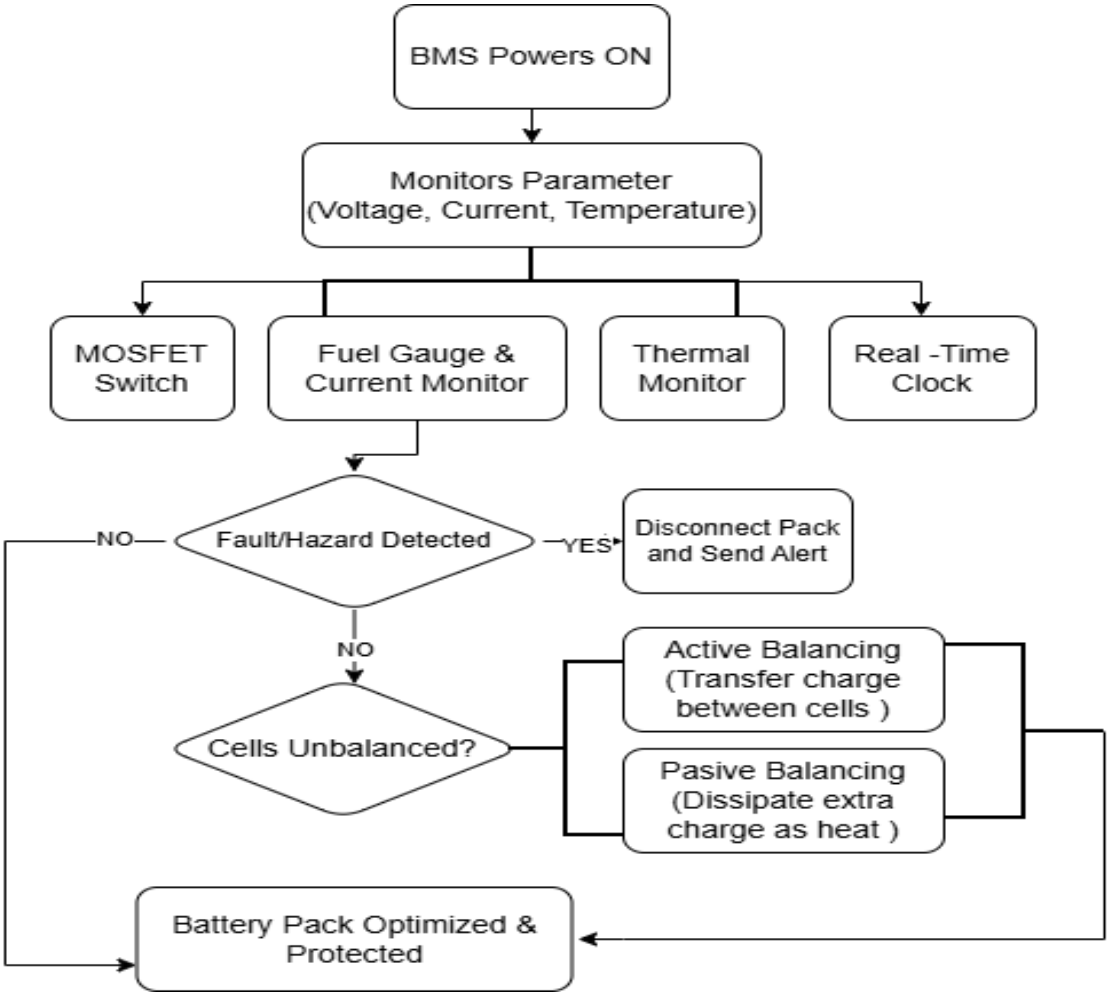

Figure 1: BMS Architecture

2. Hardware Architecture and the Main Functional Blocks

2.1 Isolation Switches: Cut-off MOSFETs and How They Are Controlled

The direct level of protection that the BMS can offer is the physical disconnection, which is the cutting of the route between a set of cells and the external world. This task is done by power MOSFETs, which can make rapid switches and can conduct high currents without a high loss, and can be directly driven using a microcontroller.

The MCU monitors cell voltage and pack current. When there is an appearance of something being wrong, such as a cell crawling toward its overvoltage cut-off point, or spike current hitting a safe cut-off point, the MCU pulls the corresponding

FET gate to ground, and the circuit will open within a few microseconds. It typically has two FETs, one of them being a Charge FET (CFET), which is used to control the charging path, and a Discharge FET (DFET), which is used to control the load path. When their operation is reversed, the BMS can use only one switch pair to block current in one direction or the other.

The arrangement of those avenues varies with the product. The charger and the load are connected in a single-bus design, reducing the number of components and simplifying the bus structure. The charger and load have separate connections in a dual-bus design, and this provides flexibility but increases the cost and complexity of the PCB. The single-bus approach is practical in most EV applications. The MCU differentiates the two modes, sensing the presence of voltage on the input pin: voltage present indicates a charger is connected and that the CFET must be enabled; no input voltage, in combination with a load request, indicates that the DFET must be enabled.

2.2 Knowing How Full the Pack Is: Coulomb Counting and Fuel Gauging

One of the more difficult tasks in BMS design is State of Charge estimation, and the approach you take does have real implications on both precision and system integrity. The best method to use in EV applications is Coulomb Counting: current is measured continuously and accumulated with time, maintaining a running count of charge in and charge out(3).

The hardware of this is simple. There is a shunt resistor with a low resistance in the circuit with the primary battery rail. Current linearly responds to the voltage drop across it, but the voltage drop across the device is minuscule, in the millivolt range, and therefore is sent across a differential current sense amplifier to the ADC of the MCU. The MCU uses the sign of the current to determine whether the pack is giving or taking charge: a negative indicates it is giving, and a positive indicates it is taking.

Specific fuel gauge ICs are available that are capable of estimating SOH as well as SOC using onboard algorithms. They did not, however, suit traction conditions, in which current may be started at almost zero and switched up to hundreds of amperes in an individual acceleration stroke. A more sampled shunt-based technique deals with transients much faster and with them without saturation. It is also a hardware route to overcurrent protection, thus the MCU can switch the DFET the moment the current rises beyond a safe limit - a slow-responding IC would never be able to do this consistently.

2.3 Temperature Monitoring and the Safe Operating Area

Lithium chemistry and heat do not get along. charged up a lithium cell when too cold and you may plate metallic lithium on the anode--an irreversible process that eventually may lead to internal shorts. Dump it (or discharge) when it is hot, and the electrolyte is beginning to decompose, causing ageing to accelerate and leading to thermal runaway in the worst case. These two outcomes are unacceptable, and hence the BMS considers thermal management as a hard requirement instead of a nice-to-have.

This is normally done by placing NTC or PTC thermistors all over the pack, around cells, down busbars, and locations where hot spots might happen. They are temperature-sensitive resistors; the MCU measures their resistance and transfers this to a temperature value. It then contrasts these temperatures with the Safe Operating Area of the cells: a plot of which voltage, current, and temperature combinations are safe according to the manufacturer. When the pack is not within that range, the BMS acts- it disables the charging or limits the current or opens the protection FETs as needed.

2.4 Keeping Time: The Real-Time Clock and Long-Term Data Logging

A BMS that cannot recollect what occurred between the sessions are of little importance in health monitoring. The number of cycles a pack has experienced, the amount of time it spent in a high state of charge, and the temperatures it experienced throughout its life are all inputs to SOH estimation. To facilitate this, the majority of the BMS designs have an integrated Real-Time Clock (RTC).

The RTC ensures that it continues to run even when the car is parked, and the main system is in a sleep state. It consumes very little power, of the order of microamps, and thus it does not significantly contribute to parasitic drain. What it includes is the correct time-stamping of all the events logged, which is useful when you need to retrace the history of a pack many months or years later, either to do warranty tracking or second-life evaluation.

3. Cell Voltage Monitoring and Why Balancing Exists

3.1 The Voltage Window Lithium Cells Have to Stay In

Li cells are not amenable to voltage (4). All it takes is to allow a cell to drop to say, less than 2.5 V, and then you begin to damage the anode. Voltages over 4.2 V cause the degradation of the cathode, and the danger of the evolution of gases grows dramatically. The BMS must ensure that each of the individual cells in this window is maintained all the time, and this is not as easy as it sounds when the cells are in series.

The pack voltages needed by EV traction systems require series connections to achieve. But series connections imply that the same current passes through all the cells of a string, whether all the cells are of the same capacity or resistance. That similarity in current does not carry to similarity in voltage or state of charge, and that is where it starts to go wrong.

3.2 Cell Mismatch and the Weakest Cell Problem

Even cells of the same production batch are not absolutely the same. Minor variations in capacity, internal resistance, and self-discharge rate are a cumulative phenomenon. This can be applied to a series string such that some cells are brought to the voltage limits before others, and because the BMS must protect all the cells of the system, it must do so when the first cell

reaches a limit, regardless of whether there is still headroom in the rest of the string.

On the charge side, the cell of maximum resistance or minimum capacity is discharged first. The BMS prevents charging to avoid damage; however, the other cells never received a complete charge. At the discharge end, the cell reaches 2.5 V initially. To protect the BMS, it only discharges when it gets to the hardest cells, leaving the energy that remains in the healthier cells on the table. This difference magnifies over hundreds of cycles: the effective capacity of the pack is reduced, the range is reduced, and the most vulnerable cell, weaker than the others, is worn away more rapidly than the others since each time it is exposed to more stress.

This happens to be the issue that cell balancing is solving. This is aimed at redistributing charge among cells so that they enter and leave each cycle in similar states of charge, minimising the penalty paid by the worst cell in the string(5).

4. Balancing Strategies: A Practical Comparison

4.1 Passive Balancing—Simple, Cheap, and Wasteful by Design

Passive balancing operates by providing a place to dump excess energy. The BMS measures the voltage across the battery, and when it realises that one of the cells is ahead of the rest of the cells during the charging process (that is, it will reach a voltage ceiling before its neighbours), it switches on a MOSFET that directs current through a bypass resistor in parallel with that cell(6). The resistor converts the extra energy into heat, bleeding the cell down until the other cells follow suit.

The appeal is simplicity. The circuit is simple, the parts are cheap, and the logic is simple to execute. This is one of the reasons why passive balancing is in the lead in cost-sensitive applications. The constraint is also quite simple; all the energy finds its way to heat, and it must go somewhere. The thermal limits of the controller IC typically limit the balancing current to significantly less than 100 mA, and it can therefore take many hours to bring a severely out-of-balance pack under control. That is manageable in case of packs of small capacity differences, and the charging windows are long (7). It is a practical limitation in the case of large EV packs where significant cell divergence occurs.

4.2 Active Balancing—Moving Energy Instead of Burning It

Active balancing is done differently: it does not dissipate the energy in the higher-charge cells, but transfers the energy to the lower-charge cells. The most used is the switched-capacitor topology, also known as a charge shuttle or flying capacitor system.

The idea is straightforward. Two single-pole double-throw switches (SPDT) are used to connect a capacitor to a high-voltage cell. The capacitor is charged until it reaches the voltage of that cell. The switches are then reversed, and the capacitor is connected to a cell with lower voltages. Since the capacitor is at a higher voltage than the destination cell, the current is conducted between the capacitor and the cell to transfer the charge (8). Do this quick and you will be able to transport significant quantities of energy without transforming it to heat.

The efficiency benefit is factual, and it is amplified by the pack energy density, since the pack that contains more energy per kilogram can store more energy as waste in case balancing is inefficient. The tradeoff is complexity. The switching circuitry will increase the cost and PCB space, and the control logic is more complicated. Topological limitation. It is also good to know about a topological limitation: a capacitor can only move charge between adjacent cells in a simplistic switched-capacitor design(9). Transfers of energy through the first cell of a long string to the final one necessitate the flow of energy through each of the intermediate ones, sequentially. With a 100-series pack, it may take a long time to bring equilibrium.

4.3 Side-by-Side Summary

Criterion	Passive Balancing	Active Balancing
Topology	Dissipative—energy is burned off through a resistor	Non-dissipative—energy is shuttled from cell to cell via a switched capacitor
Circuit Complexity	Low; a FET and a resistor per cell is all that is needed	High; SPDT switches, a storage capacitor, and more involved control logic
Hardware Cost	Inexpensive and well-understood	Higher, due to the additional switching components
Energy Efficiency	Poor—all balancing energy is lost as heat	Good—most of the transferred energy reaches the destination cell
Balancing Speed	Slow; limited by the IC's thermal ceiling, usually under 100 mA	Faster in principle, though adjacent-only transfer creates latency in long strings

5. CONCLUSION

An efficient battery pack is what makes the difference between a dependable EV battery pack and a potential safety risk. The hardware mentioned here, isolation MOSFETs, shunt-based current sensing, distributed thermistors, and an RTC, is a coherent system in which all of the components are mutually supportive (10). The code that lies on top of this hardware must make real-time choices with incomplete information, and therefore, the quality of the sensing route is extremely important.

The conflict between the cost and the performance is most evident in cell balancing. The default will be passive balancing in the products that have tight margins and small packs. However, with increasing energy density and increasing pack sizes, the thermal and efficiency cost of dissipation through resistive heating becomes difficult to pay(11). The industry is headed towards switched-capacitor active balancing, although that may not yet be cost-effective in all applications. Picking an appropriate topology is not the only engineering challenge, as getting that topology to work with a BMS architecture capable of fully exploiting it, which in turn means that the monitoring and protection foundations must be properly established in the first place.

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