Designing Safer, Smarter and More Connected Battery Management Systems

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The automotive industry is evolving rapidly as it goes through an electrification transformation

At a glance

With vehicle architectures trending toward more centralized processing and smarter systems, the semiconductor technology in these systems also need to evolve. This paper examines trends that are changing the structure of hybrid electric vehicle (HEV) and EV powertrains and how the technologies within battery management system (BMS) are shifting to support the requirements of safer, smarter vehicles.

1 **Evolving the powertrain to domain and zone control**

Understand the shift to domain and zone architectures and how it impacts system designs and semiconductor technology.

2 **Technologies enabling intelligence within BMS: the MCU**

Take a look at how the transition to safer, smarter BMS evolves MCU technology, communication interfaces, and battery junction box designs.

3 **Digital twin, machine learning and fleet management**

See how machine learning algorithms can be applied to drive trends such as intelligent battery digital twins.

Driven by increasing consumer expectations for safety, convenience and a personalized experience, modern vehicles are undergoing a software-centric transformation. Much like how smartphones redefined the role and meaning of a mobile phone, software-defined vehicles are redefining the hardware architecture of a car and giving drivers flexibility over the features they want in the car.

Car-manufacturers are now finding themselves with the opportunity re-engineer the hardware and software architecture of a car. You can see the impact of software-defined vehicles in various subsystems within the car, from the shift towards powertrain domain control and zone control architectures to designing smarter systems and reducing the number of MCUs, all enabled by more intelligent semiconductor technology.

How Innovation in Battery Management Systems is Increasing EV Adoption examines the architecture and important subsystems of battery management systems (BMS). More details are discussed on how the trend of moving towards software-defined vehicles impacts the BMS in HEVs and EVs.

Evolving the powertrain to domain and zone control

Historically, designers added MCUs to vehicle designs where sensors or actuators required more intelligence, creating a need for more complex control or communication. But combining the additional complexity of options within different vehicle platforms resulted in complex vehicle system descriptions, high development effort and challenging maintenance. For example, over-the-air updates required testing against all configurations, adding significant time and complexity to the process.

To help solve the challenges of complexity, weight and cost, domain and zone control architectural concepts have emerged. Take a look at what these different architectures require of the subsystems within a vehicle.

In a domain architecture, each domain accumulates certain electronic control units (ECUs) based on related function. As an example, the onboard charger, DC/DC converters, traction inverter and BMS would encompass the HEV/EV control domain and share a single, centralized MCU, as shown in Figure 1. This reduces the number of distributed MCUs, puts functions in proximity to simplify interfacing, and enables the sharing of computing resources by centralizing identical functions into a single MCU. For example, the OBC and inverter would not be operating the same time and would instead share computing capacity.

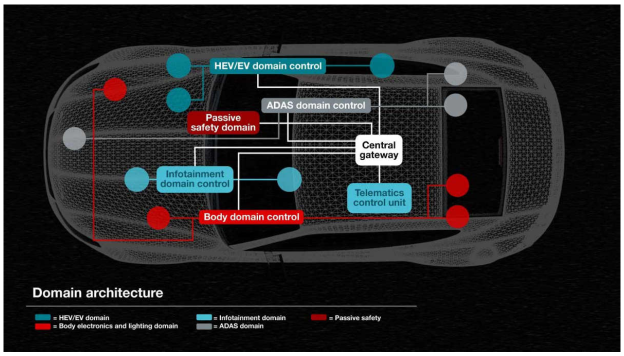

Figure 1. *The domain control architecture.*

Zone architecture takes the idea of domain control one step further, with functions grouped into zones and controlled by MCUs based on the location in the vehicle, as shown in **Figure 1**. The zones are connected through a high-bandwidth communication backbone, since distributed sensors and actuators among zones require timely communication. While reducing the number of required MCUs, zone architecture reduces wiring harness complexity and weight, resulting in further cost savings and increased driving ranges. Hardware and software update cycles are decoupled and automakers can move to a service-based software structure.

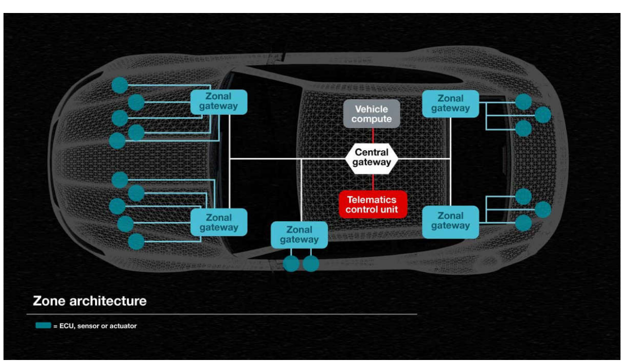

Figure 2. *The zone control architecture.*

While domain and zone architectures have different advantages and challenges, they can also coexist in the same vehicle within a crossover architecture. For example, the BMS can use a domain control approach while automated driver assistance systems (ADAS) leverages zone at the same time. The transformation of powertrain to domain or zone control architectures often happens later, after addressing application-specific challenges in the areas of functional safety and system agility. Following the original philosophy to centralize MCU functions as much as possible means that the BMS must communicate through sophisticated or standardized interfaces with no MCU intelligence at the edge. This type of implementation meets the goal to reduce the number of MCUs.

However, a technical challenge then arises: cell or pack high-voltage chipset data (voltage, current and temperature readings and related safety measures) will transfer as raw data. Since fault detection time interval, fault reaction time interval and safe states are tightly defined, the available bandwidth of the interface needs close observation and optimization and the zone- or domain-controlling MCU requires tight time-slotting to process within a given time interval. **Figure 3** compares embedded system architectures within the BMS.

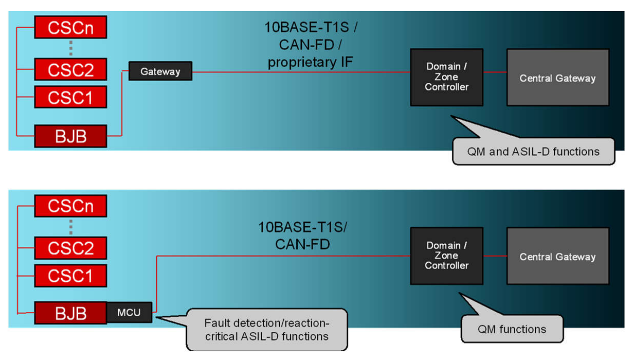

Figure 3. *Comparison of embedded system architectures in BMS.*

Equipping the high-voltage chipset with more intelligence or adding a smaller safety MCU at the edge of the BMS, such as in a smart battery junction box, simplifies this challenge.. By locally addressing functional safety measures, no data except tasks will transmit within the BMS – the local safety MCU at the edge transmits and locally obtained OK/nOK data to the centralized MCU instead of the underlying raw data to reduce timing and bandwidth challenges significantly.

While this approach contradicts the original intention to reduce the number of MCUs, it brings further benefits. The local MCU can enable standardized interfaces such as Controller Area Network-Flexible Data Rate (CAN-FD) or Ethernet 10BASE-T1S, and further introduce a uniform abstraction layer that helps enable pack multi-sourcing as well as cross-vehicle, cross-platform and cross-generation compatibility.

Let's discuss some of the technologies within the BMS that can support these architectures and enable a more intelligent system.

Technologies enabling intelligence within BMS: the MCU

At its most foundational level, the MCU has two primary roles within the BMS: connect to sensors to receive data and communicate that information back to the vehicle network. These two functions help bring functional safety and important diagnostic information, such as state-of-charge, to the BMS. Trends in MCU advancements today scale higher in both of those two main functions as more advanced sensing and computation and more advanced networking are required. Advanced MCUs, make it possible to send higher quality data from the batteries to the rest of the vehicle, helping provide a more accurate picture of what is happening within the car.

Look at advanced scenarios for MCU operation within the BMS. Computing power is increasing because of the need for complex algorithms to handle the intelligence required to maximize the usefulness of the battery. As the size of the battery increases, the number of individual cells that need measuring also increases. There are higher voltage levels and higher overall power stored within the battery. This all means that there are more signals coming in than ever before, requiring both an increase in MCU package size as well as the number of input/outputs as vehicle architectures transition from domain to zone control.

One approach to meet the requirements of these advanced algorithms and sensing needs is to increase the core computing performance. Traditional MCUs may have been able to operate in a BMS taking simple current and voltage measurements and temperature measurements with 100 MHz on a single core. Now there are multi-core devices running up to 1GHz that can compute and then act within the system. Designers could leverage digital signal processors and field-programmable gate arrays to build compute engines that are able to run at much higher speeds. TI's Arm® Cortex®-based 32-bit MCUs portfolios include high-performance and power-efficient devices to help meet system needs.

The communication from the battery ECU to the rest of the car is also becoming more complex. Systems may need to perform diagnostics or implement dynamic changes such as predictive functions or toggling between task type depending on battery load. For example, if the car is running at a high speed, the battery will have a full load; thus it would be inefficient to perform tasks such as diagnostics or updating the cells. While the car is charging, however, there is more time and system bandwidth to perform these tasks and communicate back to the vehicle network, either wirelessly or wired over protocols like Ethernet, which provides much higher data rates than what a CAN or CAN-FD BUS could in the past. Depending on the level of modularization within the battery, there could even be communications required within the BMS itself.

The most important criteria for MCUs within the BMS is functional safety capability. Security is also becoming increasingly important, as networking levels continue to increase. MCUs need to support Automotive Safety Integrity Level (ASIL) D and have a built-in hardware security module to help meet the safety and security requirements of the system. Devices such as the **AM263P4-Q1 MCU** are multi-core and have much higher operating frequencies for computing with advanced peripherals for networking and the quality of the sensing and actuation IP. The MCU also needs to support open and standardized automotive software architectures such as the Automotive Open System Architecture (AUTOSAR) to help improve safety and reduce development time.

Technologies enabling intelligence within the BMS: wireless capability

The integration of edge processing into a wireless BMS marks a pivotal advancement. Pushing computational processes to the edge enhances real-time decision-making, reduces latency, and optimizes the overall performance of automotive systems.

Minimizing the need for data to travel to centralized ECUs results in faster response times, which are crucial for applications requiring immediate feedback, such as adaptive battery management and dynamic energy distribution. A wireless BMS can leverage edge computing to perform real-time analytics on battery health, usage patterns, and environmental factors. Such data empowers the system to adapt and optimize battery performance instantaneously, helping the vehicles operate at peak efficiency under varying conditions. Processing critical data locally also reduces vulnerability to cyberthreats associated with transmitting sensitive information over extended networks.

TI’s software-defined radio solution, shown in **Figure 4**, eliminates the constraints of traditional cables, allowing for more creative and efficient integration within the intricate architecture of software-defined vehicles.

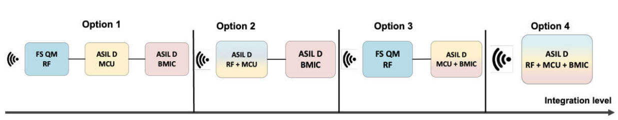

Figure 4. *Integration levels within a software-defined radio solution for a wireless BMS.*

A wireless BMS provides dynamic adaptability to changing vehicle configurations. As battery packs evolve, a wireless approach ensures seamless integration with updates or modifications, offering a future-proof solution for these systems. A wireless BMS also incorporates advanced technologies such as secure communication protocols and redundancy across multiple layers, bolstering system reliability.

Technologies enabling intelligence within the BMS: the intelligent junction box

An intelligent battery junction box helps measure high voltages in the battery directly through a voltage, current and insulation resistance pack monitor. There are multiple voltage and current measurement channels available in a typical pack monitor, which can measure voltage across fuses and contractors and check the isolation. **Figure 5** is a simplified system diagram of a battery junction box

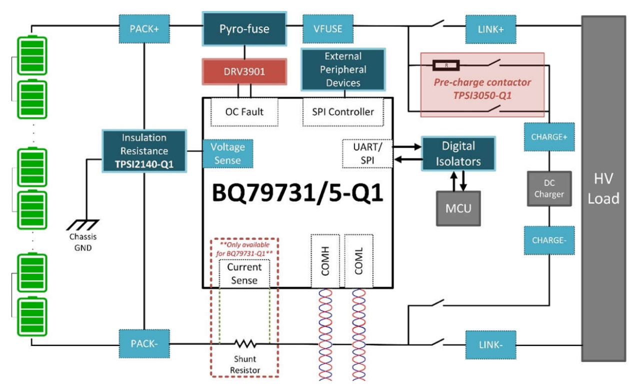

Figure 5. *Simplified BJB system block diagram.*

In the battery management systems there are two critical functions, battery disconnect and power distribution. An intelligent battery junction box incorporates digital control of contactor drivers and pyro fuse squib drivers to disconnect the battery pack to the EV system during a crash.

A high voltage battery disconnect can be handled with either a melting or pyro fuse. Higher current systems within vehicles introduce new conditions, causing the market to shift away from traditional melting fuses, which are triggered by an overcurrent thermal event, to pyro fuses, which are triggered through an MCU/HUB. Today, pyro fuses are driven by discrete, complex circuits that can be a source of inefficiency. TI's single channel squib driver for automotive EV pyro fuse deployment, DRV3901-Q1, provides a highly-integrated, safety-developed solution for fast-acting overcurrent disconnection of the battery through a pyro fuse in place of traditional melting fuses systems.

High voltage power distribution contactors need to handle higher currents as well, but options are either limited and expensive or overly complex. Economized contactors have an additional high resistance economizer coil that is used to improve the efficiency of the main contractor by reducing current draw and heating while the contactor is energized. While these economized contactors sound like they are the solution improving system efficiency, there is a limited selection available today and they are often cost-prohibitive. Non-economized contactors in contrast, do not have this additional coil, which reduces the cost, but must be driven by a more complex discrete circuit in order to meet safety and efficiency standards. Texas Instruments has invested in reducing the complexity and cost of the circuitry needed to drive non-economized contactors while also improving the efficiency and robustness by developing the DRV3946-Q1, a fully integrated duel channel contactor driver that enables designer more freedom and design flexibility.

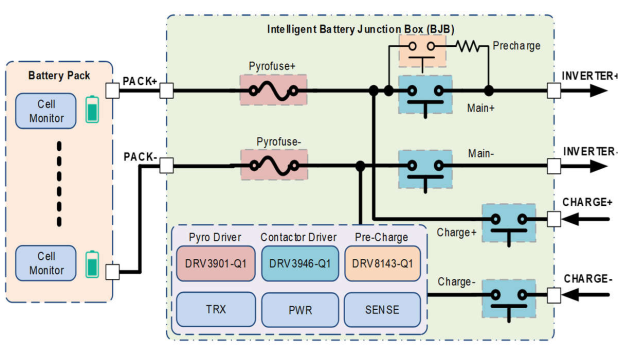

Figure 6. *Battery disconnect and power distribution for high power within BMS.*

The battery pack uses mechanical contactors controlled by the pack monitor to connect or disconnect subsystems throughout the vehicle. Mechanical high-voltage contactors can weld or be damaged through arcing and pitting in the event of uncontrolled inrush current. ***Why Pre-Charge Circuits are Necessary in High-Voltage Systems*** explains the use of the **TPSI3050-Q1** isolated switch driver to form a reliable solid-state relay for pre-charging in an automotive battery junction box. For intelligent battery junction boxes, the **TPSI3100-Q1** can be implemented in such pre-charge applications to further enhance diagnostic capabilities with its integrated isolated comparators and fault reporting outputs. These features can be combined with over-current or temperature monitoring circuits to allow such fault detection circuitry to reliably feedback this information through the TPSI3100-Q1 and report any of these events to the pack monitor.

Both the positive and negative terminals of the high-voltage battery pack must be sufficiently separated from the chassis of the vehicle in order to protect the driver or a technician from potential electrical shock. Periodic monitoring of this separation is known as isolation check or insulation resistance monitoring. Solid-state relays such as the **TPSI2140-Q1** connect and disconnect a known resistance value (such as 1 MΩ) in parallel to the unknown resistance value (between a battery terminal and chassis ground). By measuring the combined resistance using a pack monitor such as the BQ79731-Q1, you can determine whether the battery separation is within tolerance or potentially harmful.

Digital twin, machine learning and fleet management

Innovations are also happening in software implementations within the BMS. Acquired pack- and cell-measurement accuracies are the basis for more advanced state-of-X algorithms than a Kalman filter or Coulomb counting.

The ability to monitor individual driving behavior, traffic situations, and geographical and road conditions enables more precise vehicle range predictions and battery state-of-health data and state-of-charge estimations. If centralizing data in the cloud, machine learning algorithms can monitor a whole fleet of vehicles and enable predictive service. For example, if a failure pattern had been observed and stored before, the algorithms can detect early indications and calculate the likelihood of future failures of other vehicles to ask for garage service proactively. This function, known as creating a digital twin, enables further commercial models such as temporary vehicle range upgrades in a software-defined vehicle.

TI works with Electra, which makes artificial intelligence-powered battery-pack solutions, to make the BMS smarter and more connected by bringing EV batteries online. Electra's EVE-Ai 360 fleet analytics software is a battery analytics tool that harnesses vehicle-specific and fleetwide battery-pack data to generate battery state-of-health trends and predictive models. It uses data from the battery, the vehicle and the environment, along with machine learning, to identify potential battery issues and failures before they occur, optimizing fleet efficiency and performance.

TI's AM263P4-Q1 Arm-based, AutoSAR-enabled MCU includes a library to use an adaptive cell modeling system and enables machine-learning services to improve fleet and vehicle state-of-X measurements, helping enable smarter charging and optimizing battery health as well as range.

Conclusion

The BMS is at the heart of many disruptive and innovative concepts. Device solutions from TI cover the full BMS portfolio to unfold system-level benefits and make vehicles smarter, safer and more connected.

Additional resources

1. Learn more about intelligent battery management for electric vehicles. (**https://www.ti.com/applications/automotive/hev-ev-powertrain/overview.html#BMS**)
2. View reference designs for hybrid, electric and powertrain systems. (**https://www.ti.com/reference-designs/index.html#search?applid=209,84,235167**)

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