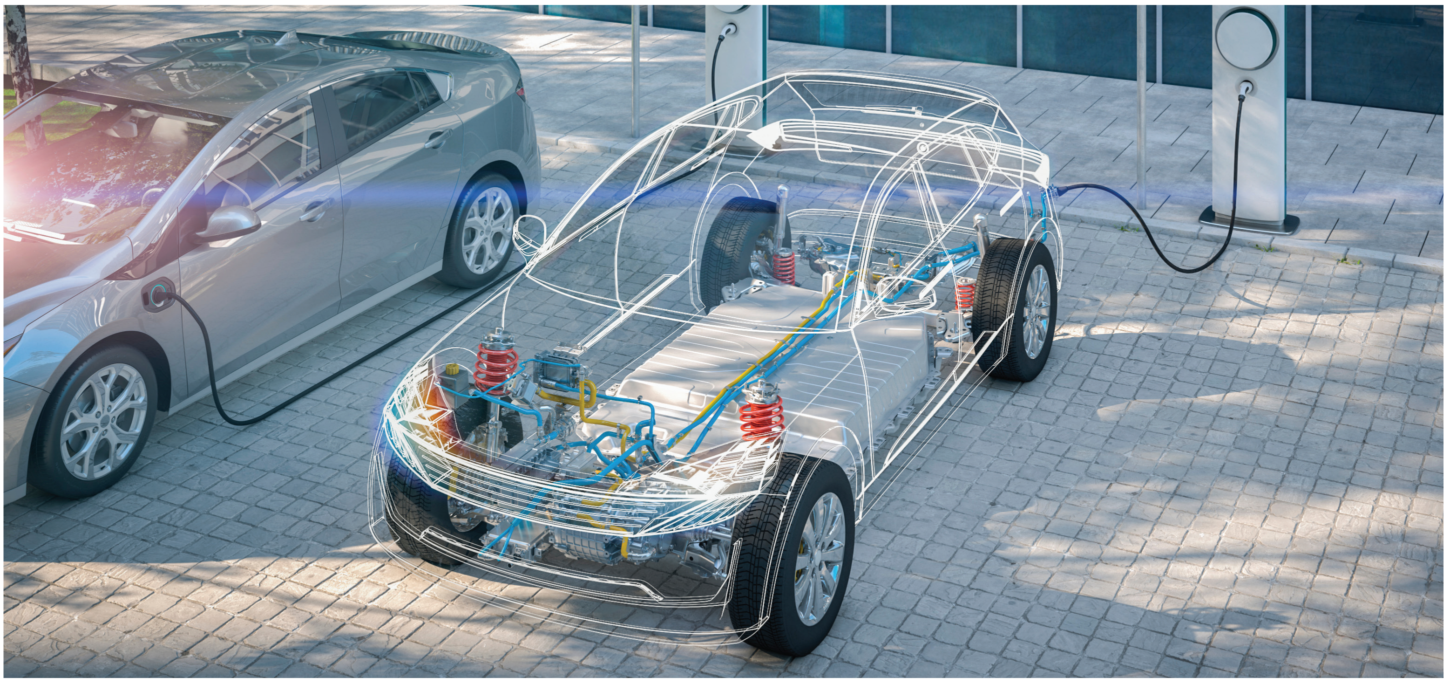
The Intersection of Electric Isolation and Thermal Transfer in EV Battery Systems: OBC, Dc-Dc and Inverter



Where Safety Isolation Meets Thermal Mitigation Challenges

The electric/autonomous vehicle (EV/AV) is the quintessential case study on so many electrical systems with those subsystem requirements overlapping and impacting each other on a growing basis. This whitepaper shall focus on the safety isolation and thermal solution challenges and support needs. The EV use case represents where the utmost in safety meets the utmost in reliability with some of the most challenging cost targets. Whether directly involved in EV/auto development or not, the market vertical is driving the entire electronics industry along with its adjacent supply chains so it is important to be up-to-date in this space, nearly irrespective of your industry, application focus, or stakeholder perspective.

Advanced packaging, wide-bandgap (WBG) semiconductors, and new thermal interface materials (TIM) are enabling denser, yet safer designs. No matter how efficient things get and how much power converters may shrink, feature set (and therefore overall system power budgets) only tend to increase. This also means the power density demands of increasing levels of integration are driving this continuous trend of packing more and more loads into tighter and tighter spaces. The only way to support a technology roadmap of continuous improvement is to have it track closely with roadmaps of technologies that support a pace of technological, heterogeneous integration demanded by the application space.

This ever-increasing need for load demand and packaging density in EVs translates directly to the power subsystem. This starts with the main battery bank, which itself dictates a host of challenges associated with the ac-dc (i.e. – charging station or on-board charger a.k.a. – OBC), dc-dc (i.e. – isolation, major distribution bus, load power rails), and dc-ac (i.e. – motor drives, inverters) power topologies. As the “fuel” for an EV, the main battery bank not only is the key source of power, but also a major consumer (mostly due to its weight and with associated conversion/commutation losses to a much lesser degree). Any kind of fuel for a vehicle tends to also contain the densest form of energy storage, which means there are major safety implications. For battery banks, a high level of safety is critically tied to the thermal mitigation strategy of the packaging/assembly. Whether from the ac-input of a charger or the high voltage of the battery bank, there are also numerous requirements for electrical isolation to protect operators along with expensive hardware.

For the main battery bank to support increasing load demand (in a relatively similar volume from one generation to the next), the batteries must either increase their energy density or run at higher bus voltages (and potentially be aged faster by larger-transient electrical loads). This is a classic tradeoff of size, weight, and power (a.k.a. – SWaP) factors, also known as SWaP-C factors when combined with a cost metric. Simply going to larger and/or heavier batteries will immediately have an overhead cost of not just space, but require extra power to cool and cannibalize some of the EV's range due to the consumption of "fuel" just to support the added weight. If moving to a higher bus voltage, for example, then there can be the advantages of reduced distribution losses and mitigation of wiring mass, but potentially at the cost of a more complex thermal mitigation scheme and/or higher isolation requirements to meet safety certification.

Lastly, one should also consider the implications of the mechanical subassemblies and the manufacturing processes required to enable them into fruition. Squeezing all this stuff into an increasingly denser space means the integrated materials for electrical (i.e. – galvanic) isolation and thermal conductivity must be sandwiched into very tight spaces with complex tolerance stackups. This is where the thickness of these integrated materials, along with tight management of the compression force requirements to assemble the entire stackup, can really differentiate in terms of pragmatic ability to build something, let alone ensure its high performance.

▪ Keeping Batteries Happy

The technical aspects and economics of successful EV/AV deployments all orbit around the system's energy storage solution(s). This will be the rechargeable (a.k.a. – "secondary") battery bank for the grand majority of electrified drive trains. A deep focus on the most effective utilization of the battery bank yields many benefits in terms of performance, range (e.g. – "fuel" range, regardless of what that fuel happens to be), reliability, maintenance/replacement costs, and even the sustainable reuse/recycle of the batteries at end-of-life (EOL).

It is quite remarkable just how nuanced and complicated the design, manufacture, transport, and utilization of what are seemingly very simple, two-terminal, dc "dumb" devices can be [1]. In order to properly understand successful decision-making in terms of selecting and SAFELY implementing an energy storage solution, namely batteries in the context of this discussion, then one must first internalize a handful of terms and most importantly, what the physical/chemical characteristics are of the specific battery chemistry chosen. At that point, it is also helpful to understand the hierarchy of what ultimately makes up the system's battery management system (BMS) and supporting circuitry (i.e. – charge controllers, protection circuits, etc.). Finally, the investigation into how all these components are combined into an EV's energy subsystem yields the ultimate visibility on requirements for design/assembly, particularly for the critical support needs in terms of electrical isolation and thermal management.

The most basic, functional unit of a battery is a cell, which consists of a cathode, anode, an electrolyte, and some packaging to hold it all together and contain all but the exposed electrodes. A cell has an intrinsic open-circuit voltage (i.e. – VOC, organic voltage measurement across terminals with no impact from external loads), which is the direct result of the battery chemistry and assembly materials/processes. Cells can be combined in any number of arrangements to form battery packs, which is typically referred to as a "battery" though this is actually a misnomer given a battery pack is a collection of cells often combined with protection circuitry built right into the terminals. In fact, these protection printed circuit assembly (PCA) boards are often so small and integrated that many designers are unaware a battery pack ships with intrinsic protection circuitry. For instance, if one ever measures a battery voltage and sees it essentially drops to 0 V from the discharge threshold (~3.0 V for Li-ion chemistries), but then suddenly climbs to some non-zero value upon being connected to a charging circuit, then this is clear evidence of a battery pack with embedded undervoltage lockout (UVLO) protection to prevent deep discharge that can permanently and negatively impact battery performance.

Battery cells are arranged in series and parallel to build packs that achieve higher output voltages and support higher output currents. Higher voltages are achieved by arranging cells in series to scale VOC, which is effectively stacking a bunch of small batteries to make one big one. These higher-voltage series stacks can then be paralleled with like stacks to increase the maximum amount of output current. Battery pack capacity is classified by how much a current can be sustained for an hour so a battery pack delivering a 5 A, continuous output for an hour will be considered to have a capacity of 5 Ah. If the same pack supported that same current for two hours, then it will be considered to have a capacity of 10 Ah.

Keeping a battery "happy" means keeping its chemistry happy. Every kind of energy storage chemistry will have tons of unique characteristics and behaviors that shall dictate every aspect of its ability to charge, discharge, source a load, and support many recharge cycles…all while remaining safe and viable even under the harshest environmental conditions and/or physical trauma. Chemistries can differ, are all "picky" in their own way, but the key is to keep the chemistry happy for both safety, performance, and long-term reliability. Any one of these factors can be the entire subject of much more extensive documentation, which is mostly beyond the context of this whitepaper. While not deep diving on each one of these, some important terms and their meanings can be found as follows –

- **State of Charge (SOC)** = battery charge level relative to capacity (based on open-circuit terminal voltage), 0-100 %
- **Charge Rate (C-rate)** = battery charge or discharge rate, typically a min/max specification given by battery's datasheet and expressed as a ratio of the battery's capacity (e.g. – a 2.0 C max discharge rating for a 20 Ah-rated cell means the max discharge rate is 40 A)
- **Fast Charge Rate** = current limit (typically set by BMS) for constant-current portion of the charge cycle
- **Depth of Discharge (DOD)** = battery discharge level relative to capacity, 0-100 % (opposite of SOC)
- **Charge Cycles** = number of charge/discharge cycles supported before battery considered out of specification (minimum capacity on datasheet)
- **Equivalent Series Resistance (ESR)** = intrinsic, internal resistance (typically ac or frequency-dependent resistance) of cell as measured at terminals
- **Constant-voltage (CV) Charging Mode** = BMS controller applies a constant voltage to battery, while cell organically draws current based on charge transfer
- **Constant-current (CC) Charging Mode** = BMS controller applies a constant current to battery, while cell charges to end-of-charge target potential

There are many common standards used to dictate design, qualification, testing, and performance targets of batteries along with every other aspect of subsystem and component found in an EV. For automobiles in general, an organization called the Automotive Electronics Council (AEC) [2] dictates many standards to specify and qualify components to stringent levels and can split focus to different levels in the subassembly hierarchy ranging from passive component stress testing (AEC-Q200) to tests designed to accelerate life factors for integrated circuits (AEC-Q100). Even the United Nations (UN) has established standards for the qualification and safe transport of high-energy-density storage, such as UN 38.3 [3], which determines how to conduct hazardous testing and certifies batteries for conveyance. A more comprehensive list of battery-related standards can be found in the table below.

STANDARD	DESCRIPTION
IEC 62619	Safety requirements for secondary lithium cells and batteries, for use in industrial applications
IEC 62660	Secondary lithium-ion cells for the propulsion of electric road vehicles
ISO 12405	Electrically-propelled road vehicles
ISO 6469-1	Electrically-propelled road vehicles – safety specifications – part 1: on-board rechargeable energy storage system (RESS)
GB 38031	Electric vehicles traction battery safety requirements
GB/T 31486-2015	Electrical performance requirements and test methods for traction battery of electric vehicle
SAE J2288	Life cycle testing of electric vehicle battery modules
SAE J2464	Electric and hybrid electric vehicle Rechargeable Energy Storage System (RESS) safety and abuse testing
SAND 2005-3123	Electrical energy storage system abuse test manual for electric and hybrid electric vehicle applications
UN 38.3	Recommendations on the transport of dangerous goods – manual of tests and criteria part III 38.3
UL 2580	Standard for safety – batteries for use in electric vehicles
UN ECE R100	Uniform provisions concerning the approval of battery electric vehicles with regard to specific requirements for the construction and functional safety
GB/T 31484-2015	Cycle life requirements and test methods for traction battery of electric vehicle

Table 1 – Battery-Related Standards Applicable to EV Applications

An excellent goal to keep in mind for keeping EV battery packs safe and happy is to carefully design and manage their thermal performance. Ideally, one will want to mitigate active cooling (i.e. – forced air, water-cooled, etc.) as much as possible since such approaches can be quite costly (in terms of SWaP-C factors and reliability). That being said, one does not want to go overboard in attempting to cost-optimize the thermal management solution(s) and should always consider the risk of thermal runaway in addition to mere performance. This point is particularly salient in EV/AV applications since they most often use very energy-rich battery chemistries such as Li-ion and LiFePO4 (lithium iron phosphate or LFP) that can induce uncontrolled energy discharge (e.g. – thermal runaway and unsafe scenarios) once an internal temperature threshold is exceeded.

▪ Considerations for Electrical Isolation in EVs

Now moving on to more focused discussion on electrical or galvanic isolation in EVs, one should consider isolation requirements at multiple levels: battery packs, OBC, and various dc-dc converters throughout the system, especially those contacting passengers. Examples are any power conversion stages connected to an off-line power source (i.e. – ac wall power) or contacting voltages > 60 V (the threshold for safety extra-low voltage or SELV, dictating isolation needs [4]). Dc voltages experiencing these levels can be found at the battery pack's output or associated with the inverters used to power electrified drive trains.

Electrical isolation can be achieved by a number of different techniques. The most fundamental isolation is to provide physical distance between points of isolated contact. Given using free air alone as an insulator is typically not practical for a modern assembly, materials and substances boasting much higher figures of merit (FOM) for electrical isolation enable denser assemblies. Some applicable metrics are a breakdown voltage (a.k.a. – withstand voltage) in which a maximum voltage level can be safely blocked by the isolating solution or even a time-based metric that qualifies a material to withstand a certain voltage for a certain amount of time. This means the same material can be qualified to withstand both a longer-duration, lower-voltage potential and a shorter-duration, higher-voltage potential, which are all called out in the manufacturer's datasheet and validated with dielectric withstand test (a.k.a. – high potential or hipot test).

Performance improvement can be achieved WITH enhanced density, efficiency, and safety via the selection of isolation methodology. For instance, if there are lots of high voltages in very tight spaces without room to grow the system size, then isolation requirements can be met with the use of potting compounds in which the circuitry is physically immersed in a substance (i.e. – epoxy, oil, deionized water, etc.). Physically affixing an assembly in a cured epoxy also provides great mechanical support, which may mitigate the most common modes of electromechanical failure (i.e. – broken wires/leads, components rubbing against each other, etc) even if the assembly becomes totally inaccessible at the circuit level. If volume and weight are very constrained, then conformal coatings can be used to isolate components though this tends to be a time-consuming process and make rework a nightmare.

Hybrid solutions can yield the combined benefits of material properties along with factory automation. For instance, there are thermal potting compounds that provide electrical isolation, while also supporting thermal transfer of dissipated heat. The space/cost of mutually-exclusive solutions yields improvement by reducing design and manufacturing overhead alone, but also provides further opportunities to optimize SWaP-C factors. A single material can be optimized for properties of electrical isolation and thermal transfer, while being semi-rigid or even liquidus to ensure volumetric efficiency, even in non-standard geometries.

If isolation requirements can be met with automated processes, then the results tend to be very high quality, while driving a pattern of regular cost reduction. A manufacturing strategy that includes the integration of materials inherently brings an integration of manufacturing processes to be combined and automated, which is a win for every stakeholder imaginable. Such intelligent integration of manufacturing processes is also a critical enabler to assurance of supply by streamlining business continuity planning against major supply chain disruptions and mitigating the number of bottlenecks that can bring a manufacturing line to a screeching halt.

▪ Summary & Conclusions

Technology improvements drive product roadmaps, particularly for futureproofing product development cycles requiring a high amount of leverage/reuse to support ever-decreasing product development times. Advancements in semiconductors and packaging are helping with all of the above.

Isolation and thermal management are very important to an EV's successful deployment because they can directly impact some of the most challenging contributors to SWaP-C factors, while safely and reliably shedding weight (e.g. – increased range or "fuel life"). State-of-the-art (SOTA) solutions in this space can even combine key properties of several material classes. For instance, there are TIMs that can be great conductors of heat, but electrically-isolating. There are also TIMs that are optimized to absorb specific radio frequency (RF) spectrum, which means they can help a design run smooth and pass electromagnetic compatibility requirements concurrently.

The increasing integration of heterogeneous materials/components and multifunctional solutions all support the very important bottom line of meeting design targets for thermals, isolation, and other critical requirements, while still leaving some opportunity to optimize SWaP-C factors. The desire of being able to bring denser designs to market safely and cost effectively is a forgone conclusion. But doing so while also mitigating thickness and compression forces in subassemblies and larger mechanical stackups is highly enabling to the economies of scale that might otherwise bottleneck an automaker's ability to drive continual improvement in manufacturing process optimization, automation, and a streamlined supply chain.

The best practices outlined in this whitepaper are also very conducive to supporting process improvements to mitigate supply chain assurance of supply gaps/disruptions. Though very focused on design, development, and optimization of thermal/isolation solutions here, one should not forget the importance to recognize and characterize sustainability impacts (i.e. – embodied energy, manufacturing process optimization, EOL/recycling) [5]. This becomes that much more important as EVs are predicted to migrate to a circular economic model in future years, particularly when it is hypothesized that there are not enough raw materials on the planet to support market demand for Li-ion batteries alone!

References

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